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AN EXPERIMENTAL INVESTIGATION OF THE GROWTH OF SMALL CORNER FATIGUE CRACKS IN ALUMINIUM 6061-T651

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Abstract—Results of an experimental investigation of the fatigue growth of small corner cracks emanating from small flaws are presented. Growth-arrest behaviour was observed, and increases in crack length during growth periods were of the order of the transverse grain size. For the test material, the corner crack front intersects, on average, only three–six grains in the small crack regime monitored, so only a small number of constrained, interior grains is encountered. It is suggested that the presence of partially constrained surface grains may contribute to the 'anomalous' growth behaviour which has been observed by a number of investigators.

The crack growth histories of the test data presented exhibit considerable scatter. It is shown that a Student's t-test can be used to estimate confidence intervals in order to provide a measure of the observed scatter. The variation in confidence intervals in the transition from small to long fatigue crack growth is discussed.

Keywords—Small fatigue cracks; 6061-T651 aluminium alloy; Grain size effects; Student's t-test.

NOMENCLATURE

a = crack length
D = grain diameter
ΔK = range of LEFM stress intensity factor
m = number of samples
n = number of grains intersected by crack front
R = ratio of minimum to maximum load
s = variance
t = Student's t-test
X = sample mean
μ = population mean

INTRODUCTION

The discovery by Pearson [1] that the growth behaviour of 'small' fatigue cracks differed from that of 'long' cracks has served as an impetus for the initiation of many subsequent research investigations. Some of these have been designed to discover basic, operative mechanisms, and others have focused on the development of analytical procedures for predicting growth histories. The latter approach has been motivated by the desire to provide methods that can be used by designers of structural systems. The results of these investigations have been reported in numerous papers. In a recent paper, Halliday *et al.* [2] have referenced results which have been reported on both aspects of the small fatigue crack problem.

Many of the studies which have been reported have concentrated on the growth of 'natural' cracks which started on the surface of highly polished specimens. Often, the surface 'thumbnail' cracks which have been produced emanated from cracks in brittle intermetallic inclusions. Investigations which have been based on crack initiation from small notches have also been conducted [3,4].

The objective of this paper is to present and analyse data which have been obtained from an investigation of the fatigue growth of small corner cracks.

EXPERIMENTAL PROGRAM

The results presented were obtained by use of the test specimen which had circular cross-sections at the ends and a gauge section which had a square cross-section. A three-point bending state of loading was used. By virtue of the orientation of the specimen, the maximum tensile stress is developed at the middle of the gauge section and at a top corner edge. The neutral axis is therefore horizontal and on a diagonal of the square cross-section. Since the region of high tensile stress is localized, the specimen should be suitable for developing 'natural' corner cracks in a reasonably predictable location.

For the test results presented here, small corner notches were introduced at the high tensile stress location to serve as the site of crack initiation. This procedure was chosen to represent the presence of small mechanical flaws, e.g. nicks or gouges, which are often introduced during manufacturing or maintenance operations. Note that the loading state used differs from that of Pickard *et al.* [3] who used tensile loading.

The test material for the investigation was the aluminium alloy 6061-T651 and specimens were machined from 16-mm diameter bar stock. The 0.2% offset yield strength was 283 MPa and the ultimate strength was 293 MPa. The average transverse grain size was 200 microns. The longitudinal grains were elongated and varied widely about an average of ≈350 microns.

Corner notches with a 60° included angle were cut at the midpoint of the specimen cross-section by use of a digitally controlled slitting saw. The faces adjacent to the notch were then polished with five grades of abrasive papers ranging from 600 to 2000 grit. Final polishing was performed by use of a 3 micron then a 1 micron diamond paste.

Experiments were conducted on an Instron servo hydraulic testing machine, which applied sinusoidal loading at 10 Hz. For the data reported, the load ratio $R = 0.0625$. A telemicroscope system was used to monitor crack growth. The crack image was viewed by use of a video camera and a monitor. Details of the experimental procedure used are presented in a previous publication [4].

Cracks from the notches were initiated by the application of a nominal maximum stress which was 0.9 of the yield stress. Small cracks were initiated after ≈200 000 cycles of loading. The maximum load was then reduced to produce a maximum stress of either 0.55 or 0.6 of the yield strength for three of the tests for which data are presented. Crack length measurements included the notch depths which were ≈150 microns. Small crack measurements were initiated when the cracks lengths were ≈400 microns.

Two types of experiments were conducted. In one, growth of a moderately long crack was monitored to establish the near threshold region. In three additional experiments, the growth of small cracks was monitored.

A photograph of the fatigue fracture surface of one of the specimens tested is shown in Fig. 1. The corner notch is at the top. After the fatigue crack had extended ≈2000 microns from the corner, cyclic bending was discontinued, and the specimen was fractured under a tensile load. The small region at the bottom edge is part of the surface resulting from the tensile fracture. Note that the crack front at the end of the cyclic loading is very nearly on a circular arc centred at the corner.

A fractograph of a representative site on the fatigue fracture surface is shown in Fig. 2. The crack advance was upward and angled towards the left. The direction of crack propagation is indicated by the small white arrow. An examination of the surfaces revealed that they were non-flat or torturous, and typical of Stage 1 crack propagation. Separation was dominantly by shearing with discrete, petal-like or tunnelling advances. Some evidence of ridge-like offsets was observed.

Although the use of the stress intensity factor as a correlation parameter for small crack growth has been questioned [5–8], its use does provide a means of comparing long and small crack

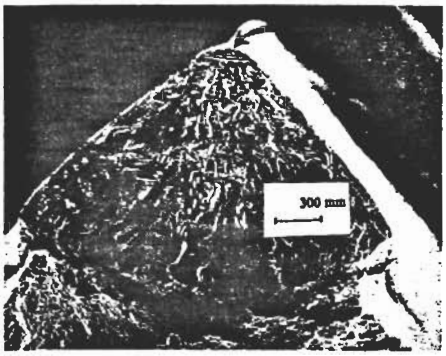

Fig. 1. Fatigue fracture surface.

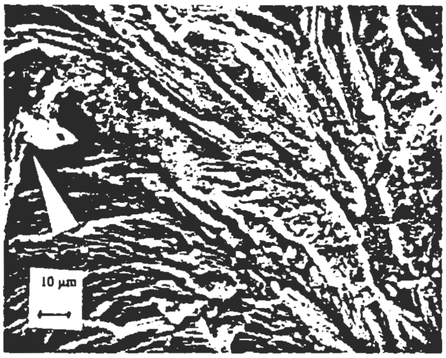

Fig. 2. Fractograph of fatigue fracture surface.

growth. It is therefore used for that purpose here. Its incorporation as a parameter for design for small crack growth is another issue.

The stress intensity factor used is based on results for a corner crack in a bar with a rectangular cross-section in the NASA/FLAGRO computer program [9]. The test specimen had a square cross-section. For computations, two equal bending moments parallel to the sides of the cross-section were used to provide the required bending moment about the neutral axis (a cross-section diagonal).

For the long crack test, growth beyond a crack length of 1500 microns was monitored. Data for both a decreasing and constant load were obtained. It has been found [4] that the data points can be represented by the equation

$$da/dN = 10^{-8}[\Delta K/6.7]^{28} \quad (1)$$

The exponent in Eq. (1) is not to be confused with the exponent in the Paris equation for region II growth. The large value of 28 is the result of the fact that the slope in the threshold region is much steeper than that for region II.

Log–log plots distort the relationship between growth rate and range of stress intensity factor. Since the range of variables in the threshold region is not too large, it is possible to examine the threshold behaviour by use of the linear, Cartesian coordinate plot presented in Fig. 3. The solid curve shown is a plot of Eq. (1). As expected, the growth rate goes to zero as ΔK goes to zero. The data points and dashed curves shown are discussed in a subsequent section.

Small crack data are presented in Fig. 4. Crack length readings on one face were taken at regular intervals and checked on the second side intermittently. The applied loads for Specimens 2 and 3 were chosen to produce a maximum nominal stress of 55% of the yield stress. The load chosen for Specimen 4 produced a maximum stress of 60% of the yield stress.

DISCUSSION

Test results

Miller [5] has given a qualitative description of crack growth history by using crack length on a left-hand ordinate and sizes of microstructural features on a right-hand ordinate. This provides a perspective for comparing the length of a growing crack with such features as inclusions and grain size. If, for the corner crack, it is assumed that the arc of the crack front is centred at the crack corner, the number of grains, on average, intersected by a crack front for a given crack

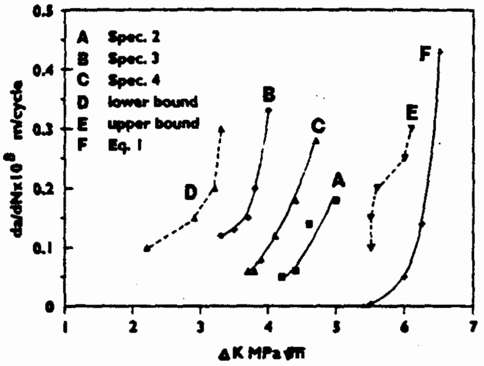

Fig. 3. Linear plot of the threshold curve and the small crack growth rate data.

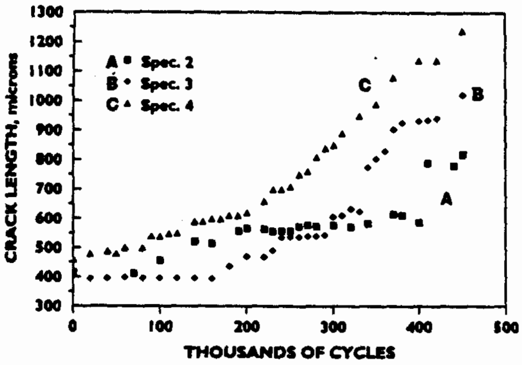

Fig. 4. Plot of crack lengths versus load cycles for Specimens 2–4.

length can be determined from the equation

$$n = \pi a / 2D \tag{2}$$

where a is the crack length (or radius to the crack front from the corner), n is the number of grains along the crack front and D is the transverse grain size. Equation (2) has been used to estimate the number of grains intersected by a crack front for a given crack length. The number of grains intersected by the crack front as the crack grows from 400 to 1000 microns ranges from about three to eight.

When a crack front encounters a small number of grains, the effects of grain boundary walls and grain orientations can be expected to influence the manner in which the crack extends [10–12]. Each of the curves in Fig. 4 exhibits the growth-arrest behaviour which has been reported previously by other investigators. For the initial portion of the growth histories, the abrupt growth steps are about one third of the transverse grain size.

An examination of the initial growth features in Fig. 4 would indicate that an elaborate scheme for computing growth rates is not warranted. Often, in fact, growth rate data are simply represented by clusters of unconnected data points on log–log plots of growth rate versus the range of stress intensity factor [11,13]. Nevertheless, continuing growth is occurring and a growth trend is indicated. A simple method for representing the growth rates has been adopted. Trend curves have been developed by connecting successive inner corners of the steps. The rates, so determined, are indicated in Fig. 3 for Specimens 2–4. The dashed curves indicate the trends of the data for the three tests. Note that the small crack growth data are to the left of the near threshold curve for Eq. (1). Thus, for a given ΔK, the small crack growth rates are greater than those for long cracks, for the test material.

One important feature of the crack growth histories in Fig. 4 is the lack of reproducibility. This is also apparent for the results presented in Fig. 3. The successful use of linear elastic fracture mechanics in the development of codes for predicting fatigue crack growth for 'long' cracks stems from the fact that for the same crack geometry and loading conditions, experimentally observed growth histories have been shown to be fairly reproducible. This is in contrast to the behaviour exhibited during crack initiation. This latter behaviour is manifested in the considerable scatter which is observed in the development of S–N diagrams. Since small fatigue crack growth is a phase between these two extremes in behaviour, a transition region in which scatter is present is not surprising.

Predictions of long crack growth are based on deterministic methods of analysis, whereas predictions based on results from S–N data require the use of statistical methods of analysis. Manning and Yang [14] have proposed a method of analysis in which the analysis is based on the introduction of an 'equivalent initial flaw size' which is stochastically modelled. The identification of a small crack range could be considered to be implicit in this method, and it proposed that fractographic data be used to extrapolate backwards to the initial state.

Scatter of small crack growth data has been considered by Torng and McClung [15], who proposed the use of a generalized Paris-type, growth rate relation. A statistical representation is introduced by the use of growth rate data. Also, it is assumed that the use of LEFM stress intensity factor is valid for small cracks, and that the 'anomalous' behaviour of small cracks is a result of a reduction in plasticity-induced crack closure.

The primary objective of the statistical representation presented here is to examine features of the observed growth scatter. Although the amount of data presented cannot be considered to serve as a basis for a rigorous statistical analysis, the primary features of the growth behaviour can at least be examined by the application of a Student's *t*-test [16].

For this analysis, the equation for the estimation of a confidence interval is given as

$$\mu = X \pm (ts)m^{-0.5} \tag{3}$$

where μ is the population mean, and t has a value which depends on the level of confidence to be evaluated. This can be obtained from a table. X is the sample mean, s the variance and m the sample size. Our objective is to illustrate how a confidence interval for ΔK can be estimated for a given rate of crack growth. Thus, from Fig. 3, values of the range of the stress intensity factors for a growth rate of 0.2×10^{-8} m per cycle are 3.9, 4.5 and 5.1 MPa$\sqrt{\text{m}}$, $s = 0.60$ and m, the sample size, is 3. For a 95% confidence interval $t = 4.303$. For these values, the confidence interval is $\mu = (4.5 \pm 1.49)$ MPa$\sqrt{\text{m}}$. The lower limit for this case, i.e. $\Delta K = 3.01$ MPa$\sqrt{\text{m}}$, is the value which should be selected for the given crack growth rate, i.e. crack growth could be expected to be possible for larger values of ΔK.

By repeating the computation performed above for additional values of crack growth rate in Fig. 3, confidence intervals for a level of 95% have been constructed. The dashed segments connecting the upper and lower data points describe the results of the confidence interval computations. An examination of Fig. 3 reveals considerable data scatter. Also, the lower bound values for ΔK are substantially less than those for long cracks, as represented by Eq. (1).

It may be anticipated that the size of the confidence interval would decrease with increasing crack length. This observation is a consequence of the fact that reproducibility for long crack growth is good. It follows that the lower limit curve described above for small crack growth should ultimately merge with the crack growth rate versus ΔK curve for long cracks. It should, of course, be noted that the effects of load ratio, R, can also be expected to be operative for short, as well as for long cracks.

Small crack growth mechanisms

A number of mechanisms has been proposed to account for the features observed in small fatigue crack growth. The number of grains encountered by the crack front of a long crack can generally be expected to be relatively large. For corner and 'thumbnail' cracks this number increases with increasing crack depth, i.e. as the small crack grows and becomes a long crack. An examination of Eq. (1) indicates that over the range for which growth-arrest behaviour is observed, the number of grains intersected by the crack front is small. When four grains are encountered, two, or half of the grains, have free surfaces. Thus, only the two internal grains are completely surrounded and constrained. Even when the number of grains is five, two grains are not constrained on their free surfaces. It has been suggested [17] that when the number of grains is small, the effect of surface grain contributions to crack extension may be expected to be greater than when the surface grains are a small fraction of the total number of grains along the crack front.

Thus, although reduced closure obstruction for small cracks has often been cited as the reason that growth rates for small cracks can be larger than those for long cracks, the small number of grains encountered may be a contributing factor, i.e. the surface grains may result in an overall reduction in the resistance to crack advance. If this conjecture is correct, there could be, for the same alloy and crack depth, differences in crack growth rates for small corner cracks, small thumbnail cracks and short cracks. Note that for the alloy tested, a short, through edge crack in a 5-mm-thick sheet would encounter ≈25 grains. Also, since the number of grains along the front of a small thumbnail crack would be about twice that for a small corner crack of the same depth, the ratio of the total number of grains to the number of surface grains differs by a factor of 2. The stress intensity factor is insensitive to these details, so it cannot be expected to account for behaviour which may result from these differences.

The growth-arrest behaviour observed during small crack growth has been attributed by many researchers to a mechanism in which grain boundary walls act as barriers to continuous growth. The size of the growth steps observed here supports this contention. Since crack advance along its front can be expected to be microscopically non-uniform, it would not be expected that the steps would be equal to the grain size, but a fraction of it. Local, intermittent growth increments along a wavy crack front may be expected to occur for long as well as small cracks. For long cracks, however, these increments, being a fraction of the grain size, would be a very small fraction of the measured crack length. Thus, when a crack front reaches a depth along which more than, e.g. eight grains are encountered, the grain boundary walls may still act as local barriers to growth, but continuing growth may be expected to be smoothed out.

CONCLUSIONS

(1) The crack extensions during growth followed by arrest periods of small corner cracks were of the order of the grain size for the 6061-T651 aluminium alloy tested.

(2) Small cracks were observed to grow below the LEFM threshold for a load ratio of $R = 0.0625$.

(3) An application of the Student's t-test statistical analysis to the test data provides estimates of confidence intervals which can be used to provide measures of data scatter.

(4) The initial growth behaviours of small cracks and short cracks may differ because of the large difference in grains along their crack fronts. Also, since small thumbnail cracks can, for the same crack depth, be expected to have about twice as many grains along their fronts as small corner cracks, their growth behaviours may differ. The LEFM stress intensity factor is insensitive to these differences.

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