DELFT UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF AEROSPACE ENGINEERING

Report LR-289

ENVIRONMENTAL EFFECTS ON FATIGUE FRACTURE MODE TRANSITIONS OBSERVED IN ALUMINIUM ALLOYS

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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 macroscopic transition from tensile mode to shear mode. The transition is suppressed by an aggressive environment, whereas it is promoted by an inert environment. As a consequence there is no unique correlation between the state of stress and the mode of cracking. Both the state of stress and the environment have a significant effect on the mode of cracking. A simple model for the effect of environment on fatigue crack growth is presented. The implications for crack growth under corrosion fatigue conditions are discussed.

NOTATIONS

a	half crack length
da/dn	crack growth rate
ΔK	range of stress intensity factor
R	stress ratio = $\sigma_{min}/\sigma_{max}$
t	thickness
σ	tensile stress
τ	shear stress
σ_{cr}	critical tensile stress
τ_{cr}	critical shear stress
σ_m	mean stress
σ_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 ΔK-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 the formation of shear lips at the two surfaces.

Many investigators have suggested that a state of plane strain will produce a tensile mode crack, and a state of plane stress a shear mode crack. Vogelesang [1,2] has pointed out that such a physical correlation between the state of stress and the mode of cracking is not a unique correlation. 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 some recent test series will be surveyed. The main variables are the environment, frequency, wave shape 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 mode of crack growth is controlled by a competition between the shear stress (τ) and the tensile stress (σ) at the tip of the crack. Critical stresses for "shear decohesion" and "tensile decohesion" are τ_{cr} and σ_{cr} respectively. The competition is whether either τ or σ will reach a critical value first. If τ reaches τ_{cr} first the shear mode will predominate and if σ reaches σ_{cr} first the tensile mode will occur. It is then postulated that an aggressive environment will effectively reduce σ_{cr} and as a consequence σ will control the cracking mode, which leads to a suppression of shear lips. On the other hand in an inert environment τ will be critical and the development of shear lips is promoted. This environmental effect is the main topic of the present paper. Fractographic evidence on shear lip development as affected by the environment and related variables will be presented first. Afterwards the above model will be discussed in some more detail.

EVIDENCE OF THE ENVIRONMENTAL EFFECT ON SHEAR LIPS AND THE TRANSITION FROM TENSILE MODE TO SHEAR MODE

In the Department of Aerospace Engineering of the Delft University of Technology several test series were carried on centre cracked sheet specimens of aluminium alloys. Observations made on the fracture surfaces of these specimens provided the information required for the present study. Fatigue tests were performed under tension-tension loading in an Amsler 200 kN machine and a 60 kN home-made machine. Both aparatus were electrohydraulic closed loop machines. The sheet specimens (width 100 mm) had a small central crack starter consisting of a small hole (diameter 1 mm) and two saw cuts. A survey of the test conditions is presented in Table 1, which illustrates that the tests were carried out to determine the effect of various conditions on fatigue crack growth, such as: sheet thickness, environment, frequency, wave shape and temperature. For each test condition three tests were carried out and in view of low scatter average results will be shown only.

For the present purpose the development of shear lips will be characterized by the crack length (a_{tr}) corresponding to the so-called transition point (see Fig. 1). At this point the shear lip width has increased until half the thickness, which implies that the transition from tensile mode to shear mode is just completed. Sometimes the boundary between shear lips and the tensile mode area is easily observed (Fig. 2a). In other cases it is more difficult to indicate the end of the tensile mode (Figs. 2b and 2c), but even in the latter cases the effect of the environment on the transition is obvious. Results on the transition point are presented in Figures 3 to 5.

In Figure 3 (test series I) the wellknown effect of environment on crack growth rate is clearly evident. The transition points indicated in the graphs illustrate the effect of the environment on these points. In an aggressive environment (salt water) the transition is postponed to larger crack lengths and in vacuum the transition is completed at small crack lengths. Actually there is hardly any tensile mode for crack growth in vacuum, since the fracture surface macroscopically is very rough right from the beginning (see Fig. 2b). Since it is impossible to have fully developed slant shear lips directly from a saw cut, the initial part of crack growth occurs by forming a number of small slant parts (macroscopically "multiple shear"), which then constitutes a very rough fracture surface. The material in Figure 3 is 7075-T6 Clad, but similar results were obtained for 2024-T3 Alclad.

Figure 4 shows the results of crack propagation tests at different temperatures in three environments (testseries II and III). The effect of environment on crack growth rate is observed again, when comparing Figures 4a, b and c.
In salt water the average crack length for the transition point was about 22 mm ($\Delta K = 17.7$ MPa $\sqrt{m}$) and for distilled water about 16.5 mm ($\Delta K = 14.4$ MPa $\sqrt{m}$), while for vacuum a tensile mode area did not really occur. This is in agreement with the observations from Figure 3. With respect to the effect of temperature, crack growth in salt water is somewhat faster at higher temperatures, whereas in distilled water the opposite trend is found. In both cases the temperature effect is small but systematic, contrary to the tests in vacuum where a temperature effect could not be observed. The latter observation suggests that the effects of temperature in salt water and in distilled water should be associated with an environmental contribution. It is interesting then, that the temperature causing the fastest crack rates (and thus being the more aggressive condition) produced the largest tensile mode area (transition point at higher a-value). This can be observed also from the fractographs in Figure 2c.

The effect of frequency and wave shape is shown in Figure 5. For tests in salt water a small but systematic frequency effect is found for sinusoidal load cycles. At the lowest frequency (0.5 Hz) the higher crack rates occur due to more time per cycle for an environmental contribution to crack growth. Correspondingly a larger tensile mode area is found, see Figure 5a where the transition point shifts to higher a-values. For the tests with a square wave the frequency effect in salt water is almost negligible with crack rates very much similar to those obtained with sinusoidal cycles at 20 Hz. Apparently the loading rate is controlling the environmental contribution, rather than the period of one load cycle, and the loading rate is always high for a square wave irrespective of the nominal frequency. This explanation was recently confirmed in test series with various wave shapes (to be published shortly).

With respect to the environmental effect on the mode of failure supporting evidence was occasionally published in the literature. Schijve [5] also observed a small but systematic frequency effect during tests in laboratory air, see Figure 6. Corresponding to this effect the transition point shifted to higher a-values for the lower frequencies with the higher crack rates.
Hartman et al [6] 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 [7]). Krupp, Hoeppner and Walker [8] 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.

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 plasticity behaviour of the material 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 [9] and later by Westwood et al [10] was applied by these authors to liquid metal embrittlement. This model is also very helpful in explaining the behaviour during fatigue crack growth, and more specifically the occurrence of tensile mode cracking under corrosive conditions and the promotion of shear lips and shear mode fracture in an inert environment.

The idealized crack in Figure 7a will propagate either by cleavage or by shear, which requires tensile decohesion or shear decohesion respectively. Let us consider shear decohesion first. If slip occurs on slip planes I the situation sketched in Fig. 7b is obtained. Crack extension by slip requires dislocation movements flowing either into the crack or emitted by the crack [11]. Moreover slip will produce crack extension in this way only if it occurs on planes I, and it will not do so if it occurs on nearby parallel planes [12]. Whether dislocations flow into the crack tip or are emitted by the crack tip, the result is the same. As illustrated by Fig. 7b crack tip blunting can be the result, which seems to be a logical result from plasticity effects at crack tips. However, if in Fig. 7a slip occurs first on the upper plane I, see Figure 8a, then slip plane III is more critical than slip plane I'. The situation obtained then (see Fig. 8b) gives the same crack extension as in Fig. 7b, but without crack tip blunting. The process can be repeated until strain hardening away from the crack tip reduces the effective shear stress τ at the crack tip. The process does not become unstable, and in order to continue crack extension the external load has to be increased. Then τ at the crack tip can again exceed τ_{cr} and a further shear decohesion is possible.

A different rupture process will occur if it starts with tensile decohesion, i.e. with breaking the bond between atoms AA. It is postulated that tensile decohesion will be assisted by foreign ions near the crack tip (F in Figure 7c). They will effectively reduce the critical tensile stress (σ_{cr}) to start tensile decohesion. The first result of atoms AA moving apart is a crack tip sharpening (!) (see Fig. 7c), with atoms BB forming the new crack tip. As a result shear planes II will carry a much higher τ at the crack tip than planes I in the situation of Fig. 7a. At the same time tensile decohesion between BB will not be promoted by the foreign ion F, because it cannot yet move inwards. Consequently, tensile debonding of AA is very likely to be followed by shear decohesion on planes II. The crack tip profile obtained then has remained unchanged (Fig. 7c). The process can also be repeated in this case and it will do so, but again not to an unbalanced extent. Tensile decohesion is accompanied by slip and will therefore also meet with strain hardening in the plastic zone. Again, a further increase of nominal stress is required to continue crack growth. The mechanism has the character of stable unzipping, depending on repeated brittle initiation (quasi cleavage) due to the environment.

If the environmental effect is a consequence of tensile decohesion as outlined above it explains three observations.

(1) Fatigue crack growth rates are faster in a more aggressive environment. This observation is wellknown for a long time.

(2) A more aggressive environment promotes cracking in the tensile mode and suppresses shear lips. Until now this observation was not very well documented in the literature. If σ_{cr} is lowered by the environment crack growth in planes perpendicular to σ_{max} should be expected, and σ_{max} is parallel to the Y-axis (Fig. 1). Consequently tensile mode cracks are to be expected.

(3) Crack extension by tensile decohesion requires increasing load. Consequently it should be expected that the loading rate during uploading (rise time depending on wave shape) is the more significant parameter. This is confirmed by the results of experiments with different wave shapes and frequencies.

It now remains to be explained why inert environments promote shear mode cracking. According to Figure 8 the cracking plane can still be perpendicular to the Z-axis. However, it will be realized that this requires a perfectly symmetric slip activity with respect to the crack growth direction (X-axis in Fig. 1). This cannot be satisfied in a crystalline material with a limited number of slip directions on a limited number of slip planes. As soon as tensile decohesion does not control the fracture process it is fully depending on slip alone. This can lead to fairly complex crack tip geometries as recently shown by Bowles [13]. He 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, see Figure 9a.
A fairly irregular crack front both with respect to shape and orientation are characteristic for crack growth in an inert environment. The fracture surface is much rougher, also macroscopically, see Figure 2b.
This already explains part of the lower crack growth rate in addition to the absence of the environmental contribution.

Close to the material surface plane stress conditions will prevail and as a result planes with maximum shear will no longer be perpendicular to the material surface (i.e. parallel to Z-axis). Slip with a component in the Z-direction should be expected, which will meet with a lower deformation restraint at the material surface. For this reason shear lips start at the surface. However, the shear lip width is not equal to the plane stress zone along the crack front. If this were true the shear lip width should be independent of the environment. The fractographic results discussed before clearly show that the shear lip width is highly depending on the environment. The width is small in an aggressive environment and large in an inert environment. Consequently a unique relation between shear lip width and state of stress cannot exist in view of the environmental effect.

EFFECT OF TEMPERATURE

Tensile debonding was assumed to be stimulated by foreign ions. However, metal dissolution or oxide layer effects may also be important. It is very difficult to indicate the precise mechanism, that will reduce σ_{cr}. With respect to temperature it should be expected that any electrochemical reaction will be more successful at higher temperatures. This was confirmed by the tests in salt water, see Figure 4a. However, in distilled water the opposite trend was found, see Figure 4b. At higher temperatures ($64^{o}C$) crack propagation rates are slower and tensile mode areas are smaller as compared to lower temperatures. The same tests performed in vacuum show no temperature influence at all (Fig. 4c), 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 [14] found that in de-ionized, multi-distilled oxygen-poor water, crack propagation rates are virtually independent of temperature (Fig. 10). However, if the same water was saturated with oxygen, crack propagation rates decreased with increasing temperature. In artifical seawater crack propagation rates increased with increasing temperature, while oxygen saturation stimulated the effect even more. Boer's analysis suggeststhat 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 electochemical reactions are involved, or a number of reactions are balanced, resulting in a constant crack propagation rate with respect to temperature. Adding oxygen affects the environmental conditions and reactions at the crack tip in such a way that non-aggressive reactions are stimulated by raising the temperature. It should be noted that the lower crack rate in oxygen saturated distilled water of higher temperatures is associated with a smaller tensile mode area (Fig. 4b). This supports the idea that the inversed temperature effect is indeed an environmental effect.

SUMMARY AND CONCLUSIONS

1. Fractographic analysis of fatigue cracks in two aluminium alloys (7075-T6 and 2024-T3) have revealed a significant observation. The development of shear lips and the macroscopical transition of the fracture surface from the tensile mode to the shear mode are systematically affected by the environment. An aggressive environment suppresses the forming of shear lips and postpones the transition from tensile mode to shear mode to a larger crack length (or a higher ΔK-value). In an agressive environment the tensile mode is larger and the fracture surface relatively smooth. An inert environment promotes shear lips and the transition to the shear mode. In vacuum fatigue cracks immediately start with shear lips and a macroscopically rough surface in between (multiple shear type fracture).
2. In view of these observations it has to be concluded that there is no unique correlation between plane stress conditions at the crack tip and shear mode cracking on one hand, and between plane strain conditions at the crack tip and tensile mode cracking on the other hand.
3. Different environmental conditions were obtained by varying the environment (salt water, distilled water, air, vacuum), frequency, wave shape and testing temperature. In all cases more aggressive conditions, leading to higher crack rates, implied smaller shear lips and a larger tensile mode area for the same cyclic stress. In

vacuum a temperature effect on crack growth rate was not observed. With respect to wave shape it was the loading rate (or rise time) which was significant for the aggressiveness of the cycle rather than the frequency perse.

4. Starting from the promotion of the tensile mode failure (and the suppression of shear lips) by a more aggressive environment a simple model is developed which can account for this behaviour. In an inert environment crack extension is due to shear decohesion, whereas in an aggressive environment it starts with tensile decohesion. Whether shear decohesion or tensile decohesion will control the fracture mechanism depends on which critical condition at the crack tip is reached first, either $\tau \geq \tau_{cr}$ (shear decohesion) or $\sigma \geq \sigma_{cr}$ (tensile decohesion). An aggressive environment will lower σ_{cr} because it will assist in tensile decohesion. Each step of tensile decohesion is accompanied by shear decohesion, but the tensile decohesion controls the fracture mode, i.e. it promotes the tensile mode. In inert environments σ_{cr} is sufficiently high to have crack extension by shear decohesion only. This invariably leads to a macroscopically rough fracture surface, a rapid development of shear lips and an early transition to the shear mode.

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Table 1: Test conditions in various test series carried out in Delft.

Test series	Material (clad)	Thickness (mm)	Fatigue loading			Environment	Frequency (Hz)	Temperature (^{o}C)	
			σ_m	σ_a (MPa)	R				
I	2024-T3 7075-T6	1 2.5 6	54	44	0.1	vacuum air salt water	20	room temperature	
II	7075-T6	2.5	78.5	29.5	0.45	vacuum pure water (*) salt water (*) (*) with and without O_2	5	vacuum 20 53 88	water 20 35 50 60
III	7075-T6	6	78	39	0.33	distilled water	5	4 24 44 64	
IV	7075-T6	2.5	78 sinus and square waves	39	0.33	vacuum air salt water	0.5 5 20	room temperature	

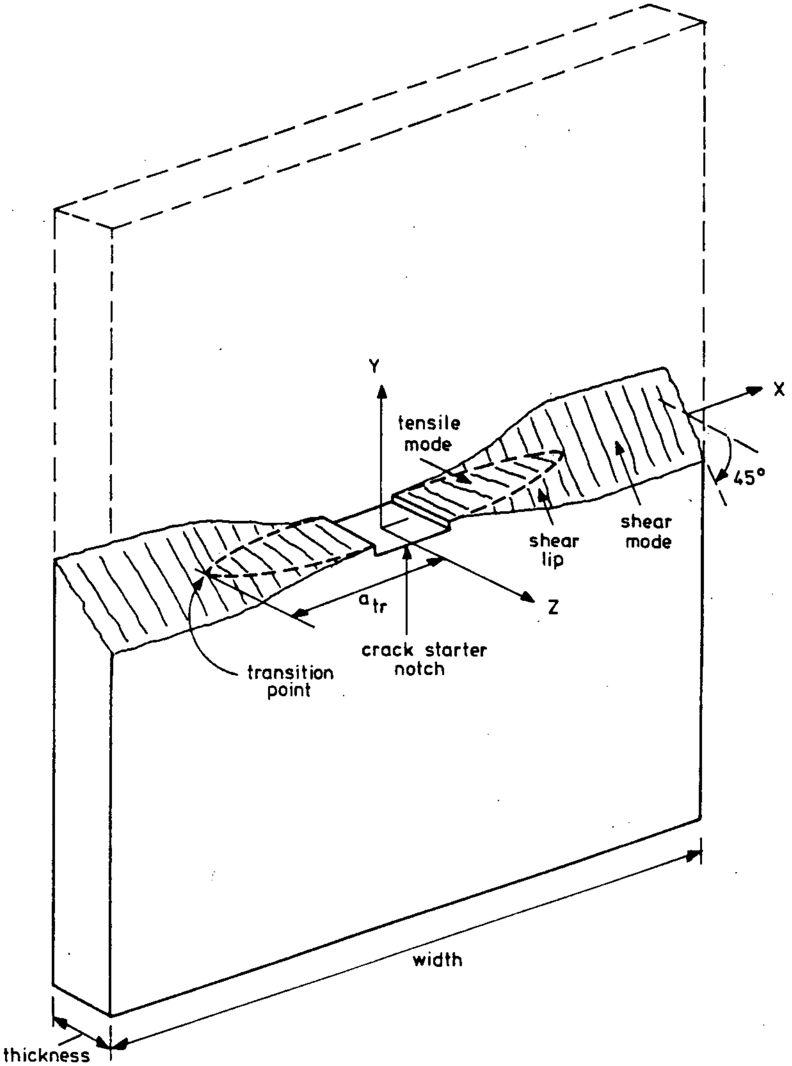

Fig. 1 : Transition from tensile mode to shear mode on fatique crack facture surface in sheet specimen.

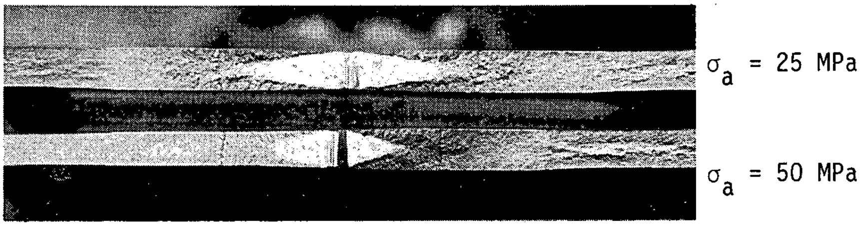

Fig. 2a. 2024-T3 Alclad, t = 4 mm.
Two stress levels, tests in air (σ_m = 80 MPa).

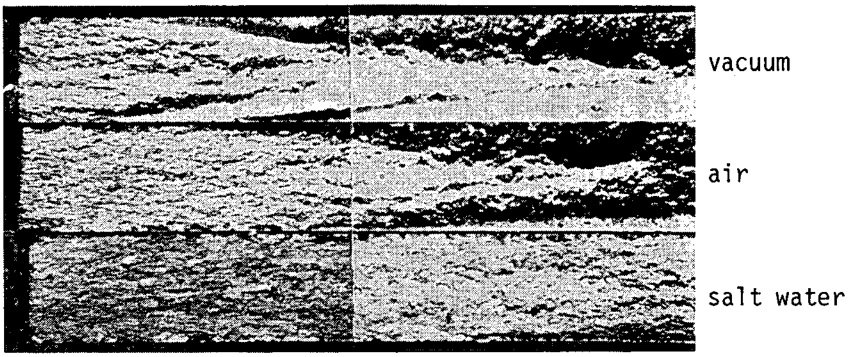

Fig. 2b. 7075-T6, t = 6 mm.
Three environments. Crack starter notch at left hand side.

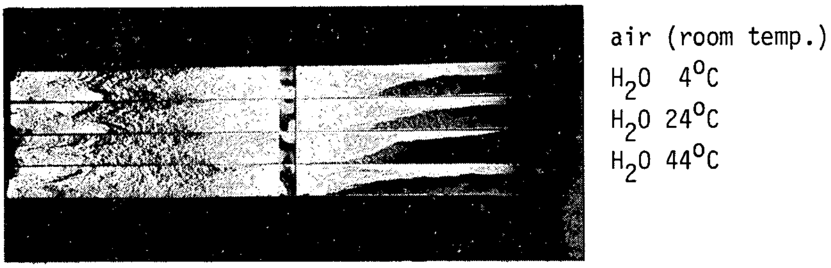

Fig. 2c. 7075-T6, t = 6 mm.
Air and distilled water of different temperatures.

Fig. 2. Shear slips and the transition from tensile mode to shear mode as observed on fatigue fracture surfaces.

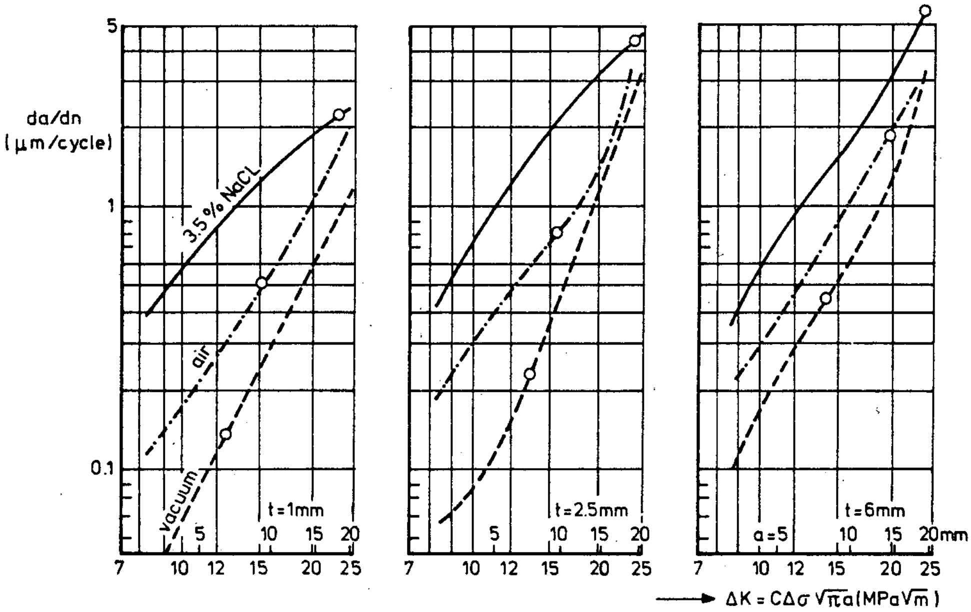

Fig. 3: Effect of environment on the transition and the crack rate [3]
(σ_m = 54 MPa, σ_m = 44 MPa, R = 0,1, material 7075-T6 Clad)
o = transition point, t = sheet thickness

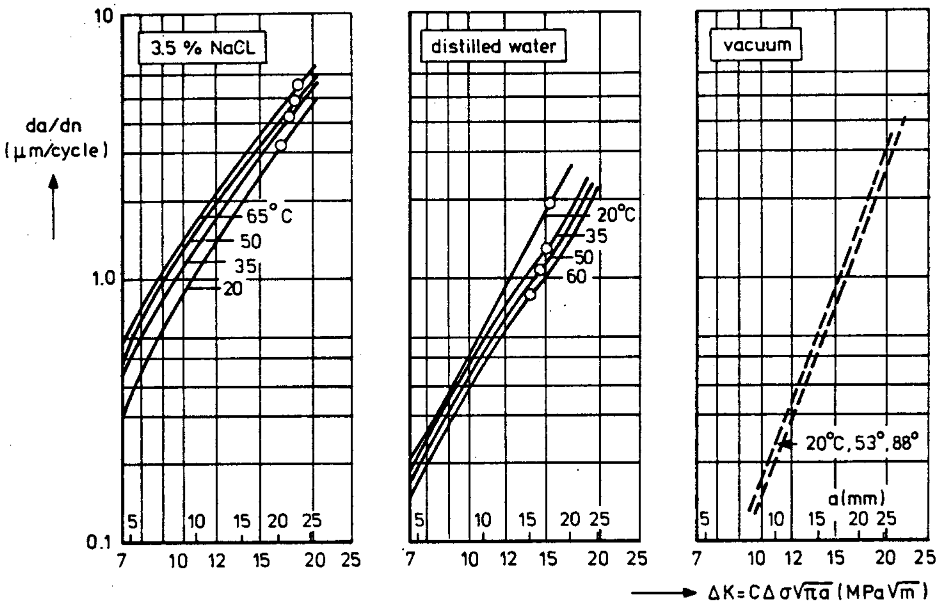

Fig. 4a Fig. 4b Fig. 4c

Fig. 4 : Effect of temperature on crack growth rate and location of the transition point (o) for different environments.
σ_m = 78.5 MPa , σ_a = 29.5 MPa, R = 0.45 , 7075-T6 Clad , t = 2.5 mm

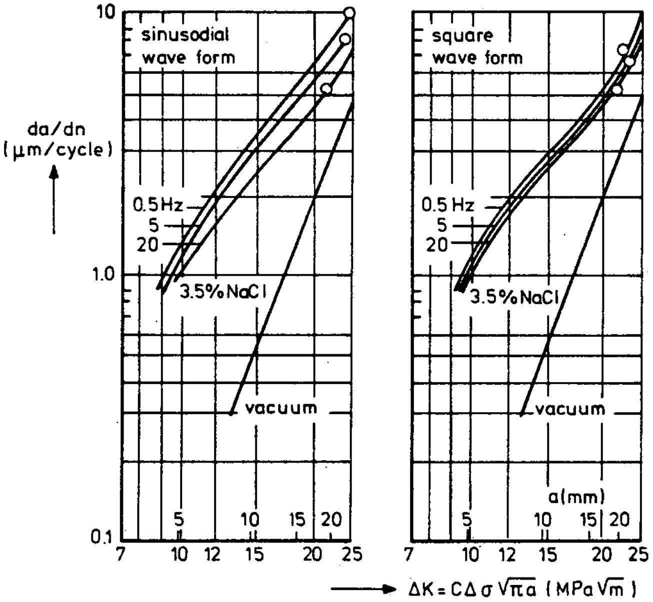

Fig. 5a

Fig. 5b

Fig. 5: Effects of frequency and wave shape on crack growth rate and location of the transition point (O)
σ_m = 78 MPa, σ_a = 39 MPa, R = 0.33, 7076-T6 Clad, t = 2.5 mm.

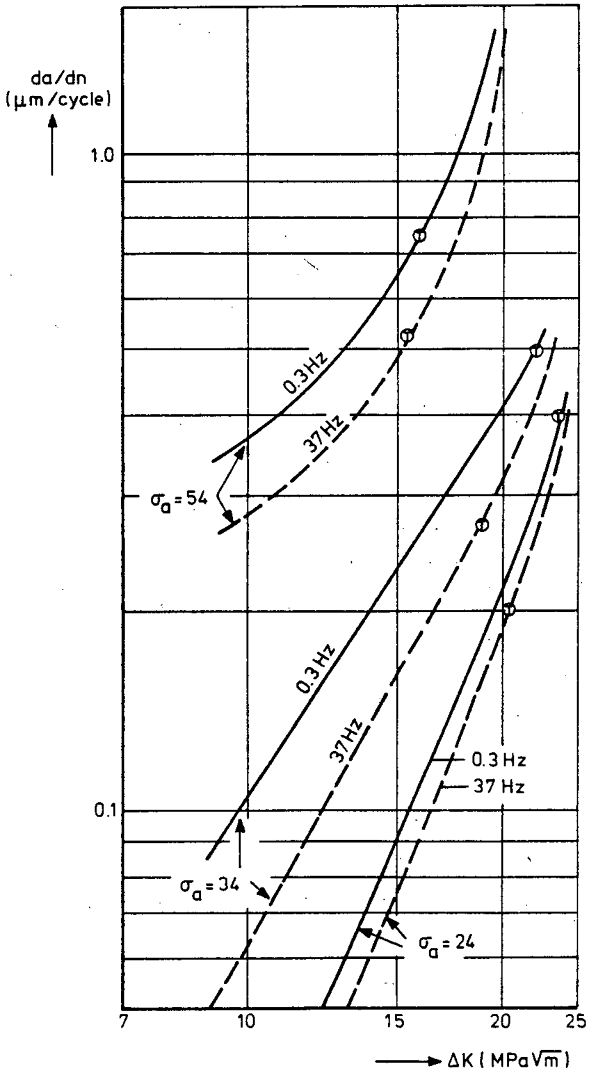

Fig. 6 : Effect of frequency on crack growth rate and location of the transition point (O) [5]. $\sigma_m = 80$ MPa, 2024-T3 Alclad, t = 2 mm, tests in air.

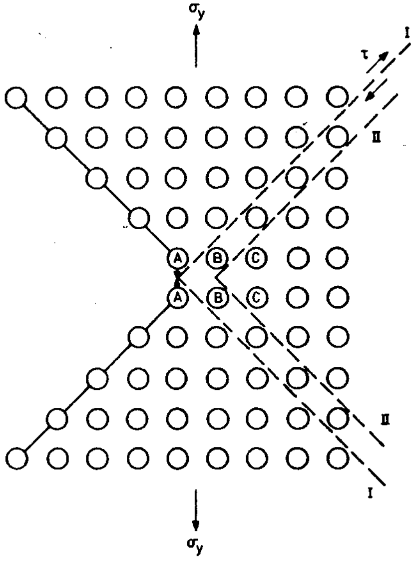

Fig. 7a : Idealized crack with high tensile stress between atoms AA and high shear stress on planes I

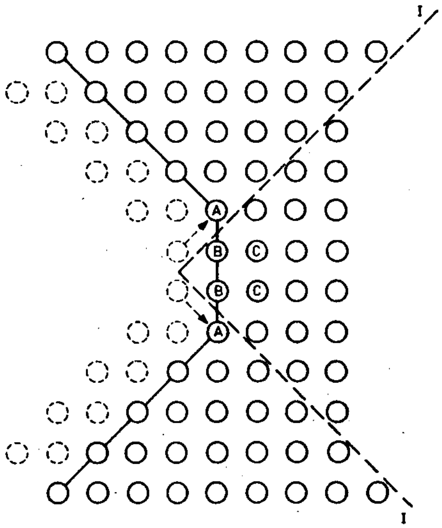

Fig.7b : Shear decohesion on slip planes I with blunted crack tip

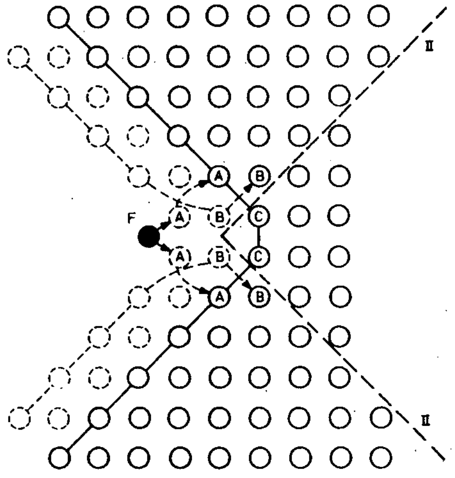

Fig. 7c : Tensile decohesion between atoms AA assisted bij foreign ion F, immediately followed bij shear decohesion along slip planes II

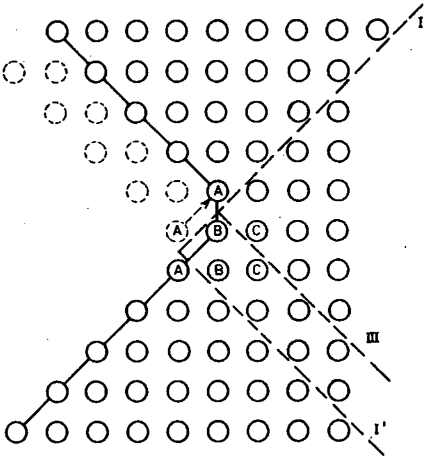

Fig. 8a : A single shear decohesion step on slip plane I

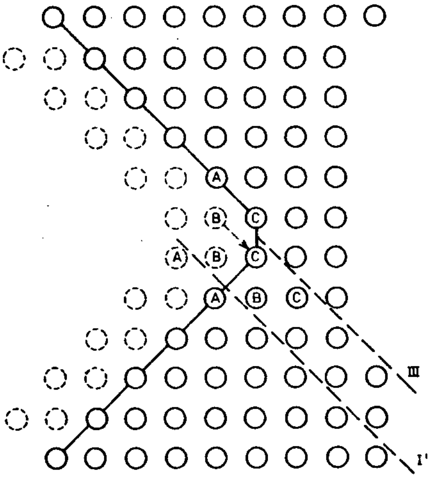

Fig. 8b : A second shear decohesion step on slip plane III, no crack tip blunting

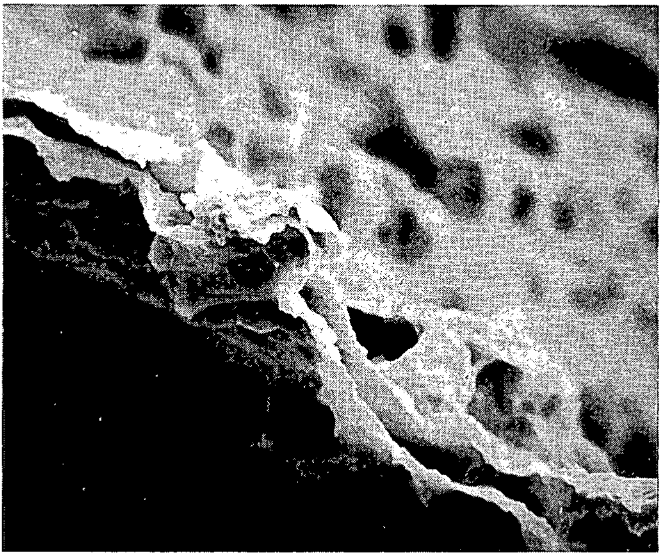

Fig. 9a. Irregular crack front with branching as a result of fatigue in vacuum. Material 2024-T3, magnification 2000x, crack infiltration at σ_{max} (courtesy C.Q. Bowles [13]).

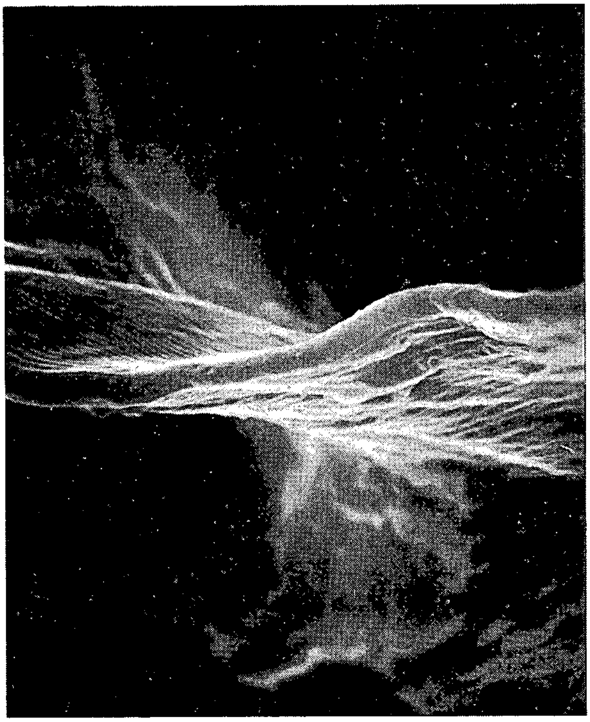

Fig. 9b. Coherent crack front with rounded crack tip as a result of fatigue in air. Material 2024-T3 magnification 3500x, crack infiltration at σ_{max} (courtesy C.Q. Bowles [13]).

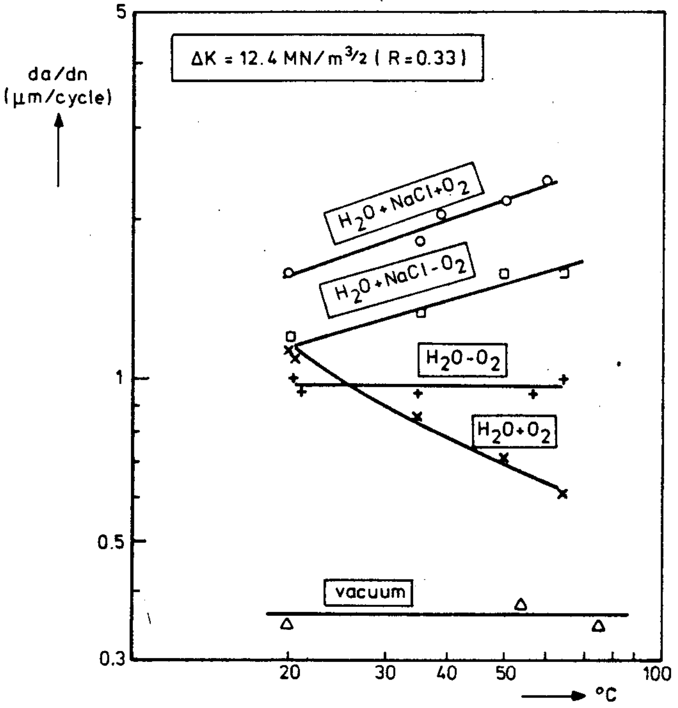

Fig. 10 : Effect of temperature and oxygen on crack growth rate [14]
7075 - T6 Clad, t = 2.5 mm