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CRACK CLOSURE DURING FATIGUE CRACK GROWTH FOR TWO THICKNESSES OF MATERIAL

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SYNOPSIS

Crack closure measurements have been made on an aluminum alloy (BS 2L71) during tension only, constant amplitude, fatigue crack growth. The results, together with those of an earlier paper in which variable amplitude loading was used, show that the value of K_{clo} is primarily dependent upon the K_{mean} value. However, the closure stress rarely exceeds the minimum stress of the dynamic loading so that its effect on the growth mechanism will be small. The main usefulness of such measurements is to give local information on how the material at the crack tip is responding to the remote stress. Closure was also measured during a random load test. This showed that changes in closure stress were related to changes in growth rate.

INTRODUCTION

The most widely used method for the analysis of fatigue crack growth data is that based on the stress intensity factor range, ΔK. This approach assumes that the nominal stress field can be used to characterize the plastic strain at the crack tip and that damage occurs only during the tensile portion of the load cycle. The specimen may be considered as homogeneous during compressive loading as load transference can occur across the crack faces. This implies that the remote loading conditions are capable of indicating whether the crack is open or closed. This is not always the case as, for example, where residual stresses are present. Under these circumstances the combined effect of both local residual stresses and the remote nominal stress must be assessed in order to determine the crack growth behaviour.

It is also possible for crack closure to be produced by the deformation that occurs at the crack tip during cyclic loading. This could be due to the monotonic and reversed plastic deformations associated with the external loading [1] or possibly as a result of previous deformations necessary for material production [2]. Given that this phenomenon of self induced closure can occur it is likely that it will influence the crack growth process.

For many materials measurements of the remote stress and crack length will be sufficient to describe fatigue crack growth but in some cases it may be necessary to make local measurements of crack closure in order to define the K range for which the crack is open. The earliest measure of this type was made by Elber [1] using constant amplitude loading on the aluminum alloy 2024-T3. His results appeared to show that self induced

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closure formed a very significant part of the dynamic range. More recent work [3], using stationary broad-band random loading on a similar aluminum alloy (BS 2L71), has shown the effect to be much smaller and to be related to the K_{mean} value. The work to be presented here describes further tests on the same alloy as used in [3] but this time using constant amplitude loading.

EXPERIMENTAL DETAILS

Centre notched sheet specimens of aluminum alloy BS 2L71 (similar to 2024) were subjected to a constant amplitude, 2.5 Hz, tension only load variation. The mean load was varied such that Q_r (= mean/rms) was either 2.25 or 4.5. The width of the specimens was 300 mm and the distance between grips 600 mm. Two thicknesses were used at each Q_r value, namely 6 mm and 16 mm.

The random load test was conducted on a 16 mm thick specimen using broad band random loading. The frequency content was flat (D.C. to 5 Hz) and the probability density function was uniform, test employed a variable mean content switching alternately from Q_r = 2.25 to Q_r = 4.5. The test was started with Q_r = 4.5 and the mean load was changed twice. The r.m.s. stress used was the same as that in the C.A. tests, i.e. 7.4

The tests were conducted on a Keelavite servo-hydraulic test system of 700 kN capacity. Closure measurements were made with a small extensometer fitted across the crack. In all cases several closure measurements were made along the crack so that there could be confidence in the value determined at the tip.

RESULTS AND DISCUSSION

The results for crack closure in all of the constant amplitude tests are shown in Figure 1. Also included in this figure are dashed lines which show the general trend of the variable amplitude data [3]. It can be seen that there is a broad similarity between the variable and constant amplitude results for both Q_r = 2.25 and 4.5.

For Q_r = 2.25 the closure stress seems to decrease slowly as the crack length increases, with the thicker specimens showing a consistently higher value. The fracture mode during the part of the test where closure measurements were made was predominantly square mode.

Also included in Figure 1 is the minimum stress value for the dynamic loading. All the results for the constant amplitude tests show a closure stress below the minimum stress, i.e. the closure stress at no time impinges on the dynamic range. In contrast the random loading used in [3] had a higher crest factor so that the minimum stress was lower for a given signal r.m.s. Under these conditions the closure stress did impinge upon the dynamic range.

At the higher Q_r value the closure stress values increased slowly with crack length and in most cases the values for the 16 mm thick material were greater than those for 6 mm. The fracture mode observations on these specimens showed that the slant mode developed fairly quickly and that probably only the first two measurements, a = 35 and 45 mm, were under

predominantly square mode conditions. For all the tests at Q_r = 4.5, both constant and variable amplitude, the closure stress was outside of the dynamic range.

The fatigue crack growth rates for these tests were also recorded. Some of the results are shown in Figure 2 together with the data from the variable amplitude tests already reported [3]. These values are not directly comparable because of the different frequency and amplitude contents of the two signals. The figure does show however that the behaviour at low growth rates and high growth rates differed considerably, with respect to the thickness, and that this occurred with both constant and variable amplitude loading.

On the basis of the variable amplitude results it was suggested [3] that closure could cause this change in behaviour with thickness. However it can be seen now that the same transition in crack growth behaviour occurs with the constant amplitude tests but this time, even at Q_r = 2.25, the closure stress is at all times outside of the dynamic range. It would seem that altering the ΔK value to allow for the apparent shift in the zero stress will not of itself account for this effect. It is more satisfactory to regard these measurements as an indication of the local conditions at the crack tip rather than as values to be used to adjust the stress intensity factor calculated from nominal conditions. For instance, in the present work the crack propagation rate was found to be dependent upon the material thickness in a similar way for both constant and variable amplitude loading. This dependence upon thickness could not have been predicted from a consideration of the conventional parameters such as ΔK but was shown up by the closure measurements.

Several problems are still unresolved in the determination of the crack closure level. For instance in the load displacement plot the transition region can occupy a significant load range and it is still not clear which value within this range should be chosen especially as this is a surface measurement and one is trying to characterize full thickness behaviour. In the work presented here the intersection of two lines, extrapolated from the fully open and fully closed behaviour, was taken as the closure value. This gives a slightly conservative value for the closure stress. Also differences of the order of 15% have been found between measurements made on opposite faces of the specimen. This sort of error or different interpretation could possibly mask whether the closure stress impinged on the dynamic range, especially in the case of constant amplitude, Q_r = 2.25, tests.

One of the main findings of all this work is that the closure measured is much less than that found by Elber [1]. Indeed, the closure value in many cases may be so low that it is unlikely to have any direct effect on fatigue crack growth rates. However, by plotting all the results produced in our laboratory to date on BS 2L71, it may be possible to see where the effect is significant. Figure 3 shows such a plot for K_{clo} against K_{mean}. It can be seen that K_{clo} increases as K_{mean} increases even within one particular test. Viewed on this scale the influence on K_{clo} of variable amplitude loading, specimen thickness, Q_r ratio, etc. seem insignificant compared to the effect of K_{mean}. It would appear that at low K_{mean} values K_{clo} changes only slowly but that after reaching a K_{mean} value of about 12 $^{1/2}$ the K_{clo} value increases more rapidly. By examining the fracture surfaces it has been possible to ascertain that the low K_{mean} behaviour occurs with predominantly square mode fracture. The results indicate that the maximum effect due to closure is likely to exist in tests with very low Q_r ratios or even where compressive loading is present.

Previous work [3] showed that crack closure behaviour along the entire length of the crack changed considerably as the fracture surface changed from square to slant. The same sort of behaviour was also found in the C.A. tests reported here and in conjunction with the evidence in Figure 3 it would seem quite possible to predict the change in fracture mode from the closure measurements. These measurements also seem to indicate that the major influence on closure is in the near tip region and that the deformation left in the wake of the crack plays only a minor role. This change in mode could be quite important in predicting crack growth behaviour as, for example, with the aluminum alloy studied here accelerated growth occurs after the transition to slant mode.

Another situation where closure effects may be important is where the load signal changes its nature very rapidly. In effect the crack is attempting to grow using a load signal different to the one that produced the plastic zone at the crack tip. A single peak overload could represent this situation, for example, but probably the most important type is the sort of load interaction that occurs when the signal characteristics of a random load change suddenly. Closure studies on this type of load interaction could produce some useful information on the nature of the physical mechanism as well as indicating whether the closure will interact with the crack growth so as to mitigate the damaging fatigue action. In situations where the signal characteristics are varying, but only slowly, closure would appear to play an insignificant role in influencing the growth rate but can yield some interesting information on local effects at the crack tip.

In the present work the former case was studied using a random load test where although the dynamic signal was held constant the mean load content was varied periodically throughout the test. Closure measurements were made and a record of the crack growth with time was taken. This data is shown in Figure 4.

The first change in mean stress, high to low, was at a = 45 mm. This change caused crack retardation and apparently uneven growth. Despite the fall in mean stress the closure stress increased for a short while. Eventually the closure stress fell and continued to fall in a way similar to that found in the constant and variable amplitude tests mentioned earlier.

The second change in mean stress, low to high, caused the growth rate to immediately adopt the growth rate appropriate to the prevailing K_{rms}, K_{mean} value. At the same time the closure stress dropped for a short while before returning to something like the value one would expect. It would appear from this that although it was proposed earlier that closure was primarily dependent on K_{mean}, the K_{rms} action must have some influence as the steady state closure value differed from the value measured immediately after a change in mean stress. In addition the closure stress seems to act in the opposite sense to the change in mean stress, i.e. a decrease in mean causes instantaneously an increase in closure and vice versa.

The increase in closure stress coincided with a period of crack retardation. The value of this closure stress would cause a considerable portion of the dynamic signal to be lost and hence one could expect crack retardation. For the situation where the mean stress was increased the closure stress fell. The new value was well outside of the dynamic range and should have led to no interference with the crack growth. The crack growth plot showed there was no delay and the expected growth rate occurred immediately.

The uneven growth seen after the first change in mean stress coincided with changes in the crack front shape seen on the fracture surface after failure. The crack front seemed to change to being bowed out in the centre and also slightly skew. This would seem to indicate that closure was greater at the outside even though the fracture surface was predominantly square during this period. These differences in the fracture surface may have led to some errors in the growth rate calculation but could not have been large enough to influence the measured retardation.

As suspected from the earlier work this type of non-stationary random loading does give rise to closure effects which are large enough to interact with the dynamic range and possibly be the cause of crack retardation It is just possible that if these changes in closure can be quantified the interaction effects can be predicted for this type of signal.

To summarize it would appear that under essentially steady state conditions the effect of closure is small except possibly where the mean stress is low or compressive in nature. However circumstances can arise where the information on the external loading and crack geometry are in themselves not sufficient to predict the crack tip behaviour. This would include situations where residual stresses were present, where changes in thickness occurred or non-stationary random loading. In these circumstances it may be necessary to measure local conditions and crack closure methods could be employed. It would seem helpful if closure measurements were made as widely as possible in fatigue crack growth work so that the assumptions regarding crack tip plasticity could be confirmed.

CONCLUSIONS

For the aluminum alloy studied (BS 2L71) it would appear that under fully tensile C.A. loading the effect of self induced crack closure is negligible except possibly at very low mean stress levels.

The closure measurements made under constant amplitude loading followed the same pattern as found earlier using variable amplitude loading and correlated with the effect of thickness on the fatigue crack growth rate. Thus although there was no interaction between closure and the growth rate the closure measurements did show important differences in crack tip behaviour which could not be predicted from the remote loading.

The closure effect is much smaller than has been proposed [1] and the widescale use of the equation relating the effective stress intensity factor and the stress ratio [1] would be considered unwise.

Under non-stationary random loading conditions crack closure could be important especially in predicting the crack retardation that occurs when the signal characteristics change rapidly.

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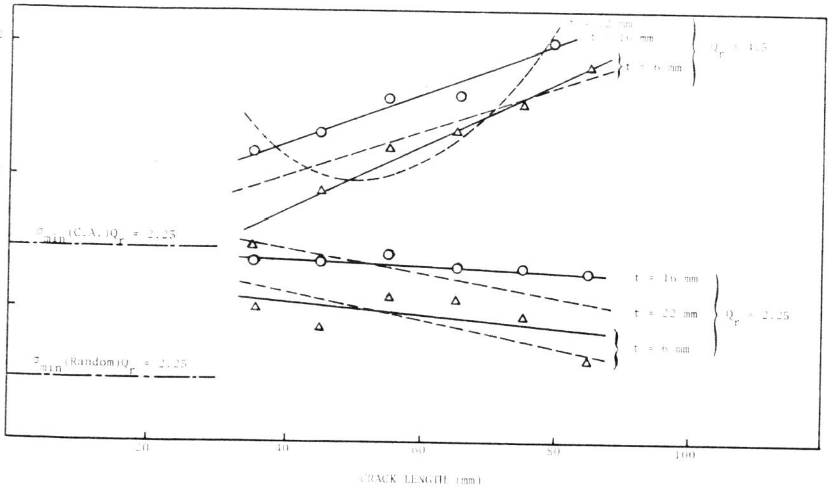

Figure 1 Variation of Crack Tip Closure Stress with Crack Length. C.A. Tests Shown by Solid Lines, Random Tests by Dashed Lines

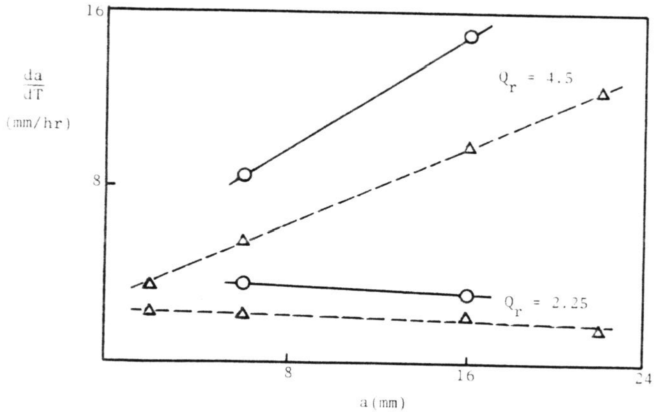

Figure 2 Variation of Growth Rate with Thickness at K_{rms} = 4.0 MPa$\cdot$m$^{1/2}$. The Solid Lines are C.A. Tests, the Dashed Lines are Random Load Tests

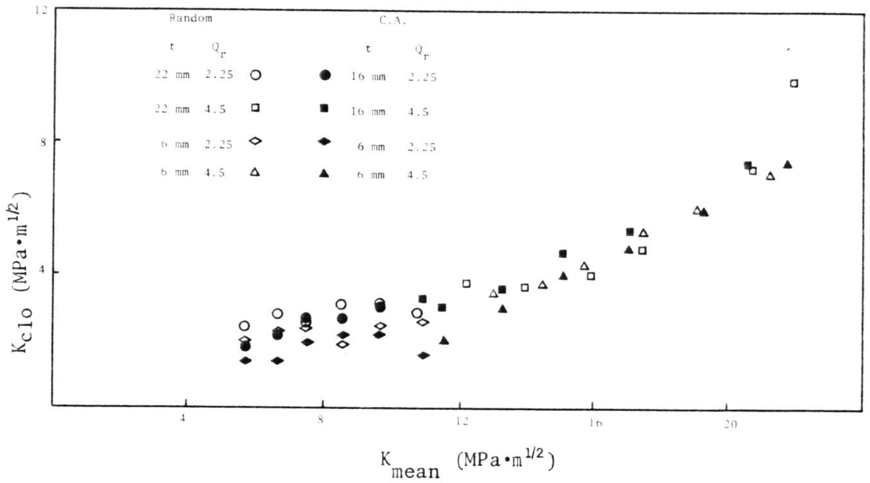

Figure 3 Variation of K_{clo} with K_{mean} for all Tests. K_{clo} and K_{mean} are the K Values Calculated Using the Closure Stress and Mean Stress

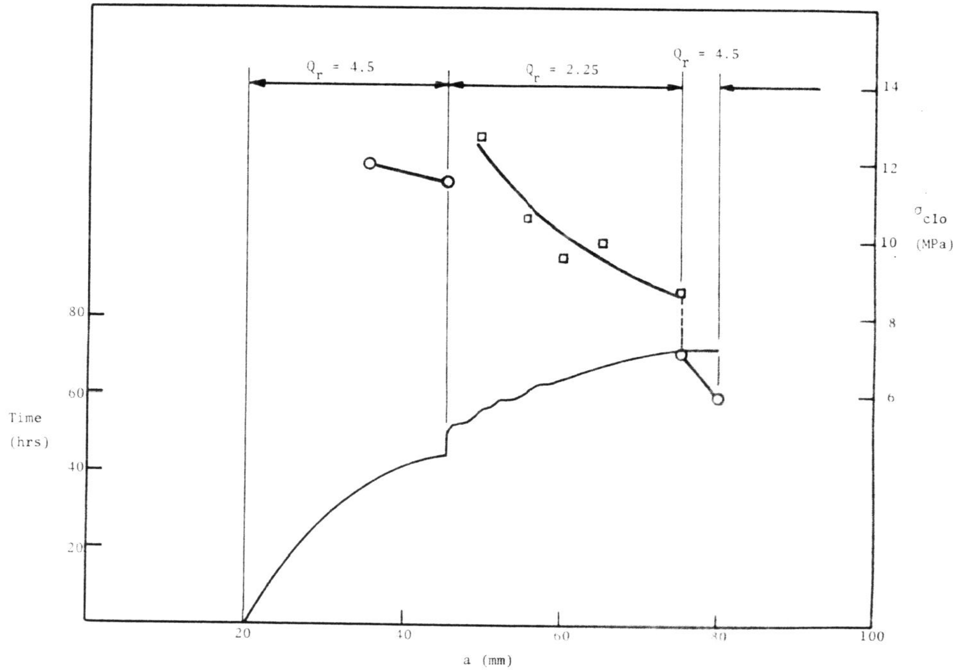

Figure 4 Crack Closure and Crack Growth Data Taken from a Variable Mean Random Load Test