The Influence of Loading Cycle and Environment on Fatigue Crack Propagation in Ti6246 Alloy

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ABSTRACT

Fatigue crack growth tests on Ti-6Al-2Sn-4Zr-6Mo(Ti6246) alloy were carried out at 773K with either cyclic and dwell waveforms in air, an intermediate vacuum and high vacuum. Results for the DEN (Double Edge Notch) specimens showed that the fatigue crack growth rate with the dwell waveform was the highest among the various waveforms presently studied. Particularly at low stress intensity factor range (ΔK), the fatigue crack growth rate was considerably affected by different waveforms. The difference in fatigue crack growth rates between cyclic and dwell waveforms was, however, reduced at intermediate and high ΔK regions. The effect of environment on fatigue crack growth rate in Ti6246 alloy was also significant at 773K. The highest resistance to fatigue crack growth was observed in a high vacuum, followed by air and an intermediate vacuum. The highest fatigue crack growth rate was obtained in an intermediate vacuum, but there was only slight variation on the fatigue crack growth rates in between air and an intermediate vacuum.

Keywords: fatigue crack growth, potential drop, titanium alloy, environmental effect, loading cycle

1. INTRODUCTION

For modern aerospace engine materials, there is a great need for improved performances concerning thermal stability, compression rates and dynamic efficiency. For decades, titanium alloys have been developed as attractive aerospace engine materials because of their high strength to weight ratio, combined with excellent resistance to fatigue crack growth and corrosion /1,2/. Preliminary studies have demonstrated that Ti-6Al-2Sn-4Zr-6Mo(Ti6246) has properties that could meet some significant design requirements for aerospace engine applications /3,4,5/. The designers are, therefore, considering this $\alpha+\beta$titanium alloy, Ti6246, as a possible replacement for the current disc material. At present, it is believed that Ti6246 alloy can withstand temperatures up to 723K without any significant degradation in strength and other mechanical properties. Many researchers are trying to further increase the tolerable temperature of Ti6246 for the applications in more severe environments.

To overcome the present operational limits, the information on environment-crack growth interactions, including crack initiation and growth response, environmental influences and interaction between fatigue and creep damage processes of Ti6246 alloy, are greatly needed. The objective of the present study was, therefore, to examine the influence of environments and loading cycle on fatigue crack propagation of the alloy.

2. EXPERIMENTAL

2.1 Material

The Ti-6%Al-2%Sn-4%Zr-6%Mo (in wt.%) alloy used in this study was forged from billet to pancake geometry at 313K above the β transus. Forgings were solution heat treated for up to 2 hours at 303K below the β transus temperature. This was followed by aging at 868K for 8 hours and air cooling to room temperature. The resulting microstructure shows transformed Widmanstätten colonies, consisted of both aligned α phase and basketweave structure (Fig. 1). The room temperature and high temperature mechanical properties of this alloy are listed in Table 1, suggesting that this alloy has reasonably good mechanical properties up to 773K.

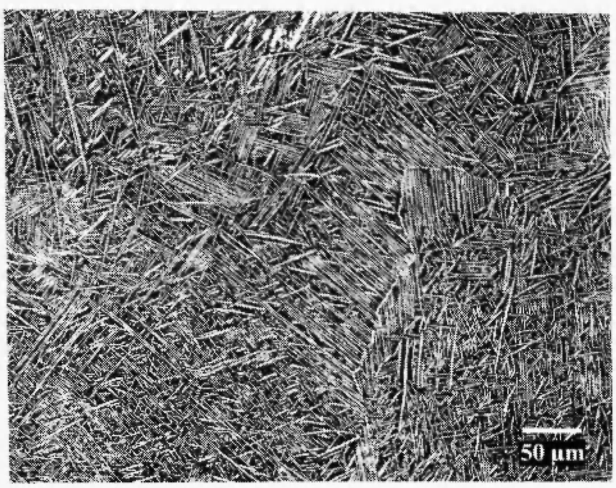


Fig. 1: Optical micrograph of Ti6246 alloy.

2.2 Fatigue test

The fatigue crack propagation tests were carried out under load control on a servo-hydraulic test machine. The tests were conducted at 773K in air, in an intermediate vacuum and in high vacuum. Two types of cyclic loading waveforms, sine and trapezoidal, were used. The dwell cycling consisted of 1 second rise, 120 second maximum hold, 1 second fall and 1 second minimum hold times. The waveforms used in the tests were created by using a automated waveform generator. Throughout the fatigue crack growth tests, crack length was monitored using the direct current potential drop (DCPD) method /6/. The potential drop (PD) at across the face of the crack and the reference probes was measured using a high sensitivity scanning voltmeter. For fatigue crack propagation tests, DEN (double edge notch) specimens were machined from forged discs. The schematic of the DEN specimen is shown in Fig. 2. The 3mm radius of the notch induces a stress concentration factor of 1.8 at the notch root. The effect of a notch has already been explored in detail elsewhere for the DEN specimen /7/. Fatigue fractured surfaces were examined and documented using a scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

3.1 Loading cycle effect on fatigue crack growth rate

The variation of crack length for Ti6246 is shown in Fig.3 as a function of cycles at 773K. This figure clearly

Table 1
Mechanical properties of Ti6246 alloy studied at room and high temperatures

Test Temperature (K)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Reduction of Area (%)
293	1194	1072	9.3	18
723	952	747	11.0	32
823	852	683	20.0	72

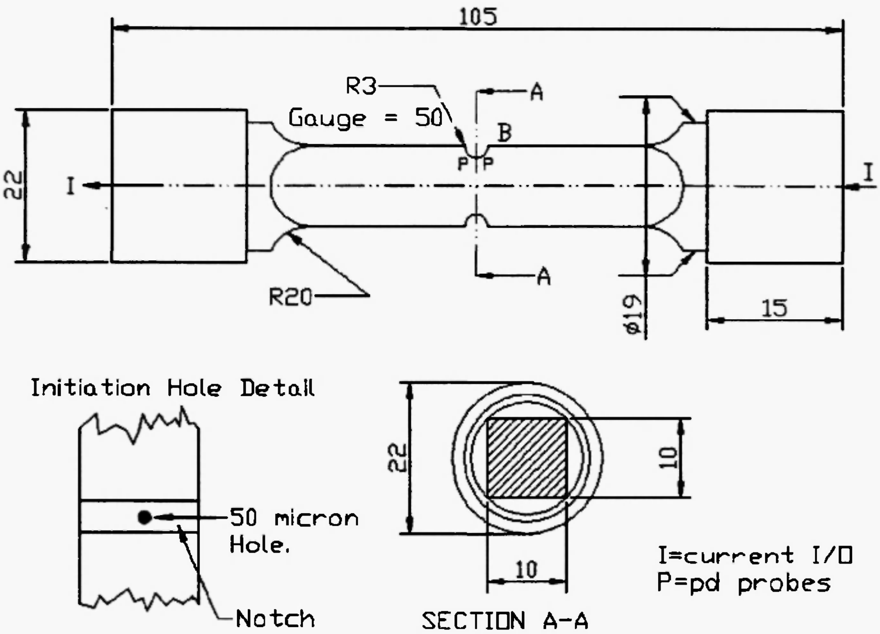


Fig. 2: Schematic of DEN specimen

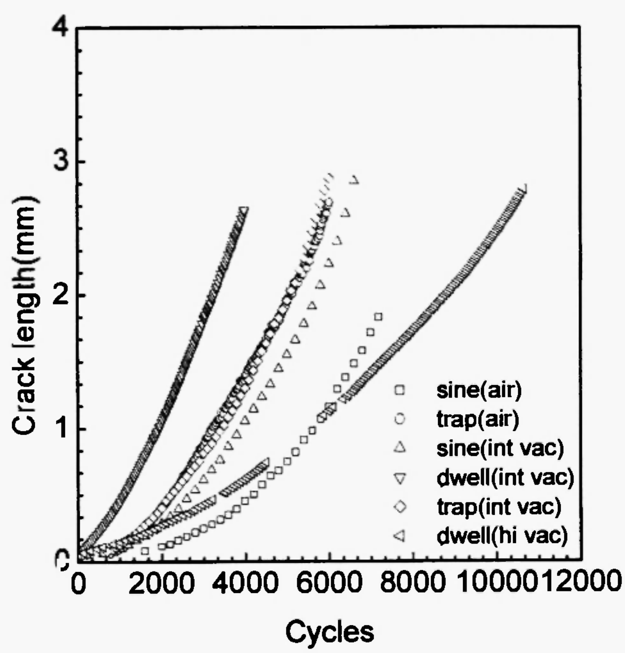
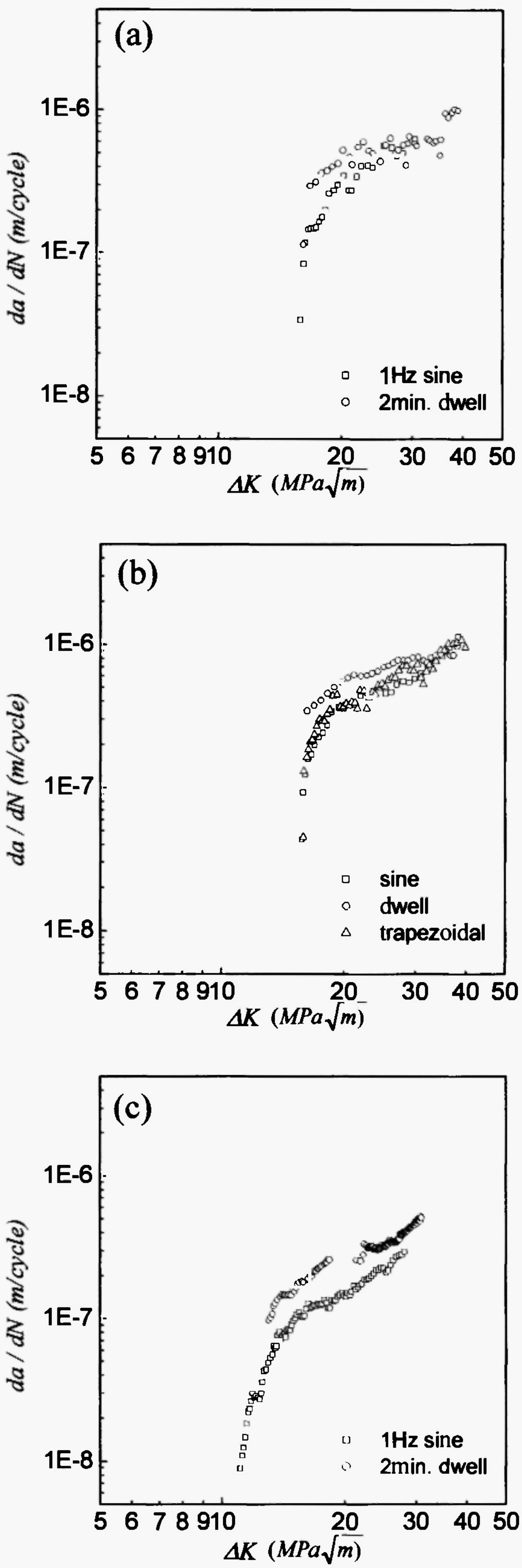


Fig. 3: Variation of crack length with a number of cycles.

demonstrates that fatigue crack growth behavior of Ti6246 alloy is strongly dependent on the environment and loading waveforms. For example, the fatigue crack growth rate of Ti6246 increases significantly with dwell loading compared to that with cyclic loading. The fatigue crack growth rates of this alloy were found to be also affected by different environmental conditions.

In order to understand the environmental effect on fatigue crack growth in Ti6246, fatigue crack growth rate (da/dN) versus ΔK plots for Ti6246 alloy with various loading waveforms are presented in Fig. 4. A direct comparison can be made between dwell and cyclic loading from these crack growth curves. The present experimental data clearly support the existence of a substantial effect of loading waveform on fatigue crack growth rates with respect to ΔK for each environment. The fatigue crack growth rate with dwell loading was generally higher than that with cyclic loading in all test conditions. The fatigue crack growth rates in air, as shown in Fig. 4(a), are higher with a dwell loading than those with a cyclic loading at low ΔK (below 15MPa√m) regime. However, there was no notable difference in fatigue crack growth rates between sine waveform and dwell waveform at high ΔK.

In an intermediate vacuum, the fatigue crack growth rate is found to be the highest for the 120 seconds dwell waveform, as shown in Fig. 4(b). The tests carried out with cyclic loading (sine and trapezoidal waveform)



showed lower fatigue crack growth rates at low ΔK compared to those with dwell loading, but the difference was mostly diminished as ΔK increased. Eventually, there was no significant difference in crack growth rates between sine waveform and trapezoidal waveform at high ΔK.

The trends observed for high vacuum tests were similar to those for the intermediate vacuum, such that the fatigue crack growth rate with the dwell loading was higher than that with the cyclic loading. There was, for example, a clear difference in the crack growth rate between cyclic and dwell loading, the difference of which was less evident when tested in air and an intermediate vacuum, as shown in Fig. 4(c). Below the applied ΔK value of approximately 12MPa√m, the slope increased and tended to approach a pseudo-threshold regime. Each vacuum test showed a knee in the fatigue crack growth curves at low ΔK, which has often been observed in some materials at elevated temperatures and commonly attributed to the change in fatigue crack growth mechanism /8,9/. With increase in ΔK above the knee, the slope gradually increased and finally converged to the plane stress fracture toughness value, where environment and creep components were of less importance for fatigue crack growth.

3.2 Environmental effect on fatigue crack growth rate

The effect of environment on fatigue crack propagation rates in Ti6246 alloy tested with a sine waveform is illustrated in Fig. 5(a). No considerable effect of environment on fatigue crack growth rates was observed as between air and an intermediate vacuum. A high vacuum, however, showed substantially reduced fatigue crack growth rates. Fig. 5(b) shows the crack growth rate of Ti6246 with dwell waveform in various environments. Similar trends were observed to those with sine waveform in Fig. 5(a). Interestingly, the

Fig. 4: Fatigue crack growth rates of Ti6246 with various waveforms in (a) air, (b) intermediate vacuum and (c) high vacuum, respectively.

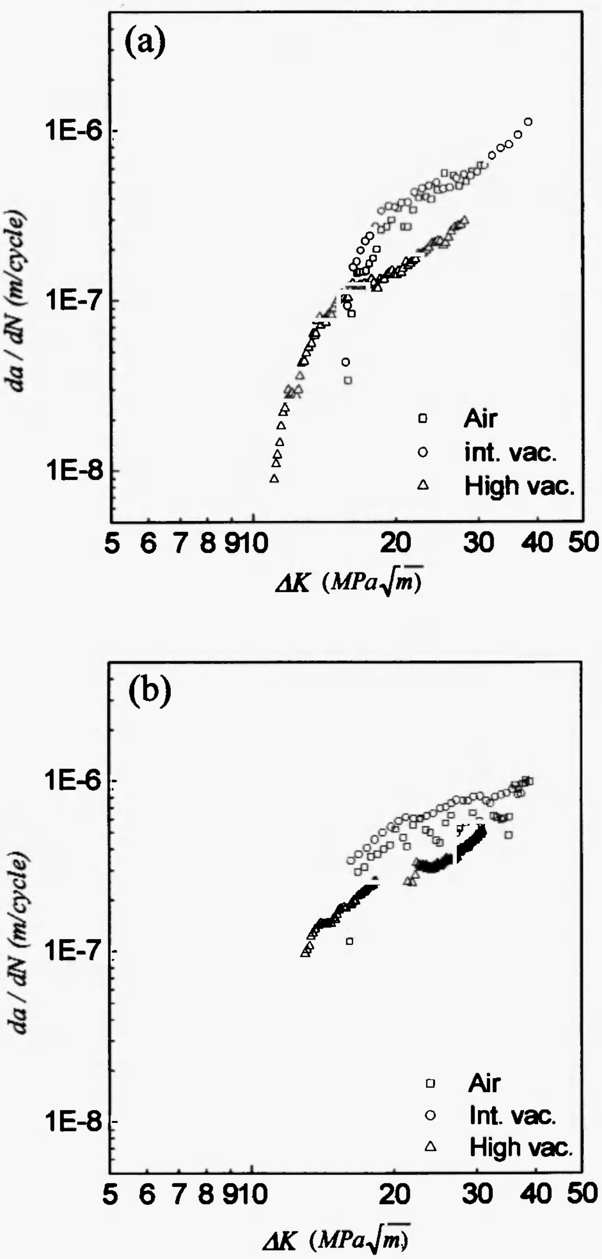


Fig. 5: Effect of test environment on fatigue crack growth rate in Ti6246 alloy with different waveforms of (a) cyclic loading and (b) dwell loading, respectively.

fatigue crack growth rates in an intermediate vacuum were higher than those in air, when tested with 120 second dwell waveform.

Fractographic features observed in Ti6246 alloy, fatigued in air and with a sine waveform, are represented in Fig. 6. The preferential cracking paths

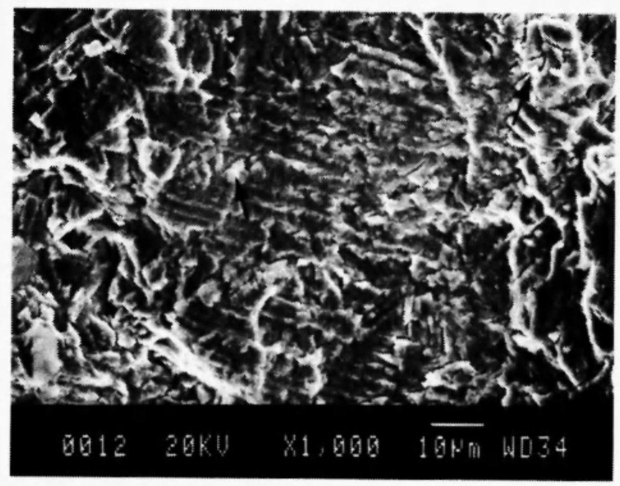


Fig. 6: SEM fractograph of Ti6246 tested in air and with sine waveform.

were found to be along the α/β interfaces, and some secondary cracks were often observed at the end of the fatigued area. Many acicular α-phase packets were found to form flat facets which developed into fine, well-defined striations. In addition, a considerable amount of oxides were distributed on the fracture surface, as indicated by arrows. SEM-EDS analysis suggests that the oxides mainly consist of oxygen and titanium, as represented in Fig. 7. These oxides facilitate

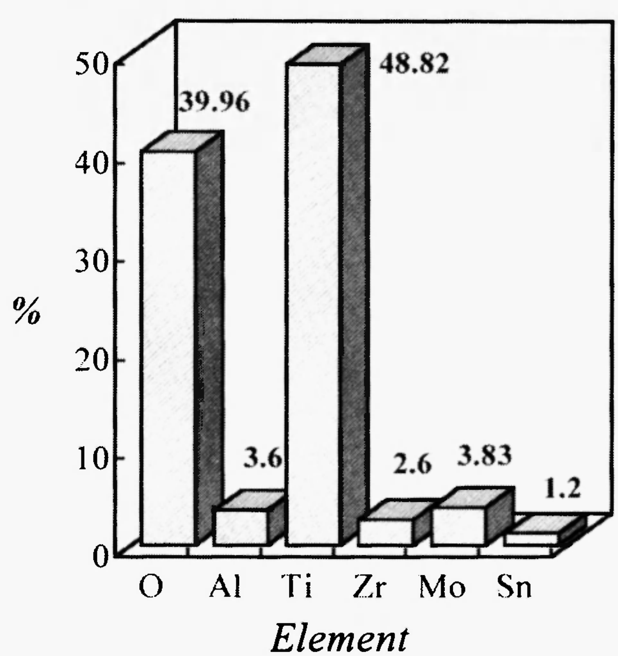


Fig. 7: EDX analysis of the oxides on the fractured surface of Ti6246 tested in air.

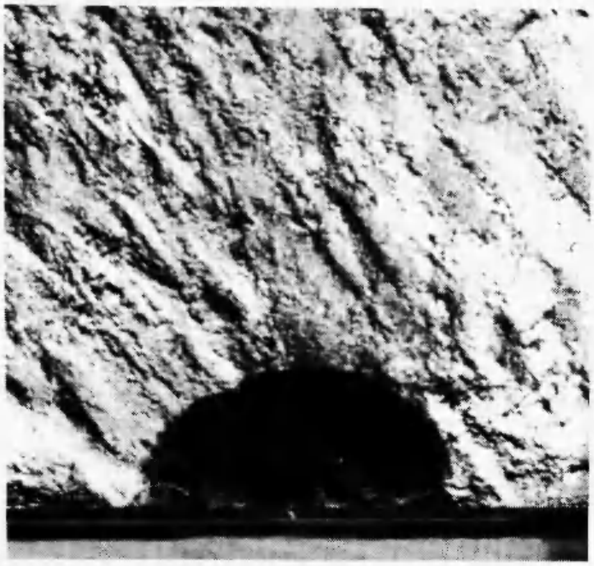


Fig. 8: Heat tinted fracture surface of a DEN specimen tested in air and with a 1Hz sine waveform.

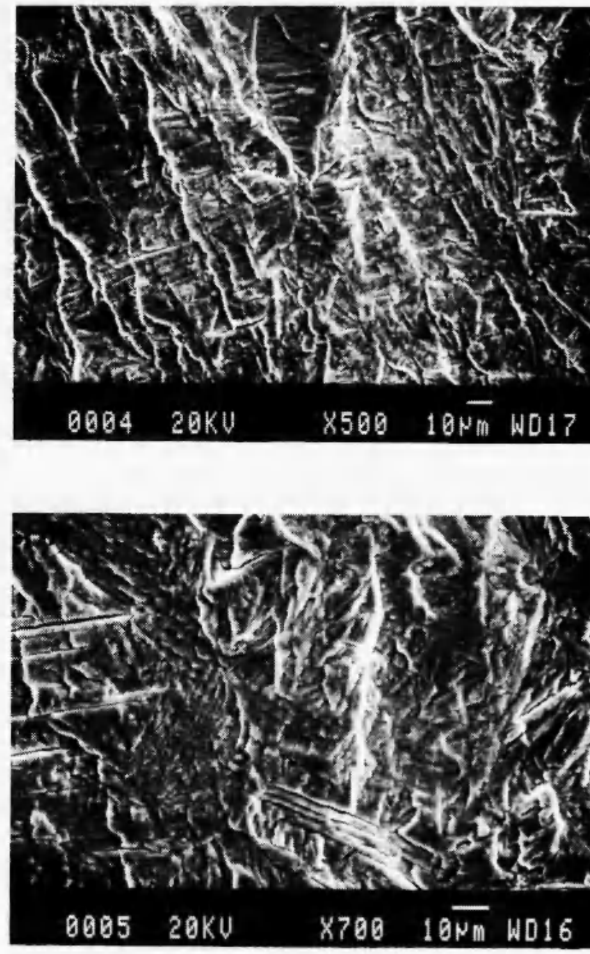


Fig. 9: Fracture surface morphologies of Ti6246 fatigued in high vacuum: (a) high ΔK and (b) low ΔK.

the crack growth to the surface, which gives rise to the appearance of the crack spread out on the surface, as shown in Fig. 8, although we cannot draw any definite conclusion from the present results alone.

The fracture morphology observed in high vacuum was rather different compared to that in air. The oxides which were observed in air were not seen in high vacuum. Figure 9 gives the SEM fractographs of Ti6246 tested in high vacuum, showing crack morphologies and striations at low and high ΔK regions. At low ΔK, the fracture was predominantly crystallographic and the cracks appeared to be initiated at the α/β interfaces. The fracture morphology at low fatigue crack growth rates represented features corresponding to the elongated primary α ; compare Fig. 9(a) with Fig.1. However, the striations and the delamination in the α/β interfaces were observed at high ΔK. Similar fracture morphology was observed for the specimens tested with sine waveform in an intermediate vacuum.

4. SUMMARY

The following conclusions have been drawn from the present experimental results with respect to the effects of loading cycle waveforms and environment on fatigue crack propagation in Ti6246 alloy:

1) The fatigue crack growth rate with dwell loading was generally higher than that with cyclic loading in all test environments. However, such a trend mostly disappeared as ΔK increased.
2) The sine and trapezoidal waveforms did not show any notable difference in fatigue crack growth rate for each environment.
3) The effect of environment on fatigue crack growth rate of Ti6246 at 773K was considered to be significant. In a high vacuum, the fatigue crack growth rates at a low ΔK region were largely reduced compared to those in air and an intermediate vacuum.

4) In air, a considerable amount of oxides were observed on the fractured surface, which could be induced for accelerating the fatigue crack growth rates in Ti6246. On the other hand, the fracture morphology in high vacuum was predominantly crystallographic.

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