FATIGUE CRACK GROWTH BEHAVIOUR AT ELEVATED TEMPERATURES OF TITANIUM ALLOYS

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A experimental study of fatigue crack propagation at 500°C in a selection of Titanium alloys including Ti6242, Ti6246 and IMI834 is presented. The resistance against crack growth of the alloys is discussed with respect to their microstructures. The comparison of the respective behaviour in different environmental conditions including air and high vacuum, shows a comparable sensitivity to environment of the three alloys which is related to the presence of water vapour. The role of test frequency and mean stress intensity level is specially investigated on the Ti6246 alloy, and critical conditions for the occurrence of corrosion-fatigue and stress-corrosion are discussed.

INTRODUCTION

The investigation of the fatigue crack propagation behaviour of Titanium alloys used in turbine engines has concentrated attention of researchers in view of increase operating temperatures (1). One of the main difficulties encountered to clearly understand the governing mechanisms resides in the complex interactions of an active environment with other parameters which influence the propagation, including intrinsic parameters as microstructure and alloy composition, or extrinsic parameters as loading conditions, test frequency, temperature and crack closure. Hence, a critical issue for the modelling of fatigue crack growth is to uncouple the specific influence of these different factors.
This paper deals with a study of the resistance to Fatigue Crack Propagation (FCP) at 500°C in the near-threshold and in the mid rate range of three titanium alloys, namely Ti6246, Ti6242 and IMI 834 in two microstructural states. The influence of environment at 500°C with respect to the microstructure and the role of the maximum of the stress intensity factor K_{max} is specially examined in the near-threshold area and the potential governing mechanisms are discussed.

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EXPERIMENTAL

The three tested Titanium alloys are α-β Ti6246 and a near α Ti6242 which form Widmanstätten microstructures, and a near α IMI834 in bimodal and lamellar microstructural states. The Ti6246 alloy consists of 75% of α platelets either aligned or intermeshed forming a basketweave structure contained in prior β grains with size around 300 μm. The α laths size in the Ti6242 alloy is larger and can reach 70 μm with a volume fraction of α phase around 90%. The IMI 834 alloy consists of 90% of α phase, both in lamellar and bimodal microstructures.

Fatigue crack growth experiments were carried out on Compact Tension (CT) specimens (10 mm thick and 40 mm wide) using a servo-hydraulic machine. Tests were performed in ambient air, high vacuum (10^{-4} Pa) and controlled atmospheres at 500°C. The test frequency was varying from 0.01 Hz to 35 Hz and the load ratio was 0.1 or variable for tests carried out at constant maximum stress intensity factor Kmax. Crack lengths were monitored by a potential drop method. Crack closure measurements were by mean of a capacitive detector using the differential procedure proposed by Kikukawa and al (2). Constant Kmax tests were conducted in conditions where K_{min} was higher than the stress intensity level for crack closure so as to eliminate closure in all the explored range of growth rate. This last procedure was used for the evaluation of the role of the mean stresses.

INFLUENCE OF MICROSTRUCTURE AND ENVIRONMENT

The figure 1 presents the FCP behaviour of the tested titanium alloys with respect to their microstructure and composition. All the curves have the same trend with a change in the slope for growth rates around some 10^{-8} m/cycle corresponding to a plateau range which is typical of active environments. Ti6246 and Ti6242 alloys present a poorer resistance against crack propagation than the IMI alloy in the two microstructural states. In order to discriminate the influencing parameters, crack closure is first taken into account and crack growth data are plotted in figure 2 with respect to the effective stress intensity factor range ΔKeff. Except for Ti6246 alloys which presents the poorest resistance specially in the low rate range, no substantial difference between the three other alloys is observed and data fall within the same scatterband. These three alloys present quite similar highly crystallographic fracture surfaces (figure 3) consistent with a propagation retarded by microstructural barrier effect associated to secondary cracks, crack deviation and crack branching. In contrast, the surface of the Ti6246 alloy is flat with traces of lamellae structure and oxide deposits. A more detailed investigation (3) has revealed an enhanced oxidation effect on Ti6246. RBS analysis of the fracture surface reveals a TiO2 oxide which thickness in the near-threshold is comparable to the ΔCTOD. Such observation is in accordance with an enhanced crack closure contribution by oxide wedging. To detect a possible effect of environment and analyse the intrinsic influence of microstructure, tests were performed in high vacuum. Nominal and closure corrected data presented in figure 3 do not present the plateau phenomenon observed in ambient air which is consequently related to an active environment, but the classification of the alloy resistance is the same as in air for the intrinsic FCP with the poorest resistance for the Ti6246 alloy. Finally, it appears that for higher α volume fraction, coarser microstructure or/and the more heterogeneous microstructure, a better resistance against crack propagation is obtained, which is in accordance with several previous studies (4,5). The coupled effect of environment and frequency is illustrated in figure 5. The enhancement of the propagation rates in active environments has been previously investigated on the Ti6246 alloy (2) and has been related to a corrosion-fatigue mechanism induced by a detrimental effect of water vapour which can be observed under very low partial pressures of water vapour when operating at very low frequency. Crack growth rate for this cracking regime can be described by the law : da/dN = 0.5 ΔCTOD. However, near the threshold, some tests conducted at low frequency (0.1 Hz) and relatively high Kmax levels (21 to 26 Mpa√m) are not in agreement with this description, and suggest the occurrence of an additional process leading to very critical conditions of crack propagation. Tests conducted in humidified Argon (1.3 kPa of water vapour) are illustrated in figure 6. A threshold test run at a constant Kmax of 21 Mpa√m shows a large environment effect in comparison to high vacuum. At such a Kmax level, instead of a threshold, further steps in the decrease of ΔK below 2.3 Mpa√m, exhibit a re-acceleration of the crack propagation. Such a behaviour is comparable to that described by Marci on an IMI834 alloy tested at 120°C (6). It is consistent with a substantial Kmax effect. In the same figure, are compared crack growth data obtained at 0.1 Hz in humidified Argon with a R ratio of 0.1 (very low Kmax ranging from 6 to 12 Mpa√m), and R=0.9 (very high Kmax ranging from 21 to 55 Mpa√m). These data also support a huge influence of the mean stress intensity level and suggest, in such condition, the existence of an additional mechanism which could be creep or stress-corrosion (7,8). This will be examined in the following.

INFLUENCE OF MEAN STRESS INTENSITY

Reference data in high vacuum are plotted in figure 7. Threshold tests performed at 35 Hz under different Kmax levels ranging from 24 Mpa√m up to 36 Mpa√m clearly demonstrate the absence of Kmax effect on the near-threshold crack propagation behaviour with a threshold ΔK range of about 37 Mpa√m. A creep effect is detected at a Kmax level of 42 Mpa√m. Crack growth data for tests run at a constant level of about 24 to 26 Mpa√m in different environmental conditions, i.e., air (40% RH), medium vacuum (130 Pa with 100 Pa H_2O) and low vacuum (1.3 Pa H_2O), are also plotted in figure 7.
Compared to high vacuum, for the same Kmax level, it can be noticed the absence of threshold in the other environments, including low vacuum. A partial pressure of about 1 Pa is sufficient to induce a stress-environment interaction at the crack tip at such a Kmax level. The two other environments (air and 100Pa H_2O) present a similar behaviour with a propagation being much faster than in high vacuum. All these results are in accordance with a large influence of the mean stress level coupled with an environmental effect specially in the very low ΔK range. A first approximation of the critical conditions for the occurrence of what appears to be a combination of stress-corrosion cracking and fatigue-corrosion can be made. For low vacuum and medium vacuum, such conditions can be estimated respectively at 23 and 20 Mpa√m for the critical mean stress intensity levels and

about 2.3 Mpa√m in both cases for the critical ΔK range for a localisation of the deformation.

CONCLUSION

This study of the FCP behaviour of Ti6246, Ti6242 and IMI 834 leads to the following conclusions :

- higher α volume fraction, coarser or/and more heterogeneous microstructures lead to better resistance against FCP.
- a great influence of environment, related to a detrimental effect of water vapour is observed in the three alloys, specially near the threshold for growth rates lower than a plateau range characteristic of environmentally assisted propagation.
- Tests conducted at various frequencies and mean stress intensity levels on the Ti6246 alloy, suggest a prominent corrosion-fatigue mechanism at low mean stress intensities and a combination of fatigue-corrosion and stress-corrosion cracking in moist environment for mean stress intensity higher than a critical level depending slightly on the partial pressure of water vapour (about 20 to 22 Mpa√m) but much lower than the critical level for creep in vacuum (40 Mpa√m) and much lower than the fracture toughness.
- On the practical side, these results are very important. For example, the case of a turbine disc containing a crack, subjected to constant stress and very small cycling loading can be encountered and can lead to component failure. A conservative evaluation of the critical size of defect must be done on the base of the above mentioned critical stress intensity level instead of the fracture toughness which is more than two times higher. On going studies will give a complete description and modelling of such a critical behaviour for Titanium alloys and will be explored on some other metallic materials.

REFERENCES

(1) Margolin, H., Williams, J.C., Chesnutt, J.C. and Lütjering, G., Fracture Fatigue and wear, 1988, p.171.

(2) Kikukawa and al 1977. J. of Mat. Sci.: 1964.

(3) Lesterlin, S., Ph.D. thesis, University of Poitiers, France,1996.

(4) Peters, M., Gysler, A. and Lütjering, G., Proceeding of titanium 80, Science and Technology TMS-AIME, Warrendale P.A., Vol 4, 1980, p.1777.

(5) Rhodes, C.G., Chesnutt, J.C. and Wert, J.A., Proceeding of titanium 80, Science and Technology TMS-AIME, Warrendale P.A., Vol 4, 1980, p.1691.

(6) Marci, G, Fatigue 96, G. Lütjering et al.eds, Pergamon Press, Vol. 1,1996, pp.493-498.

(7) Parkins R.N. and Greenwell B.S. : Metal Science,1977, p. 405-413.

(8) Ford F.P., ASTM STP 821, 1984, pp. 32-51.

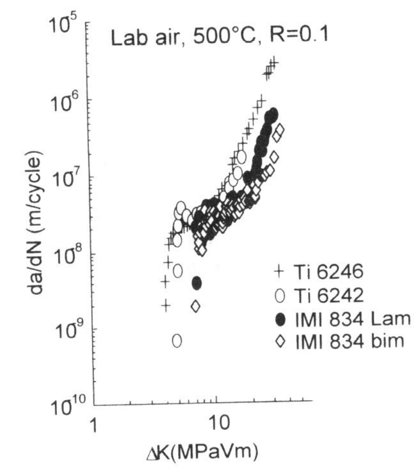

Figure 1 Influence of microstructure on the FCP at 500°C in air, R = 0.1

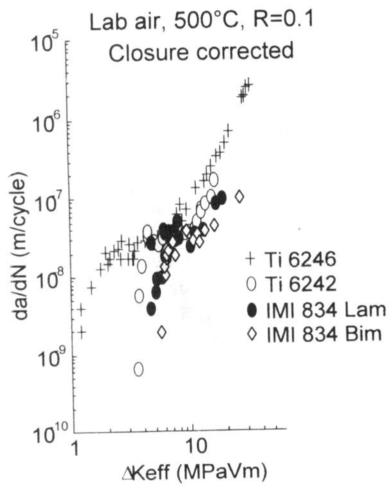

Figure 2 Influence of microstructure after crack closure correction

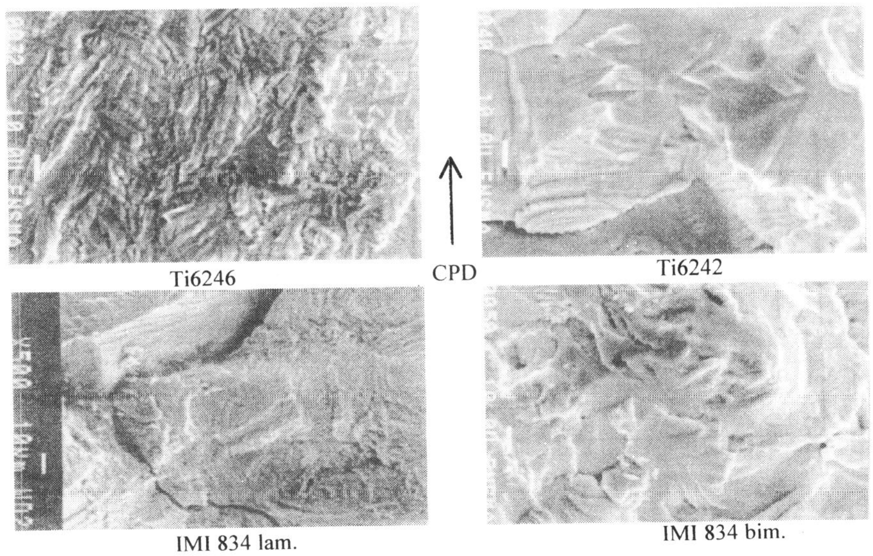

Figure 3 Cracking surfaces obtained in the low-rate range in ambient air at 500°C

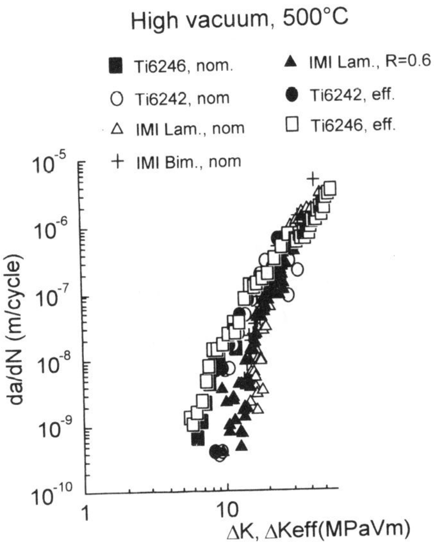

Figure 4 Influence of microstructure in high vacuum

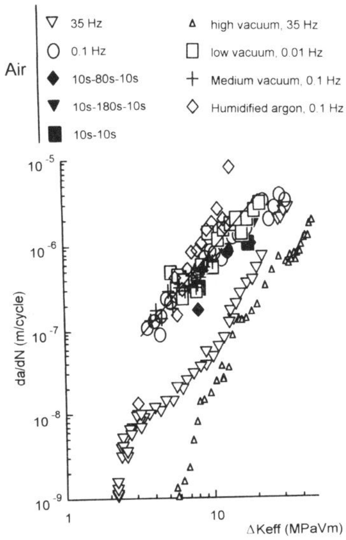

Figure 5 Influence of test frequency in air compared with crack growth data in different environments

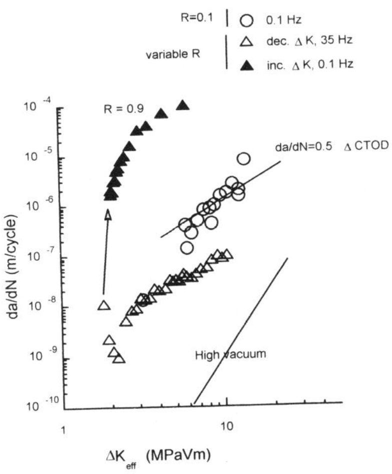

Figure 6 Influence of test frequency and load ratio in humidified argon

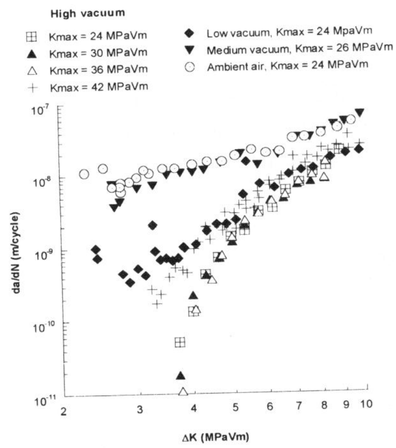

Figure 7 Effect of Kmax in high vacuum and influence of environment at a fixed Kmax value