CRACK GROWTH RETARDATION PHENOMENA IN CONSTANT ΔK FATIGUE TESTS

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A study of the fatigue process in Technically pure Zinc has been made. Zinc is a useful model material . Both constant load amplitude and constant ΔK fatigue tests have been carried out. The constant ΔK fatigue tests involved precracking at low ΔK up to crack length a_0, at which a transition to a different loading range took place. The crack growth rate retardation following this loading transition was studied.

Introduction

In spectrum loading the overloads and underloads that are applied can cause crack growth rate retardation or acceleration. Conventional studies of this process are carried out under constant load amplitude, ΔK increasing, test conditions. These tests conditions mask the very effect that is being investigated because the ΔK increasing conditions cause an increase in crack growth rate during the test.

This problem is avoided in the constant ΔK fatigue test, where the load is decreased as the crack grows to keep the cyclic stress intensity constant. Overload effects can now be studied in more detail as done by Fleck (1). A problem is that crack growth retardation has been observed by Zuidema during constant ΔK fatigue tests in Al 2024-T351 (2). This has been attributed to the tensile/shear transition that occurred in these tests, the

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mechanisms involved including changes in crack closure level due to increased surface roughness as the shearlip is formed and a decrease in stress intensity caused by the increase in crack front length.

To study this retardation, fatigue tests have been carried out on cold rolled Zinc sheet material. Zinc has an hexagonal lattice and therefore only three slip directions, all in the basal plane. During cold rolling a texture develops, with all the slip directions oriented in the plane of the sheet (3). A consequence is that shear deformation during fatigue is impossible and no tensile/shear transition can take place. Eliminating this as a cause of retardation, the retardation process during constant ΔK fatigue tests can studied with more accuracy.

Experimental Procedure

Constant ΔK and Constant load Amplitude fatigue tests have been carried out on Center Cracked Tension specimens of length 350mm, width 100mm and thickness of 3.5 or 7mm. Composition and mechanical properties are given in tables 1 and 2. Tests were carried out using MTS and Schenck fatigue testing machines controlled with specially developed software. The crack length was monitored continuously using pulsed direct current potential drop apparatus. During the constant ΔK fatigue tests the loads were adjusted as the crack length increased to keep the stress intensity constant using the ASTM secant relation for CCT specimens (4). Crack length and number of applied fatigue cycles were periodically written to a datafile by the control computer for post-test analysis.

Fatigue in Zinc under constant amplitude loading

Constant load amplitude fatigue tests have been carried out on Zinc specimens at different loadratios. Results from three tests are shown in figure 1. The material behaves like any conventional metal under constant amplitude loading except that no shearlips are formed. If the specimen is loaded to failure necking takes place in the ligament but no shearlips are formed.

Using the crack growth rate results from the different load ratios, we can normalize the data to ΔK_{eff} by least squares fitting to :

$$\frac{da}{dN} = c*\Delta K_{eff}^{m} \quad (1)$$

$$\Delta K_{eff} = (a+b*R)\Delta K \quad (2)$$

This resulted in :

$$\frac{da}{dN} = 0.0017*[(0.4+0.6R)\Delta K]^{3.7} \ \mu m/cycle \quad (3)$$

Under constant amplitude loading conditions the results can be described by conventional crack closure theory.

Fatigue in Zinc under constant ΔK loading

Following the tests at constant load amplitude a series of fatigue tests using constant ΔK loading have been carried out. These tests are carried out using precracking at low ΔK to starter crack length a_0 before the actual test. To avoid overload effects, K_{max} after the loading transition was always higher than before the loading transition.

Crack growth rate retardation was observed after the loading transition in all tests. Figure 2 shows the results of three tests which have the same loading values during precracking and during the test itself, but which have starter crack lengths of 7,15 and 22 mm respectively. The three tests show a similar retardation pattern, but the size of the retardation effect seems to depend on the starter crack length.

Considering this result it appeared that the loading transition played a role in the retardation process. To investigate this additional tests were carried out without precracking, using the same ΔK and R from the notch until 40 mm crack length. The results of these tests were compared with results from tests which were precracked to a crack length of 20 mm before changing the loading to the ΔK and R used in the first test. Figure 3 shows the results of a pair of these tests.

The test that was started at the notch showed, after a short interval in which the crack initiates to a proper fatigue crack, a decrease in crack growth rate to a minimum value, da/dN_{min}, after which the crack growth rate increases slowly until the test is stopped at 40 mm crack length.

The second test shows crack growth retardation immediately after the loading transition. After some mm of crack growth, the crack growth rate at any crack length in this test is the same as the crack growth rate at the same crack length in the first test. This suggests that the retardation that is observed is merely the build-up of an "equilibrium condition", which is represented by the crack growth rate curve of the test that started at the notch.

A crack growth rate curve from the notch to the final crack length can therefore be considered as a "mother curve" for the ΔK and R used in the test. The retardation after precracking is merely a settling process from the non-equilibrium conditions after the loading transition to the "equilibrium" conditions of the mothercurve.

During constant ΔK fatigue tests in Zinc the crack growth rate can, as is seen in figures 2 and 3 decrease up to a fifth of its initial value. The question remains how to correlate this with ΔK_{eff}. Taking the minimum crack growth rates from all constant ΔK fatigue tests on Zinc and fitting this to (1) and (2) produced:

$$\frac{da}{dN} = 0.0018*[(0.375+0.55R)\Delta K]^{3.8} \quad \mu m/cycle \qquad (4)$$

This is virtually identical with (3). The minimum crack growth rate in constant ΔK fatigue test in Zinc seems to be the same as the crack growth at the same ΔK_{eff} in a constant load amplitude test.

The final point that will be discussed is the relation between the size of the retardation and the loading transition parameters. The loading transition can be described by the following three parameters :

$K_{max}R$ = K_{max} after transition / K_{max} before transition
$\Delta K_{eff}R$ = ΔK_{eff} after transition / ΔK_{eff} before transition
a_0 = crack length at which the loading transition takes place

To describe the scale of the retardation the following parameter is used :

da/dN-R = da/dN$_{min}$ / da/dN just after the loading transition

It can be seen from the results in figure 2 that an increase in a_0 causes a decrease in da/dN-R. Figure 4 shows a plot of da/dN-R against the sum of $K_{max}R$ and $\Delta K_{eff}R$ for a group of tests at constant a_0=15 mm. Increasing $K_{max}R$ and/or $\Delta K_{eff}R$ causes an increase in retardation up to a limiting value. At a_0 =15 mm the greatest decrease is da/dN-R=0.33 .

Discussion of the results

It has been shown that crack growth retardation is normal during constant ΔK fatigue tests in Zinc. Even if the specimen is fatigued from the notch to the final crack length at a constant ΔK and R a systematic decrease in crack growth rate will take place as is shown in figure 3. Two mechanisms for this can be identified, the effect of the plastic zone on the stress distribution and changes in crack closure levels after loading transitions.

The stress intensity factor is calculated using as its basic premise that only the physical crack length, the applied stress and the width of the specimen play a role in determining the stress intensity. The elastic stress field, on which the stress intensity factor is based, however only starts at the edge of the plastic zone. In order to calculate the exact stress intensity, the plastic zone size (or a fraction of this) should be added to the the physical crack length. By not correcting for the plastic zone size we introduce an error into the calculation of the stress intensity, the error decreases with increasing crack length as $(a+r_p)/a$ approaches 1. In a ductile material such as Zinc plastic zones are relatively large and at short crack lengths this causes a considerable error. A plastic zone size of 1 mm for a crack of 6 mm crack length will give a crack growth rate that is 1.4 times the crack growth rate which should occur at the given ΔK, given the fourth power fatigue crack growth rate in Zinc. At a crack length of 25 mm the same plastic zone would only give a crack growth rate of 1.15 times the intended crack growth rate. From 6 to 25 mm the crack growth rate would decrease 20% as a result.

This explains in part the form of the "mother curve" in figure 3, because as the crack grows, the error in the stress intensity decreases, causing a slow decrease in crack growth rate, such as has been observed in this investigation. It can also explain, in part at least, the observed effect of the starter crack length on the crack growth retardation. The observed decreases are however larger than can be explained by the effect of the plastic zone size alone.

After a loading transition several mm of crack growth is needed before the crack growth rate reaches its "mother curve". This delay in reaching an equilibrium condition presumably is the result of the build up of crack closure after the loading transition. If K_{max} is increased at the loading transition the plastic zone will increase in size, this will only affect the crack closure level when the crack tip has grown through the post transition plastic zone. A similar situation occurs when a crack is grown from a notch which explains the initial rapid decrease in crack growth rate of the mothercurve.

The initial crack at the notch has no crack wake and therefore no crack closure. As the crack grows the crack wake builds up until an equilibrium crack closure level is reached.

The two mechanisms outlined above can explain, qualitatively, the observed results. These results show that if the minimum crack growth rates during constant ΔK fatigue tests are correlated with ΔK and R, the crack growth rate can be normalized to ΔK_{eff} in a similar fashion as when using constant load amplitude test results. The minimum crack growth rates can be determined very accurately, but a relatively large number of tests have to be carried out in order to determine a function like (4).

At present tests are carried out on Al 2024-T351, Al 7075-T6 and AISI 304 stainless steel specimens in order to study these effects in technical materials. Preliminary test data suggest that the results found for Zinc also apply to these materials but that the crack growth retardations are much smaller and are determined by the ductility of the material which is tested.

Conclusions

1: Constant ΔK fatigue tests in Zinc show a systematic crack growth retardation during the test.

2: This retardation is due to the effect of the plastic zone size on the stress intensity and the build up of crack closure as the crack wake increases.

3: The minimum crack growth rate during a constant ΔK fatigue test can be normalized to ΔK_{eff} in a similar fashion as for CA test results.

Literature

1: N.A. Fleck ;"Influence of stress state on crack growth retardation" ASTM stp 924, p157, 1988.

2: J.Zuidema, H.S.Blaauw; Journal of Engineering Fracture Mechanics vol.29, p401 ;1988

3: E.A. Anderson; "the physical metallurgy of Zinc" in " Zinc the science and technology of the metal, its alloys and compounds" American Chemical Society 1959 ; p400

4: 1989 Annual book of ASTM standards section 3 norm E647-88a "standard test method for measurement of fatigue crack growth rates" ; ASTM 1989

Table1 :Mechanical properties of the Zinc sheet used

$\sigma_{0.2}$	112 MPa
σ_{max}	130 MPa
ε_f	>50%
K_c	18 MPa$\sqrt{m}$

Table2 : Chemical Composition of the Zinc used

Pb	1.21%
Cd	0.18%
Fe	0.03%
Cu	0.01%
Zn	balance

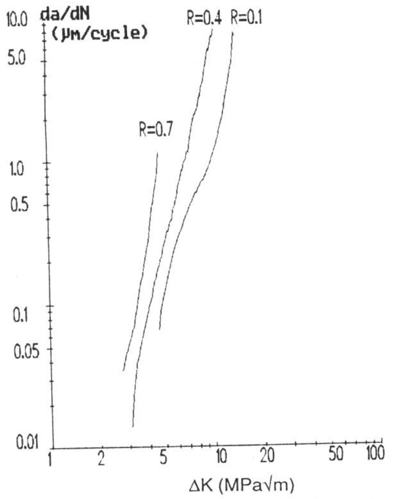

Figure 1: C.A. fatigue crack growth rates in Zinc at three load ratios

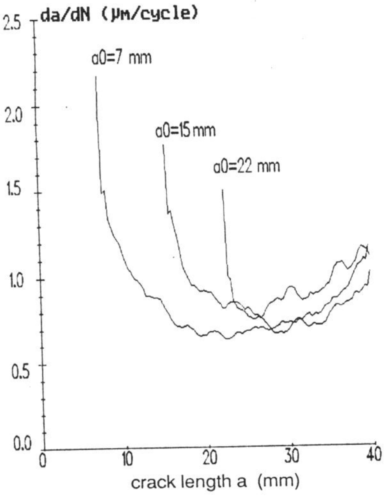

Figure 2: Fatigue crack growth rate during a constant ΔK fatigue test

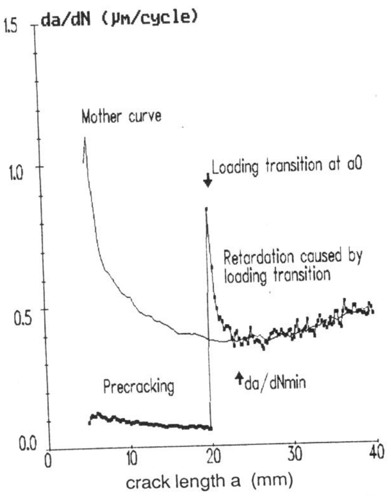

Figure 3: Example of a mother curve in Zinc during constant ΔK fatigue testing

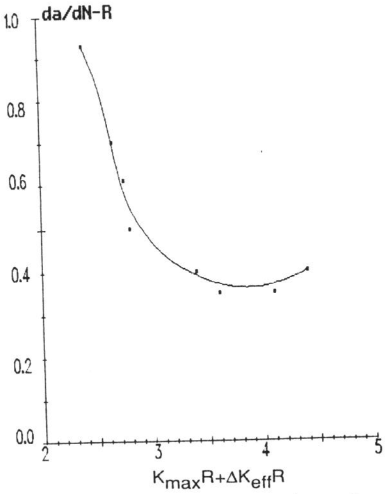

Figure 4: Relation between crack growth retardation and transition parameters