Int. J. Fatigue Vol. 19, Supp. No. 1, pp. S119–S125, 1997
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Printed in Great Britain
0142–1123/97/$17.00+.00

PII: S0142-1123(97)00033-9

Fatigue growth of small corner cracks in aluminum 6061-T651

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Results of an experimental investigation of the fatigue growth of small corner cracks emanating from small flaws are presented. A three-point bending state of loading was used and, by virtue of the orientation of the square cross-section of the specimen, the maximum tensile stress was developed at the middle of the gage section and on a corner edge. A growth-arrest behavior was observed and increases in crack length during growth periods were of the order of the transverse grain size, so it is inferred that grain boundaries act as barriers to continuing growth. © 1998 Elsevier Science Ltd.

(Keywords: small cracks; anomalous growth; corner cracks; intermittent growth; grain boundary wall barriers)

INTRODUCTION

The discovery by Pearson [1] that the growth of 'small' fatigue cracks differed from that of 'long' cracks has served as an impetus for the initiation of many subsequent research investigations. Early papers by Miller [2], Suresh [3], Lankford and Davison [4] and Suresh and Ritchie [5] identified some of the important parameters and provided classification schemes which emphasized the importance of crack size scale relative to microstructural features. The importance of microstructural features has been established further in research conducted by Chan and Lankford [6], Navarro and de Los Rios [7], Tanaka and Akiniwa [8], and Halliday [9]. Some of the investigations conducted have focused on the development of analytical methods for predicting growth histories. Edwards and Newman [10] have suggested that the 'anomalous' growth of small cracks is caused by either an absence or a reduction in obstruction to closure. They have proposed the use of an effective range of stress intensity factors formulated to account for a reduction in closure obstruction.

EXPERIMENTAL DETAILS

Specimens

The objective of the study presented here was to introduce a new experimental procedure for investigating small corner crack growth. In contrast to surface cracks, corner cracks provide a capability for measuring crack depth. Also, cracks are often observed to be initiated at corners in service, and should be of concern for the development of predictive codes.

The specimen used in the present investigation is shown in *Figure 1*a. The specimen had circular cross-sections at the ends and a gage cross-section which was square. The loading state applied to the specimen is shown in *Figure 1*b. By virtue of the orientation of the square cross-section of the specimen, and the application of three-point bending, the maximum tensile stress is developed at the middle of the gage section and on a corner edge, i.e. the neutral axis of bending coincides with a diagonal of the square cross-section. Since the region of high tensile stress is localized, the specimen should be suitable for the development of 'natural' cracks in a reasonably predictable location. Initially, of course, multiple cracking could be expected, but ultimately a dominant crack could be expected to develop. Swain [11] has suggested criteria for evaluating data for which multiple surface cracks occur.

For the initial tests, using the specimen and loading state described in *Figure 1*a and 1b, a small corner notch was introduced at the location of maximum tensile stress to serve as a site for crack initiation. The test material for the investigation was the aluminum 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 μm. The longitudinal grains were elongated and varied widely about an average of 350 μm.

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 paper, ranging from 600 to 2000 grit. Final polishing was performed by use of a 3 μm and then a 1 μm diamond paste. By polishing after notching, it is possible to obtain very small notches.

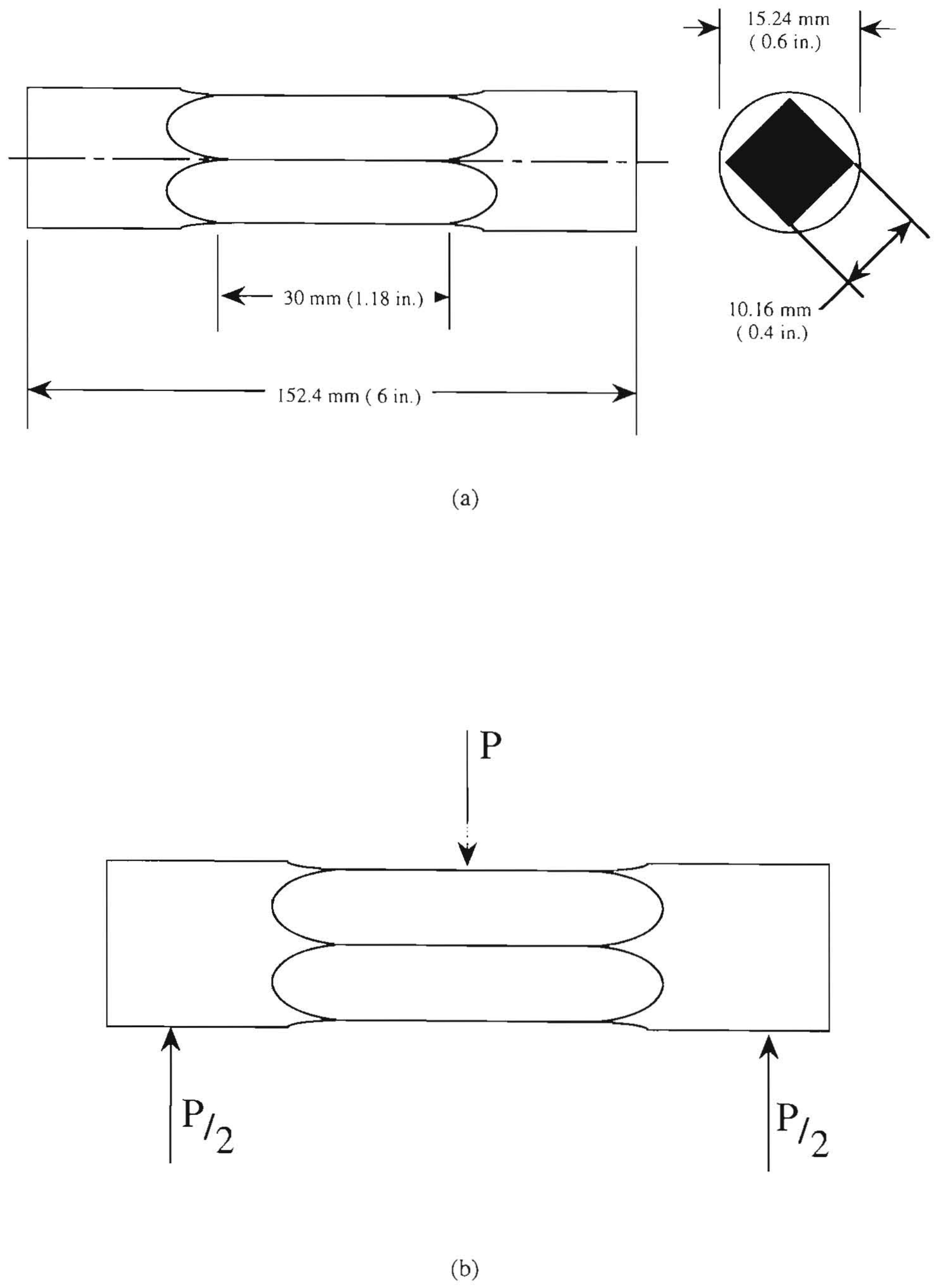

Figure 1 (a) Test specimen used; (b) loading state used

Test procedure

Experiments were conducted on an Instron servohydraulic testing machine which applied sinusoidal loading at 10 Hz. For the data reported the load ratio was $R = 0.0625$. A telemicroscope with a video camera and a monitor were used to measure crack length growth. Details of this system have been described previously [12]. Crack lengths were measured at fixed intervals to obtain data for records of crack length versus loading cycle.

Cracks which started from notches were initiated by the application of a nominal maximum stress which was 0.9 of the yield strength. Small cracks were initiated after about 200,000 cycles of loading. The load was then reduced to produce a maximum stress of about 0.5 of the yield strength. Two types of experiments were conducted. In one test the growth of a moderately long crack was monitored. Notch depths for these tests were about 150 μm.

Although the use of the stress intensity factor as a correlation parameter for small crack growth has been questioned, its use does provide a means of comparing long and small crack growth. It is, therefore, used for that purpose here. Its incorporation as a parameter for design for small crack growth is another issue which is discussed in a subsequent section. The stress intensity factor used is based on results for a corner crack in a bar with rectangular cross-section in the NASA/FLAGRO [13] computer program.

Test results

Results for a long crack test are presented in the log–log plot of *Figure 2* for the near threshold region.

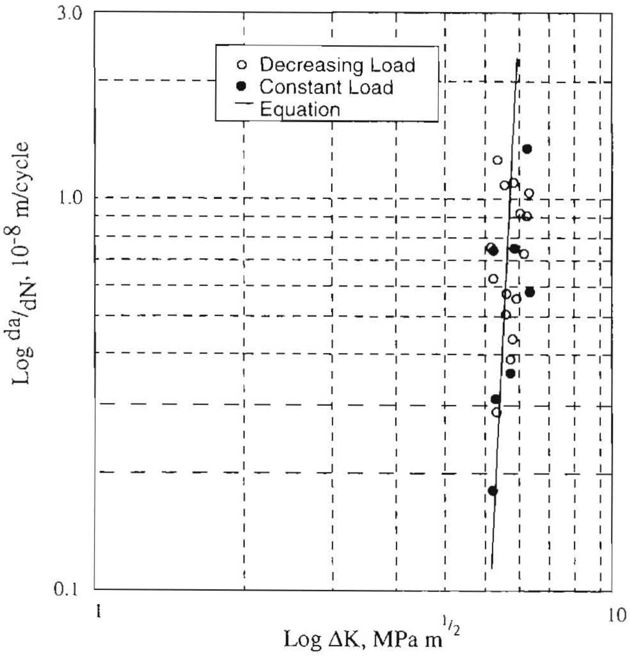

Figure 2 Growth rate in the near threshold region

A straight line through the data points can be represented by the equation

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

The exponent in Equation (1) is not to be confused with the exponent of the Paris equation for region II growth rate behavior. The large value of this exponent is the result of the fact that the da/dN vs. ΔK curve in region 1, the threshold region, is much steeper than that for region II.

Data obtained from small crack experiments are presented in *Figure 3*a and *3*b. The load applied at the midpoint of the test specimens was 854 N, and crack length values shown include the notch depth. The growth-arrest behavior which has been reported previously by other investigators is clearly evident. In addition to the crack lengths not being initially the same on the two corner faces, the directions of the crack paths were not always normal to the specimen axis and branching was sometimes observed. When branching occurred, one branch eventually became dominant.

Miller [2] has given a qualitative description of crack growth history by using the 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 circular and centered at the crack corner, the number of grains, on average, along a crack front for a given crack 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 determine the scale of the right-hand ordinates of *Figure 3*a and 3b. Comparisons of the two ordinates then indicates the number of grains encountered, on average, for a given crack length.

An examination of the initial growth-arrest features in *Figure 3*a would indicate that an elaborate scheme for computing growth rates is not warranted. Nevertheless, continuing growth is occurring and a growth trend is indicated. A simple method for representing the growth rates has been adopted. A trend curve has been developed by connecting successive inner corners of the steps. The rates so determined are represented by round data points on the Cartesian coordinate plot of *Figure 4* for both faces of the corner. The small crack growth data are to the left of the near threshold curve of Equation (2). Thus, for a given ΔK, the small crack growth rates are greater than those for long cracks.

Data for a second small crack growth experiment are presented in *Figure 2*b, and they reveal that the crack length versus cycles histories for the two tests are not reproducible. The data of *Figure 3*b also exhibit an abrupt increase in crack length at a value of about 420,000 cycles. This may be attributed to the nature of crack initiation for this test. Cracks were initiated at the intersection of the root surface of the notch and the outer faces. On each face the direction of the initial crack deviated from a normal to the corner edge by about 40°. The crack on one face was about a plane normal to the corner edge, whereas the crack on the other face was below the normal plane. It has been inferred from this observation, and from the abrupt crack length increase, that the initial microcrack planes associated with the observed surface cracks were distinct and not connected, i.e. they were separated by an uncracked ligament which introduced a bridging mechanism. It is suggested that when this ligament was fractured, the observed sudden increase in crack length occurred. The development of multiple microcracking and subsequent coalescence has been observed and discussed by Swain [11] for surface cracks.

In view of the initial behavior indicated in *Figure 3*b, no attempt was made to calculate growth rates for this phase of growth, since the use of a stress intensity factor here is not considered reasonable. Growth rates beyond 420,000 cycles were, however, calculated, and these results are represented on the growth rate versus range of stress intensity factor plot of *Figure 4* by square data points. Clearly, a comparison of these data with those for the growth data from *Figure 3*a again indicates a lack of reproducibility. The crack lengths used for this latter computation ranged from about 800 to 1300 μm. These crack lengths may appear to exceed limits used to define small cracks. It has, however, been observed [14] that small crack behavior may extend to crack lengths which are about 10 times the grain size. Since the grain size in the plane of crack growth is about 200 μm, the growth range for which the calculations were made is within this size limitation. Consequently, the results reaffirm the importance of grain size.

DISCUSSION OF RESULTS

Two distinct features of small fatigue crack growth distinguish it from long crack growth. One is the observation that early growth for small cracks is intermittent, i.e. periods of growth and arrest are observed. The second is that if long crack methods of analysis

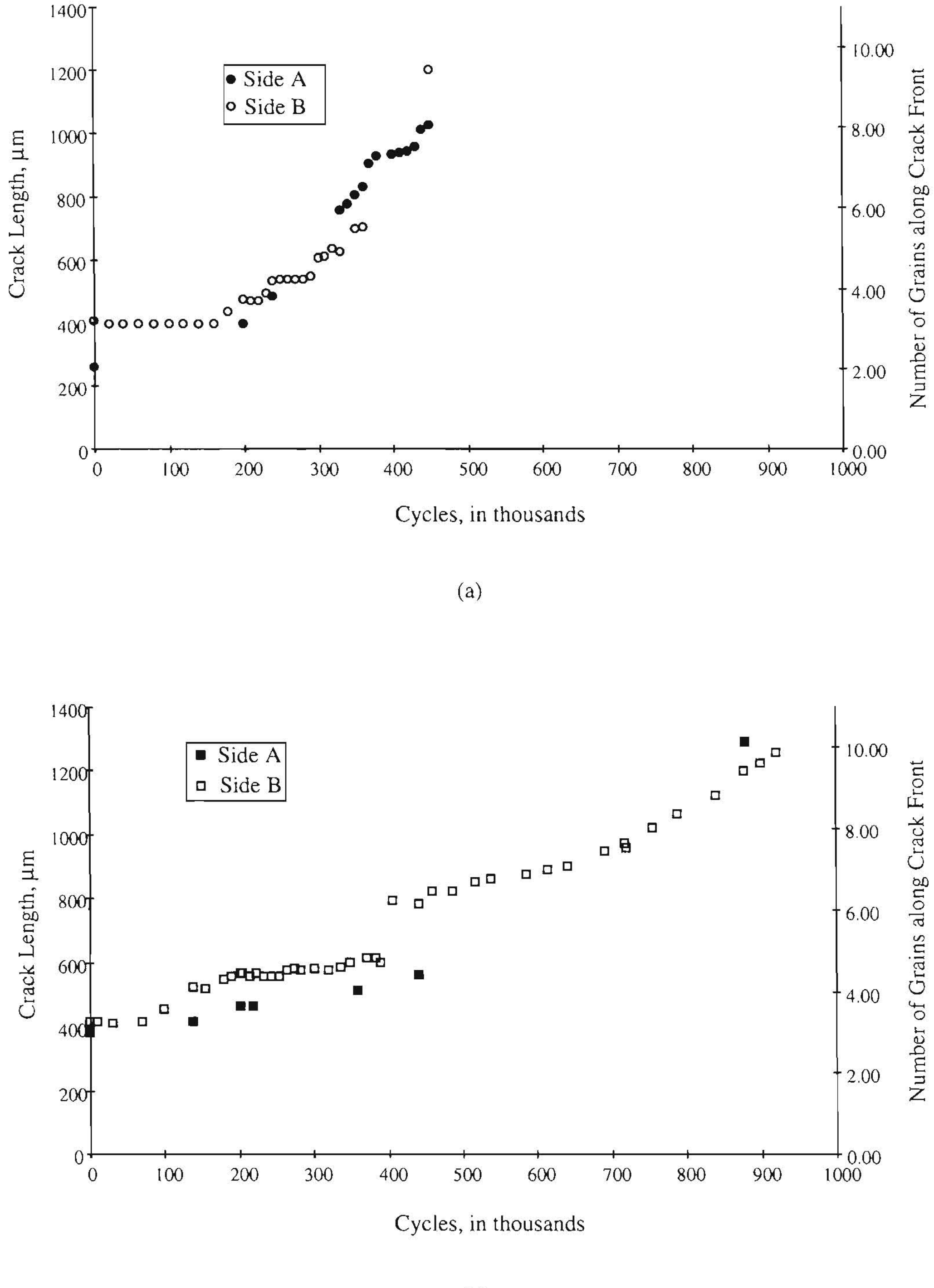

Figure 3 Growth data for small cracks: (a) first test; (b) second test

are used, the small crack growth rate can be greater than would be predicted. The use of the term 'anomalous' was introduced to describe this latter behavior. The so-called anomalous growth rate behavior will be discussed first.

Anomalous growth rate behavior

Results from a number of investigations have indicated that low load ratio tests on small cracks appear to correlate well with long crack data for high load ratio tests. It has been suggested [10] that either an absence or a reduction in obstruction to closure for these test conditions provides an explanation for the anomalous small crack behavior. The early deviations observed here from planar growth, however, could promote obstruction to closure for small cracks. Also, Halliday [9] found evidence that substantial levels of closure can also occur for small surface cracks. The difference observed here between the orientations of the initial microcrack planes on the two adjacent corner surfaces suggests that initially there can be an internal, unfractured ligament. This could introduce a bridging mechanism which would result in an effort which would be counter to the absence or reduction of closure obstruction hypotheses. It is also of interest to note that Vasudevan and Sadananda [15,16] maintain that the

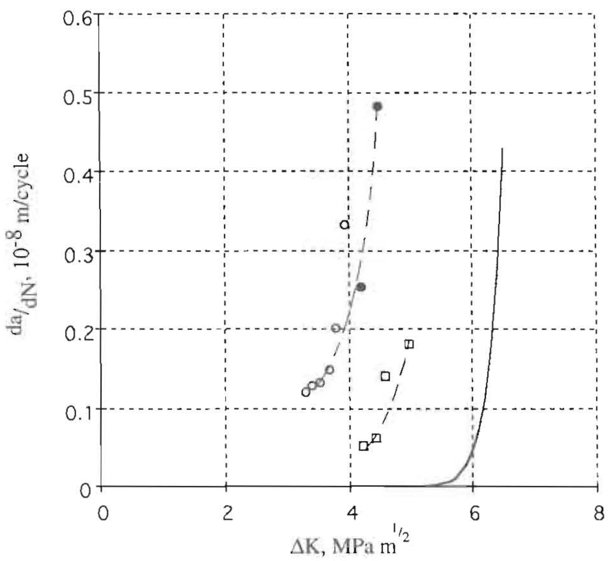

Figure 4 Cartesian plot of long and small crack results in the near threshold region

effects of obstruction to closure need not be invoked to explain fatigue crack growth behavior. They have presented results which suggest that the growth can be correlated by the use of two parameters, ΔK and K_{max}.

Just after crack initiation a crack front encounters a small number of grains. Microstructural features such as grain size, grain orientation and inclusions may then be expected to affect the mechanics of crack growth[2,4,6-9,17,18].

For corner and surface cracks the number of grains increases with increasing crack depth, i.e. as the small crack grows and becomes a long crack. An examination of *Figure 3* indicates that over the range for which growth-arrest behavior has occurred, the number of grains encountered by the crack front is small. Thus, 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. It has been suggested [19] that when the number of grains is small, the effect of the 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. 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. The thickness of a sheet with a short, through-edge crack would have to be very thin for the crack front to encounter a small number of grains. For the alloy tested the sheet would be about 0.6 mm thick for the crack front to encounter only three grains. The crack front of a 5 mm thick sheet would cross about 25 grains. Note also that whereas the crack front lengths of corner and thumbnail cracks increase with increasing crack length, the crack front lengths for through-edge cracks remain the same. Since the stress intensity factor is insensitive to these details, it cannot be expected to account for behaviors which may result from these differences.

Some of the proposals which have been offered to account for small crack growth are based on the introduction of an 'effective' range of stress intensity factors which, by being increased, yields predictions which provide increases in crack growth rate. They do not, however, explicitly account for microstructural features.

It has been suggested here that the anomalous small crack growth behavior may be due at least in part to the fact that the ratio of the total number of grains on the crack front to the number of partially constrained, surface grains is small. This ratio increases, of course, with increasing crack size or decreasing grain size. An alternative to previous proposals for crack growth rate could be to introduce a function of this ratio. Thus let

$$da/dN = f[n_t/n_s]F[\Delta K, \Delta K_{th}, R, K_{IC}] \tag{3}$$

where n_t is the total number of grains intersected by the crack front, and n_s is the number of surface grains crossed by the crack front. The value of n_s will here be taken as 2.

A form of f which could be used is

$$f = [1 + g(n_t/2)] \tag{4}$$

where the function g should be constructed so that f is large for small cracks and approaches unity for long cracks. A function g which satisfies these requirements is

$$g = C_1 \exp[-C_2(n_t/2)] \tag{5}$$

Note that since the number of grains on a crack front depends upon the size of the grains, grain size is explicitly included in Equation (3). Also, it distinguishes, through the ratio n_t/n_s, the difference between small corner cracks and surface cracks of the same depth, i.e. n_t for a surface crack is twice that for a corner crack.

The total number of grains along a crack front depends on crack geometry and crack depth. The growth rate modification introduced in Equation (3) merely illustrates how the feature of grain size could be introduced, and it provides an example of how microstructural features may be included in analyses of very small crack growth.

Growth-Arrest behavior

The data of *Figure 3* indicate that the increases in crack length during the growth periods were of the order of the grain size. This supports the contention [20-23] that grain boundaries introduce barriers to continuing growth. Since it may be inferred that the use of 'grain boundary' describes a two-dimensional encounter, it may be more descriptive to visualize a three-dimensional geometry in which the advancing crack encounters a 'grain boundary wall'.

When there are only a few grains on the crack front, the growth-arrest phenomenon can be expected to be readily detectable. This is illustrated in *Figure 5*a, in which a hexagonal array has been chosen to represent grains on the crack plane. The size of the hexagons corresponds to the transverse grain size of the 6061-T651 aluminum alloy tested. When the crack is passing through the first few grains near the corner, the grain size is a large percentage of the crack length and few grains are encountered by the crack front. If crack lengths of this order are detectable, the role of grain boundary barriers to growth could easily be detected. When the crack front reaches a depth along which there are more than, for example, eight grains, the grain boundaries can still act as barriers to growth, but continuing growth can be expected to be smoothed

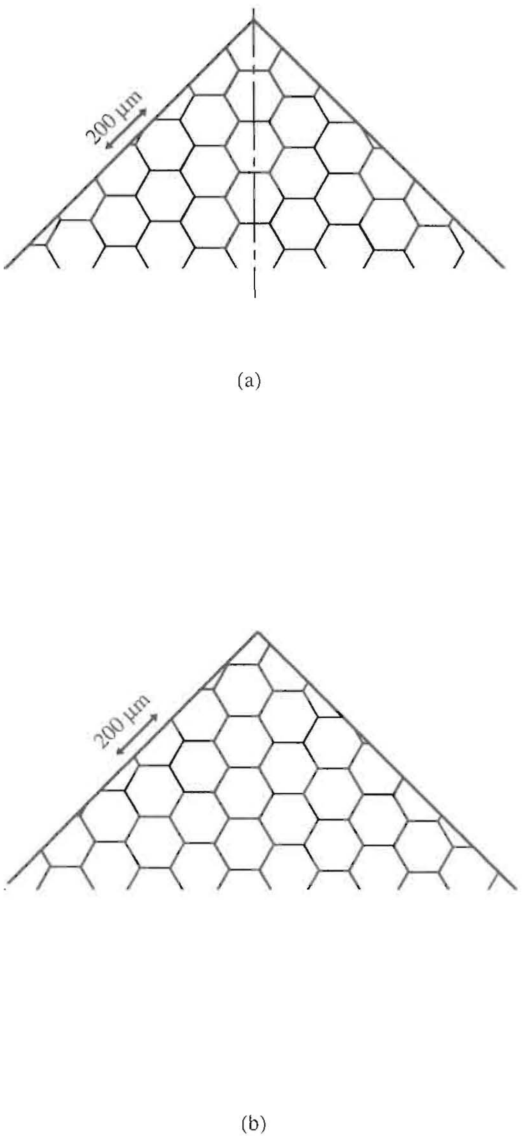

Figure 5 Models of grains on the crack plane

out. This probably occurs as the size of grains becomes a small fraction of the crack front length. Thus, although the crack front may have a local waviness, the amplitudes of the waves may be of the order of the grain size, and they in turn are also a small fraction of the measured crack depth.

The consequences of a wavy crack front have been examined by Rice [24]. He performed an analysis for a wavy crack front in a homogeneous, isotropic material and obtained conditions for the stability of a given front, i.e. would the amplitude of the waves increase or decrease. The driving force for crack advance was the stress intensity factor which varied along the front. For the small crack problem the individual grains are anisotropic and a grain boundary wall represents a transition zone between grains of different crystallographic orientation. The introduction of local barriers and localized regions of anisotropy may provide an analytical basis for extending the analysis presented by Rice. An extension of Rice's research has been presented by Bower and Ortiz [25]. They performed an analysis in which the crack front in a brittle material is locally retarded by the presence of particles. Although the encounter of a crack front with a small particle differs from that of a crack front with the wall of a grain which is large compared to a particle, the crack growth barrier mechanism is common to the two cases.

The grain pattern of *Figure* 5a is symmetric with respect to a line which bisects the corner angle. *Figure* 5b represents a somewhat more realistic, nonsymmetric arrangement of grains, and it can be seen that initially crack growth on the right side of the top corner grain could be retarded by the inclined grain boundary. Again, however, when the crack depth is large compared to the grain size, the crack front would encounter a relatively large number of grains, and differences in growth rates could be expected to diminish, i.e. although local differences in crack advance may persist, the dimensions of the differences become a small fraction of the crack length.

CONCLUSIONS

1. Crack extensions during the growth periods of the growth-arrest behavior of the small corner cracks were of the order of the grain size for the 6061-T651 aluminum alloy tested. This supports the contention that grain boundary walls may introduce local barriers to continuing growth.
2. Small cracks were observed to grow below the threshold for the small load ratio R used.
3. The data obtained indicate that even for relatively well-controlled test conditions, the initial growth phase of the small fatigue cracks is not reproducible.
4. The initial crack growth behaviors 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 behaviors may differ. The stress intensity factor is insensitive to these differences.
5. The 'anomalous' growth rate observed for small cracks may be due in part to the fact that surface grains, which are a large fraction of the total number of grains along the crack front of a small crack, do not have the complete constraint that interior grains have. The form of a modified crack growth rate equation illustrates how the effects of a difference in internal and surface grain constraints may be introduced.

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