Environment effect on high temperature fatigue crack propagation of nickel-base superalloys

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Abstract

Riassunto

The high temperature fatigue crack propagation (FCP) behaviour of nickel base superalloys can be dramatically influenced by the creep and specially by the oxidation processes taking place at crack tip. These time dependent mechanisms are enhanced when the frequency of the applied load is reduced or when a dwell period is included in the fatigue cycle. Detailed analysis has been devoted to oxidation contribution to FCP behaviour that can increase or decrease FCP resistance of superalloys depending on temperature and microstructure. The aim of this work is to study the FCP behaviour of traditional and more innovative superalloys in their different temperature range of application. Air tests conducted in the 650 - 750°C temperature range on wrought and cast alloys have shown an increase of FCP rate when test frequency is reduced. On the other hand, decreasing the test frequency, the single crystal superalloy tested at 950°C shows a decrease of FCP rate mainly due to a closure process induced by oxidation at crack tip that is the predominant mechanism at very high temperatures. The same tests performed in vacuum for all the examined alloys, being essentially independent on the applied frequency, have confirmed the effectiveness of oxidation rather than creep mechanisms on FCP behaviour.

La velocità di propagazione di cricca per fatica (PCF) ad elevata temperatura nelle superleghe di nichel può essere drasticamente influenzata da fenomeni di ossidazione e di creep che hanno luogo all'apice della cricca. Questi meccanismi dipendenti dal tempo acquistano particolare rilievo quando si riduce la frequenza di applicazione del carico o quando si inserisce nel ciclo un periodo di mantenimento del carico al valore massimo. Di notevole importanza è apparso il contributo dell'ossidazione che può aumentare o ridurre la resistenza alla PCF delle superleghe di nichel in funzione della temperatura di prova e della microstruttura. Scopo del presente lavoro è lo studio della resistenza alla PCF in superleghe di nichel tradizionali e di formulazione più innovativa, nel loro tipico campo di temperature di utilizzo. Prove in aria effettuate tra 650 e 750°C su leghe forgiate e leghe fuse hanno mostrato un aumento della velocità di PCF al diminuire della frequenza di prova. Al contrario, alla temperatura di 950°C, la superlega monocristallina mostra una diminuzione di velocità di PCF al diminuire della frequenza di prova, principalmente a causa di un meccanismo di chiusura attivo all'apice della cricca e indotto dall'ossidazione. Le stesse prove sperimentali effettuate in vuoto su tutte le leghe esaminate, non essendo influenzate dalla frequenza di applicazione del carico confermano il ruolo primario dell'ossidazione all'apice della cricca nel governare la velocità di propagazione ad elevata temperatura.

INTRODUCTION

Nickel base superalloys are extensively used in high temperature components of gas turbines. In this condition fatigue is often referred to as regime of time dependent fatigue: creep and oxidation processes at crack tip can take place in addition to the cyclic damage, usually leading to an acceleration of fatigue crack propagation rate (FCPR).

The influence of time dependent mechanisms on high temperature fatigue crack propagation behaviour of superalloys is enhanced when test frequency is reduced or when a dwell period is included in the fatigue cycle (1). In fact at lower frequency, time under load rather than number of cycles becomes important, owing to factors promoting creep processes at crack tip and/or environmental factors that can control the phenomenon at lower frequencies in air. These mechanisms are often difficult to separate from each other.

In wrought and conventionally cast (CC) superalloys, typically operating in the intermediate temperature range (up to about 750°C), FCPR increase increasing test temperature and the contribution of time dependent processes lead to an increase of FCPR in air tests with respect to vacuum tests (2, 3). This behaviour has been related to several factors like yield

stress and elastic modulus reduction, change in slip character of deformation and, in polycrystalline materials, transition from transgranular to intergranular cracking.

Studying an advanced single crystal (SC) alloy, tested at higher temperatures, a new trend appears: i) at a given test frequency the increase of temperature in the 750 - 950°C range leads to a decrease of FCPR and ii) at 950°C FCP rates measured in air are significantly slower than in vacuum. This effect has been related to a crack closure mechanism (4) that involves formation of corrosion debris on freshly exposed surface at the crack tip that may wedge-close the crack at stress intensities well above K_{min} when the oxide deposits reach a thickness comparable to the crack tip opening displacement (CTOD). This effect is stronger at low stress intensities due to the smaller CTOD involved with respect to the oxide layer thickness.

In this work the study of the influence of oxidation effects on fatigue crack propagation behaviour of several nickel base superalloys at different temperatures and frequencies is illustrated and discussed, also in terms of crack closure effects (5).

MATERIALS

The materials studied in the present investigation are:

- a) Inconel X-750 and Inconel 718 wrought alloys
- b) IN 792 + Hf cast alloy
- c) CMSX-2 single crystal alloy.

The chemical compositions of the examined alloys are shown in Tab. 1.

The Inconel X-750 alloy used in this investigation was supplied in the form of 12.7 mm thick plates, solution annealed at 1150°C for 2h and aged at 850°C for 24h and air cool and finally aged at 700°C for 20h and air cool. Average grain size is about 0.12 mm.

	Ni	Cr	Co	Мо	Fe	W	Ta	Nb	Al	Ti	Hf	c
X-750	73	15	-	0.5	7		-	1	0.7	2.5	-	0.04
718	53	18	0.03	3	19		-	5.3	0.6	1	-	0.03
792+Hf	61	12	9	1.9	•	3	3.9	•	3.1	4.5	1	0.12
CMSX-2	67	8	4.6	0.6	•	8	6	106-2010	5.6	1		-

TABLE 1 - Chemical composition of the studied alloys

Inconel 718 was supplied in form of extruded bar, annealed at 1093°C/1h/AC, aged at 720°C/4h, furnace cooled to 620°C at the rate of 50°C/h and aged at this temperature for 8h. Grain structure was uniform with average grain size of 0.10 mm.

The cast material IN 792 + Hf was supplied in form of a small gas turbine disk. The cast disk was heat treated at 1120° C for 2h/FAC + 845°C for 4h/AC + 760°C for 16h/AC and then hipped: 198 MPa at 1177°C for 4h. However, the structure of the cast alloy was very inhomogeneous. Grain size was increasing from the external region of the disk to the central zones from 0.6 to 1.5 mm.

The CMSX-2 single crystal was cast and solution treated by Thyssen. It was obtained in cylindrical bar form with 12 mm diameter and 160 mm length. The principal axis of the bars was within 6° off the <001> direction. Due to the strong anisotropy of the mechanical properties of this alloy (6) special attention has been payed also to the crack propagation direction with respect to the secondary crystalline orientation. The standard heat treatment was carried out at 1080°C for 4h followed by 870°C for 20h and produced a 2/3 volume fraction dispersion of cuboidal γ ' precipitates of 0.5 µm average size.

EXPERIMENTAL PROCEDURES

Single edge notch tension (SENT) specimens were used with a rectangular cross section of 11.7 x 4.4 mm² and a 0.8 mm deep starter notch. The FCPR tests were carried out in air and in vacuum ($p_{02} < 10^{-5}$ torr) in load control with triangular wave shape (R = 0.05) at frequencies ranging from 0.01 to 10 Hz and at different temperatures. The fatigue specimens were precracked at 10 Hz. Induction heating was controlled to $\pm 3^{\circ}$ C. To better understand the influence of time dependent mechanisms on FCPR some tests were also performed with a dwell period at maximum load added to the triangular wave.

Crack lengths were measured by the d.c. potential drop technique. Crack rates were calculated by the secant method according to ASTM specifications and correlated to the stress intensity factor range $\Delta K = K_{max} - K_{min}$.

The stress intensity factor was calculated as follows (7): $K=(P/BW)\sqrt{\pi a \{1.12-0.23(a/W)+10.6(a/W)^2-21.7(a/W)^3+30.4(a/W)^4\}}$

where P is the maximum load, W the specimen width, B the specimen thickness and a the crack length.

As far as the conditions of small scale yielding linear elastic fracture mechanics are respected for the examined alloys FCPR can be considered a unique function of the stress intensity range.

EXPERIMENTAL RESULTS AND DISCUSSION

The Fig. s 1a - d show the temperature effect on FCP rate behaviour of the alloys examined. For each class of material the temperature range of interest for application was studied: up to 650°C for the Inconel X-750 and Inconel 718 wrought alloys, up to 750°C for the IN 792 + Hf cast alloy and up to 950°C for the CMSX-2 single crystal alloy.

From the analysis of these data an increase of FCP rate appears when temperature is increased up to 750°C, while a decrease of FCP rate is observed for the SC alloy after a further increase of temperature up to 950°C.

The FCP rate increase of wrought alloys with temperature seems to be mainly due to the environmental effect on this small grain size materials, since the FCP rate behaviour in vacuum at 650°C, also reported in Fig.s 1a and b is not much different from the room temperature behaviour in air. In the case of the conventionally cast alloy the oxidation effect is not enough to explain the FCPR acceleration with temperature up to 750°C, as it can be seen comparing air and vacuum curves of Fig. 1c. At the highest temperature 950°C, in the SC alloy, oxide crack closure decreasing the effective stress intensity factor range produces a slower FCPR; this inversion of the trend of FCPR behaviour at the highest temperature could be partially also due to crack tip blunting.



Figure 1: influence of temperature on FCPR of several nickel base superalloys: b) Inconel 718



Figure 1: influence of temperature on FCPR of several nickel base superalloys: a) Inconel X-750_____



Figure 1: influence of temperature on FCPR of several nickel base superalloys: c) IN 792+Hf_____

In Fig. 2 and Fig.s 3 a and b is shown the effect of frequency, in the 0.01 - 10 Hz range, on air and vacuum FCPR of wrought alloys Inconel X-750 and Inconel 718 at the temperature of 650°C. A marked influence of frequency appears in air tests, while the vacuum results are almost independent from the test frequency. In the Inconel 718 alloy the addition of a 90 s hold time at maximum load to the 0.1 Hz triangular wave results in the most damaging cycle in both air and vacuum, indicating that also creep phenomena intervene in these experimental conditions.

In Fig. 4 the FCP behaviour of the IN 792 + Hf alloy in air and vacuum at 750°C for two different loading frequencies appears. The oxidation effect accelerates FCPR, but it is smaller than in the wrought alloy and it faints out at low values of ΔK , where oxidation crack closure slowing effect could compensate the environmental acceleration of the phenomenon. It should also be noted that lower frequency produces an acceleration effect also in vacuum, consistent with creep phenomena being operative at 0.01 Hz and 750°C in this alloy.

The FCPR curves of the CMSX-2 single crystal alloy are shown in Fig. 5: the 4 Hz vacuum curve represents the pure fatigue component of the crack propagation phenomenon that is quite close to the CTOD model prediction (8), shown by the dashed line. The 4 Hz curve in air is more than an order of magnitude slower at the smallest ΔK . This FCPR gap continuously decreases with increasing ΔK and the two curves finally converge at high ΔK , consistently with an oxide in-





duced closure process. When the hold time is added in vacuum no creep effect appears at low ΔK , but when ΔK is increased the hold time curve and the triangular curve continuously



Figure 2: influence of test frequency at 650°C on FCPR of Inconel X-750 ____alloy in air and vacuum





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Figure 3: influence of test frequency at 650°C on FCPR of Inconel 718 alloy: b) vacuum tests

diverge. The difference between these two curves in vacuum represents the creep contribution to the FCPR. The hold time curve in air appears still slower than the triangular curve for all the ΔK range explored indicating that: i) oxide closure is more effective, and ii) oxide blunting of the crack tip occurs,



Figure 4: influence of test frequency at 750°C on FCPR of IN 792+Hf alloy in air and vacuum______

when hold time is added. These two phenomena could also explain why no creep acceleration is clearly observed in the hold time curve in air.

When the environment is repeatedly changed from vacuum to air and vice versa, during a single test at 950°C applying 5



Figure 5: hold time (HT) and environment effect at 950°C on FCPR of CMSX-2 alloy (<001> loading and <110> propagation directions)



Figure 6: effect of repeatedly changed environment from vacuum to air and vice versa at 950°C on a hold time FCPR of CMSX-2 alloy

s hold time the FCPR behaviour confirms slower propagation in air than in vacuum, sometimes showing a transient stage, Fig. 6.

Microstructure of the examined alloys definitely plays an important role in the FCPR response; it is widely accepted that grain boundaries are a weakening factor when environment damage plays a role, hence a small grain size wrought alloy is expected to be less resistant than single crystals that do not contain weak points for oxidation. Nevertheless the oxide closure type slowing down of FCPR in SC material at 950°C could be essentially a temperature rather than microstructure effect, and hence can not be excluded to occur also in wrought and conventionally cast materials at very high temperature, although it has not been verified experimentally.

CONCLUSIONS

Air FCP rates of wrought and cast alloys in air at intermediate temperatures increase when frequency decreases. Opposite behaviour has been shown by CMSX-2 at 950°C.

Oxidation effects are considerable in wrought alloys at 650°C: air FCP rates are significantly higher than in vacuum. At 750°C and low ΔK the conventionally cast alloy shows a lower sensitivity to oxidation than the wrought alloy, but still air FCP rates are higher than in vacuum.

Rising temperature to 950°C in CMSX-2 alloy air FCP be-

comes slower: the effect of oxidation is to slow down FCP rates through oxide induced closure mechanism at low ΔK and possibly through crack tip blunting.

In CMSX-2 at 950°C air FCP measurements are not conservative since FCP rates in air are much slower than in vacuum, specially when hold time is applied; vacuum measurements in fact simulate growth of a crack starting and propagating inside the component

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