Effect of Environmental Condition and Frequency Variations on the Fatigue Crack Path in Aluminum Alloy

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ABSTRACT. *The resistance of metals against fatigue crack growth is experimentally determined with standardized specimens and procedures (for example ASTM E-647). We have studied the environmental effect on the crack growth resistance of 7075-T651 aluminum alloy. Three environmental conditions have been chosen: humid air, technically purified nitrogen and a fine vacuum. Load increasing and load decreasing tests with three R-ratio's have been performed. The loading frequency was 83 or 54 Hz. In all the tests we observed, as expected, a crack path which followed macroscopically the symmetry plane of the CT-specimen, with one exception: In nitrogen, with R = 0.1 and 83 Hz macroscopical crack branching was observed when ΔK reached approximately 5.0 MPa√m. The two crack branches propagated simultaneously in the +/- 38°-plane. This crack branching was observed both in the load increasing and load decreasing test mode. Such a change of the crack path can be understood as a result of a change of the dislocation motion at the crack tip. Possible explanations of this phenomenon are discussed*

INTRODUCTION

The role of the environment and the test frequency in fatigue and fatigue crack growth has been studied extensively in the past [1]. Much experimental work with various materials and environments has been done. The interaction of chemical reactions with the micromechanical changes of the material during the fatigue process has been found to be very complex. On the other hand various models of fatigue crack growth have been proposed, but only very few of them are able to account for the environmental effect. We have been interested in the environmental effect on the near threshold crack growth behavior in aluminum alloys. As typical aerospace materials we have chosen 2024-T351 and 7075-T651 for our experiments. Early in our work we have focused on the role of the oxide film built up in corrosive environments at the crack. Already in 1964 Schijve [2] has proposed a qualitative model of the interaction of cyclic slip with the oxide film at the crack tip. We have developed a semi-empirical model of the kinetics of the oxidation reaction in corrosive environments, such as air or technically purified nitrogen gas [3]. The thickness of the naturally formed oxide film on

2024-T351 and 7075-T651 has bee measured. A fatigue crack propagation mechanism has been proposed based on an oxide film growth model [3]. This model has been applied on variable amplitude loading tests in air, purified nitrogen and vacuum. A consistent interpretation of the environmental and frequency effect on fatigue crack growth could be found [4]. These three environments have bee used by other researchers to study the environmental effect on near threshold fatigue crack growth, [5,6].

During the tests in nitrogen an unexpected crack branching effect occurred in 7075-T651. This exceptional crack path was found only in the tests run with a frequency of 83 Hz and in nitrogen gas. The experimental conditions and possible theoretical explanations of this effect will be given below.

MATERIAL AND EXPERIMENTAL CONDITIONS

The material 7075-T651 is a commercially available Al-Zn-Mg-Cu alloy used in aircraft structures. The specimens were cut out of a plate such that the crack plane was in the long-transverse (L-T) orientation. The three different environment were: fine vacuum ($<5 \cdot 10^{-4}$ Pa), technically purified nitrogen (3 ppm H_2O, 1 ppm O_2) and humid air (approx. 60% relative humidity). The crack growth tests have been performed with an electromechanical resonance machine (RUMUL Microtron 654/5 kN) equipped with a high vacuum chamber, connected to a BALZERS turbomolecular pumping station and a pressurized bottle with technically purified nitrogen. All the tests have been conducted according to the Standard ASTM-E-647. The specimens were compact tension (CT-) specimens (W=60mm) with a thickness of 10 mm. An electro eroded sharp notch (notch depth = 17 mm) was introduced. The crack propagation was optically measured with two traveling microscopes, one on each side.

Constant load and load decreasing test modes were applied. In the first case the load applied was such, that at the beginning of the test the stress intensity range ΔK was 5.0 MPa√m. In the second case the load applied resulted in a ΔK of 10.0 MPa√m. In both tests the R-ratio was 0.1 and the test frequency was 83 Hz. The data for 7075-T651 with R=0.1 in all three environment could be compared with data from Petit et al. [6] and Kwon [7]. They have tested the same material at the same R-ratio but with a test frequency of 35 Hz. Our da/dN-data in air and vacuum have been compared to the data from these two independent laboratories and no significant difference has been found. Therefor we concluded, that our test set-up was verified for all environments, including nitrogen.

RESULTS

The test series in nitrogen started with R = 0.1 and a frequency of approximately 83 Hz. For the first specimen the load amplitude was chosen such that a ΔK value of 4.50 MPa√m resulted for the crack at the starter notch. Two cracks initiated at the front side approximately in the ± 36°direction from the symmetry plane of the specimen, see Fig. 1 top. On the backside the crack initiation point was first in the symmetry plane, as expected, see Fig. 1 bottom. During the first part of the test, both cracks on the front side propagated simultaneously but not continuously. The crack on the backside propagated with an expected crack growth rate of approximately 2.0 nm/cycle. In the second part of the test, the crack on the back side in the 0°-direction stopped and suddenly the cracks in the ± 36°direction, first only observed on the front side, broke through and were seen also on the back side. The loading was changed three times from ΔK increasing to ΔK decreasing and to ΔK increasing again. The ΔK value calculated based on the projected crack length on the symmetry plane varied between 4.5 and 8.0 MPa√m and the crack growth rates varied between 1.0 nm/cycle and 100 nm/cycle. In the last phase of the test a poor resonance characteristic of the system dominated and only the upper crack propagated. The test was stopped, the specimen was photographed and the crack paths were measured under the microscope. The results are shown in Fig. 1 right.

The interpretation of the test history is as follows. At the beginning of the test, two cracks initiated in the ± 36°direction on the front side and one crack in the symmetry plane on the backside. For the loading condition of ΔK approximately 5.0 MPa√m this coexistence of three crack fronts was in a metastable condition. When ΔK decreased further, the cracks in the ± 36°direction propagated faster than the crack in the symmetry plane. The crack in the symmetry plane stopped, when it was shadowed completely by the two cracks in the ± 36°direction. This happened, when ΔK was below 5.00 MPa√m. Increasing ΔK could not reverse this crack branching.

For the second specimen the load level at the beginning of the test was higher than for the first one, such that a ΔK value of 10.0 MPa√m resulted for the crack at the notch. After crack initiation a load shedding test was performed. The expected crack growth path in the symmetry plane was observed on both sides, until the ΔK value reached 5.0 MPa√m. The crack growth rate was stable at approximately 1.5 nm/cycle. The crack length had reached approximately 28.5 mm on both sides, when below and above the crack in the symmetry plane additional cracks appeared. The position of the top crack tip was measured on the backside and the position of the lower crack tip was measured on the front side of the specimen. Both cracks were propagating more or less simultaneously. The load was further decreased until a crack length of approximately 33 mm was reached, when the test was stopped. The specimen was photographed and the crack paths were measured under the microscope. The results are shown in Fig. 2.

The interpretation of the test history with the second specimen is as follows. At the beginning of the test, one crack initiated in the symmetry plane as expected. The crack propagated to a length of approximately 25 mm, when ΔK reached 6.5 MPa√m. Probably at this stage two additional cracks initiated in the ± 40° direction, but only in the bulk of the specimen. As in the first specimen the situation was that three crack fronts were in a metastable condition. On both surfaces the crack in the symmetry plane was propagating with 1.5nm/cycle. When ΔK decreased further, the cracks in the ± 40°direction propagated also towards the free surfaces, until they were visible at approximately 28.5 mm. Due to the shadowing effect the crack in the symmetry plane then stopped. This happened, when ΔK was approximately 5.0 MPa√m.

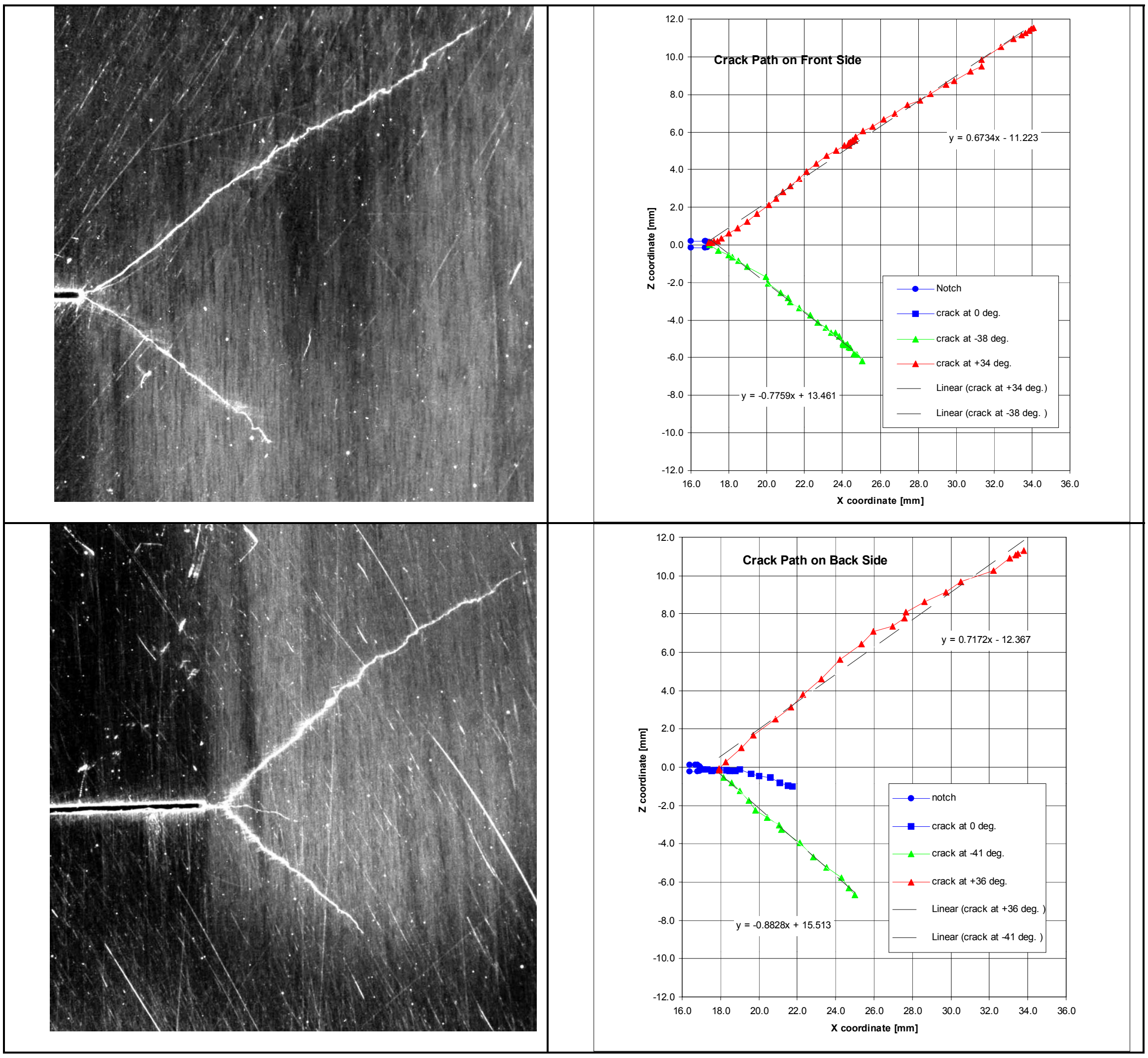

Figure 1. Crack Path on the front- and back-side of the CT-specimen tested in nitrogen at 83 Hz (load increasing test).

DISCUSSION

The situations found in these two specimens have been addressed in the literature as forked crack geometry. Bilby, et al. [8] has defined the stress intensity factor solution for the specific case shown in Fig. 3 left. For a fare-field tensile stress, the stress intensity factor of a crack, which is perpendicular to the stress field, is K_I. In this case the crack is loaded in mode I, the opening mode. If the crack is forked it is in a mix mode loading condition. The local mode II stress intensity factor is no more zero, see

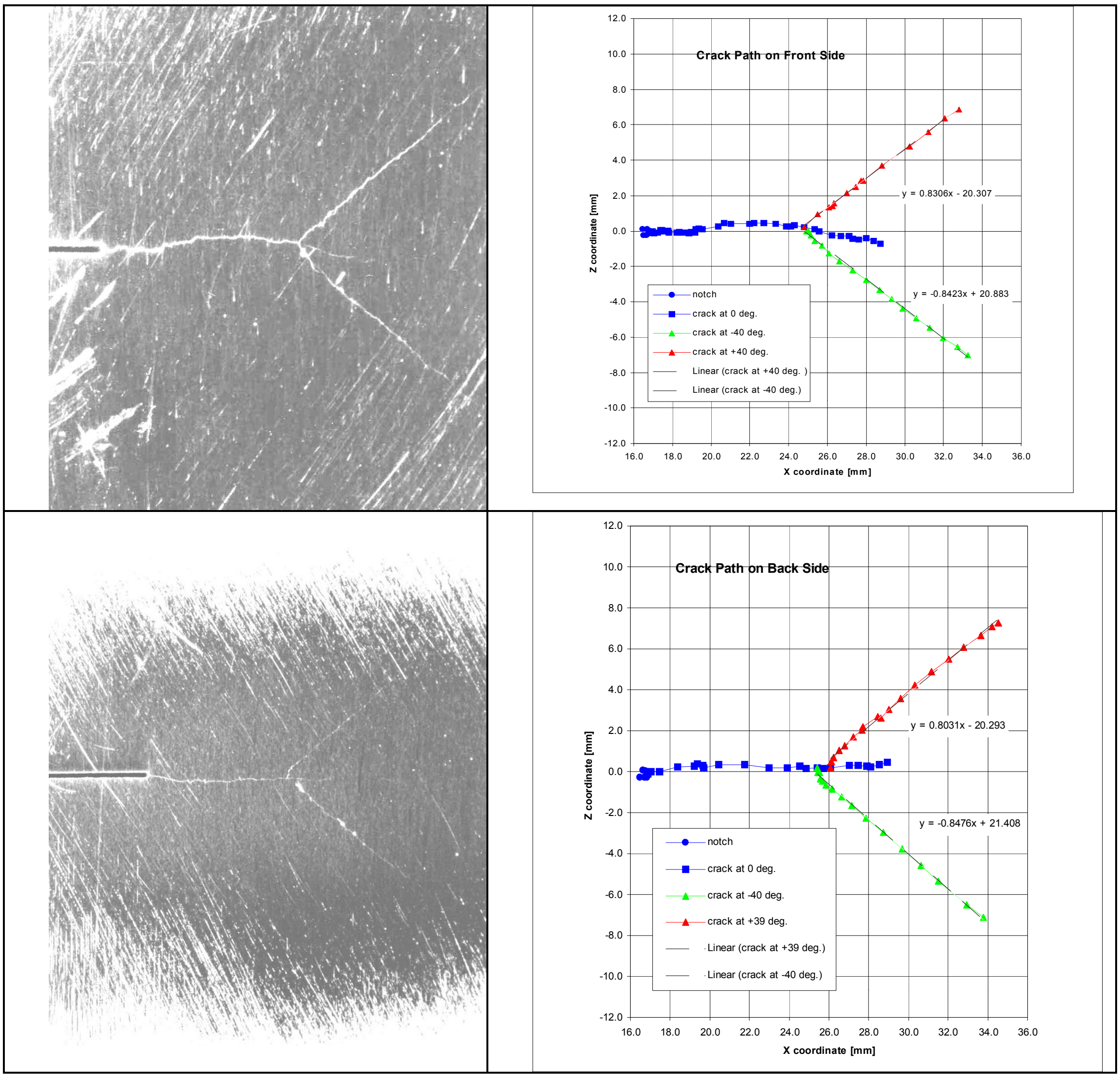

Figure 2. Crack Path on the front and backside of the CT-specimen tested in nitrogen at 83 Hz (load decreasing test).

Fig. 3 right. Following the solution for a forked crack with b/a = 0.1 from Kitagawa et al. [9] the local mode I stress intensity factor k_1 for an angle α of 38° is approximately 65% of K_I. The local mode II stress intensity factor k_2 is approximately 28% of K_I. If the b/a-ratio is bigger than 0.5 the local stress intensities can be calculated from a kinked crack with an inclined angle $\beta = 90° - \alpha$:

$$k_1 / K_I = \sin^2(\beta) \qquad (1)$$

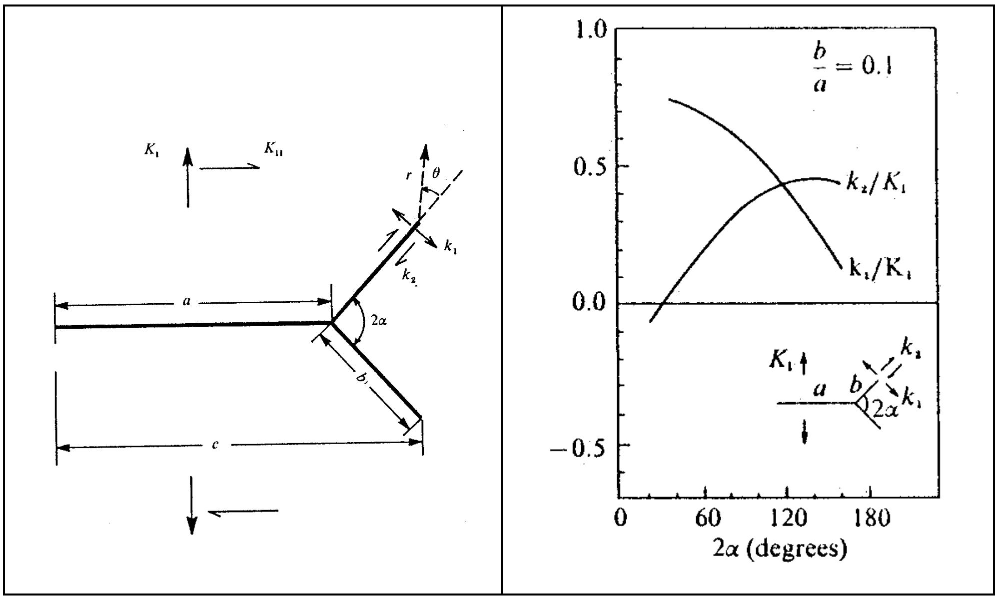

Figure 3. Stress intensity factors for a forked crack [8].

$$k_2 / K_I = \sin(\beta) \cdot \cos(\beta) \qquad (2)$$

If $\alpha = 38°$ an asymptotic value of 62% for k_1/K_I and 49% for k_2/K_I is reached when b is much longer than a.

It is important to note, that so far this crack branching has only be observed in technically purified nitrogen at a test frequency of 83 Hz, with an R-ratio of 0.1 and ΔK below 6.5 MPa√m. Already the reduction of the test frequency to 54 Hz or the increase of the R-ratio to 0.3 or 0.5 could eliminate this effect. This critical stress intensity factor range of $\Delta K = 6.5$ MPa√m is very close to the value below which only dislocations on single slip planes are operative. According to the oxidation kinetics model described in [3], normal chemisorption is in process for these test conditions. The oxide film thickness build up at the crack tip has reached only 0.4 nm after a half cycle, see Fig. 4. This is in the order of a monolayer (the dimension of a monolayer is between 0.15 nm and 0.5 nm) and it must be assumed that the surface at the crack tip is not yet fully covered by the oxide. The damage mechanism of the dislocations moving on the slip planes to this partly oxidized crack tip results in a shear fracture mode instead of a tensile fracture mode. If the oxide film is thicker the tensile fracture mode occurs.

To the authors knowledge such a crack growth mode has not yet been observed under cyclic loading. It supports the importance of the interaction of oxidation processes with the purely mechanical crack growth mechanism in specific environment like nitrogen.

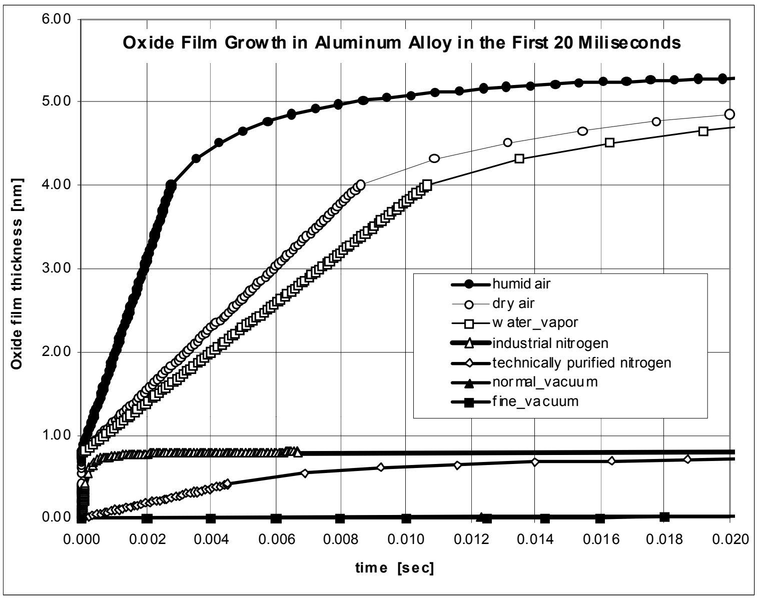

Figure 4. Oxide Film Growth in the first 20 Milliseconds after exposure to in various environments [3].

CONCLUSION

Crack growth in metals is a complex phenomenon. Various factors have a significant influence on the path a crack follows and his propagation velocity. In the experiments performed in three different environments, humid air, technically purified nitrogen and vacuum, we have found an exceptional macroscopic crack path. Macroscopic crack branching was found for constant amplitude tests when the following conditions were fulfilled:

1) Environment: technically purified nitrogen (3 ppm H_2O, 1 ppm O_2)
2) R-ratio: $R = 0.1$
3) Test frequency: $f = 83$ Hz
4) Loading history passes $\Delta K = 6.5$ MPa$\sqrt{m}$

This phenomenon did not appear, when one of the conditions mentions above was not fulfilled. This phenomenon has been explained as a metastable situation, when the oxidation process at the crack tip has not yet fully built up one monolayer of oxide and the dislocation activity at the crack tip changes from a single plane slip mechanism to a multi plane slip mechanism.

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