ENVIRONMENTAL-ASSISTED FATIGUE CRACKING OF ALUMINIUM ALLOYS AT DIFFERENT FREQUENCIES

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ABSTRACT

Near-threshold fatigue crack growth of two aluminium alloys has been studied in humid air at a frequency of 20 kHz with ultrasonic fatigue equipment and at 20 Hz with a servo-hydraulic machine. Testing materials were the aluminium alloys 2024-T3 and 7075 alloy in underaged condition, both being planar-slip materials and in addition the same 7075 alloy after overaging, leading to homogeneous-slip properties. The experiments were performed at different load ratios (R=-1, +0.05 and +0.5) and were compared with measurements in vacuum. Resulting thresholds and crack growth rates are reported and environmental, as well as frequency effects are discussed. The mechanisms leading to the observed corrosion-fatigue crack growth or crack arrest properties and rate controlling effects are considered.

1 INTRODUCTION

The aluminium alloys 2024 and 7075 being used as structural material for aircraft components, for example, have to endure very high numbers of cycles at relatively low stress amplitudes. The environment mostly is ambient air, which has to be considered as a corrosive medium for aluminium alloys. This means that air humidity leads to corrosion fatigue effects and thus shorter life times. For this, not only crack initiation, but also short and long crack growth behaviour is responsible. Of special interest is the crack growth and threshold behaviour at low cyclic loads and very high numbers of cycles. Quite often the question arises, if a defect or an already existing short crack will propagate and at which rate, or if it will remain dormant. Measuring corrosion fatigue data in the very high cycle regime needs extremely long testing times, if conventional hydraulic equipment with testing frequencies around 20 Hz is used to perform the experiments. On the other hand, the ultrasonic testing technique, working in the frequency range of 20 kHz, allows to shorten testing times by a factor of 100 to 1000. Corrosion and corrosion fatigue, however, are time dependent processes, so that an influence of the testing frequency on deformation and cracking properties and therefore on life time and crack propagation rates must be expected. It was the aim of the presented studies (Holper et al. [1, 2]) to contribute to the understanding of environmental-assisted fatigue cracking at high testing frequencies in comparison to lower ones.

2 MATERIAL AND EXPERIMENTAL PROCEDURE

Testing material was wrought and naturally aged aluminium alloy 2024 (2024-T3) and overaged as well as underaged 7075-alloy. The chemical composition of the 2024 alloy is (in wt.-%): Cu 4.5, Mg 1.5, Si 1, Fe 0.2, Mn 0.7, Cr < 0.05, Zn < 0.05, Ti < 0.03, Al balance. Static strength properties of 2024-T3 are: ultimate tensile strength R_m = 460 MPa, yield strength $R_{p0.2}$ = 352 MPa, fracture strain A_5 = 18 %, fracture toughness K_{IC} = 35 MPa$\sqrt{}$m and Youngs modulus E = 72 GPa. The chemical composition of the 7075 alloy is (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 and water quenched. Part of the material was overaged by tempering at 107 °C (8 h) plus 163 °C (65h). The resulting static properties are: R_m = 464 MPa, $R_{p0.2}$ = 524 MPa, A_5 = 10.8. The other part was underaged by additionally quenching in liquid nitrogen (15 min) and tempering at 50°C (10 min) plus 117°C (90 min). This led to R_m = 424 MPa, $R_{p0.2}$ = 567 MPa and A_5 = 15.2.

Specimens for the servo-hydraulic tests were machined from rolled sheets of 20 mm thickness as standard middle tension (M(T)) specimens (ASTM [3]). Thickness was 5 mm and centre notches were introduced with a saw and razor blades. The crack growth experiments were performed in LT-direction (2024) or TL-direction (7075), respectively. In the ultrasonic tests, tube specimens with a wall thickness of 2 mm were used. A hole was drilled and a notch was introduced by spark erosion to start crack initiation there. The cracks grew along the circumference of the tube in the plane of maximum normal stress. The notch was placed such that the crack growth direction at a crack length 6 mm (without notch) was in LT-direction (2024) or TL-direction (7075). No influence of specimen thickness could be detected [2].

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 by Stanzl et al. [4]. The experiments were performed in ambient air of 18 – 22 °C and 40 – 60 % relative humidity and in addition in vacuum of maximum $3x10^{-3}$ Pa. Testing was performed with servo-hydraulic equipment at 20 Hz and with ultrasonic equipment at 20 kHz. In the 20 Hz tests, specimens were cycled continuously and the maximum temperature of the specimens was 30 °C. In the ultrasonic 20 kHz tests, specimens were loaded with pulses consisting of 1000 cycles (50 ms) with periodic pauses in between each pulse. The pauses of 25 – 100 ms (in ambient air) and 50 – 200 ms (in vacuum) served to cool the specimens and keep their temperature below 25 °C (ambient air) and 30 °C (vacuum). The stress intensity factor range, ΔK, was lowered until crack growth could not be observed within $1.5x10^6$ cycles in the servo-hydraulic tests and within $2x10^7$ cycles in the ultrasonic tests. With the optical resolution of 20 µm (in servo-hydraulic tests) and 7 µm (in ultrasonic tests), limiting hypothetical growth rates of $1.3x10^{-11}$ m/cycle and $3.5x10^{-13}$ m/cycle, respectively, result and characterise stop of fatigue crack growth. In the 20 Hz experiments a limiting growth rate of 10^{-10} m/cycle was used to characterise the threshold according to the recommendations of ASTM [3], whereas in ultrasonic experiments threshold stress intensities were additionally determined at $3.5x10^{-13}$ m/cycle.

3 RESULTS

3.1 Fatigue crack growth and thresholds in vacuum

Fig. 1 shows (Δa/ΔN vs. ΔK) curves of 2024-T3 (Fig. 1a) and the overaged 7075 (7075-OA) alloy (Fig. 1b), which were measured in vacuum. Closed symbols characterise data obtained with servo-hydraulic equipment at 20 Hz and open symbols show ultrasonic data measured at 20 kHz. Arrows indicate that no crack growth could be determined within $1.5x10^6$ cycles (20 Hz) and $2x10^7$ cycles (20 kHz), respectively [1].

The threshold values increase and the fatigue crack growth rates decrease with decreasing R-ratio. Experimental data determined at 20 Hz and 20 kHz are closely similar, not differing more than by a factor of 2, which is similar to the scatter of crack growth data. This means that no frequency (strain rate) influences can be detected in the inert environment and growth rates below 10^{-9} m/cycle are comparable, varying the cyclic frequency by three decades. Most remarkable, thresholds do not appear at crack growth rates of several 10^{-10} m/cycle (which would be a mean crack extension rate of one lattice spacing per cycle), but may be defined several decades lower, at approximately $3.5.x10^{-13}$ m/cycle.

3.2 Fatigue crack growth and thresholds in ambient air

Results of measurements in ambient air of 18 – 22 °C and 40 – 60 % relative humidity are plotted in Fig. 1c and 1d (Fig. 1c: 2024-T3 and Fig. 1d: 7075-OA).

Comparing ultrasonic fatigue crack propagation in ambient air with that in vacuum, a pronounced influence of air humidity is obvious in both aluminium alloys. Threshold stress intensities at 3.5×10^{-13} m/cycle are approximately 60 - 70 % lower in ambient air than in vacuum, and threshold stress intensities at 10^{-10} m/cycle are 45 - 55 % lower than in the inert environment.

The ($\Delta a/\Delta N$ vs. ΔK) curves, measured in ambient air, show a pronounced change of slope as stress intensity approaches threshold. Fatigue cracks grow with minimum mean growth rates of approximately 5×10^{-11} m/cycle, or they remain arrested. Lower mean growth rates in ambient air result, if a crack propagated first and stopped afterwards (at constant stress intensity range). Therefore, the difference of ΔK_{th} at 10^{-10} m/cycle and ΔK_{th} at 3.5×10^{-13} m/cycle is smaller (approximately 10 %) in ambient air than in vacuum.

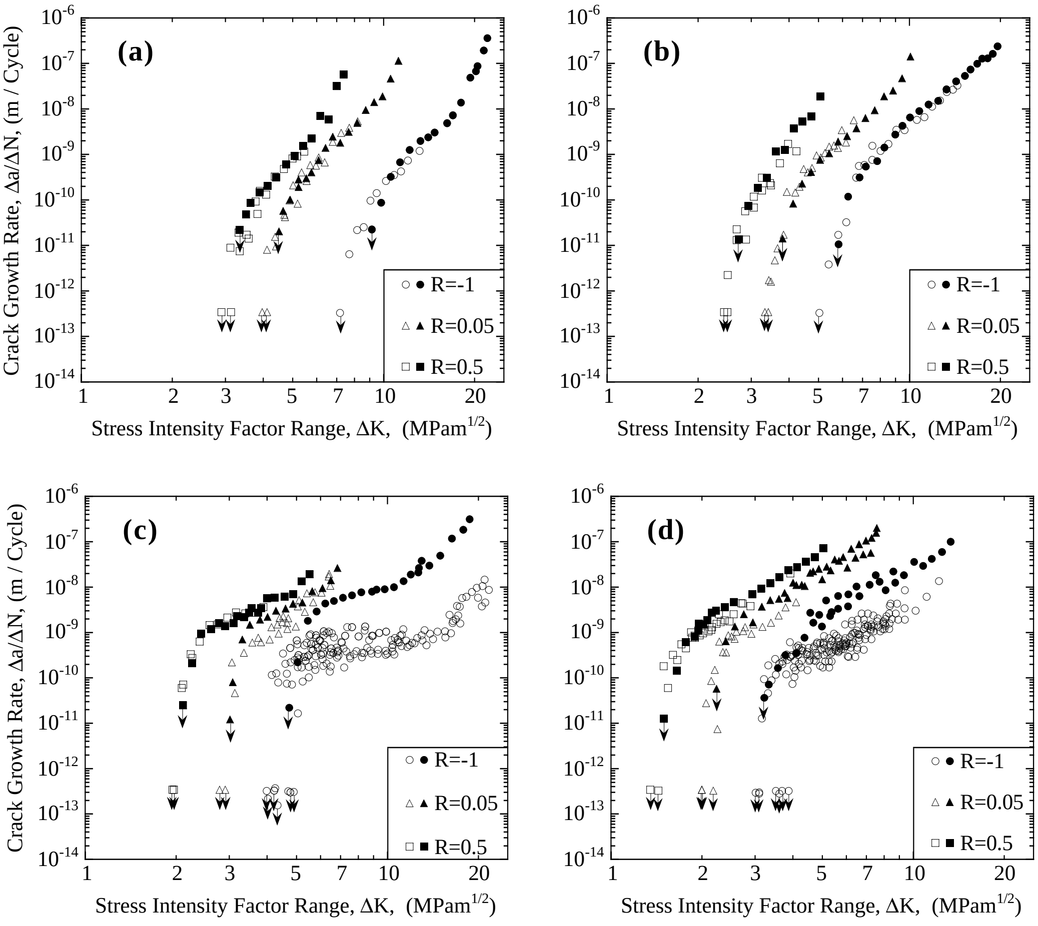

Figure 1: Fatigue crack growth in 2024-T3 (1a, c) and 7075-OA (1b, d) at R-ratios = -1, +0.05 and +0.5 at loading frequencies of 20 Hz (closed symbols) and 20 kHz (open symbols) in vacuum of 10^{-3} Pa (Fig. 1a, b) and ambient air (40-60% R.H., 20°C) (Fig, 1c, d).

The environmental influence above threshold is more pronounced for the planar-slip material 2024-T3 than for the homogenous-slip 7075 OA. A plateau-like regime is found cycling 2024-T3 in ambient air, whereas the crack propagation rates of 7075-OA continuously decrease in the investigated regime. That this effect is correlated with the slip properties and not with the material, is supported by the results on the underaged version of the alloy 7075 (7075-UA), showing likewise a pronounced plateau regime when cycled in air (Fig. 2a).

Surprisingly, the threshold stress intensities, ΔK_{th} at 10^{-10} m/cycle measured with servo-hydraulic and with ultrasonic equipment in humid air are identical. Above threshold, however, a significant difference of growth rates determined with the two experimental procedures is visible. Cycling at 20 Hz results in approximately a factor 5 to 50 higher growth rates at a load ratio R =-1. At load ratios R=+0.05 and R=+0.5, the influence of cyclic frequency on crack propagation in ambient air is less pronounced, i.e. ultrasonic cycling above threshold leads to somewhat slower (R=+0.05) or similar (R=+0.5) growth rates compared to servo-hydraulic testing.

An evaluation of the threshold stress intensity values shown in Fig. 1, is presented in Fig. 2b. There, the maximum stress intensity factor K_{max} and the stress intensity factor range ΔK are plotted according to Vasudevan et al. [5] for the limiting threshold crack growth rates of 10^{-10} m/cycle and 3.5×10^{-13} m/cycle, respectively. Threshold values, characterising loading at the three R-ratios in ambient air and vacuum, are plotted for each material. With increasing load ratio, threshold K_{max} values increase and threshold stress intensity factor ranges ΔK_{th} decrease. At crack growth rates of 10^{-10} m/cycle, the threshold stress intensities are shown for 20 Hz and 20 kHz. Main result is that they are similar for 20 Hz and 20 kHz cycling. Whatever mechanism causes stop of fatigue crack growth at threshold stress intensity, it is similarly acting at low and ultrasonic frequency.

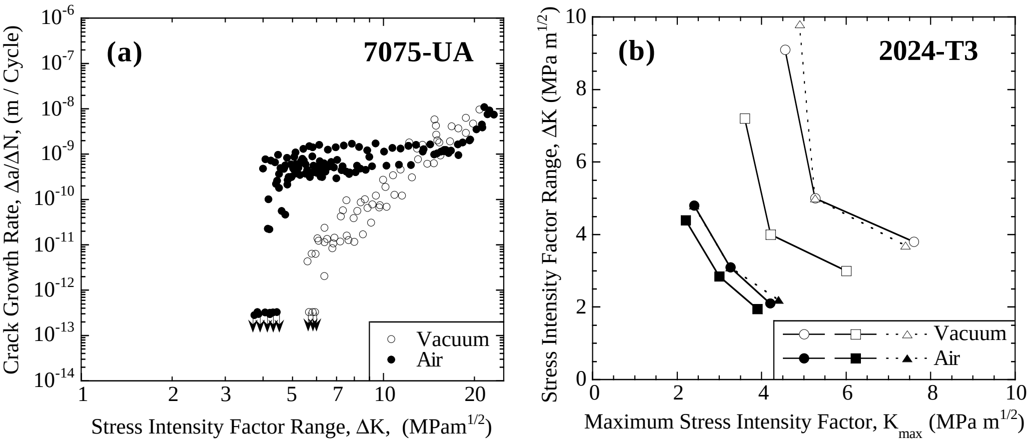

Figure 2a: Fatigue crack growth in 7075-UA at 20 kHz loading frequency in ambient air (dots) and vacuum (circles).

Figure 2b: ΔK and K_{max} threshold values in 2024-T3 measured in ambient air (closed symbols) and in vacuum (open symbols). Thresholds at 10^{-10} m/cycle were determined at 20 Hz (triangles) and 20 kHz (circles) and additional thresholds at 3.5×10^{-13} m/cycle at 20 kHz (squares).

3.2 Fractography

The testing environment does not only influence the crack growth rates, but likewise the fracture surface appearance. The left sides of Figs. (3a, b) show 2024-T3 and 7075-OA specimens, respectively, which were cycled near threshold in ambient air first. After evacuating the vacuum chamber, loading was continued in vacuum at cyclic stress intensities causing crack growth rates of 10^{-11}-10^{-10} m/cycle. Fracture surfaces produced in vacuum are visible on the right sides each of Figs. 3(a, b), with crack orientation in LT for the 2024-T3 alloy and in TL for 7075-OA.

The fracture surfaces of both alloys show transcrystalline features with low ductility after loading in ambient air (left sides of both images). They are rather smooth and oriented approximately normal to the applied maximum normal stress (stage-II fracture mode). Loading in vacuum leads to crystallographic stage-I-like fracture of the planar-slip 2024-T3 alloy (Fig. 3a, right side). The fracture surfaces of the homogeneous-slip 7075-OA alloy do not show such a pronounced difference for loading in vacuum or ambient air and appear more ductile with transcrystalline fracturing features (Fig. 3b, right side).

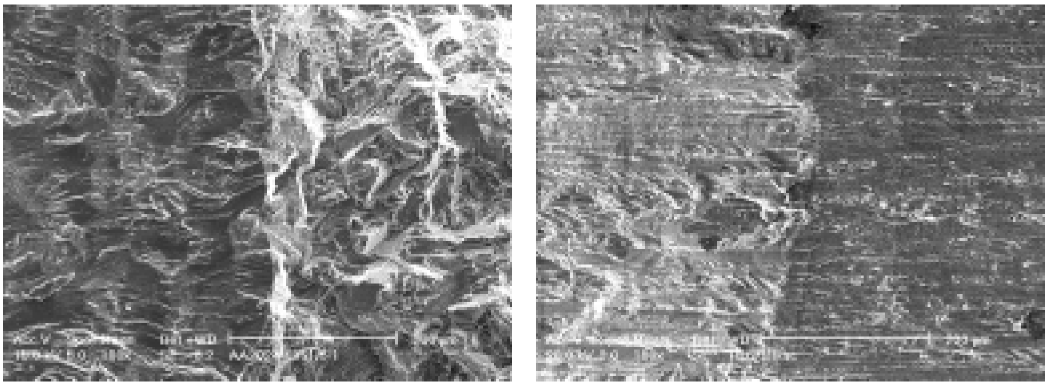
(a) (b)

Figure 3 Fracture surfaces after ultrasonic loading in the threshold regime in vacuum and in ambient air, with crack growth direction is from left to right. a) 2024-T3 and b) 7075-OA

4 DISCUSSION

Differences of the fatigue crack growth rates in ambient air and vacuum in ultrasonic experiments become obvious at crack growth rates below approximately 10^{-9} m/cycle. The question is, which mechanisms are responsible and which are the rate controlling processes. Considering humid air as environment, surface diffusion of water vapour to the crack tip could be a time limiting process. Second, the possibility to generate a water-vapour monolayer at the crack tip could be rate controlling (Stanzl and Tschegg [6]). Third, bulk diffusion of hydrogen entering the material at the crack tip may be considered. Estimations of the limiting crack growth rate in order to obtain environmental reactions at the crack tip have been performed by Stanzl-Tschegg [7]. It has been shown that the limiting growth rate is approximately in the range of 10^{-9} m/cycle, for both, surface coverage of the crack tip area by water vapour molecules, as well as bulk diffusion of hydrogen into the crack tip material at the ultrasonic loading frequency of 20 kHz. These estimations agree fairly well with the experimental results above. Surface diffusion of water vapour to the crack tip, however, shows to be at least by a factor of 10 faster, so that it is fast enough to not act as a time limiting process.

Comparison of the results of both frequencies shows higher fatigue crack growth rates at 20 Hz than at 20 kHz in the plateau regime (Figs. 1c, d and Fig. 2). Corrosive processes are present at ultrasonic frequency, although their influence is smaller than at conventional testing frequencies. Increasing the cycling frequency may be considered similar to decreasing the partial pressure of water vapour, and environmental effects are found by Henaff et al [8] at very low pressures. The different response at the two frequencies is most pronounced at R=-1 and becomes smaller at higher load ratios. The larger influence of air humidity on fatigue crack growth at 20 Hz can clearly be attributed to the longer time for the corrosive environment to react during each load cycle. The almost identical crack growth values at higher mean loads (R =+0.5) demonstrate that crack opening during the tensile portion of loading is an additional important factor, leading finally to a similarly pronounced reactivity at the crack tip as 20 Hz loading frequency.

Identical thresholds are obtained with loading frequencies of 20 Hz and 20 kHz in both aluminium alloys in ambient air environment. This result demonstrates that time available in the threshold regime obviously is sufficient for a full development of the reactions at the crack tip, which is in accordance with the above mentioned estimations.

5 CONCLUSIONS

- Humid air leads to corrosion fatigue in aluminium alloys at crack growth rates below approximately $1x10^{-9}$m/cycles at a loading frequency of 20 kHz.
- Under fully reversed loading conditions, the planar-slip alloys show in ambient air a plateau-like regime in the ($\Delta a/\Delta N$ vs. ΔK) curves, whereas growth rates decrease monotonously with decreasing stress intensity amplitudes for the homogeneous-slip 7075-OA alloy. The crack growth rates are up to two decades higher in ambient air in the plateau regime than in vacuum.
- The near-threshold stress intensities for cycling at 10^{-10} m/cycle are 53 – 62 % (2024-T3) and 54 -78 % (7075-OA) at R=-1, R=+0.05 and R=+0.5 and 40 % at R=-1 (7075-UA) in ambient air of the respective values measured in vacuum. Minimum crack growth rates of $5x10^{-11}$ m/cycle are observed in ambient air, whereas lower values like 10^{-12} m/cycle are measured in vacuum.
- Loading at 20 kHz ultrasonic frequency above threshold results in 5 - 50 times lower fatigue crack growth rates in ambient air at R=-1, depending on material and propagation rates, and similar growth rates at R=+0.5 in comparison to 20 Hz testing.
- The threshold stress intensities are identical at 20 Hz and 20 kHz loading not only in vacuum but also in ambient air for all R-ratios.

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