THE EFFECT OF ENVIRONMENT ON THE TRANSITION FROM TENSILE MODE TO SHEAR MODE DURING FATIGUE CRACK GROWTH IN ALUMINIUM ALLOYS
A MODEL FOR ENVIRONMENTALLY ASSISTED CRACK GROWTH

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ABSTRACT

Fatigue crack propagation tests were carried out in different environments on 7075-T6 and 2024-T3 centre-cracked sheet specimens. Observations were made on the transition from tensile mode to shear mode. It will be shown that there is no unique correlation between the state of stress and the mode of cracking. Together with the state of stress the environment has a significant effect on the mode of cracking. The implications for crack growth under corrosion fatigue conditions and the fatigue mechanism are discussed.
NOTATIONS

\( a \)  
(semi) crack length

\( da/dn \)  
crack rate

\( \Delta K \)  
range of stress intensity factor

\( R \)  
stress ratio = \( \sigma_{\text{min}} / \sigma_{\text{max}} \)

\( t \)  
thickness

\( \sigma \)  
tensile stress

\( \tau \)  
shear stress

\( \sigma_{cr} \)  
critical tensile stress

\( \tau_{cr} \)  
critical shear stress

\( \sigma_m \)  
mean stress

\( \sigma_a \)  
stress amplitude
INTRODUCTION

Fracture surfaces of centre-cracked sheet specimens subjected to cyclic loading in air show some characteristic features (Figure 1). Initially crack growth occurs macroscopically in the so-called tensile mode on a plane perpendicular to the loading direction. As the crack length increases, or at higher $\Delta K$-values, cracking occurs in the shear mode on a plane inclined at about 45 degrees to the loading direction. Transition from the tensile mode to the shear mode occurs gradually, starting with shear lips at the two surfaces.

Many investigators have suggested that a state of plain strain will produce a tensile mode crack, and a state of plane stress a shear mode crack. The present author [1,2] has stated that such a physical correlation between the state of stress and the mode of cracking does not exist. It was shown that the environment has a significant effect on the mode of cracking. In the present paper relevant information on the transition from tensile mode to shear mode obtained in recent test series will be surveyed. The main variables are the environment, sheet thickness and temperature. The implications of the observations for understanding corrosion fatigue will be analysed. The results support the crack growth model discussed in reference [1].

In this model the competition between $\tau_{cr}$ and $\sigma_{cr}$ at the crack tip determines the crack growth behaviour. The fracture mechanism will depend on the question whether $\tau$ or $\sigma$ is more critical. In those cases where $\sigma$ determines the crack growth behaviour, crack propagation will occur in the tensile mode and in those cases where $\tau$ determines the crack growth behaviour, crack propagation will occur in the shear mode. This question is depending on the aggressiveness of the environment and related aspects.
A MODEL FOR THE ENVIRONMENTAL EFFECT ON FATIGUE CRACK GROWTH

In the literature there is no general agreement about the various mechanisms proposed to describe crack propagation in fatigue. Most of the mechanisms can be classified into two types, one based on a plastic flow mechanism of crack advance, whereas the other one involves brittle fracture at the crack tip. Theoretical studies on crack growth usually consider only the behaviour of the material (plasticity) and the state of stress. With respect to the environment it is generally recognised that an aggressive environment will accelerate crack growth. However, the environment is doing more: it can essentially change the mechanism of crack growth. A model used first by KELLY et al. [3] and later by WESTWOOD et al. [4] was applied by these authors to liquid metal embrittlement. This model is very helpful to explain the corrosion fatigue behaviour.

The crack in Figure 2 will either propagate rapidly by quasi cleavage or slowly by shear, depending on the question which critical stress will be exceeded first: the tensile fracture stress $\sigma_{cr}$ of the bond $A-A_0$ constituting the crack tip, or the shear stress $\tau_{cr}$ to cause dislocation motion on the most favourably oriented slip plane $S-P$. The tendency to fail by cleavage increases if $\sigma_{cr}$ is lower or $\tau_{cr}$ is higher, i.e. if the ratio $\sigma_{cr}/\tau_{cr}$ is low. This can be obtained for example by cold work (increasing $\tau_{cr}$) or by a reduction of $\sigma_{cr}$. In general the environment will reduce $\sigma_{cr}$ and this is the major reason for the larger tensile mode area and higher crack growth rates in more aggressive environments.

The balance between $\tau_{cr}$ and $\sigma_{cr}$ will determine the crack growth behaviour. The fracture mode will depend on the question whether $\tau$ or $\sigma$ is going to be more critical.

In this respect it is important to note on which planes $\tau$ and $\sigma$ will be maximal. For the tensile stress this will always be a plane ($x/z$ plane, see Fig. 1) perpendicular to the loading direction, which is also perpendicular to the plane of the specimen ($x/y$ plane).
For the shear stress, however, this plane is not perpendicular to the loading direction, and even more important, it need not be perpendicular to the plane of the specimen [5]. Since planes making an oblique angle to the plane of the specimen may carry the maximum $\tau$, the tendency for growing in the $x/z$ plane will not be promoted if $\tau$ is controlling the mechanism. This explains the rougher fracture surface (multiple shear) in vacuum (see Figure 3). It also explains the larger flat area ($x/z$ plane) if $\sigma_{cr}$ is controlling the mechanism, which applies if the environment significantly contributes to crack extension. In vacuum crack propagation in aluminium alloy is the result of localized plastic deformation only, and as a consequence a real tensile mode area on the fracture surface does not occur. However, under conditions such as corrosive environments and low temperatures (e.g. steels) the magnitude of $\sigma_{cr}$ may decrease to such an extent that the nature of the cracking process changes from a ductile shear mechanism to a quasi-cleavage phenomenon.

Bowles [6] developed an experimental technique for producing plastic castings of fatigue cracks by a process of vacuum infiltration. This technique allows observations of the crack front and crack tip geometry in the scanning electron microscope. He found crack tip branching in vacuum, which occurred over large portions of the crack front. As soon as the environmental assistance for a quasi-brittle crack extension is missing a blunted crack tip can apparently generate two branches (Fig. 4 and 5). Crack tip branching, the much rougher fracture surface associated with a relatively poorly organized crack front and the high value of $\sigma_{cr}/\tau_{cr}$ can account for a slower crack rate in vacuum. Ion adsorption, metal dissolution or oxide film formation will reduce the energy necessary for debonding the atoms at the crack tip. The debonding will be accompanied by simultaneous dislocation movements in a quasi stationary way during uploading (see Fig. 2). The mechanism has the character of stable unzipping. This kind of brittle crack extension (quasi cleavage) will proceed at a much slower rate compared to real cleavage.
According to the above mentioned fatigue crack model the rate of brittle crack extension during one cycle will be dependant on the instantaneous K-value, sheet thickness, environment, temperature and time available for electrochemical reactions.
SURVEY OF THE TESTS

In this paper crack growth results have been collected from several investigations, carried out in the Aerospace Department of the Delft University of Technology. Crack propagation tests were carried out on centre cracked sheet specimens with different dimensions. All experiments were performed in tension-tension loading in an Amsler 200 kN electrohydraulic fatigue machine and for the smaller specimens in a home-made 60 kN electrohydraulic machine. The width of the specimens was 100 mm, the free length between the clamps was 200 mm. All specimen were provided with a small crack starter in the centre of the specimen, consisting of a small hole (diameter 1 mm) and two saw cuts. A survey of the tests is given in Table 1. Results presented in figures are averages of three tests. For the specimens 7075-T6 sheet material was used except for test series I where also 2024-T3 sheet material was used. Mechanical properties for the materials suggest that differences between the sheet materials were insignificant.

The transition point on the fracture surface is marking the crack length at which the transition from the tensile mode to the shear mode is completed (see Fig. 1). According to the fatigue crack model discussed before the location of this point will be dependent on the environment, temperature, frequency, wave shape, crack propagation rate, K-value and the sheet thickness.

Figure 6 shows the results of crack propagation tests in vacuum, air and a 3.5 percent NaCl solution [7]. Figure 3 shows fracture surfaces of three specimens fatigued in the same environments [8]. The results in these figures clearly show that:

- Crack propagation rates are higher in a more aggressive environment.
- Tensile mode areas are larger in more aggressive environments, whereas it is virtually absent in vacuum.
Figures 7, 8 and 9 show the results of crack propagation tests in different environments at different temperatures (test series II and III). Figure 10 shows the fracture surfaces of the specimens of test series III.

In vacuum a temperature effect was not observed (Fig. 9), whereas distinct temperature effects are present in the more aggressive environments. In a 3.5 pct. NaCl solution higher temperatures involve higher crack propagation rates (Fig. 7) and larger tensile mode area's. WEI [9] found a similar temperature effect in distilled water for low ΔK-values, whereas for distilled water and somewhat higher ΔK-values we found an opposite temperature effect (Fig. 8). Anyhow, it should be noted from Figures 7 and 8 that increasing the crack rate by changing the temperature also implies a larger tensile mode area.

Figures 11-16 show the influence of frequency and wave form on the crack propagation rate and the location of the transition point in different environments. The results clearly show that:

- In an aggressive environment lower frequencies are related with higher crack propagation rates, which again implied larger tensile mode area's.

- In an aggressive environment a square wave form gives lower crack propagation rates and smaller tensile mode area's compared to a sinusoidal wave form, especially if the frequency is low.

- In inert environments there is no effect of frequency and wave form.

With respect to the environmental effect on the mode of failure supporting evidence was occasionally published in the literature. HARTMAN et al [10] compared fracture surfaces of 2024-T3 and 7075-T6 specimens tested in humid air and in very dry air. They observed that the fatigue cracks obtained in dry air had a less smooth fracture surface with an alternating pattern of some type of double shear (see also [11] ).

KRUPP, HOEPPNER and WALKER [12] testing 7075-T6 specimens in dry air, wet air and salt solution noticed that the surface texture was coarser macroscopically for cracking in dry air. Secondly the transition from
the tensile mode to the shear mode was found to occur earlier in dry air than in wet air and salt water. The latter two environments did not produce significant differences. Observations of this kind emphasize once again that fatigue crack propagation studies in order to be fully recorded in the literature should also report on fractography. It should include more than EM pictures because macroscopic evidence can be equally essential.
DISCUSSION

In the previous chapter a review has been made of the effects of environment, temperature, frequency, and wave form on the rate of fatigue crack growth and the location of the transition point in high strength aluminium alloys. It was found that the effect of many of these variables depend strongly on the material-environment system involved. A systematic trend found in all test series was:

| Same material, same thickness → if the crack rate is faster, the tensile mode area is larger. |

This applies to faster crack rates as obtained by
- more aggressive environments
- changing temperature
- decreasing frequency
- changing of the wave form.

It will be explained that all these changes, in agreement with the proposed model, will affect the contribution of environmentally promoted "debonding" to crack growth.

**Effect of the environment**

In high vacuum any environmental contribution is excluded, and debonding will not occur. As a result \( \tau_{cr} \) will determine the crack growth behaviour. There is no real tensile mode area to be found on the fracture surface; the whole fracture surface consists of multiple shear mode and shear mode area's (Figure 3). In aggressive environments including laboratory air debonding will take place, even at the lower \( \Delta K \)-values. The amount of debonding as compared to the amount of plasticity will determine the location of the transition point. This is dependent on:

1. state of stress near the crack tip (plane strain or plane stress)
2. environment
3°. time available for electrochemical reactions (frequency, wave form, crack propagation rate)
4°. material properties (brittle or ductile behaviour, temperature, strain hardening effects etc.).

Especially the two observations (1) a larger tensile mode area in a more aggressive environment, and (2) a virtual absence of a tensile mode area in vacuum, are considered to provide strong evidence in support of the fatigue model presented before.

Effect of temperature

From kinetics for electrochemical reactions it follows that the reaction rate is related to the temperature. As a result a higher test temperature will promote debonding. According to the proposed fatigue crack model a higher temperature will then imply faster crack growth and, which is of more interest here, it will also imply a larger tensile mode area. This is confirmed by the test results in Figure 7 obtained in salt water.

The test results in distilled water, however, show an opposite temperature effect (Fig. 8 and 10). At higher temperatures (64° C) crack propagation rates are slower and tensile mode area's are smaller compared to lower temperatures. The same tests performed in vacuum show no temperature influence at all (Fig. 9), which means that an explanation for the temperature effect in distilled water must be found in the environmental influences and not in temperature effects on material properties.

Recently BOERS [13] found that in de-ionized, multi-distilled oxygen poor water, crack propagation rates are virtually independent of temperature. In de-ionized, multi-distilled water saturated with oxygen, crack propagation rates decrease with increasing temperature. However, in artificial seawater crack propagation rates increase with increasing temperature, while oxygen saturation stimulates this effect even more (Fig. 17). BOERS's analysis suggest that oxygen has a beneficial effect (i.e. retarding effect) on crack propagation rates if no chloride-ions are present. It seems that in case of oxygen poor distilled water either no temperature-dependent electrochemical reactions are involved, or a
number of reactions are balanced, resulting in a constant crack propagation rate with respect to temperature. Another reason for this different temperature behaviour may be associated with the fact that adsorption is more effective at lower temperatures. This effect will be opposite to the effect of temperature in raising the reaction rate. It should be noted that the higher crack rate in distilled water of a lower temperature is still associated with a larger tensile mode area (Fig. 8). This once again supports the idea that the effect of temperature in distilled water is an environmental effect.

**Effect of frequency and cyclic stress wave form**

In a load cycle crack extension will probably start immediately after the crack has been fully opened until the very tip. It is also expected to stop when the load has reached its maximum value. The influence of the environment will be limited mainly to that part of the load cycle, because it has no influence on the crack closure behaviour (lit. 7).

Electrochemical reactions are time dependent, which means that the effects of frequency, wave form and crack propagation rate must be interrelated. It is easy to understand that higher frequencies and higher crack propagation rates will imply less environmental influences and consequently smaller tensile mode area's. This is confirmed by the results presented in the Figures 11, 12 and 13.

In a fatigue test, the stress wave usually is sinusoidal and, therefore, both time available for electrochemical reactions and stress rate vary with frequency. Then it is difficult to distinguish whether the effect of frequency on corrosion fatigue is due to the stress rate or to the time available for electrochemical reactions.

In vacuum no difference was found between a sinusoidal and a square wave form. This could point to an absence of a strain rate effect during fatigue.

In a 3.5 pct. NaCl solution, however, there was a distinct difference between the crack propagation rate and the location of the transition
point under a sinusoidal and a square wave form. This difference disappeared at higher frequencies (Figures 14, 15 and 16).

The results do suggest that the effects of frequencies and wave form on crack propagation rate are dependent on time available for electrochemical reactions during the crack growth part of the cycle. The available time is much smaller for a square wave than for a sinusoidal wave of the same frequency. Since the crack growth rate and the loading rate \( \frac{d\sigma}{dt} \) are closely related it appears that the up loading rate is the more important parameter, whereas the frequency \( (f) \) proper may be less significant. This is now being studied by adopting a variety of wave forms.

One of the major problems, facing an aircraft structure in service is corrosion fatigue. The environment, even normal air, plays an important role in the fatigue mechanism as shown before. This makes a prediction of the fatigue resistance extremely difficult. The more usual approach to determine the fatigue resistance for an aircraft structure is to carry out full-scale tests, simulating service conditions as well as possible. A significant question is: how relevant is such a test from the point of corrosion fatigue [14]? One of the practical impossibilities of a flight simulation test is the use of service load frequencies, it always should be an accelerated test. Corrosion fatigue is a time and frequency dependent process. Higher frequencies means less time available for electrochemical reactions and the nature of the cracking process can change from a quasi clearage phenomenon in service to a ductile shear mechanism in test.
CONCLUSIONS

1. An unique physical correlation between the state of stress and the mode of cracking does not exist, because the environment has a significant effect on the mode of cracking.

2. The critical tensile stress for tensile debonding in vacuum will usually not be reached and crack growth is the result of localised plastic deformation only. As a result a real tensile mode area on the fracture surface will be absent and a rough fracture surface will be found.

3. An aggressive environment will reduce $\sigma_{cr}$ because debonding is facilitated by mechanisms such as adsorption, dissolution and oxide film formation. Consequently fracture planes preferably are perpendicular to the main principle stress (tensile mode). The tensile mode area is larger and smoother in a more aggressive environment.

4. No temperature influences ($20^\circ$ C - $88^\circ$ C) have been found in vacuum, which means that an explanation for a temperature effect in aggressive environments must be found in environmental influences and not in changes of material properties.

5. Temperature has an influence on:
   (a) reaction rate of electrochemical reactions
   (b) effectiveness of adsorption processes.
   Higher temperatures imply higher reaction rates, which means higher crack propagation rates and larger tensile mode area's. However, higher temperatures could also imply less effective adsorption, which could have the opposite effect. For very aggressive environments like a 3.5 pct. NaCl solution (a) predominate; for less aggressive environments like distilled water (b) can predominate in cases where temperature dependant electrochemical reactions are involved.

6. Oxygen has a beneficial effect (i.e. a retarding effect) on crack propagation rates if no chloride-ions are present.
7. Since the crack growth rate and the loading rate ($d\sigma/dt$) are closely related it appears that the uploading rate is the more important parameter, whereas the frequency (Hz) proper may be less significant.

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REFERENCES


2. L.B. Vogelesang - Some factors influencing the transition from tensile mode to shear mode under cyclic loading. Aerospace Dept., Delft University of Technology, Report LR-222, August 1976.


<table>
<thead>
<tr>
<th>test series</th>
<th>material (clad)</th>
<th>thickness (mm)</th>
<th>loading MPa</th>
<th>environment</th>
<th>frequency (Hz)</th>
<th>temperature (°C)</th>
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<td>I</td>
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<td>1/2.5/6</td>
<td>54 ± 44</td>
<td>vacuum/air/3.5 % NaCl</td>
<td>20</td>
<td>room temp.</td>
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<tr>
<td></td>
<td>7075-T6</td>
<td>1/2.5/6</td>
<td>54 ± 44</td>
<td>vacuum/air/3.5 % NaCl</td>
<td>20</td>
<td>room temp.</td>
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<td>78.5 ± 29.5</td>
<td>H₂O ± O₂ NaCl +O₂ vacuum</td>
<td>5</td>
<td>20/50/88/40/19</td>
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<tr>
<td>III</td>
<td>7075-T6</td>
<td>6</td>
<td>78 ± 39</td>
<td>distilled water</td>
<td>5</td>
<td>4/24/44/64</td>
</tr>
<tr>
<td>IV</td>
<td>7075-T6</td>
<td>2.5</td>
<td>78 ± 39 sinus square</td>
<td>vacuum/air/3.5 % NaCl</td>
<td>20/5/0.5</td>
<td>room temp.</td>
</tr>
</tbody>
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Table 1. Survey of the tests.
Fig. 1
Transition from tensile mode to shear mode.
Fig. 2
Crack growth model.
Fig. 3 Fracture surfaces of fatigue specimens in vacuum, lab. air and salt water.
(7075-T6, test series IV)
Fig. 4  Crack tip in 2024-T3 when viewed perpendicular to the crack front (courtesy of C.Q. Bowles)

Infiltration point: $\sigma_{\text{max}}$

Environment : air

Magnification : 3500 x
Fig. 5  Crack tip in 2024-T3 when viewed perpendicular to the crack front. Crack tip branching occurring at maximum load and resulting from crack growth in vacuum (Courtesy of C.Q. Bowles). Magnification: 2000 x.
Fig. 6
Effect of environment on the crack rate.
($\sigma_m = 54 \text{ MPa}, \sigma_a = 44 \text{ MPa}, R = 0.1$)
$\sigma = \text{transition point}$
The effect of temperature on crack rate and location of the transition point.

\( \sigma = 78.5 \pm 29.5 \) MPa

7075-T6

\( t = 2.5 \) mm

\( \sigma \) transition point
air (room temp.)
\( \text{H}_2\text{O} \ 40^\circ \text{C} \)
\( \text{H}_2\text{O} \ 24^\circ \text{C} \)
\( \text{H}_2\text{O} \ 44^\circ \text{C} \)

Fig. 10  Fracture surfaces of fatigue specimens in air and distilled water at different temperatures (t = 6 mm, test series III)
Effect of frequency on crack rate and location of the transition point

\( \Delta K = \Delta \sigma \sqrt{a} (\text{MPa} \sqrt{\text{m}}) \)

- 0.5 Hz
- 5
- 20
- 3.5% NaCl
- vacuum

\( \frac{da}{dn} \) (\( \mu \text{m} \)/cycle)

\( \frac{da}{dn} \) (\( \mu \text{m} \)/cycle)

\( \Delta K = \Delta \sigma \sqrt{a} (\text{MPa} \sqrt{\text{m}}) \)

- 0.5 Hz
- 5
- 20
- 3.5% NaCl
- vacuum

**Fig. 11**

**Fig. 12**

\( q_m = 78 \text{ MPa}, \sigma_a = 39 \text{ MPa}, R = 0.33 \)

\( t = 2.5 \text{ mm} \)

7075-T6

\( a = \text{transition point} \)
Fig. 13
Effect of frequency on crack rate and location of the transition point (Data from Schijve (9)).
- transition point.
Effect of cyclic wave form on crack rate and location of the transition point.

$\sigma_m = 78$ MPa, $\sigma_a = 39$ MPa, $R = 0.33$

$t = 2.5$ mm

7075-T6

t = transition point
Fig. 17
Crack rate versus temperature $^\circ$C.
7075-T6
$t = 2.5$ mm
$R = 0.33$