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

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

Table 1
Average grain dimensions for 6061-T651 rod

| Longitudinal | Transverse |
|---|---|
| 350 μm | 200 μm |

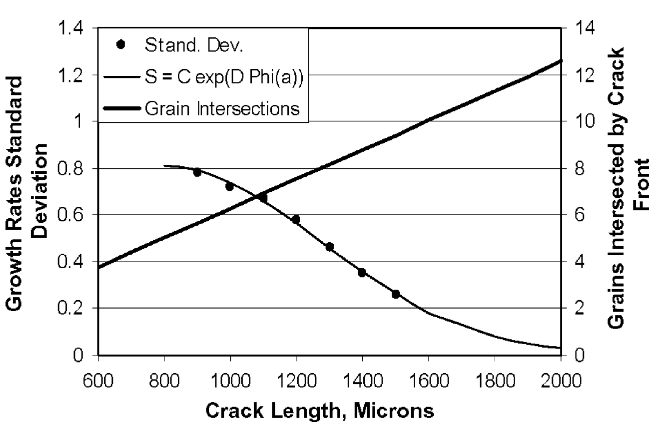


Fig. 1. Crack growth rate standard deviation/grain intersections versus crack length.

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

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