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THERMAL STABILITY CHARACTERIZATION OF NI-BASE ATI 718PLUS® SUPERALLOY

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Abstract

Thermal stability of ATI 718Plus® Alloy was characterized after thermal exposure at 760°C for up to 500 hrs. Microstructure and mechanical properties, including tensile, stress rupture, creep, low cycle fatigue and fatigue crack growth rate, were tested before and after thermal exposure. For comparison, the same experiments were conducted on alloys 718 and Waspaloy. Changes in microstructure brought out by exposure were a slight dissolution/ coarsening of γ' phase particles and formation and growth of δ phase for 718Plus alloy. The growth rate of γ' phase particles in 718Plus alloy was significantly slower than that of γ" phase in 718 and even slower than that of γ' phase in Waspaloy. The amount and formation rate of δ phase formed in 718Plus alloy during exposure was lower than that observed or predicted for alloy 718. The most significant effect of thermal exposure on properties was the acceleration of creep rate, especially Stage I, for all three alloys. Alloy 718Plus suffered moderate thermal degradation in strength and stress rupture life, but there was little change in low cycle fatigue and non-dwell fatigue crack growth rate. In fact, thermal exposure significantly reduced the dwell fatigue crack growth rate in 718Plus alloy. The observed changes in mechanical properties are explained from the standpoint of the microstructural changes in 718Plus alloy and comparisons made to alloys 718 and Waspaloy.

Introduction

Alloy 718Plus is a new Ni-base superalloy developed at ATI Allvac [1] in cooperation with the US Air Force sponsored Metals Affordability Initiative (MAI) project entitled “Low-cost, High Temperature Structural Material.” Team members included GE Aircraft Engines, Pratt & Whitney, Honeywell, Firth Rixson Viking, Ladish Co, Carpenter Technology and ATI Allvac [2]. The driving force for this development was the long standing industry need for a low cost alloy with weldability and forgeability similar to alloy 718 but with a service temperature approaching that of more expensive alloys such as Waspaloy and René 41. The chemistry design, physical metallurgy, mechanical properties and possible applications have been discussed in a number of publications [3-6].

Like 718, 718Plus alloy appears to be an excellent candidate for a wide variety of static structural and rotating parts in aircraft turbine engines. These parts are exposed to very high temperatures for long periods of time. Therefore, thermal stability becomes a critical consideration for this new alloy. The effect of thermal exposure on the microstructure and mechanical properties of Ni-base superalloys has been studied by many researchers [7-18]. In most of the previous studies, thermal stability was evaluated by the degradation of a few mechanical properties and/or microstructure changes. To obtain a thorough understanding of the thermal stability of 718Plus alloy, an extensive research project was initiated to evaluate it in comparison to alloys 718 and Waspaloy. The mechanisms of thermal degradation in this alloy were derived from mechanical tests and metallographic examinations performed before and after thermal exposure. In this paper, the results of this work will be presented and implications for future applications of this alloy will be discussed.

Experimental Procedures and Results

Test Materials and Heat Treatments

A production vacuum induction melted / vacuum arc re-melted (VIM/VAR) ingot of 718Plus alloy was converted into 200 mm Rd forged billet and test sample blanks were cut from the mid-radius location of the billet for mechanical testing and microstructural study. For comparison, sample blanks from the same locations were also cut from 200 mm Rd forged billet of production alloy 718 and from 150 mm Rd forged billet of production Waspaloy. The as-forged grain sizes for all three alloys are in the same range of about ASTM 6-7. The chemistry of these alloys is listed in Table I.

All sample blanks were heat treated as shown in Table II. No noticeable grain growth was observed after heat treatment due to the low solution temperatures employed. Half of the heat treated sample blanks then went through thermal exposure. An accelerated thermal exposure procedure was adapted in which sample blanks were held at 760°C (much higher than the maximum anticipated working temperature of 704°C) for different times up to 500 hrs. This is equivalent to exposure at approximately 10,000 hrs at 704°C based on Larson Miller parameter calculations. The validity of this accelerated method in predicting the behavior of this alloy at lower working temperature was justified from microstructures and mechanical tests of materials exposed for long time at other temperatures such as 704°C and 732°C. Details of this work will be reported elsewhere.

Tensile Properties

Tensile tests at room temperature (RTT) and elevated temperature (ETT) (704°C) were performed per ASTM standard procedures. The test results are shown in Figures 1 to 3. As expected, tensile strength decreased after thermal exposure for all three alloys. Both alloys, 718Plus and Waspaloy, demonstrated a moderate reduction of about 10-15%, but alloy 718 showed significantly higher strength loss of up to 45%, see Figure 1. Because of its high as-heat treated strength, 718Plus alloy maintains the highest strength among the three alloys after thermal exposure. It is interesting to note that the tensile ductility at room temperature and at 704°C showed different responses to thermal exposure for 718Plus and 718 alloys.

Table I. Chemical Composition of the Tested Alloys in Weight Percent

Alloy	C	Cr	Mo	W	Fe	Co	Nb	Al	Ti	P	B	Ni
ATI 718Plus®	0.02	17.4	2.7	1.0	9.7	9.1	5.5	1.5	0.7	0.013	0.005	rd
718	0.02	18.0	2.9	0.0	18.1	0.0	5.3	0.5	1.0	0.008	0.004	rd
Waspaloy	0.03	19.5	4.3	0.0	0.2	13.8	0.0	1.4	3.0	0.004	0.006	rd

Table II. Heat Treatment of the Tested Alloys

Alloy	Solution	Aging
ATI 718Plus®	954°C x 1 hr, Air Cool	788°C x 8 hrs, Furnace Cool at 55°C/h to 704°C, 704°C x 8 hrs, Air Cool
718	954°C x 1 hr, Air Cool	718°C x 8 hrs, Furnace Cool at 55°C/h to 621°C, 621°C x 8 hrs, Air Cool
Waspaloy	1016°C x 4 hrs, Water Quench	843°C x 8 hrs, Air Cool, 760°C x 8 hrs, Air Cool

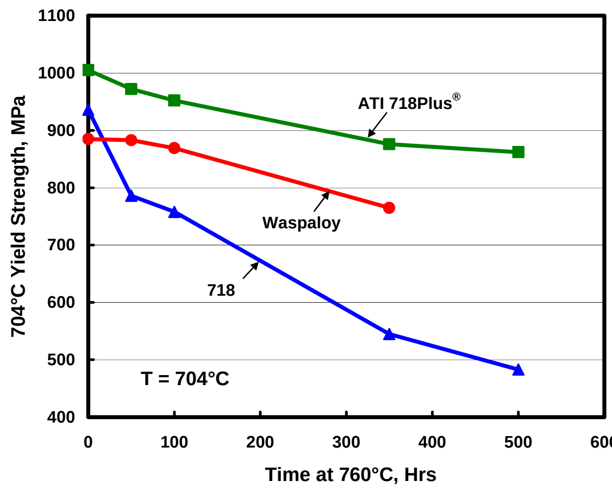


Figure 1. Yield Strength of ATI 718Plus® Alloy at 704°C as a Function of Exposure Time at 760°C in Comparison with Alloys 718 and Waspaloy.

As Figure 2 shows, the ETT ductility of 718 and 718Plus alloys was very significantly increased by thermal exposure.

Figures 3 (a) and (b) show the RTT properties of 718 and 718Plus alloy as a function of exposure time, and the reduction in ductility can be clearly seen. The ductility of Waspaloy showed a minimal change with thermal exposure, increasing slightly at ETT and decreasing slightly at RTT (see Figures 2 and 3 (b).

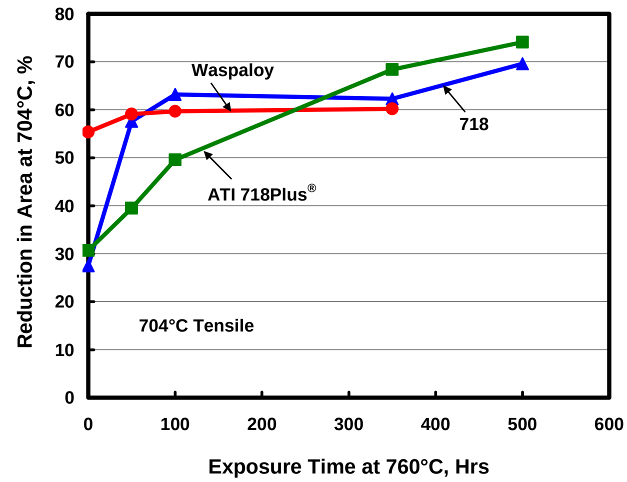


Figure 2. Tensile Reduction in Area of ATI 718Plus® Alloy at 704°C as a Function of Exposure Time at 760°C in Comparison with Alloys 718 and Waspaloy.

Based on tensile ductility, there was no thermal embrittlement for any of these three alloys at elevated temperature. Even in the cases of RTT where decreases were observed, the remaining ductility levels were quite high.

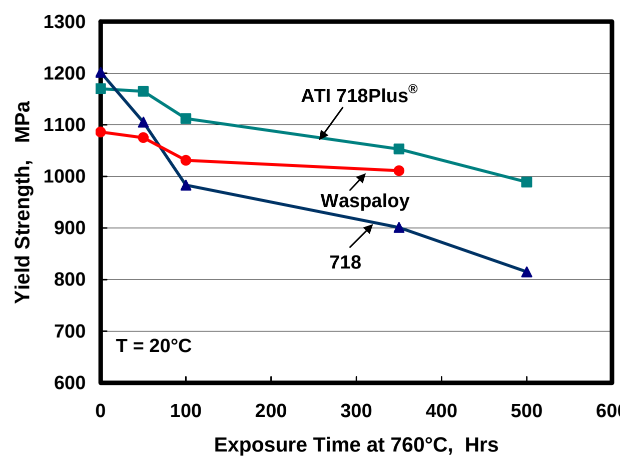


Figure 3 (a). Effect of Thermal Exposure at 760°C on Room Temperature Tensile Properties of Test Alloys - Yield Strength.

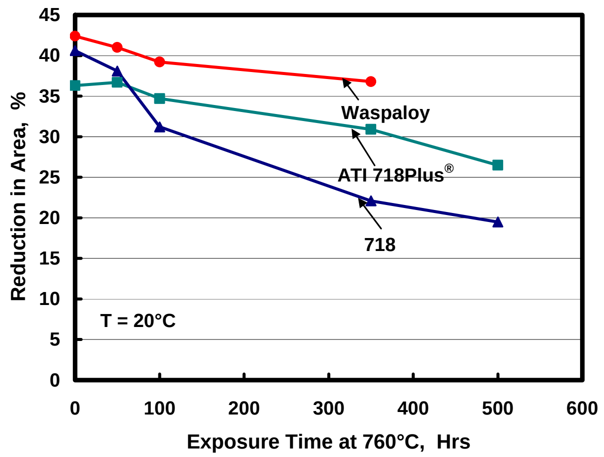


Figure 3 (b). Effect of Thermal Exposure at 760°C on Room Temperature Tensile Properties of Test Alloys – Reduction in Area.

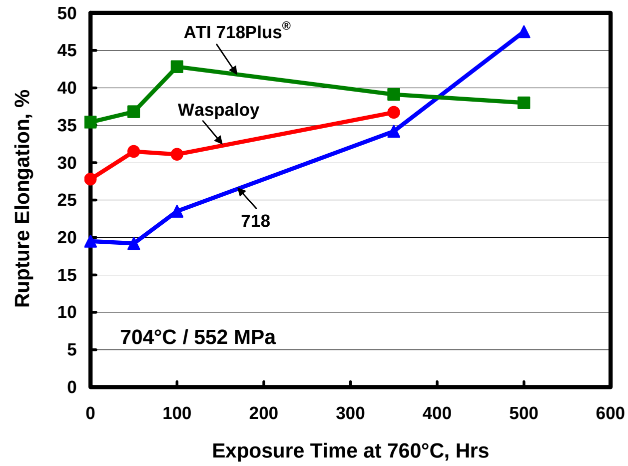


Figure 5. Stress Rupture Ductility of ATI 718Plus®, 718 and Waspaloy Alloys as a Function of Exposure Time at 760°C.

Stress Rupture Properties

Stress rupture tests were conducted at 704°C / 552 MPa, using combined notch – smooth samples and the results are presented in Figures 4 and 5. As shown in Figure 4, rupture life for all three alloys decreased with long exposure times. Alloy 718Plus had the highest stability and alloy 718 the lowest stability. No notch breaks were observed and the rupture ductility of all three alloys actually improved following thermal exposure (Figure 5). The extremely low rupture life of alloy 718 was somewhat expected since the applied stress was close to or even exceeded the yield stress of the alloy following thermal exposure. The increase in rupture life for 718Plus alloy and Waspaloy with short exposure times was not expected since the yield strength for both alloys fell following these exposures.

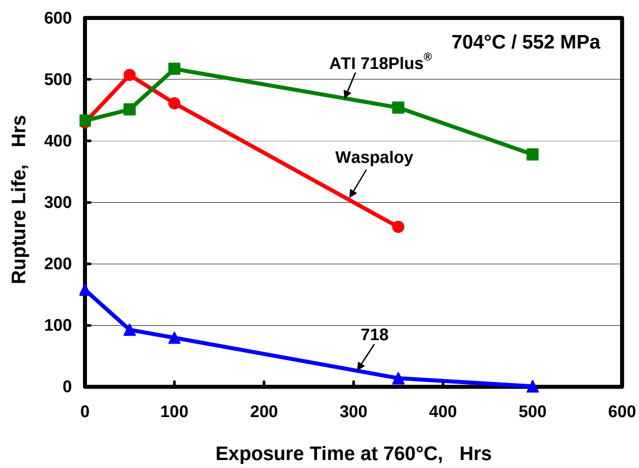


Figure 4. Effect of Thermal Exposure Time at 760°C on Stress Rupture Life of ATI 718Plus®, 718 and Waspaloy Alloys.

Creep Properties

Stress rupture tests measure the resistance of alloys to large creep strains. To evaluate the resistance to small creep strain observed in most applications, creep tests were performed at the same temperature and lower stress: 704°C / 483 MPa.

Tests were terminated when creep strain reached 0.5%, sufficient to achieve a steady state creep rate (secondary stage creep rate). Test results were presented in Figures 6 and 7. As shown in Figure 6, all three alloys experienced significant reduction in life to 0.2% creep strain after thermal exposure. The debits were much greater than those observed in stress rupture life, suggesting thermal exposure exerts a greater influence on behavior at small creep strains. This tendency is more clearly revealed in Figure 7 where the primary creep rate, represented by the reciprocal of time to 0.1% total strain, and steady state creep rate are plotted as a function of exposure time for 718Plus alloy. The increase in primary creep rate due to thermal exposure was a factor of 16 in comparison to a factor of 4 for steady state creep rate. Due to high creep resistance in the as-heat treated condition and lower degradation by thermal exposure, 718Plus alloy maintained the highest creep resistance among the three alloys tested.

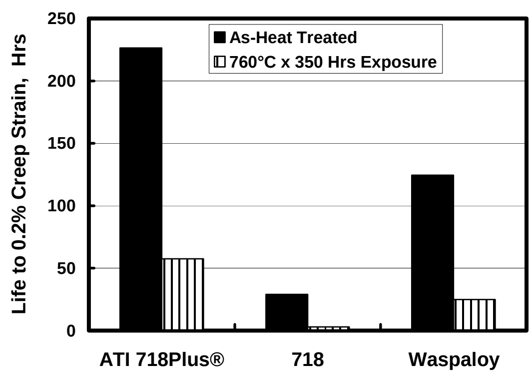


Figure 6. Effect of Thermal Exposure on Life to 0.2% Creep Strain of ATI 718Plus®, 718 and Waspaloy Alloys.

Low Cycle Fatigue Properties

Strain-controlled low cycle fatigue (LCF) testing at 650°C was performed on 718Plus alloy with the result as shown in Figure 8. It is clear that thermal exposure did not deteriorate LCF properties of this alloy; instead a small improvement may result from thermal exposure.

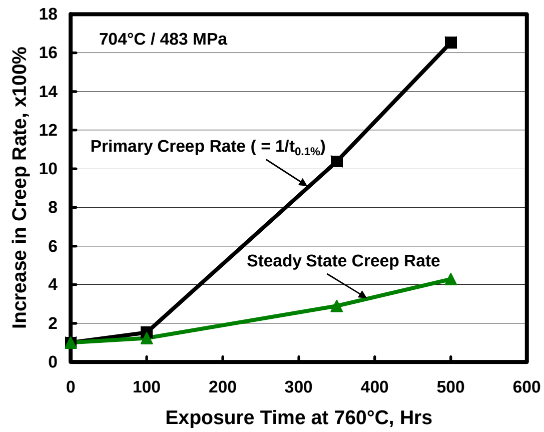


Figure 7. Increase in Creep Rate with Thermal Exposure Time at 760°C in ATI 718Plus® Alloy.

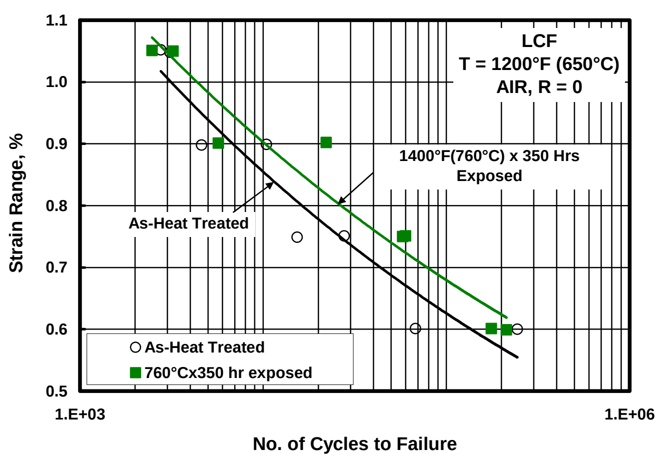


Figure 8. Effect of Thermal Exposure on Low Cycle Fatigue Properties of ATI 718Plus® Alloy.

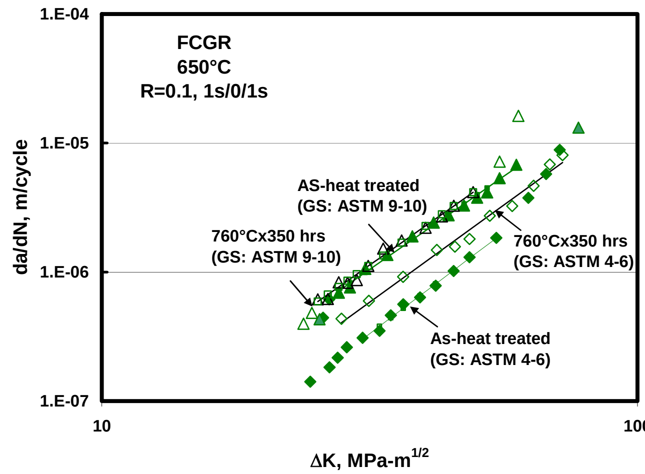


Figure 9. Effect of Thermal Exposure on FCGR of ATI 718Plus® Alloy.

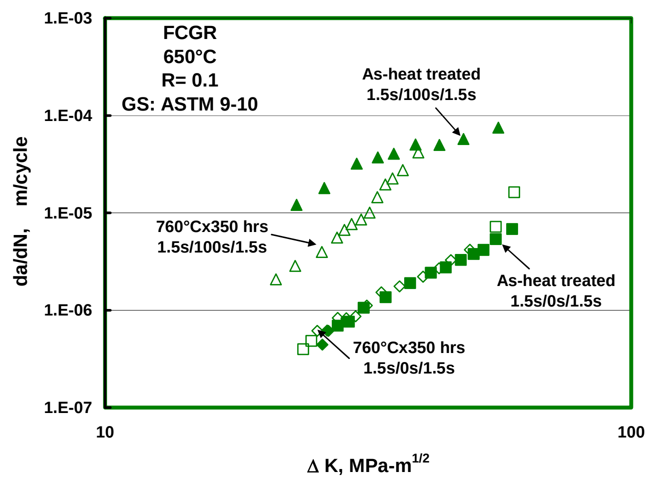


Figure 10. Effect of Thermal Exposure at 760°C on FCGR with and without Dwell Time for Fine Grain ATI 718Plus® Alloy.

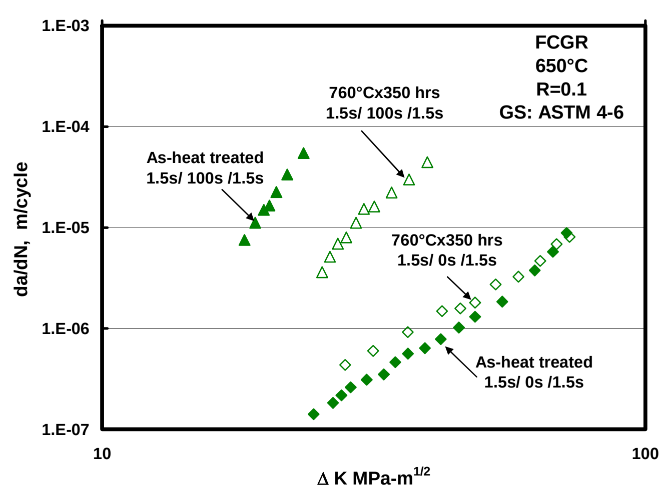


Figure 11. Effect of Thermal Exposure at 760°C on FCGR with and without Dwell Time for Coarse Grain ATI 718Plus® Alloy.

Fatigue Crack Growth Rate

Fatigue crack growth rate (FCGR) testing, both with and without dwell time, was conducted for all three alloys to characterize the effect of thermal exposure. The influence of grain size for 718Plus alloy was incorporated by using special thermo-mechanical working practices to produce fine grain size (ASTM 9-10) and coarse grained (ASTM 4-6) test material. All FCGR tests were run in air at 650°C with R=0.1. Two load profiles were used; the non-dwell time having a 1.5 sec/0 sec/1.5 sec triangular cycle (1.5s/0/1.5s) and dwell time having 1.5 sec/100 sec/1.5 sec truncated triangular cycle (1.5s/100s/1.5s). Details of the experimental procedure can be found elsewhere [19]. The major results of this study can be summarized as follows:

- Thermal exposure had little effect on non-dwell time FCGR results for 718Plus alloy. There is virtually no effect in thermal exposure on non-dwell time FCGR in fine grain structure, and it seems that thermal exposure very slightly accelerated crack propagation rate in coarse grain structure (Figure 9). A 100 second dwell time significantly increased the FCGR of as-heat treated and exposed 718Plus alloy with both fine and coarse grain structures (Figures 10 and 11). However, the detrimental effect of dwell on FCGR is remarkably less in the exposed materials, indicating that thermal exposure may actually improve the resistance of this alloy to dwell fatigue crack growth.

- Alloy 718Plus has the lowest FCGR in the non-dwell condition among the three alloys tested (Figure 12). However, Waspaloy demonstrated the lowest FCGR under dwell conditions due to the degradation of dwell fatigue resistance of 718 and 718Plus alloys. It is worth noting that the dwell FCGR of exposed 718Plus alloy was significantly reduced and approached that of Waspaloy (Figure 13). This clearly indicates that the dwell fatigue resistance of 718Plus alloy will not deteriorate, but improves during application at working temperature.

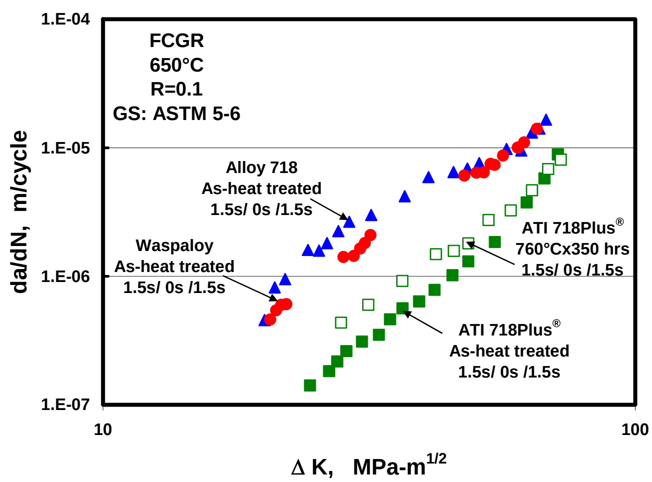


Figure 12. Comparison of FCGR without Dwell Time for ATI 718Plus®, 718 and Waspaloy Alloys.

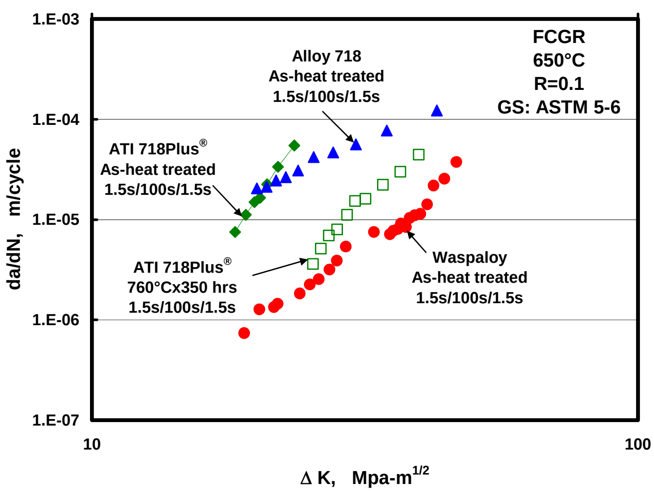


Figure 13. Comparison of FCGR with Dwell Time of ATI 718Plus®, 718 and Waspaloy Alloys.

Microstructural Changes

Microstructural changes that occurred with thermal exposure were examined by various means, including optical microscopy (OP), scanning electron microscope (SEM) and transmission electron microscope (TEM). Alloy 718Plus is a predominantly γ' strengthened alloy with a small amount of γ" phase. Therefore, the chemistry, volume fraction and size of γ' and γ" phases before and after thermal exposure were investigated by electrolytic extraction / X-ray diffraction analysis (XRD) and electron beam energy dispersion spectroscopy (EDS/TEM). The chemistry, volume fraction, particle size and distribution of those phases were determined. The relevant experimental procedures and partial results have been reported elsewhere [20]. The particle size and distribution of precipitation hardening phases following long-term exposure (350 and 500 hrs) were also analyzed by high magnification SEM to double check TEM results. The formation and growth of any other phases were also examined, using the same techniques. Alloys 718 and Waspaloy were analyzed, using the same methods except no TEM work was performed on Waspaloy because of earlier published work.

Major findings from the microstructural study can be summarized as follows:

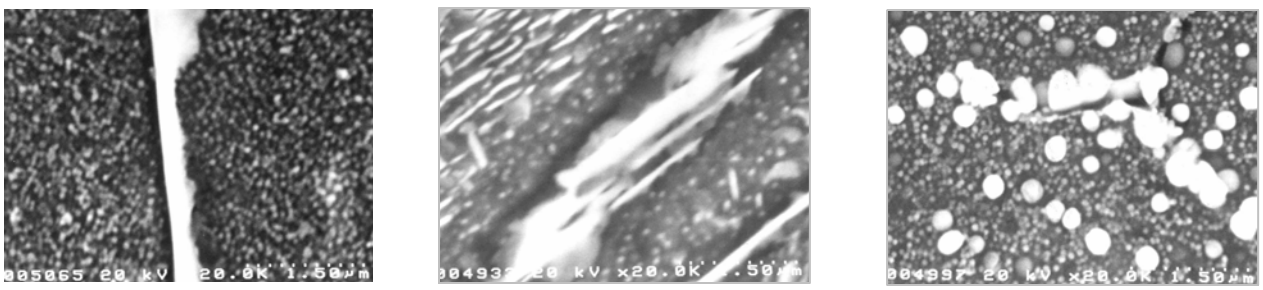
- The chemistry of γ' phase in 718Plus alloy is significantly different from that in Waspaloy, containing very high Nb, higher Al and W. There was little change with thermal exposure (Table III).
- Coarsening of precipitation hardening phase particles occurred in all three alloys. The greatest growth occurred in alloy 718, followed by Waspaloy and 718Plus alloy. The size of γ' particles in 718Plus alloy was smaller than those in Waspaloy and a significant grain boundary γ" / γ'–depletion zone formed in 718 (Figure 14). Typical disc-shaped γ" particles observed in alloy 718 were not seen in 718Plus alloy. As shown in Table III and Figure 15, the growth rate of γ' particles in 718Plus alloy was much lower than that of γ" particles in 718. The weight fraction of γ' particles in 718Plus alloy decreased only slightly during thermal exposure, in contrast to the large drop in γ" / γ' particles in alloy 718 (Table III).
- Other significant changes observed were the formation and growth of δ phases in 718 and 718Plus alloys, and the increase / growth of $M_{23}C_6$ carbide particles on grain boundaries in Waspaloy.
- The chemistry of δ phase in 718Plus alloy is different from that in 718, being much higher in Al content (Table IV). With thermal exposure at 760ºC, the amount of δ phase increases and its composition changes, becoming enriched in Cr and Mo, and depleted in Co, Al, and Ti.
- The formation and growth kinetics of δ phase in 718Plus alloy is much slower than in alloy 718. As shown in Table IV, the amount of δ phase in 718Plus alloy is 30% of that in alloy 718 for the same exposure condition.
- No TCP (Topologically Close-Packed) phases or other phases such as α-Cr were observed for the exposure conditions used in any of the three alloys.

Discussion

Two major changes in microstructure were observed during thermal exposure for the three alloys studied. One was the dissolution/coarsening of the precipitation hardening phase particles (γ" and/or γ') and the second was the formation and growth of δ phase particles in 718 and 718Plus alloys or $M_{23}C_6$ carbide particles in Waspaloy. The high thermal stability in mechanical properties of 718Plus alloy can be attributed to the slow growth of γ' phase particles and low quantity of δ phase particles. The growth rate of the precipitation hardening phase in the three alloys studied was evaluated by modeling, using JMatPro. Results in Figure 16 show 718Plus alloy has the lowest growth rate, k, (the slope of particle growth curve in the radius vs.

Table III. Chemistry, Average Size & Content of γ' / γ" Phases in ATI 718Plus® and 718 Alloys

Alloy	Exposure Time at 760°C	Chemistry, wt%									Size nm	Content wt%
		Cr	Mo	W	Fe	Co	Nb	Al	Ti	Ni		
ATI 718Plus®	0 hr	2.97	0.46	0.63	1.37	2.96	14.8	4.79	2.57	69.4	24	22.0
	350 hrs	3.48	0.46	0.57	1.59	3.81	14.0	4.98	2.56	68.5	53	18.7
	500 hrs	2.63	0.49	0.63	1.65	3.94	15.0	4.82	2.61	68.2	65	20.7
718	0 hr	2.83	1.17	0.24	1.57	0.07	20.3	1.55	4.15	68.2	144	15.9
	500 hrs	3.83	0.97	0.25	2.75	0.15	15.1	2.56	5.44	68.9	158	7.8



(a) ATI 718® Alloy (b) Alloy 718 (c) Waspaloy

Figure 14. SEM Microstructures of ATI 718Plus®, 718 and Waspaloy Alloys after 760°C/350 hrs. Exposure.

Table IV. Chemistry and Content of δ Phase in ATI 718Plus® and 718 Alloys

Alloy	Exposure Time at 760°C	Chemistry, wt%									Content wt%
		Cr	Mo	W	Fe	Co	Nb	Al	Ti	Ni	
ATI 718Plus®	0 hr	0.90	0.48	0.46	1.18	5.49	20.3	2.74	4.52	65.6	0.5
	350 hrs	0.75	0.39	0.45	1.18	4.73	20.3	3.10	2.99	66.1	2.9
	500 hrs	1.34	1.11	0.45	1.13	2.87	24.1	1.45	2.73	64.8	3.5
718	0 hr	2.31	1.66	0.22	1.71	0.14	26.6	0.01	3.59	64.8	0.6
	500 hrs	0.95	2.08	0.21	0.37	0.14	27.4	0.10	2.68	66.2	11.6

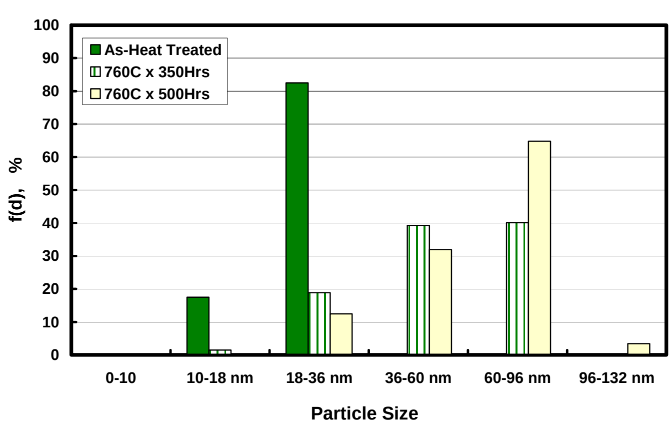


Figure 15. Size Distribution of Gamma Prime Particles as a Function of Exposure Time for ATI 718Plus® Alloy.

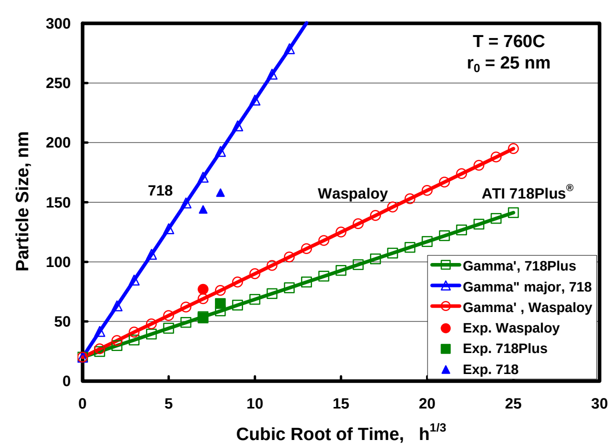


Figure 16. Coarsening Kinetics of Hardening Particles in ATI 718Plus®, 718 and Waspaloy Alloys calculated using JMatPro.

time$^{1/3}$ plot), among the three alloys. There was good agreement between experimental data and modeling results. As indicated in reference 21, the modeling calculations are built on the following equation:

$$K = [8D_{eff}\,\sigma\, N_\alpha\,(1 - N_\alpha)\,V_m / 9\,(N_\beta - N_\alpha)^2\,RT\,]^{1/2}$$

Where D_{eff} is the effective diffusion coefficient, σ is the precipitate-matrix interfacial energy per unit area, N_α and N_β are the total equilibrium mole fraction of solute in the matrix α and precipitate β, respectively, V_m is the molar volume of the precipitate, R the gas constant and T the absolute temperature. According to this equation, the slow growth rate of γ' particles in 718Plus alloy most likely results from the reduced D_{eff} by Nb diffusion between the matrix and γ' particles during particle growth and increased N_β - N_α due to large differences in solubility of Nb in γ' and the matrix.

As this study demonstrates, there is a large difference in δ phase behavior between 718 and 718Plus alloys, but the cause is not easily explained. According to thermodynamic calculations the phase content of δ in equilibrium condition at 760°C is about 14.8 wt% and 9.4 wt% for 718 and 718Plus alloy, respectively. The apparently larger difference in δ phase content observed experimentally could be the result of the very sluggish precipitation of δ phase in 718Plus alloy. The precipitation kinetics of δ phase in both alloys have been evaluated by JMatPro, and the results are shown in Figure 17. The modeling results gave reasonable agreement with experimental observation for alloy 718, but significantly overestimated the formation rate of δ phase in 718Plus alloy, suggesting the δ phase precipitation kinetics in 718Plus alloy could be significantly different from those in alloy 718.

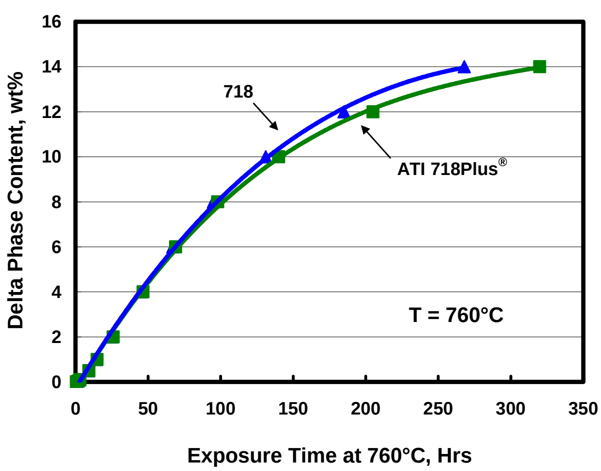


Figure 17. Delta Phase Content as a Function of Exposure Time at 760°C for ATI 718Plus® and 718 Alloys calculated using JMatPro.

In addition, modeling calculations also fail to accurately predict δ solvus temperature in 718Plus alloy. All the discrepancies indicate that the current modeling tool cannot properly handle δ phase-related problems in 718Plus alloy and a new model must be used. The slow δ phase precipitation kinetics in 718Plus alloy may have something to do with γ' / γ" morphology in this alloy. As previously stated, none of the typical disc-shaped γ" particles were observed in 718Plus alloy although modeling calculation and EE/XRD technique indicate the existence of a small amount γ" phase in this alloy. It was reported in previous work [6] that some sandwich-structured γ' particles were observed, especially after long-term exposure. It is suspected that the middle layer is γ" phase. This speculation is supported by results reported in [22] where the authors found that γ" and γ' co-exist in many cases in alloy 718. They reported the percentage of γ" with γ' particles attached increased from about 50% to almost 100% as the Al + Ti content and especially Al/Ti ratio increased from the typical atomic ratio of 0.9 in 718 to about 2. Since 718Plus alloy has an even higher Al+Ti content and an Al/Ti atomic ratio of about 4, it is very possible that all γ" particles are enveloped by γ' particles, making γ" particles essentially invisible. The stability of this type of structure may also significantly delay the formation and growth of δ phase in 718Plus alloy.

It is important to compare the effect of thermal exposure on mechanical properties in 718Plus alloy with other superalloys and to establish the mechanisms of such effects. Table V summarizes the effect of thermal exposure on microstructure and mechanical properties of a number of Ni-base superalloys. It can be seen that the effect of exposure on mechanical properties is alloy sensitive, depending on microstructural changes caused by exposure. Generally speaking, two types of microstructural changes occurred during exposure. One was the dissolution/coarsening of hardening phase particles and the other was the formation and growth of other phases such as δ phase in alloys 718 and 718Plus, $M_{23}C_6$ carbide in Waspaloy and σ or other TCP phases in some alloys. Degradation in strength can be attributed mainly to dissolution/coarsening of hardening particles. Since there is little dissolution and slow coarsening of γ' phase particles in 718Plus alloy, its strength degradation is moderate, especially compared to 718 where significant dissolution and coarsening of γ" particles occurred. Of all of the mechanical properties, creep was the most significantly effected by thermal exposure. The observed increase in creep rate is also controlled by the dissolution/coarsening of hardening phase particles. The most significant effect on creep rate occurred at the primary creep stage and diminished at large creep strains. This phenomenon has been reported by many studies where a dislocation mechanism of creep predominates. It was suggested that the early stage of creep involves significant motion/multiplication of dislocations and dissolution/coarsening of hardening phase creates much larger inter-particle matrix "channels" leading to high initial creep rate.

Another mechanical property significantly affected by dissolution/coarsening would be FCGR with hold time. In general, hold time will remarkably accelerate FCGR, presumably due to the combined effect of creep and environment damage. Although Waspaloy has lower creep resistance and higher FCGR under non-dwell time conditions compared with 718Plus alloy, it still shows excellent resistance to hold time FCGR, obviously due to its high environment resistance. Thermal exposure facilitates increased plastic flow at a crack tip and therefore promotes crack tip blunting, reducing the effective ΔK, the driving force of FCGR, and therefore the sensitivity to the detrimental effect of hold time.

Table V. Summary of the Effect of Thermal Exposure in Nickel Based Superalloys

Alloys		718Plus®	718			Waspaloy		720LI	RR1000
Sources		This work	This work	Ref. [14]	Ref. [12, 13]	This work	Ref. [14]	Ref. [16]	Ref. [17, 18]
Exposure L-M parameter		23.3	23.3	23.2	22.2	23.3	23.2	23.8	23.5
Microstructure Change		γ' growth, δ phase formation and growth	γ" / γ' particle growth, γ" / γ' quantity reduction, δ phase formation and growth.			γ' particle growth, $M_{23}C_6$ Carbide formation (G.B.)		Secondary γ' growth, σ phase formation	Tertiary γ' dissolution, σ phase formation
R.T. Tensile	Strength	↓ 10%	↓ 25%	↓ 30%	—	↓ 5%	↓ 2%	↓ 5-10%	—
	Ductility	↓ 4 – 10%	↓ 25-50%	↓ 30-60%	—	↓ 5-10%	↓ 5-15%	↓ 10-20%	—
E.T. Tensile	Strength	↓ 13%	↓ 40-45%	↓ 40%	↓ 6-10%	↓ 14%	↓ 10%	↓ 10-15%	↓ 4-6%
	Ductility	↑ 75-130%	↑ 130-160%	↑ 100-250%	↑ 30-60%	↑ 2-10%	↓ 0-5%	No change	↓ 13%
Stress Rupture Life		↓ Slightly	↓ 90%	—	↓ Slightly	↓ 40%	—	—	—
Creep Rate		↑ Factor 3-10	↑ Factor 20	—	↑ Factor 3-30	↑ Factor 5-10	—	↑ Factor 5-10	↑ Factor 2-10
LCF Life		↑ Slightly	—	—	No change	—	—	↓ Factor 2-3	—
FCGR	Without Dwell	No change or ↑ Slightly	—	—	—	—	—	—	↓ or ↑ Depend on ΔK
	With Dwell	↓ Factor 5-10	—	—	↓ Factor 2-50	—	—	—	↓ up to factor 10

The formation and growth of other phases may contribute to thermal embrittlement such as reduction in ductility and toughness, depending on the nature of the precipitated phase. It seems that $M_{23}C_6$ carbide precipitation in Waspaloy has a minor effect. It appears that δ phase in 718 and 718Plus alloys has a double effect; an embrittlement effect at room temperature and no effect or even a toughening effect at elevated temperature, probably due to its highly deformable nature at high temperature. If the quantity of δ phase is not excessive, the highly ductile nature of δ phase might also contribute to crack tip blunting in FCGR and reduction of the localized plastic strain concentration during LCF, leading to improvement in LCF and FCGR properties.

For 718Plus alloy, the major concern from a thermal stability standpoint would be the acceleration in creep rate since other properties were only moderately degraded or even improved by thermal exposure.

The creep resistance of 718Plus alloy is superior to Waspaloy in the as-heat treated condition and also better after exposure due to similar degradation of both alloys. In comparison with Waspaloy, the major shortcoming of 718Plus alloy is its lower dwell fatigue resistance. The improvement in hold time FCGR brought about by thermal exposure implies that the dwell fatigue resistance of 718Plus alloy could be further improved by modifying current heat treatment to a slightly over-aged state. Since 718Plus alloy has better strength, stress rupture/creep properties and even low cycle fatigue resistance, it may be possible to develop a modified heat treatment to improve dwell fatigue resistance without significantly decreasing other properties.

Conclusions

The following conclusions can be made from this study:

1. Alloy 718Plus has thermal stability much better than alloy 718 and comparable to Waspaloy in thermal exposure conditions up to 760°C (1400°F) / 500 hrs.
2. Reduction in strength with thermal exposure time is about equal for 718Plus and Waspaloy alloys. However, 718Plus alloy maintains higher strength at temperature up to 704°C due to its higher initial strength.

3. Thermal embrittlement and degradation in fatigue resistance should not be a concern for 718Plus alloy from a thermal stability standpoint since no embrittlement was observed and fatigue properties were little affected or even improved by thermal exposure.
4. The hold time fatigue crack growth resistance of 718Plus alloy is inferior to Waspaloy but the difference was significantly reduced after thermal exposure.
5. The most dramatic change in mechanical properties upon thermal exposure occurred in creep resistance, especially primary creep resistance. The stability of 718Plus alloy is about equal to that of Waspaloy in terms of creep resistance, but 718Plus alloy has higher creep resistance at temperatures up to 704°C after thermal exposure due to its higher creep resistance in the as-heat treated condition.

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