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Fatigue crack growth and thresholds at ultrasonic frequencies

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Abstract

The existence of a threshold of fatigue crack growth is treated for the aluminium alloy 7075-OA as well as Ti–6Al–4V. Results are reported on the influence of environment (vacuum and ambient air) and load ratio ($R = -1$ to $+0.8$) on fatigue crack growth in the near-threshold regime. The main results are: in vacuum, crack growth still takes place at lower rates than 10^{-10} m/cycle, and thus thresholds – if at all – are below approximately 5×10^{-12} m/cycle. No frequency influence on crack propagation is present for loading frequencies of 20 Hz and 20 kHz. In ambient air environment, thresholds are identical at 20 kHz and 20 Hz cycling frequency, but crack growth is slower at ultrasonic frequency in humid air than at 20 Hz. Time governing processes, like surface diffusion of water vapour to the crack tip, water vapour adsorption and formation of a mono-layer at the crack tip as well as diffusion of hydrogen in front of the crack tip are discussed. The influence of load ratio is shown and discussed.

Keywords: Fatigue crack growth; Fatigue threshold; Ultrasonic fatigue; Very high cycle fatigue; Air humidity; Corrosion fatigue; Strain rate; Load ratio; 7075; Ti–6Al–4V

1. Introduction

Similar to the question about the existence of a fatigue limit, the basic question arises on the existence of a threshold value for propagation of an already existing crack or defect in metallic materials. Both questions relate to the mechanisms of deformation at very low cyclic loads (i.e., below a "fatigue limit" or a "threshold stress intensity") at very high numbers of cycles. Investigations on the mechanisms of crack initiation and propagation in this regime have been performed and reported, among others, by Sakai [1], Mughrabi [2], Murakami [3] and Tanaka [4] at the International Very High Cycle Fatigue (VHCF) Conferences in Paris 1999 and Vienna 2001. Measurement in the VHCF (10^8–10^{11} cycles) regime is most time consuming or not at all possible with conventional fatigue testing machines, which operate at frequencies of some Hz up to utmost 1000 Hz so that the question on the existence or non-existence of a fatigue or threshold limit could not be answered comprehensively until now. Therefore, development of the ultrasound fatigue testing technique has been promoted, and results on fatigue crack propagation features in the VHCF regime, that could not been obtained with conventional equipment, have been reported [5,6].

As shown in numerous investigations, ultrasonic fatigue testing is an efficient method to reduce testing times by a factor up to 1000 compared to conventional testing procedures. Specimens are vibrating in resonance, if adequate specimen designs allow adjustment to the resonance frequency of the ultrasonic system. Increasing the cycling frequency by three orders of magnitude and using adequately designed specimens to fulfil resonance criteria raises questions of comparability of ultrasonic data and data measured with conventional methods, and there especially the question on the role of the environment is important. It could be shown that fatigue crack growth in Al alloys – besides other metallic materials, like 13% chromium steel, grey cast irons and mild steel [5] – is not influenced by the cycling frequency in the crack growth regime below 10^{-7} m/cycle, if the experiments are performed in inert environment. After variation of the loading frequency by

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three decades and testing at three different load ratios it could be concluded that no (intrinsic) strain rate influence on near threshold fatigue crack growth exists in most of the studied materials [7]. Face-centred cubic [8] crystal systems are known to be relatively insensitive to rates of plastic deformation [13]. Additionally, the plastic deformation is small, if cycling is near threshold. If the crack tip plastic deformation is larger and growth rates are in the Paris regime, however, frequency influences on crack growth of several fcc metals are reported in the literature [9–11].

As another important result, crack growth rates being orders of magnitude below one lattice space per cycle, have been detected. This has been measured unambiguously in 1980 already [6], though accuracy of measurement at this time was not as good as today owing to less accurate electronic control devices. It could be shown that in bcc (very-low carbon iron, cast iron with globular graphite, 13% chromium steel) as well as fcc metallic materials (copper, steel 304) mean fatigue crack growth rates as low as 5×10^{-13} m/cycle exist. In these studies, the experiments were carried out in inert silicone oil, and in addition the influence of corrosive environment was investigated.

Ambient air, the environment usually present, is a corrosive medium for aluminium alloys, and chemical processes are caused by atmospheric moisture. Environmental influences result in time dependent processes, so that correlated influences by the frequency of fatigue loading have to be expected. Results on the environmental influence on crack propagation in the VHCF regime, with numbers of cycles up to more than 10^{10} will be reported in the following, reviewing more recent investigations [7–9] on an aluminium and a titanium alloy, considering that crack propagation in the VHCF regime is essentially determined not only by material inherent properties (chemical composition, yield strength, etc.) and loading conditions (load ratio) but also to a large degree on the surrounding environment.

The experiments, reported in this study, were obtained at $R = -1$ with overaged 7075 alloy as representative for homogeneous slip aluminium alloys, as well as Ti–6Al–4V alloy. Testing was performed at two frequencies (20 or 50 Hz and 20 kHz), and in addition the influence of the R-ratio was studied. Experiments at 20 Hz and 20 kHz were performed in ambient air and in vacuum to separate the different influences of load ratio, strain rate, air humidity and slip properties on near threshold fatigue crack growth.

2. Material and experimental procedure

Results are presented for the wrought and overaged 7075 (7075-OA) as well as the Titanium alloy Ti–6Al–4V. The chemical composition of the 7075 alloy was (in wt%): Zn 7.2, Mg 2.8, Cu 1.7, Cr 0.06, Fe 0.3, Si 0.1, Mn 0.06, Ti 0.05, Ga 0.01, Zr 0.1. The alloy was solution annealed at 470 °C, quenched and overaged by tempering at 107 °C (8 h) plus 163 °C (65 h). The resulting static properties are: $R_m = 464$ MPa, $R_{p0.2} = 524$ MPa, $A_5 = 10.8\%$ (with R_m = ultimate tensile stress, $R_{p0.2}$ = yield stress and A_5 = tensile strain). The Ti–6Al–4V alloy was received as plate in solution-treated and overaged (STOA) condition. The chemical composition of Ti–6Al–4V was (in wt%): Al 6.30, V 4.17, Fe 0.19, O 0.19, N 0.013, H 0.0035, Ti balance. The alloy was solution-heat treated (1 h at 925 °C) and vacuum annealed (2 h, 700 °C). It consists of a bimodal distribution of approximately 60% primary α phase and approximately 40% lamellar colonies of α + β. Static strength properties of Ti–6Al–4V are: $R_m = 970$ MPa, $R_{p0.2} = 930$ MPa, $K_{IC} = 67\ \mathrm{MPa}\sqrt{\mathrm{m}}$ and $E = 116$ GPa [7].

Specimens of the aluminium alloy were machined from rolled sheets of 20 mm thickness as standard middle tension (M(T) specimens [10]) for the servo-hydraulic tests. The thickness was 5 mm and centre notches were introduced using a saw and razor blades. The specimens were machined adequately to perform crack growth experiments in TL-direction (7075). Tube specimens were used in ultrasonic tests with length axis oriented in T-direction. A hole was drilled and a notch was introduced by spark erosion (with mineral oil as protective liquid) into the wall centre to cause crack initiation there (using spark erosion in order to avoid residual stresses introduced by mechanical notching). The cracks grew along the circumference of the tube in the plane of maximum normal stress with the crack front normal to the surface of the tube. The notch was positioned such that the crack growth direction at a crack length of 6 mm (without notch) was in TL-direction (7075). The specimen thickness was between 2 and 5mm and no pronounced effect of thickness could be detected [7]. The same specimen shape was used for the Ti–6Al–4V [8].

Fatigue crack growth was investigated at load ratios $R = -1$, $R = +0.05$ and $R = +0.5$. Ultrasonic equipment appropriate to perform fatigue experiments at mean loads other than zero is described in detail in [5,15]. The experiments were performed in ambient air of 18–22 °C and 40–60% relative humidity and alternatively in vacuum of maximum 3×10^{-3} Pa. Testing was performed with servo-hydraulic equipment at 20 Hz and with ultrasonic equipment at 20 kHz. In servo-hydraulic tests, specimens were cycled continuously, and in the ultrasonic experiments with pulses consisting of 1000 cycles and periodic pauses of 25–100 ms to avoid rise of temperature. The maximum temperature of the specimens in servo-hydraulic tests was 30 °C and 25 °C in the ultrasonic experiments [9].

Fatigue crack growth is measured at the surface of the specimens using an optical microscope. Crack growth rates were determined as mean growth rates over crack length increments of 0.15–0.20 mm in servo-hydraulic as well as ultrasonic experiments. If fatigue cracks propagate first and stop then, the crack length increments during 1.5×10^6 cycles in servo-hydraulic tests, or 2×10^7 cycles in ultrasonic tests are used to calculate the mean growth rate. The stress intensity factor range, ΔK, was lowered until no crack growth could be observed within these