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International Journal of Fatigue 30 (2008) 1473–1478

International Journal of Fatigue

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The transition between small and long fatigue crack behavior and its relation to microstructure

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Received 20 April 2007; received in revised form 23 September 2007; accepted 30 September 2007
Available online 6 October 2007

Abstract

The transition point from small to long crack behavior is experimentally studied in a single phase aluminum alloy. It is shown that scatter decreases until reaching a steady state value for long crack growth. This point is defined as the transition from micro-structurally small to long crack growth and is shown to correspond to the point when the growing crack front intersects approximately 15 grains. This transition point is experimentally validated from fatigue crack growth data both from single, corner micro-cracks and multi-site micro-cracks on a smooth surface.

Keywords: Transition length; Small cracks; Short cracks; Microstructure; Scatter; Fatigue

1. Introduction

It is well known that the growth of small cracks can be dominated by the influences of the local material microstructure [1]. As a crack grows in a single phase alloy, its front continually samples an intrinsically anisotropic, inhomogeneous medium consisting of grains with randomly oriented crystallographic directions. Each individual grain will either favor or discourage crack growth to a varying degree. Additionally, grain boundaries and in-homogeneities in the microstructure such as inter-metallic particles and triple points [2,3] between grains will affect the growth of small cracks.

Crack interaction with these micro-structural entities is the root cause for the observed acceleration/retardation transients observed in the growth of micro-structurally small cracks. It has been suggested [4,5] that the accelerated crack growth in some grains is caused by the presence of micro-plasticity in favorably oriented grains, while the lack thereof is the cause of retarded growth in less favorably oriented grains. It has also been suggested that crack deflections can be caused by a crack orienting itself to the local crystallographic texture [6]. Additionally, it has been shown that grain boundaries can be micro-structural barriers to fatigue crack growth [4,5,7]. However, it also acknowledged that this effect may simply be an implication of the abrupt alteration in the crystallographic texture that occurs across the boundary.

While a crack is small, these micro-structural phenomena will control the growth of the crack. Thus, crack growth rates will fluctuate with accelerated growth/arrest, and deflection behavior causing the increased scatter found in the growth rates of small cracks. However, as the crack grows longer and samples additional grains these effects will begin to average out, approaching the long crack, bulk behavior of the material. Additionally, as the crack driving force grows, micro-structural barriers such as grain boundaries can be more easily overcome and therefore lose their controlling effect over crack growth.

It can therefore be envisioned, that a growing crack that samples an increasing amount of material microstructure with growth, will reach a length that can be defined as the transition between small and long crack behavior. The objective of the research described here was to develop

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doi:10.1016/j.ijfatigue.2007.09.008

a method with which this transition point can be defined; based upon measured scatter in the growth rates of cracks, crack geometry and basic micro-structural dimensions of the material in question. This method will be applied to crack growth data obtained from an experimental program which measured clusters of cracks grown from smooth surfaces of 7075-T7351 Aluminum alloy. Once obtained, this transition length can be used to separate analyses of the traditional long crack regime (Paris curve growth) from the small crack regime where traditional analyses are not applicable. Previous work that was the precursor to this analysis will be briefly summarized first.

1.1. Small fatigue crack growth: corner micro-cracks

Research on the characterization of scatter observed in the growth of small cracks was previously conducted by Carlson et al. [8,9]. In these experiments cracks were initiated at micro-notches on the corners of a square specimen cross section made of 6061-T651 aluminum alloy. The microstructure of the rod material from which the specimens were machined from can be described as "needle" like. This type of microstructure can be described by two characteristic grain dimensions; longitudinal, along the axis of the rod and transverse in the plane normal to the rod axis. The grain dimensions for this alloy are provided below in Table 1.

A plot of the standard deviation of the measured corner crack growth rates versus crack length is presented in Fig. 1. A plot of Eq. (1), the linear relation between the average number of grains intersected by the crack front, n, and the crack length is also shown in this figure. In order to derive this relationship it was assumed that the corner

Table 1
Average grain dimensions for 6061-T651 rod

Longitudinal	Transverse
350 μm	200 μm

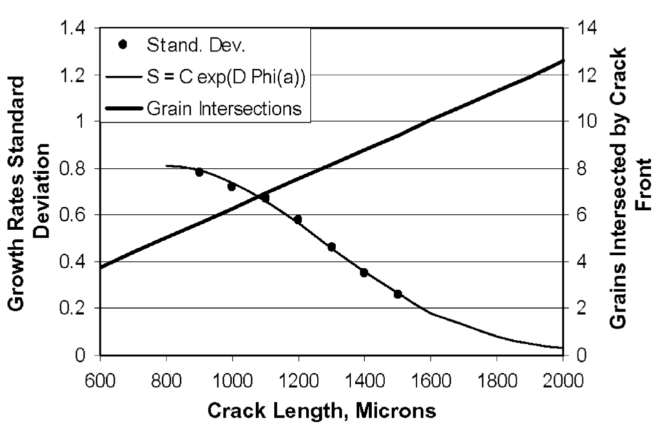

Fig. 1. Crack growth rate standard deviation/grain intersections versus crack length.

crack front was a quarter arc of a circle. Fractographic examinations of fracture surfaces confirmed this to be a valid assumption.

$$n = \frac{\pi}{2}\left(\frac{a}{d}\right) \tag{1}$$

In this equation, n is the number of grains intersected by the growing crack front, and d is the transverse grain dimension given in Table 1.

The trend of the data indicates that initially the rate of decrease in the standard deviation increases with increasing crack length. Ultimately, however, the rates of decrease begin to decrease with increasing crack length. This behavior is reasonable as the standard deviation represents the level of scatter found in the data. When the cracks are small, the level of scatter caused by interaction with the local material microstructure is large. As the small cracks grow, the micro-structural effects begin to average out, leading to a lower, steady state level of scatter for long crack growth.

It was shown that the observed behavior of the standard deviation of the crack growth rates could be represented by the exponential presented below [9]:

$$S = 0.81\mathrm{e}^{[-2.299\cdot 10^{-6}(.6366\cdot d\cdot n-800)^2]} \tag{2}$$

This result is also plotted below in Fig. 1.

From Fig. 1 it is apparent that after the crack fronts have intersected approximately 15 grains, the standard deviation of the crack growth rates and thus the measured scatter becomes exceedingly small, below 0.1 nano-meters per cycle. At this point the standard deviation and thus the level of scatter have reached a fairly stationary value, signifying that the cracks have begun to act as long cracks and can be treated deterministically using standard fracture mechanics analyses. This micro-structurally defined point can then be defined as the transition point from small to long crack behavior.

Other micro-structurally based definitions of a transition length between small and long crack behavior have also been suggested [10,11]. In a survey of a large number of alloy systems Taylor and Knott [10] showed that transition length could be approximately correlated with characteristic micro-structural sizes such as grain size, inclusion sizes and lamellae widths. Their definition of transition length however was based on the transition between the constant stress to the constant stress intensity factor, fatigue crack growth thresholds which are exhibited in the Kitagawa diagram [12].

1.2. Small fatigue crack growth: multi-site micro-cracks

The work of Carlson et al. [8,9] established the fundamental ideas of a micro-structurally based transition point from small to long crack behavior, based upon the observed scatter in crack growth rates. The objective of the current research described here, was to extend and further develop this concept; including the more general case of small cracks growing in clusters from a smooth surface. Additionally, a test effort to obtain a larger, more statistically significant set of crack growth data was conducted and will be described below.

All tests were conducted using a hot-rolled 1/4 inch thick plate of 7075-T7351 aluminum alloy. As in any rolled plate material, sections can be taken in three orthogonal representative orientations where intrinsic differences in the microstructure and material properties are exhibited. These are the long transverse, short transverse and longitudinal directions and are defined in Fig. 2.

Prior to testing, the Georgia Tech Research Institute (GTRI) provided a micro-structural characterization on a specimen taken from the bulk plate [13]. The grain structure of the plate, which can be described as ‘‘pancake like’’, necessitated the use of a cycloid method in estimating the grain size [14]. A summary of the grain sizes found is presented in Table 2.

The test specimen geometry used is shown in Fig. 3. The notched section localizes fatigue damage in the form of randomly distributed clusters of naturally initiated cracks. In addition, it creates a slight stress concentration of 1.2 over the average ligament stress [15].

Prior to being tested, all specimen gauge sections required extensive polishing. The specimens were prepared first with the use of three abrasive papers of the following grits: 240, 320 and 600. Preparation was then completed by a careful polishing procedure using 15, six and one micron diamond pastes. This level of polishing, which obtained a mirror like surface finish, not only ensured that each specimen began testing in an identical condition but also facilitated the detection of cracks with the optical detection system used.

All tests were conducted on a digitally controlled Instron hydraulic test stand, under load control, in tension. The load form used for all tests was sinusoidal of constant amplitude with a load ratio, R, equal to 0.1. A maximum load of 22,241 Newtons was used, leading to a maximum stress (σ_{max}) of 75% of the material yield strength. This led to specimen fatigue lives of around 70,000 cycles. All tests were run at a cyclic frequency of 10 Hz.

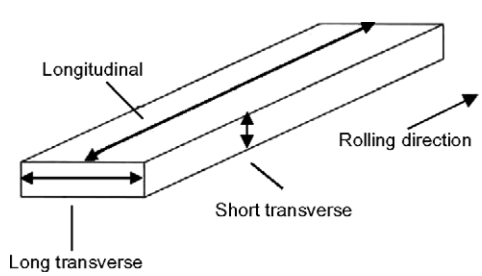

Fig. 2. Schematic defining the material directions.

Table 2
Material grain sizes

Longitudinal*	Transverse*	Short transverse*
58.8	76.1	15.0

* All dimensions in microns.

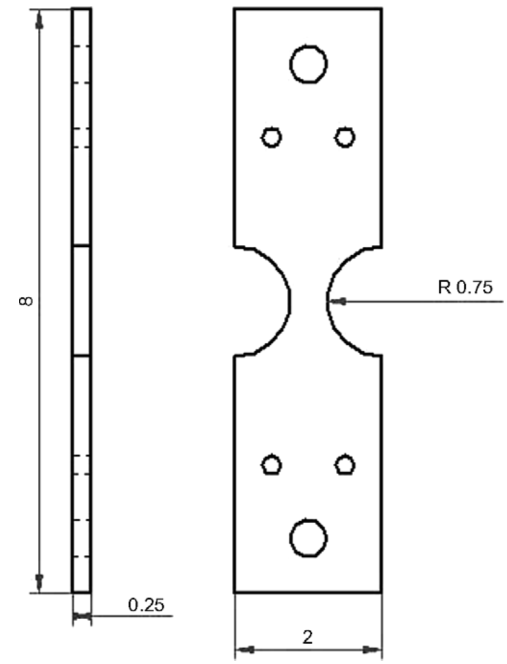

Fig. 3. Specimen geometry (all dimensions in inches).

Cracks were periodically measured optically using a Questar, QM 1 tele-microscope. The microscope had an optical resolution of 2.5 μm and a working range of 0.55–1.7 m. During crack measurements, the maximum load was applied to the specimen to assure that all cracks were fully open.

1.3. Test results and analysis

The evolution of scatter in the small fatigue crack data obtained from the current experiments was analyzed in a manner similar to that which has been discussed previously. This data included cracks measured on a total of nine specimen test surfaces from five separate specimens (one surface was scratched during handling voiding all data). However, not all of the crack data was used in this analysis. First, only the cracks considered to be ‘‘primary cracks’’ were considered. Inside the naturally initiated clusters it is only these cracks which will continue to grow out of the small crack regime towards failure. Therefore the scatter in the growth rates of what were determined to be ‘‘secondary cracks’’ will be insignificant. This separation of the total crack population into two distinct distributions will be the subject of a future detailed paper. At this point it is sufficient to note that since the secondary cracks all eventually arrest, it is only the primary cracks which can grow to cause failure [16,17]. Additionally, of the 14 primary cracks measured, two were ignored. These cracks initiated late in the fatigue lives of their respective specimens and only limited growth data were obtained for them. With such limited data it was not possible to fit meaningful regression curves to the data of these two cracks.

Cubic polynomial regression analyses were performed on the crack surface length, $2a$, versus the cycle count, N, data [9]. Close regression fits were obtained for the data of the primary cracks, with coefficient of determination, R^2, values above 0.98. Subsequently, these equations were differentiated and ultimately provided expressions for the crack growth rate versus the crack length.

With these data the relevant statistics of the crack growth rate at the various crack lengths were computed. In this analysis only the average and the standard deviation were needed. These were then used to calculate the respective coefficients of variation, C_x, for the crack growth rates.

The coefficient of variation is a non-dimensional quantity that provides a measure of the scatter found in a set of data. It is found by dividing the standard deviation of a set of data by that set's mean:

$$C_x = \frac{S}{\mu} \quad (5)$$

Calculated in this manner, this quantity provides information about the spread of data relative to the mean, with large values signifying a large variability and small values meaning the opposite. This allows for the variability of smaller growth rates to be compared with that of the larger rates.

All surface cracks measured have been assumed to grow with an approximately semi-circular crack front. The accuracy of this assumption was verified by fractographic analysis, an example of which is shown in Fig. 4. Using simple geometry, it can be shown that the average number of grains intersected by these crack fronts is given by the linear relationship presented below:

$$n = \frac{\pi a}{d} \quad (6)$$

Here, a, is the crack half length or depth. Any relationship that is a function of the crack length can now be transformed to be a function of the number of grains intersected by the crack front.

Unlike the rod material analyzed above where only one characteristic grain dimension was needed to determine the number of grains intersected by the crack front, the plate material requires the use of two. Since a wrought plate will have three characteristic micro-structural dimensions, any two-dimensional planar crack must grow through two of them. Due to the manner in which the current specimens were machined, all cracks grew into the longitudinal/short transverse plane of the plate. In order to account for this feature the two grain size values were averaged to provide the value for d. For this case d was found to be equal to 36.8 μm. This value provides the average size of grains sampled by the crack front.

A plot of the coefficient of variation of the crack growth rates, which shows the evolution of scatter throughout the crack growth process, is presented in Fig. 5. Both C_x and the number of the grains intersected by the semi-circular crack fronts are plotted versus the crack lengths.

This plot shows that the scatter present in the current experiments behaves in the same manner as that of previous experiments on corner cracks. In the early stages of crack growth a large amount of scatter is present, signifying a strong small crack effect. As the crack grows this scatter decreases quickly until the amount of scatter observed in the growth rates levels off and maintains a fairly constant value.

This type of behavior is a product of each crack's varying interaction with the local material microstructure. As discussed above, when the cracks are small the crack fronts only sample a small number of grains and the growth of the cracks is then dominated by micro-structural interactions. This leads to the large amounts of scatter observed. As the cracks grow and sample an increasing amount of microstructure, these effects begin to average out and the scatter decreases. This continues until enough microstructure is sampled to allow the cracks to approach the bulk,

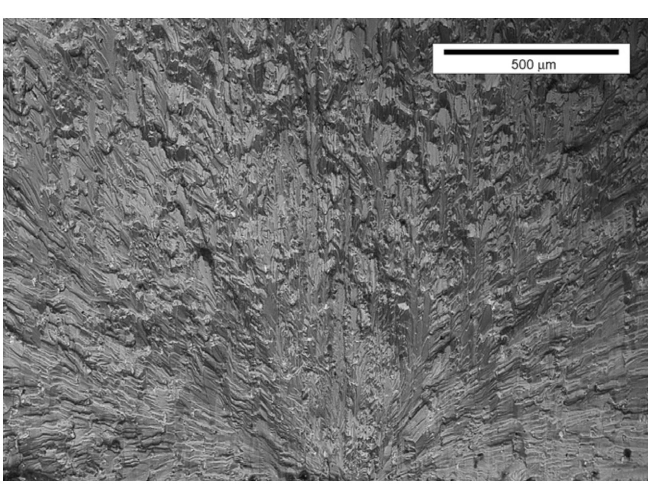

Fig. 4. SEM Micrograph of fracture surface at the crack initiation point highlighting the approximately semi-circular crack front.

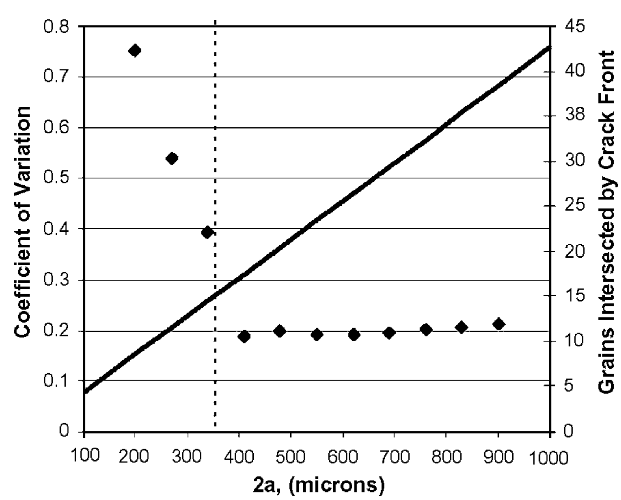

Fig. 5. Coefficient of variation of the crack growth rate.

long crack behavior expected in the material. Here scatter should stay fairly constant through failure.

As discussed above, a micro-structural transition point between small and long crack behavior had been defined as the point when the growing front of a crack intersects approximately 15 grains. Using Eq. (6), it can be found that this value is reached for cracks in the current experiments when the surface crack length reaches a value of approximately 352 μm. This value, shown as a vertical line in Fig. 5, corresponds well, within approximately 51 μm, with the actual point where the scatter in the crack growth rates reaches a steady state value.

A limitation in the procedure used to obtain the crack growth rates is that it relied on a best-fit polynomial regression curve. These curves in effect, smoothed out the perturbations in the crack growth rate masking the true growth-arrest behavior of small cracks. To observe this detailed behavior, the growth rates of the cracks were also calculated discretely using the secant method [18].

To illustrate this behavior, the crack growth rates of all primary cracks of which more than six data points had been collected are plotted in Fig. 6. These cracks provide the clearest picture of the primary crack behavior. The plot has been divided into two sections: small crack growth prior to the transition point and long crack growth after the transition point.

It is readily seen in Fig. 6 that the growth rates for small cracks fluctuate wildly, sometimes including periods of near crack arrest. However, after the micro-structurally defined transition point the growth rates tend to be significantly more stable signifying that the growth of the cracks is no longer dominated by micro-structural heterogeneities. This indicates that the defined micro-structurally based transition point predicts not only the point where scatter drops but that this point corresponds closely to where cracks cease to act as unpredictable small cracks and begin to behave as deterministic long cracks.

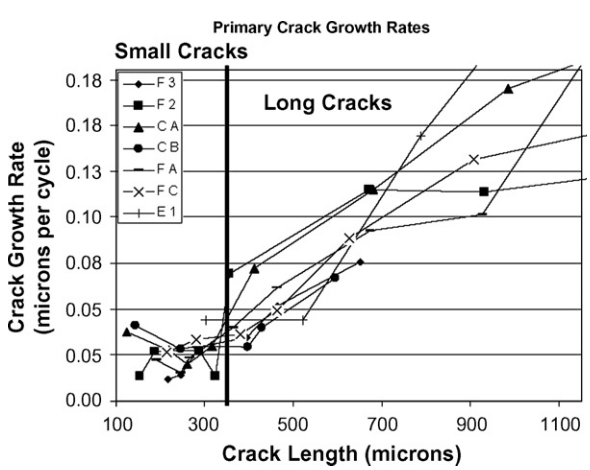

Fig. 6. Crack growth rates calculated using secant method.

1.4. Discussion of results

The definition of a transition point between small and long crack behavior, at the point when the growing crack front intersects approximately 15 grains has been shown to accurately describe the scatter behavior of fatigue crack growth for multiple crack geometries and aluminum alloys. It is at this point where the crack fronts sample a sufficient amount of microstructure for cracks to exhibit the bulk material resistance to crack growth rather than local values. These conclusions were drawn from experimental observations of the evolution of scatter in the growth rates of small cracks in single phase aluminum alloys. Additional work is necessary to extend the results to mixed phase metals.

The micro-structural definition of a transition point between small and long crack behavior, as defined, also provides a basis for anticipating differences in the evolution of scatter for different crack front geometries and varying micro-structural textures. For example, it is shown in Fig. 7a and b, that in samples with identical micro-structural textures that the crack front of a semi-circular crack intersects twice as many grains as a corner crack of the same depth. The scatter found in the growth of a semi-circular crack is therefore expected to diminish more rapidly than for the corner crack of the same depth. However, when both cracks transition from small to long crack behavior the average number of grains intersected by the crack front for both geometries will be the same.

When counting the grains intersected by the crack front, it is imperative to only include those grains through which the crack is actively growing. For most cases this will be a simple matter, but in other cases such as the crack geometry shown in Fig. 7c, care must be taken. A crack such as this can be created by the initiation and growth of a thumbnail surface crack into the decreasing stress field associated with bending about an axis and can be expected to grow predominantly outward towards the sides. Therefore only the intersections of the grains on the sides of the crack front should be counted, which means the crack will act more like a thumbnail crack than its geometry indicates.

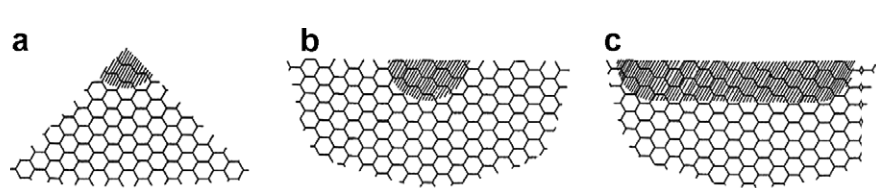

Fig. 7. Sample crack geometries with a simulated microstructure: (a) corner crack, (b) thumbnail crack, (c) surface crack in bending.

In other words, while the crack may appear to be a long crack which samples a large portion of material micro-structure, it can in fact still behave as a small crack.

While the results here were presented for a single case of constant amplitude loading it can be expected that the maximum load level may affect the definition of the transition length. Higher load levels lead to larger driving forces which allow small cracks to overcome micro-structural barriers easier. This may, in turn, decrease the small to long crack transition length as cracks under higher loads will transition away from crystallographic growth behavior sooner [19].

2. Conclusions

The transition point from small to long fatigue crack growth behavior is defined as the point at which scatter in the crack growth rates of small cracks is markedly reduced and attains a steady state value. This point has been determined experimentally for two aluminum alloys from tests on (i) single micro-corner cracks and (ii) multi-site naturally initiated micro-cracks. Scatter in the growth rates of small cracks was shown to decrease with crack growth until a steady state, long crack level is reached. It is at this point that the growth of small cracks can be considered to no longer be dominated by the local micro-structural heterogeneities and instead grow as deterministic long cracks. It was also shown that this point corresponds to when the growing portion of a crack front intersects approximately 15 grain boundaries. It has been discussed how this micro-structurally based transition point would be applied to any micro-structural texture and crack front geometry by tailoring the calculation of the number of grains intersected by the crack front towards specific situations.

Acknowledgements

The authors would like to thank the FAA for their support of this work under contract NGT 2-52274. They would also like to thank Dr. Russell Goddard for providing SEM micro-graphs of specimen fracture surfaces.

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