SOME FACTORS INFLUENCING THE TRANSITION FROM TENSILE MODE TO SHEAR MODE UNDER CYCLIC LOADING

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SUMMARY

Fatigue crack propagation tests in different environments were conducted using Aluminium 7075-T6 and 2024-T3 sheet of different thicknesses. Observations were made on the transition from the tensile mode to the shear mode on the fracture surface. It will be shown that there is no unique physical 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.
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1. INTRODUCTION

The fracture surfaces of centre-cracked sheet specimens subjected to cyclic loading in air show 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 suggest that a state of plain strain will produce a tensile mode crack, and a state of plane stress a shear mode crack. VOGELESANG [2] has stated that such a physical correlation between the state of stress and the mode of cracking does not exist. He showed that the environment has a significant effect on the mode of cracking. In the present report 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 $\sigma_{cr}$ 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.
2. ANALYSIS OF THE CRACK GROWTH MECHANISM

A model used first by KELLY et al [2] and later by WESTWOOD et al [3] was applied by these authors to liquid metal embrittlement. This model is extremely useful to explain the corrosion fatigue behaviour. The crack in Figure 2 will either propagate rapidly by cleavage or slowly by shear, depending on the question whether the tensile fracture stress $\sigma_{cr}$ of the bond A-A_o constituting the crack tip, or the shear stress $\tau_{cr}$ to cause dislocation motion on the most favourably oriented slip plane S-P, is exceeded first. The tendency to fail by cleavage increases if $\sigma_{cr}$ is lower or $\tau_{cr}$ is higher, i.e. if the ratio $\sigma_{cr}/\tau_{cr}$ decreases. This can be achieved 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 in more aggressive environments.

The competition 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) perpendicular to the loading direction and 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 [4].

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 is explaining the rougher fracture surface (multiple shear) in vacuum. It also explains the larger flat area ($x/z$ plane) if $\sigma_{cr}$ is controlling the mechanism, which applies if the environment contributes to the crack extension.

In vacuum crack propagation in Aluminium alloys is the result of localised plastic deformation only, and as a result a real tensile mode area on the fracture surface does not occur. Due to conditions such as
corrosive environments and low temperature (e.g. steels) the magnitude of $\sigma_{cr}$ may change to such an extent that the nature of the cracking process changes from a ductile shear mechanism to a quasi-cleavage phenomenon.

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 [5]. 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 dependent on the instantaneous K-value, sheet thickness, environment, temperature and the time available for electrochemical reactions.
3. SURVEY OF THE TESTS

In this report crack growth results have been used from several investigations, recently 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 20-tons electrohydraulic system and for the smaller specimens in a home-made 1-tons electrohydraulic system.

A survey of the tests is given in Table 1. Most tests were carried out in triplicate. 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 are given in Table 2. The data 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 outlined in chapter 2 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 3 shows the results of crack propagation tests in vacuum, air and a 3.5 pct. NaCl solution [6]. Figure 4 shows the fracture surfaces of three specimens fatigued in the same environments [7]. Fractographic observations of test series V have been compiled in figure 5. The results in these figures clearly show that:

- Crack propagation rates are higher the more aggressive the environment
- The tensile mode area is larger in the more aggressive environments, where it is virtually absent in vacuum.

Figures 6, 7, 8 and 9 show the results of crack propagation tests in different environments at different temperatures (test series II, III and IV). Fractographic observations of test series II have been compiled
in Figure 10. Figure 11 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. 6) and larger tensile mode area's (Fig. 10). WEI [8] found the same temperature effect in distilled water for low ΔK-values (Fig. 12), while the author, also for distilled water, found an apposite temperature effect for somewhat higher ΔK-values (Figs. 7 and 8). Anyhow, it should be noted from figures 6-8 that increasing the crack rate by changing the temperature also implies a larger tensile mode area.

Figures 13-18 show the influence of frequency and wave shape on the crack propagation rate and the location of the transition point in different environments (data of figure 18 are obtained from literature [9]).

The results clearly show that:

- In a 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 shape gives lower crack propagation rates and smaller tensile mode area's compared to a sinusoidal wave shape.

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

Figure 19 shows the results of crack propagation tests in air on 7075-T6 sheets of different thicknesses. Fractographic observations of the same specimens (test series VI) have been compiled in figure 20.

Apparently:

- Crack propagation rates are higher for thicker sheets.

- The location of the transition point on the fracture surface shifts to higher ΔK-values with increasing sheet thickness.

Figure 21 shows the results of test series I in vacuum, air and a 3.5 pct. NaCl solution on 2024-T3 and 7075-T6 specimens of different
thicknesses. These tests give the same information as the tests mentioned before. In vacuum there is no real tensile mode area, but still there is a thickness effect on the crack propagation rate.

With respect to the environmental effect on the mode of failure supporting evidence was occasionally published in the literature. Hartman et al [13] 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 [14]).

Krupp, Hoeppner and Walker [15] 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 macroscopical evidence can be equally essential.
4. DISCUSSION

In the previous chapter a review has been made of the effects of environment, temperature, frequency, wave form and specimen thickness 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:

Same material, same thickness $\rightarrow$ 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 shape

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

4.1. 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 (Figures 22 and 23). In aggressive environments including laboratory air debonding will take place, even at the lower $\Delta K$-values. Debonding will be accompanied by simultaneous dislocation movements in a quasi-stationary way during uploading. 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 (value of $\sigma_j$)
2. environment
3. time available for electrochemical reactions (frequency, wave shape, crack propagation rate)
4. material properties (brittle or ductile behaviour, temperature, strain hardening effects etc.)

Especially the observation: the tensile mode area is larger in the more aggressive environment, where it is virtually absent in vacuum, is considered to provide good evidence supporting the fatigue model presented before (see also Figure 4).

4.2. 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 figures 6 and 10 obtained in salt water.

The test results in distilled water, however show an opposite temperature effect (Fig. 7, 8, 10 and 11).

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 than an explanation for the temperature effect in distilled water must be found in the environmental influences and not in temperature effects on material properties.

The 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 also associated with a larger
tensile mode area (Fig. 11). This once again supports the idea that the
effect of temperature in distilled water is still an environmental
effect.
WEI [8] found an opposite temperature effect in distilled water, but he
performed his tests at lower ΔK-values (< 32 kgf/mm²). He found a distinct
temperature influence at ΔK-values of 21 and 25 kgf/mm³/2, which was
decreasing at somewhat higher ΔK-values (figure 12). Crack propagation
rate at these low ΔK-values is very slow, which could mean sufficient
time to make adsorption also effective at higher temperatures.

4.3. Effect of time available for electrochemical reactions

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. 6].
Electrochemical reactions are time dependent, which means that the
effects of frequency, wave shape 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 13, 14 and 15.
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 shape. 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 shape. This difference disappeared at higher frequencies (Figures 16, 17 and 18). The results do suggest that the effects of frequencies and wave shape 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.

4.4. Effect of thickness

A more difficult problem is the explanation of the thickness effect. Considering the same environment, temperature, frequency and wave shape, it appears that crack rates are faster for thicker materials. It is tempting to explain this effect by referring to plane strain/plane stress differences. Two arguments should be mentioned
- plane strain → smaller plastic zone sizes → less crack closure → larger $\Delta K_{\text{eff}}$ as observed!

However, an attempt to explain the results of Figure 21 on the basis of $\Delta K_{\text{eff}}$ alone did not give a satisfactory picture (Figure 24, same tendency for 2024-T3 and other environments [11]).
- plane strain → smaller plastic zones → larger tensile stresses → according to the model this will promote debonding.

However, this would require a smaller (or negligible) thickness effect in vacuum, but it is of a similar order of magnitude as compared to other environments.
5. CONCLUSIONS

1. A 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. In vacuum normally the critical tensile stress of the bond will not be reached and crack growth is the result of localised plastic deformation only, which means no real tensile mode area on the fracture surface.

3. In aggressive environments the local tensile stress, assisted by ion adsorption, metal dissolution and oxides film formation will make debonding easier and this is the main reason for the occurrence of the tensile mode area.

4. The tensile mode area is larger the more aggressive the environment.

5. Crack propagation rate is higher the more aggressive the environment.

6. No temperature influences (20°C - 88°C) has been found in vacuum, which means that an explanation for temperature effects in aggressive environments must be found in environmental influences and not in a changes of the material properties.

7. Temperature has an influence on:
   (a) reaction rate of electrochemical reactions
   (b) effectiveness of adsorption processes

   The higher temperatures, the higher reaction rates, which means higher crack propagation rates and larger tensile mode area's.

   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) predominates; for less aggressive environments like distilled water (b) predominates at the higher $\Delta K$-values ($> 32 \text{ kgf/mm}^3/2$).

8. Frequency, wave-shape and crack propagation rate effects are attributable to the available time for electrochemical reactions during the crack growth part of the cycle.

9. No strain rate effect has been found.
10. Crack propagation rates are higher and the tensile mode area's are larger for thicker sheets. This thickness effect is present in vacuum, air and salt water. A reasonable explanation has not yet been found.

6. ACKNOWLEDGEMENT

The author wishes to thank prof. J. Schijve for his important contribution during the preparation of the manuscript.
7. LIST OF REFERENCES


5. J. SCHIJVE - The fatigue mechanism in aluminium alloys. Aerospace Dept., Delft Univ. of Technology (to be published).


12. W.J. ARKEMA - Crack closure during fatigue and the effects of sheet


Table 1. Fatigue Crack Propagation Tests.

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<td>6/2.5/6</td>
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Table 2. MECHANICAL PROPERTIES.
Fig. 1. TRANSITION FROM TENSILE MODE TO SHEAR MODE.
Fig. 2. SCHEMATIC ILLUSTRATION OF A CRACK IN A SOLID SUBJECTED TO AN INCREASING FORCE F. THE BOND A-A_o CONSTITUTES THE CRACK TIP. B IS AN ION.
(WESTWOOD et al)
Fig. 3. THE EFFECT OF THE ENVIRONMENT ON THE CRACK RATE
\( (\sigma_m = 5.5 \text{ kg/mm}^2, \sigma_a = 4.5 \text{ kg/mm}^2, R = 0.1, \text{ Series I}) \)
(Data from Schijve en Arkema [6].)
Fig. 4. FRACTURE SURFACES OF FATIGUE SPECIMENS IN VACUUM, LAB.
AIR AND SALT WATER.
(7075-T6, specimens of series V, [7])
Fig. 5. LOCATION OF THE TRANSITION POINT ON THE FRACTURE SURFACE.
INFLUENCE OF ENVIRONMENT AND FREQUENCY.
(Series V, t = 2.5 mm)
Fig. 6. THE EFFECT OF TEMPERATURE ON THE CRACK RATE AND
THE LOCATION OF THE TRANSITION POINT IN A 3.5
PCT. NaCl SOLUTION.
($\sigma_m = 6$ kg/mm², $\sigma_a = 4$ kg/mm², $R = 0.2$, Series II)
Fig. 7. THE EFFECT OF TEMPERATURE ON THE CRACK RATE AND THE LOCATION OF THE TRANSITION POINT IN DISTILLED WATER.

\[ \Delta K = \sigma \sqrt{\pi a} \ (\text{kg/mm}^{3/4}) \]

\( \sigma_m = 6 \ \text{kg/mm}^2, \ \sigma_a = 4 \ \text{kg/mm}^2, \ R = 0.2, \ \text{Series II} \)
Fig. 8. THE EFFECT OF TEMPERATURE ON THE CRACK RATE AND THE LOCATION OF THE TRANSITION POINT IN DISTILLED WATER.

\( \sigma_{m} = 8 \text{ kg/mm}^2, \sigma_{a} = 4 \text{ kg/mm}^2, R = 0.33, \text{ Series III} \)
**Fig. 9.** THE EFFECT OF TEMPERATURE ON THE CRACK RATE IN VACUUM.

\[ \Delta K = \epsilon_0 \sigma \sqrt{\pi a} \text{ (kg/mm}^{\frac{3}{2}}\text{)} \]

\( \sigma_0 = 8 \text{ kg/mm}^2, \sigma_a = 4 \text{ kg/mm}^2, R = 0.33, \text{ Series IV} \)
Fig. 10. LOCATION OF THE TRANSITION POINT ON THE FRACTURE SURFACE. INFLUENCE OF TEMPERATURE. (Series II, t = 1.2 mm)
Fig. 11. FRACTURE SURFACES OF FATIGUE SPECIMENS IN AIR AND DISTILLED WATER AT DIFFERENT TEMPERATURES. 
(t = 6 mm, series III).
Fig. 12. RATE OF FATIGUE-CRACK GROWTH IN A 7075-T651 ALLOY AS A FUNCTION OF TEST TEMPERATURE IN DISTILLED WATER (WEI, [8]).
Fig. 13. EFFECT OF FREQUENCY ON THE CRACK PROPAGATION RATE AND THE LOCATION OF THE TRANSITION POINT.
\( (\sigma_m = 8 \text{ kg/mm}^2, \sigma_a = 4 \text{ kg/mm}^2, R = 0.33, \text{ Series } V) \)
Fig. 14. EFFECT OF FREQUENCY ON THE CRACK PROPAGATION RATE AND THE LOCATION OF THE TRANSITION POINT.
(σ_n = 8 kg/mm², σ_a = 4 kg/mm², R = 0.33, Series Π)
Fig. 15. EFFECT OF FREQUENCY ON THE CRACK PROPAGATION RATE AND THE LOCATION OF THE TRANSITION POINT. (Data from Schijve [9])
Fig. 16. EFFECT OF WAVE SHAPE ON THE CRACK PROPAGATION RATE AND THE LOCATION OF THE TRANSITION POINT.
\( \Delta \sigma = 8 \) kg/mm\(^2\), \( \sigma_a = 4 \) kg/mm\(^2\), \( R = 0.33 \), Series V)
Fig. 17. EFFECT OF WAVE SHAPE ON THE CRACK PROPAGATION RATE AND THE LOCATION OF THE TRANSITION POINT.

($\sigma_m = 8 \text{ kg/mm}^2$, $\sigma_a = 4 \text{ kg/mm}^2$, $R = 0.33$, Series $\mathcal{X}$)
Fig. 18. EFFECT OF WAVE SHAPE ON THE CRACK PROPAGATION RATE AND THE LOCATION OF THE TRANSITION POINT.
\( (\sigma_a = 8 \text{ kg/mm}^2, \sigma_a = 4 \text{ kg/mm}^2, R = 0.33, \text{Series V}) \)
Fig. 19. CRACK GROWTH RATE AS A FUNCTION OF $\Delta K$
INFLUENCE OF THE SHEET THICKNESS.
($\sigma_m = 8$ kg/mm$^2$, $\sigma_a = 4$ kg/mm$^2$, $R = 0.33$, Series VI)
Fig. 20. LOCATION OF THE TRANSITION POINT ON THE FRACTURE SURFACE.
INFLUENCE OF THE SHEET THICKNESS.
(specimens of fig. 19, series VI)
Fig. 21. THE EFFECT OF THICKNESS ON THE CRACK RATE AND THE LOCATION OF THE TRANSITION POINT IN VACUUM, AIR AND SALT WATER.
Data from Schijve and Arkema [6],
($\sigma_a = 5.5$ kg/mm², $\sigma_y = 4.5$ kg/mm², $R = 0.1$, Series 1)
Fig. 22. MACROSCOPIC FRACTURE SURFACES OF CENTRE CRACKED SHEET SPECIMENS IN VACUUM AND AIR RESPECTIVELY.
Fig. 23. CROSS SECTIONS OF FRACTURE SURFACES IN AIR AND VACUUM [11].
Fig. 24. CRACK GROWTH RATE AS A FUNCTION OF ΔK AND ΔK_{eff}

\( \Delta K = c \Delta \sigma \sqrt{\pi a} \) (kg/mm\(^{3/2}\))

\( \Delta K_{eff} \)

\( (\sigma_{m} = 5.5 \text{ kg/mm}^2, \sigma_{a} = 4.5 \text{ kg/mm}^2, R = 0.1, \text{ Series I}) \)