Fatigue Crack Growth Behavior of a near α IMI-834 Titanium Alloy at Elevated Temperature

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Abstract

From service point of view effect of two important parameters, namely, temperature and frequency on Fatigue Crack Growth (FCG) Behaviour of a near α IMI-834 titanium alloy has been investigated. In the low temperature regime (ambient to 500ºC), FCG resistance is mainly controlled by modulus and strength of the alloy. In the high temperature regime (>500ºC), the resultant FCG resistance under a given set of temperature, frequency and stress intensity conditions (ΔK) appears to be dictated by a complex interaction of several competing mechanisms such as creep, fatigue and oxide damage. The fractographic and crack path observations confirm that the crack growth mechanism is highly faceted crystallographic in nature, especially in low ΔK regime. The crystallographic growth mechanism is changed to striation mode at a critical ΔK level, with striations varying in their orientations within individual α colonies. High temperature-low frequency tests show presence of oxide features and cavitation around prior β grain boundaries and α needle boundaries.

1. Introduction

Reduction in weight is one of important aspects of aeroengine design, thereby enhancing maneourability and fuel efficiency. Recently, there has been a thrust to replace these Ni-based super alloys partially with modern titanium alloys which are half as dense and thus, have potential for reducing the over all weight of the engine. In this regard, a near α IMI-834 titanium alloy has received much attention in the recent years due to their enhanced temperature capability, mainly attributable to presence fine ordered silicide $(Ti,Zr)_6Si_3$ precipitates[2]. Recently some work on creep-fatigue interaction and damage mechanisms has been investigated under LCF conditions for this alloy[4,5]. From damage tolerance based design point of view, fatigue crack growth characterization become important under appropriate service conditions. Effect of temperature, and frequency on FCG resistance has been investigated.

2. Experimental

Material

The alloy conforming to IMI-834 composition (Ti-5.68Al-4.05Sn-3.65Zr-0.68Nb-0.52Mo-0.33Si) was received from M/s Timet, UK Limited, in form of rods of 20 mm diameter. The β transus temperature for the alloy is ≈1045ºC-1050ºC The standard bimodal microstructure was produced by a heat treatment comprising of solutionising at 1010ºC for 1 hr and air cooling, followed by ageing at 700ºC for 2 hrs and air cooling. The microstructure (**Fig.2**) consists of primary α (5-10%) in transformed β matrix. The material under heat treated condition exhibits a yield strength of 932 MPa, UTS of 1025 MPa, elongation of 11% and reduction in area (RA) of 22%.

Fatigue Crack Growth Test

The range of two basic test parameters, namely, temperature (500ºC-600ºC) and frequency (0.1 Hz -10 Hz) were selected so as to explore the full serviceability range of IMI-834 alloy for compressor disk application as shown in **Table 1**.

Table 1: Test Matrix-I : Effect of temperature and frequency

Frequency	Temperature				Test conditions
10 Hz	25ºC	500ºC	550ºC	600ºC	R=0.1 Wave form – Sine
1 Hz	-	500ºC	550ºC	600ºC	
0.1 Hz	-	500ºC	550ºC	600ºC	

The fatigue crack growth testing was performed using single edge notched tension (SENT) type of specimen having a width of 18 mm, length of 60 mm, thickness of 3.5 mm and with an initial through-thickness notch of 2 mm depth. FCGR tests were performed on MTS servohydraulic test machine at a stress ratio of R=0.1 ($R=\sigma_{min}/\sigma_{max}$). in accordance to ASTM-E647 test standard[8]. The crack length was measured using A.C potential drop technique.

4. Results

4.1 Effect of Temperature

The effect of temperature has been categorized for three frequencies, namely, 10 Hz, 1 Hz and 0.1 Hz. Here data for only 10 Hz and 0.1 Hz cases are shown in **Fig.1.** The results indicate a strong influence of temperature and frequency on FCGR behaviour. An increase in FCG rates is obvious at higher temperatures as compared to baseline ambient test temperature.

4.2 Effect of Frequency

Effect of frequency could be brought out by categorizing the test results at three temperatures, namely, 500°C, 550°C and 600°C. Here data for only 550°C and 600°C cases are shown in **Fig.2**. In general, the FCG rates are observed to increase with decrease in frequency. At 600°C, influence of frequency appears to be quite strong.

4.3 Crack Growth Mechanisms

Extensive SEM fractographic work has been performed on each test condition in order to understand the crack growth micro-mechanisms. One typical set of fractographs are shown in **Figs.3-5** bringing out effect of ΔK, temperature and frequency. The crack growth mechanism (**Fig.3**) is highly faceted crystallographic in nature, especially in low ΔK regime. The crystallographic growth mechanism is changed to striation mode, with striations varying in their orientations within individual α colonies. With increase in temperature (**Fig.4**) or decrease in frequency (**Fig.5**), irregular black and cavitated feature become more dominant. Evidence of creep damage is found around the crack tip area. The cavitation has been observed along prior β grain boundaries as well as α needle boundaries (**Fig.6**). Several independent cracks nucleate along these preferred paths crack and tend to join the main crack

5. Discussion

From the results, it could be concluded that FCG resistance of IMI-834 alloy is strongly affected by temperature and frequency. In general, FCG rates are observed to increase with increase in temperature and decrease in frequency. At elevated temperature, several additional time dependent contributions to crack growth mechanisms such as creep and oxidation become active. Several of these mechanisms could operate synergistically, while their relative contributions may vary with test parameters combination selected.

FCG rates are observed to be higher at elevated temperatures, in contrast to those at ambient temperature, though the difference in FCG rates are marginal within the temperature range 500°C-600°C. It is well documented that FCG resistance is strongly affected by basic monotonic tensile properties such as yield strength, work hardening and elastic modulus. The yield strength and the elastic modulus of titanium alloys are known to decrease significantly at elevated temperatures. Considering the CTOD based models, which take into account the strength and modulus effects on crack growth, much of the temperature effects on FCG resistance could be attributed to the changes in these properties. The FCG data for different temperatures at 10 Hz (discounting time dependent contributions as against 1 Hz and 0.1 Hz cases) when plotted (not shown here) in terms of da/dN versus the crack driving force, CTOD ($=\Delta K^2/E.\sigma_{ys}$). The data corresponding to ambient and elevated temperatures are observed to consolidate within a narrow range. A marginal divergence in case of 550ºC could be attributed to additional factors such as crack closure. Consolidation of data is indicative of the fact that FCG is mainly controlled by yield and elastic properties, rather than other time dependent mechanisms listed above. Despite normalizing the data with respect to yield strength and elastic modulus, a marginal enhancement in crack growth at lower frequencies <0.1 Hz suggests that additional creep and/or environmental controlled mechanisms such as oxidation could be the governing mechanisms.

Oxidation or / and creep could be the dominant mechanisms operative in the present investigation. In the absence of data under vacuum, it is difficult to assess the relative contributions of the two mechanisms in the present investigation. The work on a similar Si-bearing Ti-1100 near α–titanium alloy[6], used for the similar applications, have confirmed the similar frequency effects in range of 0.05-10 Hz at 593°C under both air as well as vacuum environment, thus confirming creep to be the primary mechanism. Oxidation has been attributed to have secondary effects on FCG resistance in air. Under vacuum, creep damage and strain rate responsible for modifying the slip density around the crack wake has been identified as the main governing mechanisms. The evidence of creep cavitation are found around the crack tip area, especially for lower frequency (1 Hz) and higher temperatures (>550ºC) tests. The cavitation has been observed along prior β grain boundaries as well as α needle boundaries (**Fig.6**). Several independent cracks nucleate along these preferred paths crack and tend to join the main crack.

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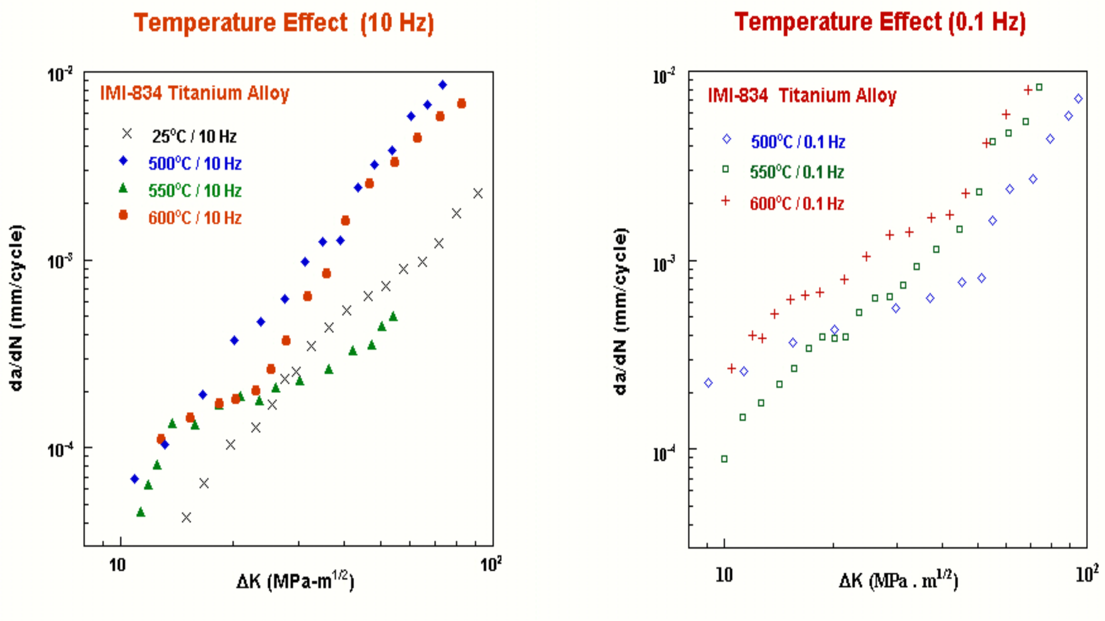
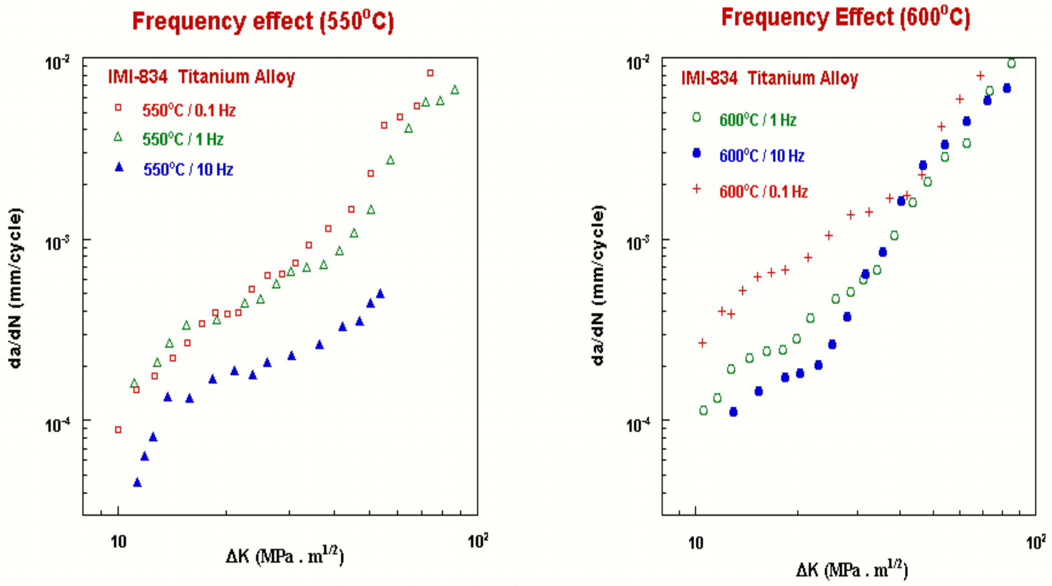


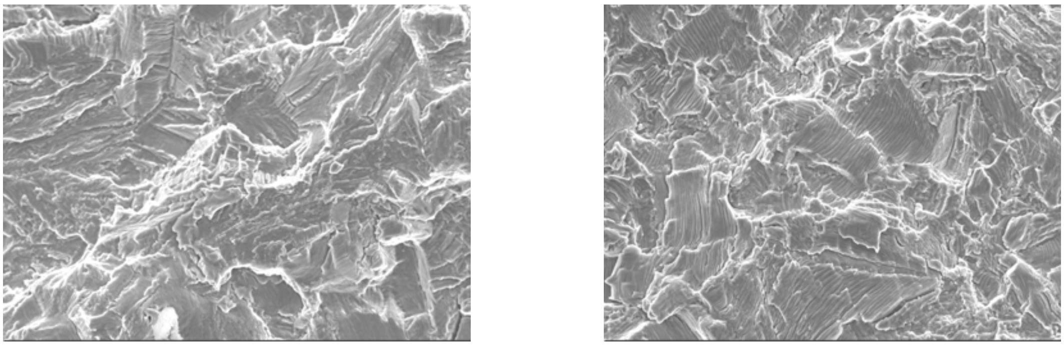
(a) (b)

Fig.1 Effect of temperature on FCG resistance at: (a) 10 Hz, (b) 1 Hz



(a) **(b)**

Fig.2 Effect of frequency on FCG resistance : (a) 550°C, (b) 600°C



(a) **(b)**

Fig3. Effect of ΔK on crack growth mechanism 1 Hz/550°C at:

(a) ΔK = 25 MPa√m, (b) ΔK=50 MPa√m

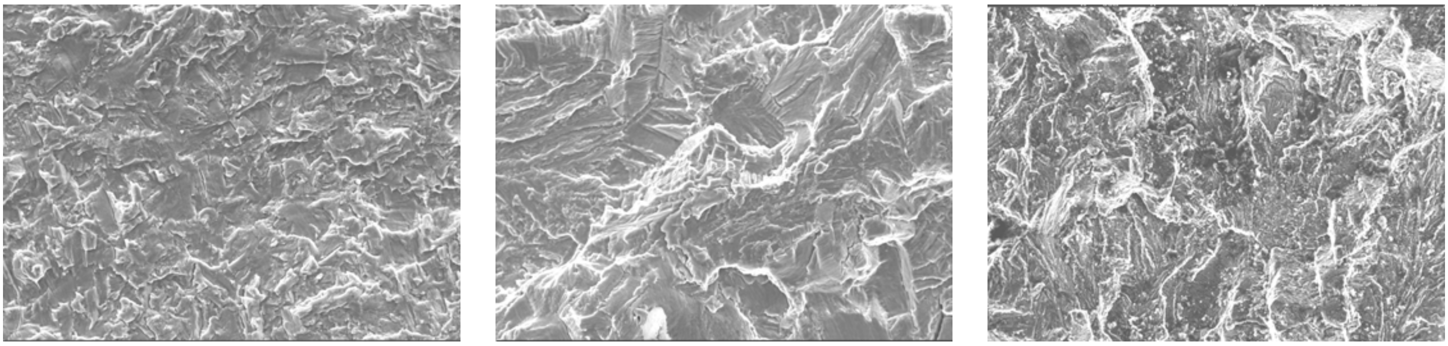

(a) **(b)** **(c)**

Fig.4 Effect of temperature on crack growth mechanism at 1 Hz,

ΔK = 25 MPa√m: (a) 25°C, (b) 550°C, (c) 600°C

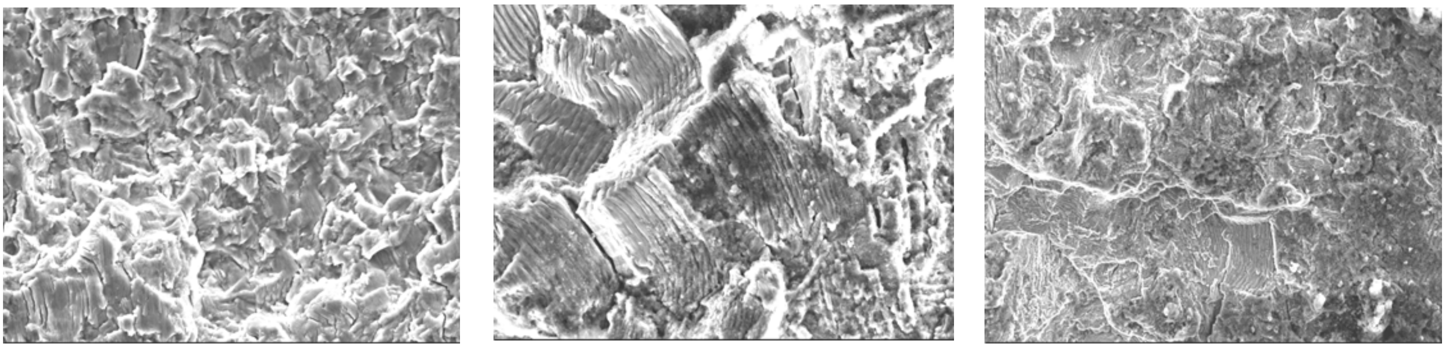

(a) **(b)** **(c)**

Fig.5 Effect of frequency on crack growth mechanism at 550°C,

ΔK = 50 MPa√m: (a) 10 Hz (b) 1 Hz, (c) 0.1 Hz

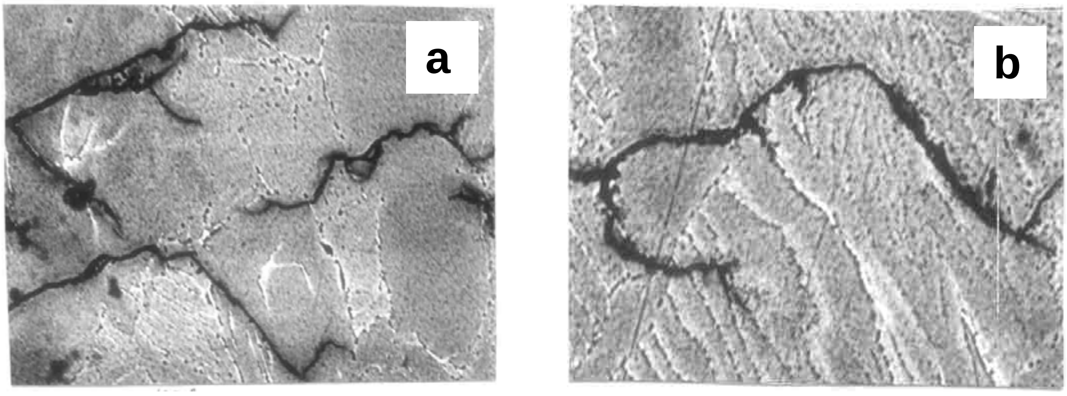


Fig.6   Evidence of creep cavitation along (a) prior β grain boundaries, (b) α laths