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FATIGUE CRACK PROPAGATION BEHAVIORS OF NEW DEVELOPED ALLVAC® 718PLUS^{TM} SUPERALLOY

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Abstract

In this paper, the mechanical properties, especially fatigue crack propagation behaviors of a newly developed Ni-base superalloy Allvac® 718Plus™ Alloy were investigated, as compared with those of Alloy 718 and Waspaloy. It is indicated that 718Plus^{TM} alloy shows better performance on tensile, creep and fatigue crack growth tests than Alloy 718 at room temperature, 650°C and 704°C. In the final section of the paper, the mechanism of fatigue crack propagation behavior of superalloys and hold-time effect are discussed.

It is clear that yield and tensile strengths of 718Plus^{TM} alloy are higher than those of Alloy 718 and Waspaloy at temperatures up to 704°C. Stress rupture life of 718Plus alloy is about the same as Waspaloy and higher than that of Alloy 718 at 704°C.

Regarding fatigue crack propagation properties, alloys 718Plus^{TM}, 718 and Waspaloy have similar fatigue crack growth rates under 3 seconds triangle loading at 650°C. In comparison, 718Plus^{TM} shows the somewhat better resistance to fatigue crack growth without hold-time at 650°C than Alloy 718 and Waspaloy. As a matter of fact, the fatigue crack growth rate of 718Plus^{TM} at 704°C is slower than that of Alloy 718 and Waspaloy at 650°C. During the fatigue crack growth under the trapezoid loading with 100 seconds hold-time at maximum stress, 718PLUS^{TM} alloy shows the comparable resistance to hold-time FCG as that of Waspaloy alloy, while both alloys have better resistance than that of Alloy 718.

Examination of the fatigue fracture surfaces by scanning electronic microscope (SEM) revealed transgranular crack propagation with striations for 718Plus^{TM} at room temperature. There is a clear border between the fracture surface of the room temperature pre-crack and 0.33Hz fatigue at 650°C. The fracture mode at 650°C is the mixture of intergranular and transgranular modes. When the test temperature is up to 704°C, intergranular is the predominant mode and the whole surface covered by a layer of oxide film, indicating that severe oxidation happens during the crack growth. The crack path of 718Plus^{TM} under 3+100 seconds' hold-time conditions at 650°C and 704°C are predominantly intergranular, with a little transgranular cleavage fraction. The fracture was rough and covered by lots of oxide products. These oxides are believed to be from oxidation asperities of δ-phase precipitates.

Fatigue crack growth of most superalloys is predominantly a cycle-dependent damage process with little frequency effect at very high frequencies. At relatively low frequencies or the test with hold-time, crack growth includes time dependent processes, which were generally ascribed to phenomena involving creep and/or environmental degradation processes. The combined mechanical and SEM fractographical analysis show the time-dependent FCG of 718Plus^{TM} is rather an environmental effect than creep effect.

I. Introduction

1.1 Allvac 718Plus® Superalloy

Because of its properties, fabricability and cost effectiveness, Inconel 718 has become the most widely used superalloy, accounting for 35% of all superalloy production in recent years [1]. However, because of the nature of the primary strengthening phase γ" in Inconel 718, it can not be employed at the temperature high than 650°C (1200°F). In recent years, there is a strong desire in industry to have an affordable alloy 718 derivative with a temperature capability 100°F higher than that of alloy 718 and with comparable processing characteristics as alloy 718. Three key goals have to be met in any of successful such alloys, i.e.,

1. This alloy can work at temperature 100°F higher than 1200°F that is considered as the upper limit of working temperature of alloy 718. The mechanical property of such alloy at 1300°F should be better or at least equal to that of Waspaloy. Thermal stability at 1300°F of such alloy should be equivalent to Waspaloy and much better than alloy 718.

2. Processing characteristics of the alloy, such as castability, hot workability and weldability, should be similar to those of alloy 718 and much better than Waspaloy.

3. The total cost of such alloy should be 20-25% lower than that of current commercial alloys that can work at similar temperature such as Waspaloy.

So far, many alloys have been developed to meet these goals, but none of these alloys was considered totally successful. Several years ago, a research program was initiated at Allvac to develop such an alloy. The new alloy developed at Allvac has been named as Allvac 718Plus^{TM}. Three features distinguish invented alloy from present alloys for similar purposes:

1) Balance of strengthening elements Al, Ti and Nb

The quantity of strengthening elements Al and Ti and their relative ratio are adjusted to proper ranges to increase the thermal stability of microstructure and mechanical properties, especially rupture and creep strength, at high temperature. The adjustment in Al and Ti levels will guarantee no unacceptable degradation in hot workability and weldability. More specifically, the adjusted Al and Ti contents in conjunction with Nb addition will make this alloy being strengthened by γ' + γ" with Nb- containing γ' as dominant strengthening phase. The Al to Ti ratio is set at a level much higher than similar current alloys. According to our study, unlike the usual high Ti- low Al combination that has a more dramatic strengthening effect and adopted in all other superalloys of this type, the high Al-low Ti combination significantly increases the thermal stability of the alloy, which is a key for increasing temperature capability. High Nb was added to significantly increase the strengthening effect of γ' particles and make γ' precipitation much more sluggish that will improve the hot workability and weldability of alloy.

2) Utilization of the strengthening effect of minor elements P and B

Our study discovered that minor elements P and B, similar to the situation in alloy 718, have a significant strengthening effect in new alloys invented. Adding P and B in the suggested range can maximize the creep/stress rupture resistance of alloys. The optimum P content is shifted to a lower level of about 0.015% in comparison with those in alloy 718 (about 0.022%), which is good for hot workability and weldability. No detrimental effect of P and B in suggested ranges on tensile strength and ductility was found. It was estimated that the effect of adding P and B in suggested ranges is equivalent to that of adding about 4% Co, but without cost penalty.

3) Strengthening by adjusting Fe, Co and W contents

The contents of Fe, Co and W were carefully balanced to ensure high strength, high creep/stress rupture resistance, high thermal stability and good processing characteristics with a minimum increase in raw material costs. Experiments demonstrated that 8 – 12% iron in alloy will generate optimum property and a combination of 9% Co and 10% Fe will give excellent performance. Adding 1 – 2% tungsten can further improve alloy without generating any detrimental effect.

1.2 Fatigue Crack Growth of Superalloys

Fatigue crack growth behaviors of superalloys, have received increasing attention in the past several decades because (1) the results of failure analyses indicate that fatigue is one of the major causes of failure in engineering structures, and (2) the fatigue life of engines is determined by the initiation and the propagation behavior of the cracks [2, 3]. It has been revealed that crack growth is induced by irreversible crack tip plastic flow, which provides the driving force for crack growth [4, 5]. It is always noted at the papers on fatigue crack growth that the crack propagation rate da/dn, can be written in terms of the cyclic stress intensity factor ΔK as

$$da/dn = B \times \Delta K^n \quad (1)$$

Table I: Chemical Compositions of Tested Alloys (wt%)

	C	Ni	Cr	Mo	W	Co	Fe	Nb	Ti	Al
718PLUS®	0.026	Bal.	17.47	2.70	1.03	9.15	9.86	5.43	0.70	1.46
718	0.033	/	18.41	3.03	/	/	17.94	4.98	0.91	0.56
Waspaloy	0.019	/	19.55	4.25	/	13.51	/	/	2.95	1.37

Table II. Heat Treatments of the Test Materials

Alloy	Heat Treatment
718	980°C/1h/AC+720°C/8h/FC→620°C/8h/AC
Waspaloy	1020°C/4h/OQ + 850°C/4h/AC + 760°C/16h/AC
718PLUS®	955°C/1h/AC +787°C/2h/FC→650°C/8h/AC

Note: AC - Air Cooling; FC - Furnace Cooling; OQ - Oil Quench; WQ - Water Quench

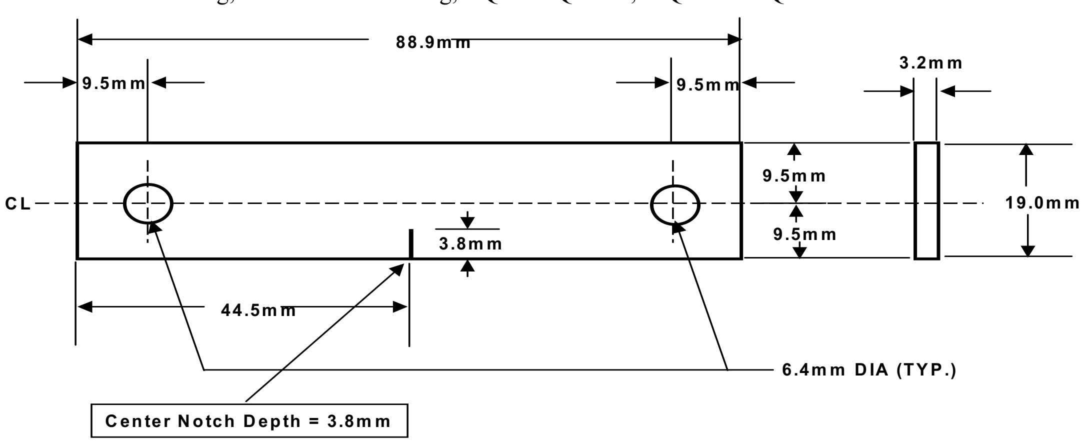


Figure 1: Dimensions of the single-edge-notched specimens

Table III. Key Thermodynamic Data of 718PLUS® Alloy

Alloy	Liquidus	Solidus	δ Solvus	γ' Solvus	γ' Weight Fraction at 650°C
718PLUS™	1350°C	1245°C	1059°C	989°C	19.2%

where B and n are constants which may depend on material, microstructure and environment [6]. There have been many models developed during the past decades to describe FCG. The major difference among these models is the description of damage, such as what constitutes damage, how it accumulates, and what is the best way to describe it [6].

Fatigue crack growth of most superalloys is predominantly a cycle-dependent damage process with little frequency effect at very high frequencies. At high temperature and relatively low frequencies, crack growth includes time dependent processes, and fatigue crack growth rates are strongly dependent on temperature, frequency, holding time and stress ratio. Time dependent effects on high temperature fatigue crack growth behavior are generally ascribed to phenomena involving creep and/or environmental degradation processes [7-12].

High-temperature superalloys are characterized by relatively simple microstructure in comparison to alloy steels and titanium alloys. Though the options to change the microstructure of a given superalloy are limited, some enhancement of fatigue cracking resistance can be achieved on the basis of microstructure. In general, best microstructure can be achieved through optimizing thermo-mechanical processing and heat treatment.

1.3 Research Objectives

The primary research objectives of this paper are (1) to investigate the mechanical properties, especially fatigue crack propagation behaviors of the newly developed Ni-base superalloy Allvac® 718Plus™ Alloy, as compared with those of Alloy 718 and Waspaloy; and (2) to study the hold-time effect on the fatigue crack growth behaviors of superalloys.

II. Experiments

2.1 Materials and Heat Treatments

718 PLUS™ Alloy: There are two batches of 718PLUS™ alloy employed in this investigation and both were vacuum-melted by Allvac Co. (Monroe, NC). The alloy used in tensile and stress rupture investigation was taken from 200 mm Rd forged billet made from a 1.5 ton VIM/VAR ingot with a grain size of ASTM 7. The roll stocks were cut from the same billet, rolled into 10 mm plates through 955°C/3passes rolling and used for fatigue crack propagation study. The grain size of rolled plates was about ASTM 8-9.

Waspaloy and Alloy 718: Both Waspaloy and 718 alloys employed in the fatigue crack propagation study were also vacuum-melted and have the grain size of ASTM 6. Chemical compositions of 718PLUS™, 718, and Waspaloy are shown at Table I. The heat treatment schedules of the alloys are shown as Table 2.

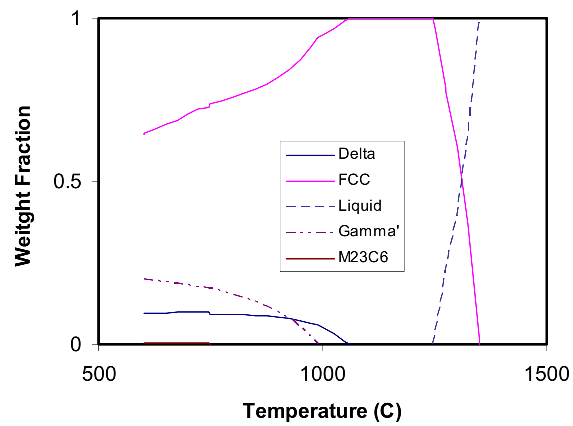
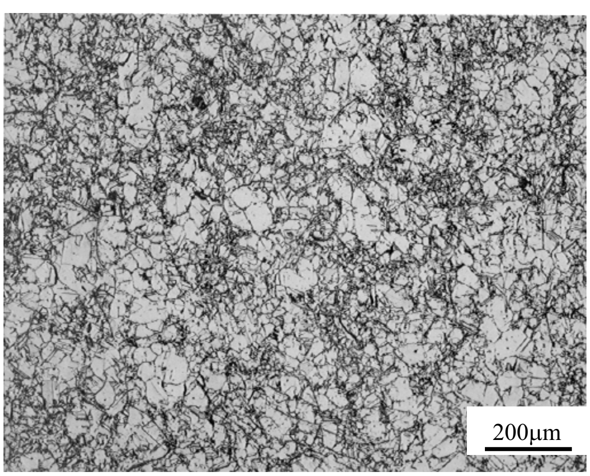
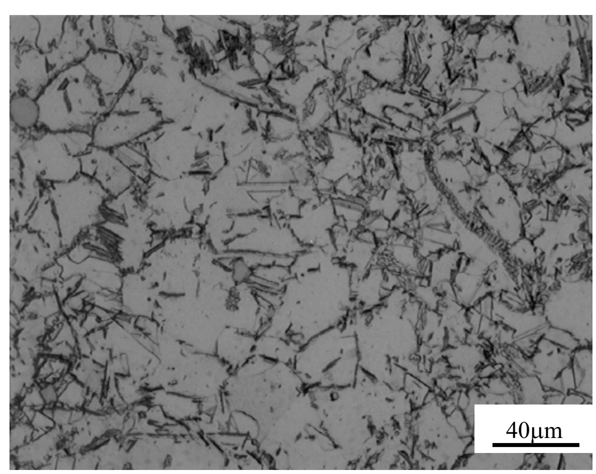


Figure 2: Phase diagram of 718PLUS® calculated by Thermo-Calc.

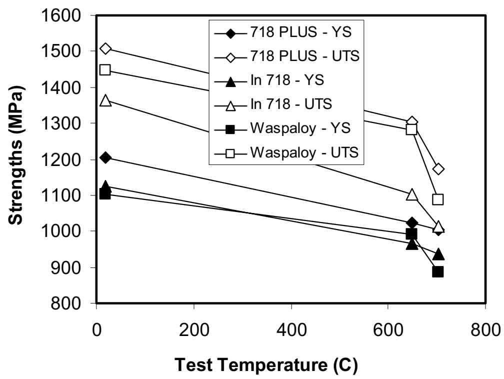


(a) – low magnification

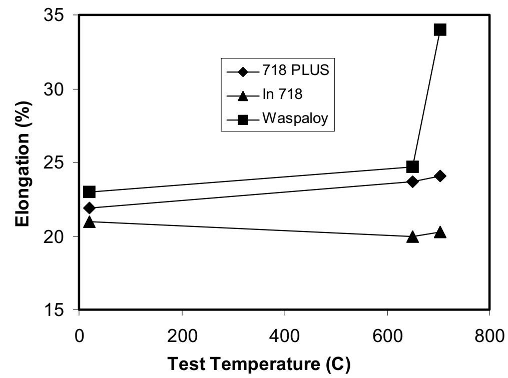


(b) – High Magnification

Figure 3: Microstructure of 718PLUS® alloy in the FCG investigation.



(a) Tensile Strengths



(b) Elongation

Figure 4: Tensile properties of 718 PLUS® alloy as compared to Alloy 718 and WASPALOY.

2.2 Mechanical tests

The alloys were tensile tested at room temperature, 650°C and 704°C and stress rupture tested at 704°C. Fatigue crack propagation tests were performed by employing the single-edge-notched (SEN) specimens. The specimen was pre-cracked with lower stress intensity triangle cycles up to 2.54mm at room temperature, and then was heated to higher temperature for the fatigue crack growth tests. The tests were carried out at various temperatures (650°C, 704°C) and with different loading cycles (3 seconds triangle wave, trapezoid wave with 3 seconds + 100 seconds loading at maximum stress). The tests were conducted under constant load control. The R ratio (K_{min}/K_{max}) was always set to 0.1. Fractographical analyses were conducted by means of SEM.

III. Results

3.1 Microstructure of 718PLUS™ Alloy

Figure 2 shows the equilibrium phase diagram of 718PLUS™ alloy calculated by using Thermo-Calc™. Several key calculated thermodynamic data of the alloy are listed in Table III. According to the diagram, the γ' solvus temperature of 718PLUS®™ is 989°C. Thermo-calc indicates that alloy 718Plus™ is a predominantly γ' phase strengthening alloy and the γ' fraction at 650°C is about 19%, which is the maximum fraction available after aging.

The main feature of 718PLUS™ alloy's microstructure is strengthening phase γ' uniformly distributed in γ-matrix. Figure 3 shows the grain structure of tested alloy. As shown in Figure 3(a), the tested alloy show an isotropic grain structure with a grain size is ASTM 8-10. Figure 3(b) shows that δ-phase are well distributed on the grain boundaries.

3.2 Tensile and Stress Rupture Properties

Figure 4 shows the tensile strengths of 718Plus™, Alloy 718 and WASPALOY as the function of temperature. It is clear that the tensile strengths (yield stress and ultimate tensile stress) of the alloys decrease as the increasing of temperature. On the contrary, the tensile elongation of the alloys increases as the increasing of temperature. As shown in the figure, the yielding and tensile strengths of 718PLUS™ alloy are higher than those of 718 and WASPALOY at temperatures up to 704°C.

Figure 5 shows the stress rupture properties of 718PLUS™ alloy at 704C, as compared to Alloy 718 and WASPALOY. It is indicated that stress rupture life of 718Plus alloy is about the same as Waspaloy and higher than that of Alloy 718 at 704°C, and the elongation of 718PLUS™ is better than that of Alloy 718 and WASPALOY.

3.3 Fatigue Crack Propagation

FCG without hold-time As shown in Figure 6, alloys 718Plus™, 718 and Waspaloy have similar fatigue crack growth rates under 3 seconds triangle loading at 650°C. In comparison, 718Plus™ shows the somewhat better resistance to fatigue crack growth without hold-time at 650°C than Alloy 718 and Waspaloy. As a matter of fact, the fatigue crack growth rate of 718Plus at 704°C is slower than that of Alloy 718 and Waspaloy at 650°C.

As shown in Figure 7(a), examination of the fatigue fracture surfaces by scanning electronic microscope (SEM) revealed transgranular crack propagation with striations for 718PLUS™

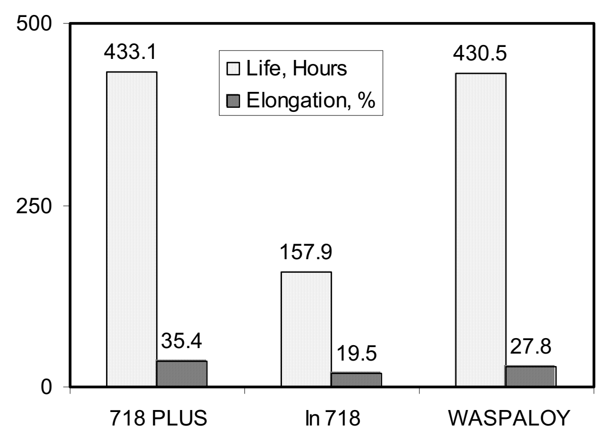


Figure 5: Stress Rupture Properties of 718PLUS® alloy at 704°C/551MPa, as compared to Alloy 718 and WASPALOY.

alloy at room temperature. There is clear border between the fracture surface of room temperature pre-crack and 0.33Hz fatigue at 650°C. The fracture mode of the alloy at 650°C is the mixture of intergranular and transgranular modes. When the test temperature is up to 704°C, intergranular is predominant mode and the whole surface covered by a layer of oxide film, indicating that severe oxidation happens during the crack growth.

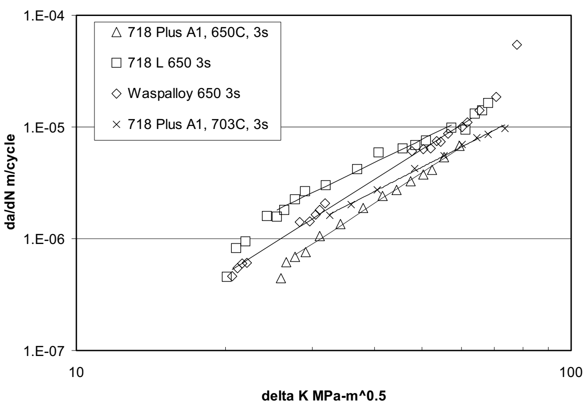


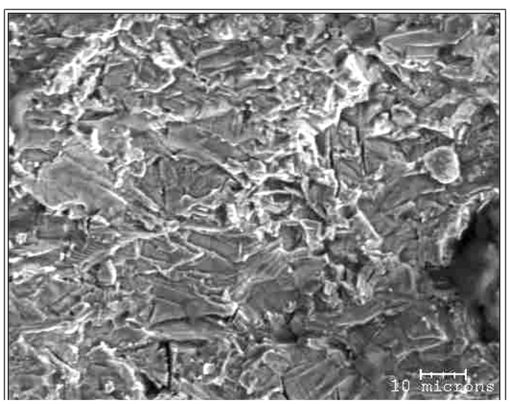
Figure 6: Fatigue crack propagation behaviors of 718PLUS^{TM} alloy under 3 seconds' triangle loading, as compared to that of Alloy 718 and WASPALOY.

FCG with 100s hold-time at maximum stress Fatigue crack growth rates (FCGR) of 718 PLUS^{TM} alloy were evaluated for test frequency of 0.33Hz and with 100 seconds hold at maximum load, as compared to that of Alloy 718 and WASPALOY. As shown in Figure 8, WASPALOY shows the best resistance to fatigue crack growth under this condition while the resistance of 718Plus^{TM} is better than that of Alloy 718. It should be pointed out that the 718PLUS^{TM} alloy employed in this FCG study has the smaller grain size (ASTM 8-9) comparing with that of Waspaloy (ASTM 6). The effect of grain size on hold-time FCG will be discussed in the discussion section.

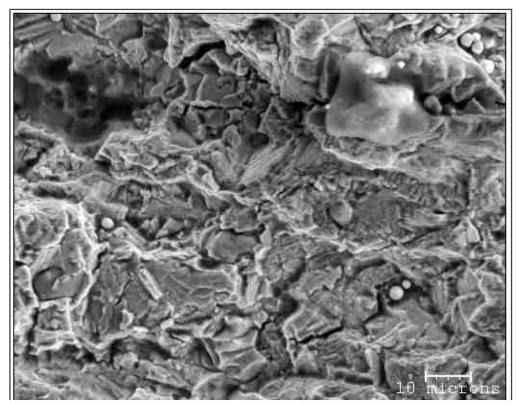
Figure 9 shows the SEM fracture surface micrograph of 718PLUS^{TM} alloy after FCG tests with 100 seconds hold at maximum load at 650°C and 704°C. The crack path of the alloy under 3+100 seconds hold-time conditions at 650°C and 704°C are predominantly intergranular, with a little transgranular cleavage fraction. The fracture was rough and covered by lots of oxide products. These oxides are believed to be from oxidation asperities of δ-phase precipitates. The comparison between Figures 9 (a) and 9 (b) indicates that oxidation becomes more severe as the test temperature increases.

IV. Discussion

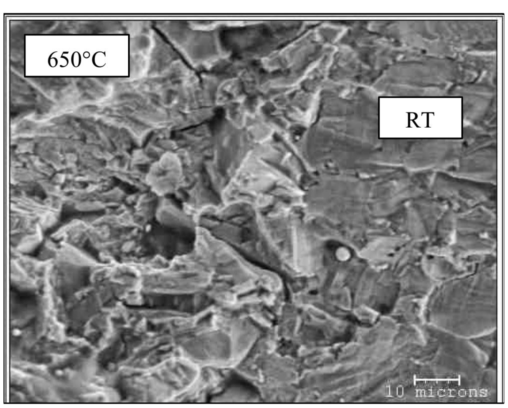
4.1 Effect of Temperature on FCG



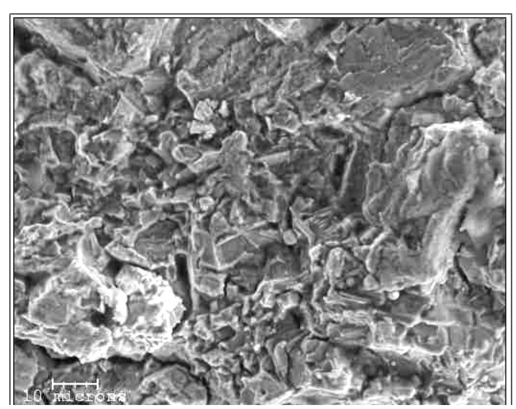
(a) room temperature



(b) 650°C



(C) benchmark between RT & 650°C



(d) 704°C

Figure 7: SEM fractography of 718PLUS® after fatigue crack growth tests under 3s triangle loading.

Cyclic plastic deformation of most metals under fatigue is primarily forward and reverse movement of dislocations. Comparing to the plastic deformation under monotonic tension, cyclic deformation features with the formation and development of persistent slip bands (PSB). As the temperature increases, there are more dislocations become activated and start to move. Figure 11 shows the various characters of striations at room temperature and 650°C, comparing with the ones at 650°C, the uniformed fine slip-marking at 650°C indicate there are more activated slip system at high temperature.

Generally speaking, FCG of superalloys becomes faster as test temperature increases. It is confirmed by Figures 6 that FCGRs of all the three alloys increase at high temperature. There are three reasons for increasing of crack growth rates with temperature. At first, the strength of the alloy is reduced at high temperature since mobility of dislocations increases. As seen in Figure 10, there are more activated dislocations at high temperature. Secondly, some high temperature mechanisms~~,~~ such as creep and recovery that can not happen at low temperature will affect fatigue process. Thirdly, environmental effect plays an important role in the FCG of superalloys at high temperature. The general agreement for the environmental effect has been established that, stress assisted grain boundary oxidation (SAGBO) plays the principal role in the environmental effect. Oxygen present in the air leads to the weakening of grain boundaries resulting in higher growth rates. As the temperature increases, the kinetics of oxygen diffusion and oxidation will be also increased.

4.2 Effect of Hold-Time of FCG

Fatigue crack growth behavior can be divided into two categories: cycle-dependent and time-dependent. For cycle-dependent fatigue crack growth, the steady state crack growth rate has been considered to be insensitive to the variations of microstructure and alloy chemistry [4], although there are some results showing that the resistance of superalloy to fatigue crack growth can be slightly improved by shot peening [14], composition adjustment [15] and microstructure control [16].

If the test is conducted at high temperature in air, fatigue crack growth rate may increase with hold-time; this kind of behavior is called time-dependent fatigue crack growth. In this study, it is found out by comparing Figure 6 with Figure 8 that the FCGRs of all the three alloys are accelerated by hold-time, i.e. $(da/dn)_{3+100S}$ > $(da/dn)_{3S}$. There are two things happened during the hold-time:, creep and environmental degradation. The effects of each individual factor are discussed as below:

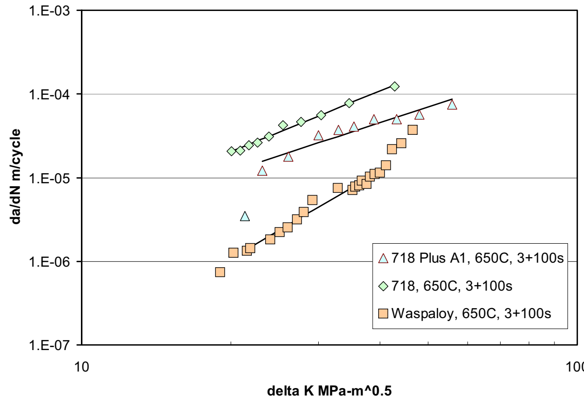
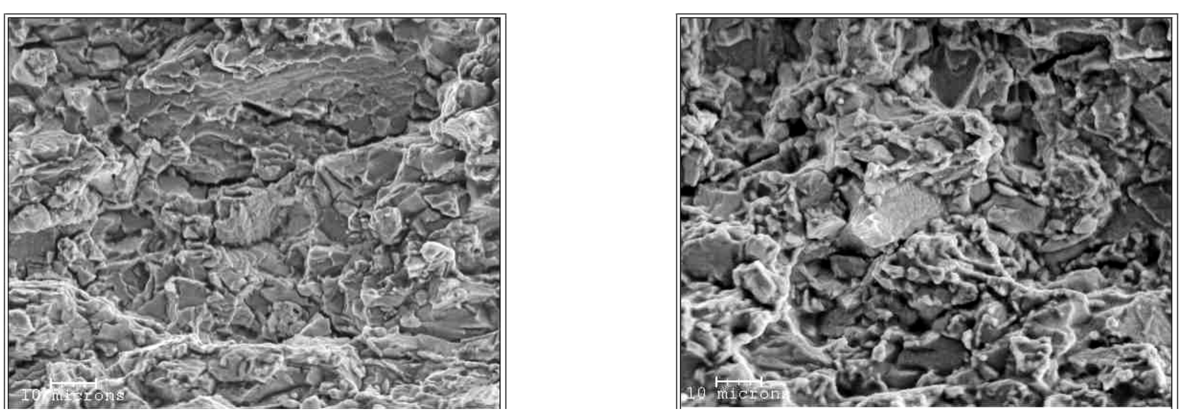


Figure 8: Fatigue crack propagation behaviors of 718PLUS^{TM} alloy under 3+100s trapezoid loading at 650°C, as compared to that of Alloy 718 and WASPALOY.

<u>(1) Creep Effect:</u> Historically, time-dependent FCG was first attributed as the result of fatigue-creep interaction. It was said that creep can increase the FCG rate of the alloys by creep damage, grain boundary cavity formation, linkage and creep crack growth [17].

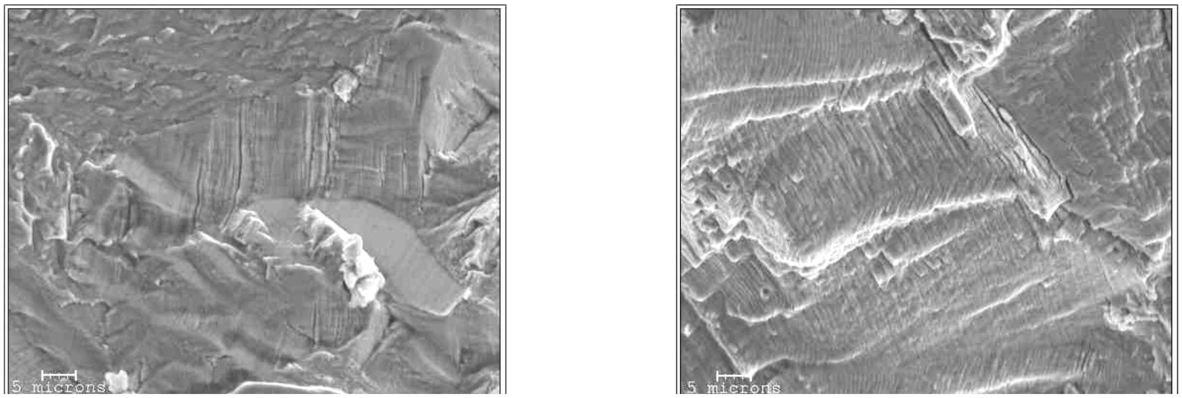
However, our previous investigation on the FCG of WASAPLOY [18] confirms that creep plays a beneficial role on the fatigue crack growth of the alloy under 760°C and lower ΔK. During the steady-state hold-time FCG, stress relaxation and crack-tip blunting caused by creep lowers the stress concentration in front of the crack tip, and the fatigue crack growth rate of the alloy. Only in the final stage of the test, creep damages lead to cavity nucleation and growth at the grain boundaries, which accelerate fatigue crack growth rate of the alloy.

Since creep plays the key role in fatigue crack growth behaviors of superalloys. It is expected that anything affect the alloys' creep properties, especially creep ductility, would impact the hold-time FCG. It has been found that the creep strength and ductility of superalloys at 600°C to 800°C can be improved by increasing



(a)– 650°C, 3+100s (b) – 704°C, 3+100s

Figure 10: SEM fracture surface micrograph of 718PLUS^{TM} after FCG tests under 3+100 seconds trapezoid load at 650°C and 704°C.



(a) – Room Temperature (b) – 650°C

Figure 11: Slip bands of 718Plus® at room temperature and 650°C

grain size [19, 20]. In this study (see Figure 8), it was found that WASPALOY seems have better resistance to hold-time FCG than that of 718PLUS™ alloy. There may be two reasons for the difference, nature of alloy and grain size effect. The grain size of Waspaloy is bigger than that of 718PLUS™ alloy tested, which may lead to better FCG resistance. Therefore, the effect of alloy chemistry on the hold-time FCG should be further investigated by comparing the alloys with similar grain sizes.

(2) Environmental effect: Regarding the environmental effect, it has been found that oxygen diffuses into the grain boundary in front of the crack tip and decreases the cohesion of the grain boundary and the alloy's resistance to crack growth [21].

Comparison of comparing Figure 6 with Figure 8 that the FCGRs of all the three alloys are accelerated by hold-time, i.e. $(da/dn)_{3+100S} > (da/dn)_{3S}$. We believe environmental degradation, in addition to creep damage plays important role in the hold-time effect on the FCGR of 718PLUS™, but it is difficult to quantify its contribution to observed holding time effect at this time.

As stated above, the fatigue crack growth rate of 718Plus™ under 3s triangle loading is slightly slower than that of Waspaloy, but the reverse was true for holding time fatigue. It seems that holding time has more significant effect in alloy 718Plus than in Waspaloy. More significant change in alloy 718Plus could be due to the inferior creep characteristics of alloy 718Plus with finer grain size in comparison with Waspaloy at larger grain size or due to inferior resistance of alloy 718Plus™ to environmental degradation. The overall effect of hold-time on fatigue crack growth depends on the competition between beneficial stress relaxation effect and harmful creep damage plus environmental effect.

Reliable conclusions regarding holding time effect can be made only after fully characterizing the creep characteristics and environment degradation resistance of alloy 718Plus™ in comparison with other alloys such as Waspaloy.

V Concluding Remarks

In this paper, the mechanical properties, especially fatigue crack propagation behaviors of the newly developed Ni-base superalloy Allvac® 718Plus™ Alloy were investigated, as compared with those of Alloy 718 and Waspaloy.

Based on the results obtained from this research, several conclusions can be drawn:

- The newly developed 718Plus™ alloy shows better tensile and stress rupture properties for temperatures up to 704°C than Alloy 718.
- The tensile and stress rupture properties of 718Plus™ are similar to that of Waspaloy for the temperature up to 704°C.
- For the fatigue crack growth without holding time, there is no significant difference between the three alloys. In comparison, 718Plus™ has the best FCGR resistance and 718 the lowest.
- 718Plus™ shows slightly lower resistance to hold-time FCG than that of Waspaloy. The cause for this difference needs to be further defined.
- Alloy 718Plus shows better hold-time FCG properties than Alloy 718.

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