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The effects of environment and internal oxygen on fatigue crack propagation in Ti–6Al–4V

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Abstract

The role of environmental and internal oxygen on fatigue crack propagation is assessed for the titanium alloy Ti–6Al–4V at laboratory temperature. Growth rates for part through corner cracks are demonstrated to be highly dependent on the amount of oxygen present. Compared to data for conventional plate material at atmospheric conditions, tests conducted under a vacuum of 10^{-6} torr illustrate a marked reduction in the rates of growth for the facet dominated phase at low values of ΔK. Intermediate vacuum levels and partial pressures of argon or hydrogen lead to growth rates that are similar to or slightly lower than the conventional atmospheric baseline. Significant growth rate accelerations are observed, however, for 6/4 material containing internal oxygen concentrations in excess of the standard 1700–2300 ppm. This acceleration is enhanced by the application of a high load ratio, $R = 0.5$. The implications with respect to current ideas on environmental interactions are discussed. © 1997 Elsevier Science S.A.

Keywords: Titanium 6/4; Fatigue crack growth; Internal oxygen; Environment

1. Introduction

The employment of fracture mechanics or 'defect tolerant' lifing techniques is dependent upon the generation of accurate crack growth data in the laboratory using pseudo component or simple geometry testpieces. For many applications this will require a database that not only incorporates testing of the specific alloy of interest but also consideration of any environmental factors that may be experienced in service.

A variety of Ti–6Al–4V titanium alloys are produced world wide and used extensively in the gas turbine, offshore and chemical industries. Their resistance to crack propagation has been characterised by a number of authors over recent decades both in terms of short and long crack behaviour [1]. The present research was intended to extend the database for such an alloy by studying the effects on crack growth rate due to varying the internal oxygen concentration of the material. It is well known that internal oxygen affects both yield strength and fracture toughness [2].

Fatigue crack propagation behaviour was assessed at laboratory temperature and initially under atmospheric pressure for standard cross rolled 6/4 plate. This material was supplied by Timet UK, and had a nominal oxygen content within the specification range 1700–2300 ppm. A corner crack testpiece was used to generate data for part through, quarter circular cracks. Subsequently, the role of environment was explored through tests under partial pressures of argon or hydrogen gas and with intermediate and hard vacuum levels. Finally, the specific effects of varying the internal oxygen content were addressed through comparisons on commissioned 6/4 material with levels ranging from 900 to 5100 ppm. The data are evaluated in relation to mechanisms of small and long fatigue crack growth processes.

2. Experimental details

Conventional Ti–6Al–4V alloy was supplied as 18-mm thick, cross rolled plate. The nominal range of internal oxygen content for this material was in the

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range 1700–2300 ppm. The material had been heat treated below the beta transus to give a microstructure consisting of primary alpha grains within a transformed beta matrix. All the specimens machined from this plate were orientated parallel to a principal rolling direction so that the cracks developed during testing always grew in the plane containing the transverse and short transverse direction.

The 6/4 material containing non-standard levels of internal oxygen were prepared as small quantities by Timet UK Research Laboratories. The 'buttons' were melted under controlled conditions to yield oxygen contents ranging from 900 to 5100 ppm. These were worked and heat treated to achieve a near typical annealed microstructure within rectangular specimen blanks with approximate dimensions of 120 × 20 × 20 mm.

Corner crack (CC) specimens were machined with a nominal 7 × 7 mm cross section (Fig. 1). Crack growth was monitored by a pulsed D.C. potential difference (pd) method. The pd values were converted to crack length by means of published calibration and analysis procedures [3,4].

A servo-hydraulic testing machine with a uni-axial load capacity of ± 100 kN was used under load control for the crack growth tests. Tests were carried out under sinusoidal loading at either 1 or 5 Hz frequency at laboratory temperature. Load ratio (R) and peak tensile stress were varied throughout the test matrix. Cracks were allowed to grow to an approximate crack length of 2.25 mm ($a/W \approx 0.3$).

Selected specimens in the conventional 6/4 alloy were tested under controlled gaseous environments (hydrogen and argon at 0.1 torr pressure) and vacuum. An environmental chamber encapsulated the specimen and loading rods of a servo-hydraulic testing machine. The chamber was evacuated under an upstream pressure control loop which regulates the flow of an inlet gas (or atmospheric air) to balance the pumping capability of the system. Vacuum control and pressure measurement were achieved through a Barocel capacitance manometer (range $2-10^{-2}$ torr) and an active inverted magnetron (AIM) gauge (range $10^{-2}-^{-8}$ torr).

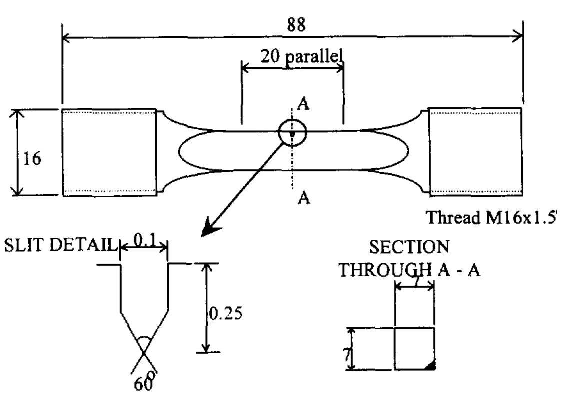

Fig. 1. Corner crack specimen design.

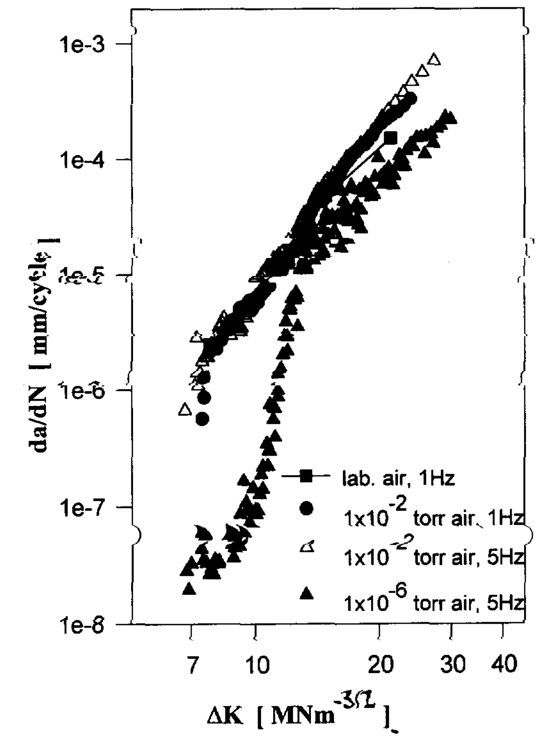

Fig. 2. Crack growth rates for conventional plate material under atmospheric and controlled vacuum pressures ($\sigma_{max} = 300$ MPa; $R = 0.01$).

3. Results

Fatigue crack propagation rates measured in the conventional cross rolled 6/4 alloy in laboratory air and under the vacuum conditions of 10^{-2} and 10^{-6} torr, respectively, are presented in Fig. 2. The growth rates under the intermediate vacuum pressure are virtually identical to those in atmospheric air. They also demonstrate that growth response is insensitive to test frequency in the range 1–5 Hz. However, under the harder vacuum of 10^{-6} torr, significantly lower rates are observed at low values of ΔK (approximately < 12 MNm$^{-3/2}$). Tests under partial pressures of both argon or hydrogen had slightly reduced growth rates across the full range of applied ΔK when compared to the atmospheric air database (Fig. 3).

Data from tests conducted on material with modified oxygen are presented in Fig. 4 and Fig. 5 for $R = 0.01$ and $R = 0.5$, respectively. In each figure the best line fit from conventional plate material tested at $R = 0.01$ is used for comparison. The initial observation is that growth rates measured from the specimen with a modified oxygen content which falls within the normal specification (i.e. 2300 ppm) are consistent with the conventional material. This suggests that the modified processing route has not significantly influenced the mechanical properties. A similar pattern is also observed for the specimen with a reduced oxygen content of 900 ppm which had propagation rates similar to the conventional material. However, on raising the oxygen level to 5100 ppm, there is a significant increase in the rate of growth at all applied ΔK values (Fig. 4). An increase in R value further accentuated this acceleration as illustrated by the result at 4000 ppm in Fig. 5.

4. Discussion

The test programme shows that environmental conditions can significantly modify the fatigue crack growth of corner cracks in the alpha-beta titanium alloy, Ti–6–4. In this respect, the work is consistent with that reported by Sarrazin-Baudoux et al. [5] for large through cracks in compact tension specimens. In both situations, a high vacuum (1×10^{-6} torr) reduces the early growth rates ($\Delta K < 12$ $MNm^{-3/2}$) by nearly two orders of magnitude. The previous authors identify these low rates with a crystallographic mode of crack development which is evident as facets on the fracture surface. They designate this as a 'Stage I-like' regime. At $\Delta K > 12$ $MNm^{-3/2}$, the growth rates differ little from the response in air. This is called 'Stage II' and is ascribed to multiple slip processes. In the present work, this regime was associated with striation formation in the air tests. Interestingly, it was found that the 'air-like' response returned for vacuum levels as low as 1×10^{-2} torr.

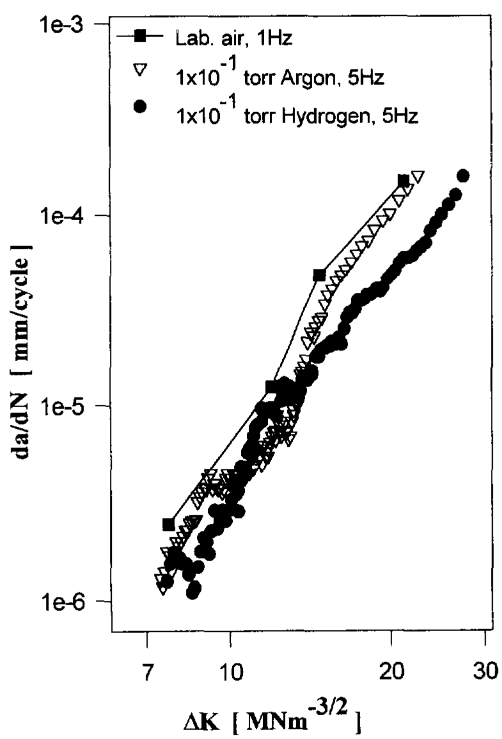

Fig. 3. Crack growth rates under partial pressures of argon and hydrogen ($\sigma_{max} = 300$ MPa; $R = 0.01$).

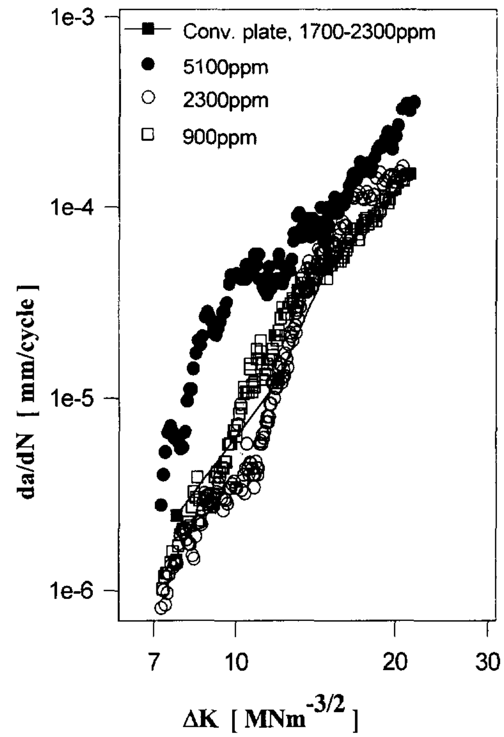

Fig. 4. Data for non-standard oxygen materials tested in atmospheric air ($\sigma_{max} = 300$ MPa; $R = 0.01$).

Sarrazin-Baudoux et al, strongly argue, with the support of some discrete experiments, that the main reason for the accelerated rates in air at low ΔK is the presence of water vapour. It is suggested that this species acts via an adsorption process through the release of hydrogen atoms. They recognise that the experiments do not completely exclude an influence from oxygen but present plausible reasons as to why this may be a second order effect. An objective of the present work was to explore precisely the role of oxygen in fatigue crack development.

It is clear that oxygen levels above specification (1700–2300 ppm) cause significant accelerations in growth rates at low ΔK. In fact, increasing internal oxygen from 900 to 2300 ppm has little effect but a further change to 5100 ppm increases the rate for $\Delta K < 12$ $MNm^{-3/2}$ by 5–10 times. Oxygen is an alpha stabilising element so that the change in composition increases the amount of primary alpha phase for a given heat treatment. Previous work, however, has shown that a change in alpha content alone cannot account for this acceleration [6]. Examination of the present fracture surfaces demonstrated that the increased rates at high oxygen levels were associated with enhanced facet formation. Sarraxin-Baudoux et al. attribute facet formation to slip on a single system. One effect of oxygen is to reduce stacking fault energy and hence make single slip more likely. On this basis, it is feasible that oxygen could cause substantial accelerations in growth rate. The data at $R = 0.5$ are important in that they show accelerated rates for both near standard (1650 ppm) and high (4000 ppm) oxygen levels. The high R value might imply that any tendency for crack closure is reduced thereby increasing the propensity for environmental ingress to the crack tip. However, an interesting alternative is that, for the $R = 0.5$ value, K_{max} and hence the monotonic plastic zone size, is significantly larger. An interaction between the level of plasticity and species such as oxygen in the formation of facets has been inferred previously [7]. The present observations are consistent with that view.

Finally, it is shown that both argon and hydrogen pressures of 0.1 torr reduce the rate of crack growth over the full range. Previous work [7] showed that a hydrogen pressure of 1 torr had a similar effect. It is believed that both species are acting by shielding the crack front from detrimental species. It is uncertain whether this species is oxygen or water vapour although considerable effort was made to ensure that the gases were dry (high purity gases, maximum water content < 3 ppm). Interestingly, the hydrogen gas does not

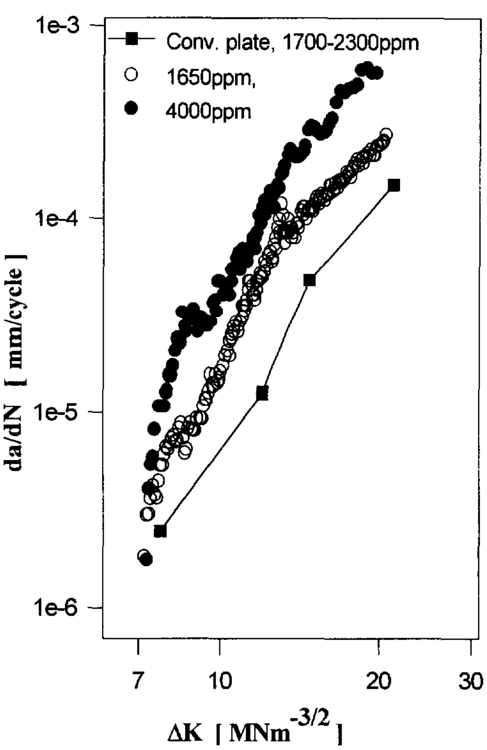

Fig. 5. Non-standard oxygen materials tested under high R value ($\sigma_{max} = 600$ MPa; $R = 0.5$).

accelerate growth rates even though it is suggested as an active species in the water vapour model. On balance, therefore, it is argued that the most likely species causing changes in the growth rate response of Ti–6–4 is oxygen which can influence behaviour even at comparatively low concentrations. It is feasible, however, that there is a synergistic interaction with water vapour in which the latter acts a catalyst for damage process. Further detailed experiments are required to quantify this interaction.

5. Conclusions

(1) The rate of crack propagation in Ti–6Al–4V is highly sensitive to both external environmental and internal oxygen concentration.

(2) Under a vacuum of 1×10^{-6} torr, the growth rates of small cracks under the application of a low value of ΔK is significantly reduced compared to normal atmospheric conditions.

(3) An intermediate vacuum level (1×10^{-2} torr) and partial pressures of argon or hydrogen all produce similar and slightly reduced rates of growth compared to atmospheric conditions.

(4) Relatively high concentrations of internal oxygen significantly accelerated growth rates. This effect is accentuated by a high R value ($R = 0.5$).

(5) Oxygen appears to enhance facet dominated growth under cyclic loading.

Acknowledgements

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