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Short Communication

Fatigue crack growth behaviour of forged Ti–6Al–4V in gaseous hydrogen

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ABSTRACT

Fatigue crack growth (FCG) tests were performed to evaluate the fatigue behaviour of forged Ti–6Al–4V in air and high-pressure gaseous hydrogen (15 MPa) at room temperature. The results indicate that the effect of gaseous hydrogen is dependent on the stress intensity factor (ΔK). The FCG rate was unaffected by hydrogen below a critical stress intensity, $\Delta K^* \approx 20$ MPa$\sqrt{m}$. Above ΔK^*, the FCG rate fluctuated and subsequently accelerated at higher ΔK values. The observed behaviour is attributed to the change in the fracture processes. A hypothesis is proposed that describes the FCG behaviour in gaseous hydrogen.

1. Introduction

Ti–6Al–4V (Ti-64) is the most frequently used titanium alloy for aerospace applications because of its high strength-to-weight ratio, good combination of strength and fatigue resistance up to 300 °C [1,2]. However, one of the concerns is its incompatibility with hydrogen [3]. Studies have shown that gaseous hydrogen degrades the critical fracture properties of Ti-64, such as fracture toughness [4,5] and fatigue resistance [6–9] at room temperature. It is worth mentioning that there is limited research on the influence of gaseous hydrogen on fatigue crack growth (FCG) of Ti-64 alloy [7,10–12]. These studies suggest that an interaction between hydrogen and titanium at the crack tip plays a major role, but the effect on the FCG behaviour is not well understood.

Increased understanding of the influence of gaseous hydrogen on the fatigue properties of Ti-64 alloy is of importance as the alloy is mainly used in aerospace applications. In a recent study [8], it was observed that the fatigue life of cast Ti-64 alloy was reduced more at higher strain ranges in the presence of gaseous hydrogen than at lower strain ranges. This indicates that the hydrogen might be affecting the FCG resistance rather than the crack initiation. The purpose of the present work was to investigate the FCG behaviour of forged Ti-64 in a high-pressure gaseous hydrogen (15 MPa) at room temperature.

2. Materials and methods

The material investigated was forged Ti-64 in the solution treated and aged condition according to AMS 4928. It has a bimodal microstructure with α phase (≈83%) and beta phase (≈17%), which consists of primary α (42.5% in volume, grain size ≈ 15 μm) and transformed β (57.5% in volume, grain size ≈ 18.6 μm) (see Fig. 1(a)). The transformed β grain consists of parallel α lamellas with retained β (see Fig. 1(b)). The test environments used were ambient air and high-pressure gaseous hydrogen (>99.995% purity), where the desired pressure of 15 MPa was achieved by pressurising the test chamber prior to testing.

Fatigue crack growth testing was carried out using a servo-hydraulic testing machine on one sample each in ambient air and gaseous hydrogen at room temperature. In the present study, the test specimens used were Kb-type (see Fig. 2(a)), having a rectangular cross-section with a surface flaw in the gauge section (see Fig. 2(b)). Detailed information about the test specimens are described elsewhere [9]. Before testing, the specimens were fatigue precracked in air at room temperature, using a frequency of 10 Hz with a stress ratio (R) = 0 to obtain an initial crack length (a) of 0.5 mm. Thereafter, FCG testing was performed in air and gaseous hydrogen by uniaxial loading of the specimens at a stress ratio $R = 0$ and a frequency of 0.5 Hz, with triangular waveform using the applicable parts of ASTM E647-08 and ASTM E740-03 standards. In these tests, the total crack lengths were recorded by the direct current potential drop technique according to the ASTM E647 standard. For testing in gaseous hydrogen, the specimen, along with the grips, was enclosed in an autoclave. In

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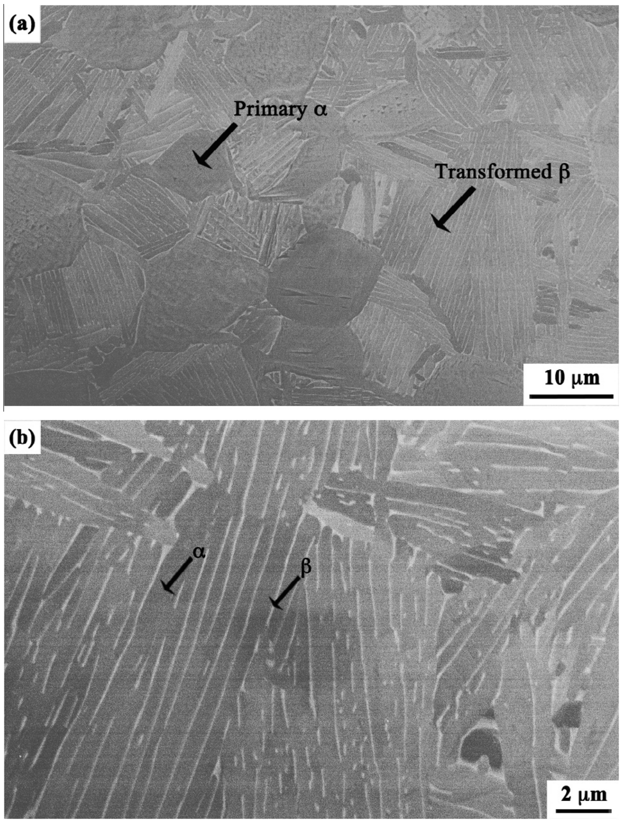

Fig. 1. (a) Scanning electron micrograph of forged Ti-64 revealing the bi-modal microstructure with primary α and transformed β grains, (b) micrograph showing the α (dark) and β (bright) in transformed β.

the present work, the stress intensity factor range, ΔK, was calculated for the deepest point of the crack according to ASTM E740 standard assuming a semi-circular shape. The applied stress ranges were different for the tests in air and hydrogen (450 and 530 MPa, respectively). Here it is assumed that the stress range have negligible influence, since it is known from the literature [7,10–12] that in presence of gaseous hydrogen, ΔK is the controlling loading parameter. Therefore, the expression to calculate ΔK was used to correlate the crack lengths between the tests and the fractographic results were compared at the same ΔK.

Scanning electron microscopy (SEM) was used to characterise the fracture surfaces and the microstructure of the specimens after FCG testing. Analysis of the fracture surfaces was conducted using a field emission scanning electron microscope (FE-SEM) from Carl Zeiss (MERLIN®). It was performed using secondary electron imaging with an accelerating voltage of 3 kV and probe current of 1 nA. Attention was paid to specific regions on the fracture surfaces. SEM was also used to observe the fatigue crack path profiles prepared by protecting the fracture surface using Lacquer from METACOAT®, then cross sectioning the samples along the FCG direction and examining from the side surface. Sample preparation for microstructural analysis was performed using conventional methods for titanium alloys involving grinding, polishing and etching using Kroll's reagent.

3. Results and discussion

Fig. 3(a) and (b) shows the FCG curves for forged Ti-64 in air and gaseous hydrogen. The FCG rate in air follows a power law relationship for the tested stress intensity factor ranges. The FCG behaviour in hydrogen is almost identical up to $\Delta K \approx 20$ MPa$\sqrt{m}$ and thereafter it changes. It is noted that at about 20 MPa$\sqrt{m}$, the FCG rate starts to fluctuate and then accelerates significantly, see Fig. 3(a). The fluctuation can also be noted at the corresponding crack length, see inset in Fig. 3(b). The extent of the hydrogen effect can be seen by dividing the FCG rate in hydrogen by that in air, see Fig. 3(c), and the FCG curve can be separated into three distinct areas. In the first region, A ($\Delta K \leqslant 20$ MPa$\sqrt{m}$), the FCG rate is unaffected showing a stable crack growth similar to the one in air. In the second region, B ($20 \leqslant \Delta K \leqslant 26$ MPa$\sqrt{m}$), the average FCG rate is lower than in air, but there were fluctuations in da/dN values

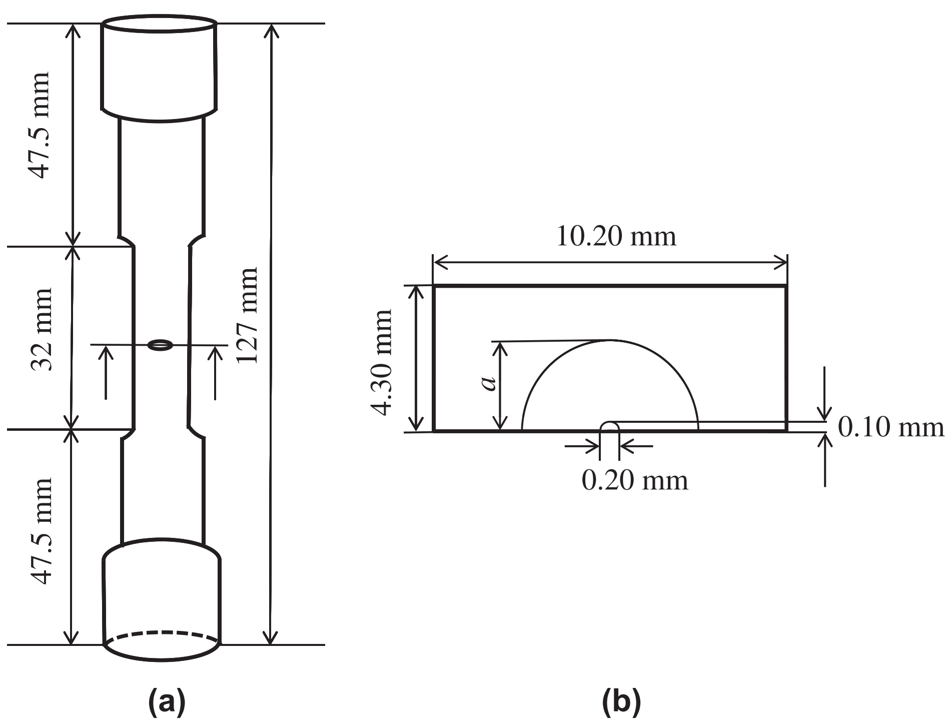

Fig. 2. (a) Schematic illustration of the Kb-type test specimens used in the study, (b) cross-section of the gauge length, including notch and crack geometry.