GENERATING FATIGUE CRACK GROWTH THRESHOLDS WITH CONSTANT AMPLITUDE LOADS

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The fatigue crack growth threshold, defining crack growth as either very slow or nonexistent, has been traditionally determined with standardized load reduction methodologies. Some experimental procedures tend to induce load history effects that result in remote crack closure from plasticity. This history can affect the crack driving force, i.e. during the unloading process the crack will close first at some point along the wake, reducing the effective load at the crack tip. One way to reduce the effects of load history is to propagate a crack under constant amplitude loading. As a crack propagates under constant amplitude loading, the stress intensity factor, K, will increase, as will the crack growth rate, da/dN. A fatigue crack growth threshold test procedure is developed and experimentally validated that does not produce load history effects and can be conducted at a specified stress ratio, R.

INTRODUCTION

Fatigue crack growth in a material is typically quantified by the size of the crack, a, the rate at which it propagates, da/dN, and the linear-elastic fracture mechanics term, ΔK, the stress intensity factor range. The relationship between crack growth rate and stress intensity was originally shown to be linear over a large range of da/dN on a log-log scale (Paris [1]). However, this relation is nonlinear near fracture (Barsom [2]) and when the crack growth rate approaches threshold (Frost [3]).

The fatigue crack growth threshold is the theoretical value of ΔK at which da/dN approaches zero (Bucci [4]). It has been shown that small/short cracks propagate at a ΔK below the threshold value (Pearson [5], Taylor [6]) determined with the ASTM constant R load reduction test procedure [4]. The constant R load reduction method reduces the maximum and minimum load applied to a cracked specimen such that the load ratio, R, remains constant. Experimental results suggest that the constant R load reduction test procedure develops remote crack closure (Newman [7], Wu [8]), i.e. crack face contact far behind the crack tip. Remote closure is

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generated because tests are initiated at high loads, and shedding load until threshold is reached. Larger plastic strains are produced along the crack wake at the high loads early in the test than in subsequent lower loads near threshold. This plastic wake, or history, can affect the crack driving mechanisms by prematurely unloading the crack tip due to crack face contact along the wake (Chen [9], Newman [10]).

In this paper the authors have implemented a procedure for generating fatigue crack growth thresholds that minimize or eliminate load history effects. A compressive precracking scheme (Topper [11], Conle [12]) was used to generate a "history-free" crack from a starter notch. Then constant amplitude loading was used (Pippan [13]) to produce fatigue crack growth data not affected by load history. The stress ratios and materials were chosen such that load history effects would be clearly identifiable, if existent, at threshold. A control study was performed at a high R value where load history effects are believed non-existent.

TEST METHODS

The constant R load reduction method generates fatigue crack growth rates into the threshold region by reducing the applied load on the specimen in a controlled manner such that the load ratio, R, remains constant, *e.g.* the maximum and minimum load are continuously reduced throughout the test. The constant K_{max} load reduction method also reduces both the maximum and minimum load to generate threshold data, however the value of K_{max} is constant, *i.e.* R increases. Figure 1 graphically depicts the constant R test procedure as a blue short-dashed curve and the constant K_{max} procedure as a black long-dashed curve. In this study, compact tension, C(T), specimens were used (width, W, of 76.2 mm, thickness, B, of 12.7 mm, initial notch length of 19.1 mm). The load reduction tests were precracked at a constant ΔK that is equivalent to the first data point in the load reduction test. Specimens were precracked until the crack length was approximately one third the width, a/W of 0.3.

A constant amplitude loading scheme was implemented to produce fatigue crack growth data with minimal load history effects. This was accomplished by first producing a crack from a notch using a high compression scheme based on the closure-free test procedures proposed by Au, *et al* [14]. The precracking loads, both maximum and minimum loads in compression, were applied until the crack growth rate was less than 10^{-10} meters/cycle. Typically, this load produced a K_{max} of -0.06 MPa m$^{1/2}$ and a K_{min} of -19.9 MPa m$^{1/2}$ and required approximately 6,000 cycles. Then, the crack was propagated using a small tensile load, such that the stress intensity factor range was approximately 0.5 MPa m$^{1/2}$, to grow out of the residual tensile stress field developed by the compressive loading (Newman [15]). Finally, constant amplitude loading was applied at a specific R value to generate fatigue crack growth rate data. Figure 1 graphically depicts the constant amplitude load procedure as a red solid curve.

EXPERIMENTAL DATA

All specimens were tested utilizing a computer-control system on a servo-hydraulic machine with a clip gage to measure compliance and determine crack length. The compliance crack length measurements were verified visually with a floating microscope. All tests were conducted in laboratory air at a mean temperature of 21° C and a mean relative humidity of 28%. Two aluminum alloys were investigated, 7075-T6 and 7050-T6. The specimens were machined in the long-transverse (L-T) grain orientation. Each specimen was used for a single experiment. All load reduction tests were conducted at a load shedding rate of -80 /meter.

The 7075-T6 aluminum was tested at $R = 0.1$ and 0.7. The experimentally derived thresholds using the constant R load reduction method were 1.23 MPa m$^{1/2}$ and 2.30 MPa m$^{1/2}$ for $R = 0.7$ and $R = 0.1$ respectively. Comparatively, the constant amplitude test method produced thresholds of 1.04 MPa m$^{1/2}$ and 1.45 MPa m$^{1/2}$ at $R = 0.7$ and $R = 0.1$ respectively. In addition, a constant K_{max} load reduction test, where K_{max} was fixed at 15 MPa m$^{1/2}$, was conducted yielding a threshold of 1.11 MPa m$^{1/2}$ at $R = 0.95$. A plot of these threshold data is shown in Figure 2.

The 7050-T6 aluminum was also tested at $R = 0.1$ and 0.7. The experimentally derived thresholds using the constant R load reduction method were 1.33 MPa m$^{1/2}$ and 2.21 MPa m$^{1/2}$ for $R = 0.7$ and $R = 0.1$ respectively. Comparatively, the constant amplitude test method produced thresholds of 1.18 MPa m$^{1/2}$ and 1.78 MPa m$^{1/2}$ at $R = 0.7$ and $R = 0.1$ respectively. In addition, a constant K_{max} load reduction test, where K_{max} was fixed at 15 MPa m$^{1/2}$, was conducted yielding a threshold of 1.17 MPa m$^{1/2}$ at $R = 0.95$. A plot of these threshold data is shown in Figure 3.

DISCUSSION

The constant amplitude data represents the steady-state behavior of the material. The constant K_{max} data is presumed to be unaffected by remote closure due to plasticity. Coincidence of the steady-state $R = 0.7$ constant amplitude data to the K_{max} data reveals this assumption to be true (Figs. 2 and 3). However, the constant R load reduction data produced a higher threshold than either the constant amplitude or constant K_{max} tests. Based on this data, it can be concluded that the constant R load reduction test procedure is not accurately representing the material response of cracks under increasing K.

Utilizing the crack closure principle, an effective stress intensity factor, ΔK_{eff}, can be used to collapse data to generate a single fatigue crack growth rate curve [7] where

$$\Delta K_{eff} = \Delta K \left(0.7 - 1.1R^2 + 0.4R^3\right)/(1 - R) \tag{1}$$

for positive stress ratios. The effective stress intensity factor curve can then be used to predict where fatigue crack growth rate curves will exist for specific R values.

Using this approach, the $R = 0.7$ data was assumed to be "closure free" for generating a *da/dN* vs. ΔK_{eff} curve and predicting where the closure corrected $R = 0.1$ curve would lie. The results of this exercise are shown in Figures 4 and 5 for the 7075-T6 and 7050-T6 alloys respectively. It is interesting to note that the spread of fatigue crack growth thresholds that is traditionally cited in the literature is reflective of the constant R load reduction test method. When comparing the constant amplitude data, which is steady-state, this trend does not exist.

It has been argued that small cracks behave differently than long cracks in aluminum. Based on experimental data, small cracks propagate at stress intensity factors much lower than corresponding long cracks (Newman [16]). Small crack data for this alloy, heat treatment and grain orientation were found in the literature for $R = -1$ [16]. Using equation (1), these data were translated to $R = 0.1$ and plotted against the 7075-T6 data generated herein. The constant amplitude long crack data encompasses the small crack data, implying there is little difference between small and long crack behavior in this material. This data is plotted in Figure 6 along with the constant R load reduction data for reference.

CONCLUSIONS

Investigating the impact a test procedure has on the data being generated is important to understanding material response. If the test procedure alters the data by introducing effects, such as remote closure, the test is not adequately describing the material behavior. In the case of fatigue crack growth thresholds, where the threshold is traditionally considered a safe value where no crack growth occurs, accurate representation of the material behavior and subsequent component fatigue life is crucial. Using the constant R load reduction test will generate artificially high threshold values when compared to steady-state data. This level of unconservatism will vary significantly from material to material, as has been shown herein with the 7075-T6 and 7050-T6 aluminum alloys. Since this variability is currently unknown, computational tools can be used to predict lower stress ratio fatigue crack growth rate behavior, such as ΔK_{eff}, until experimental data can be generated. Furthermore, it is clear that in 7075-T6 aluminum there is no "short/long crack anomaly". The load history effects introduced into the long crack data has generated a database of artificially high thresholds that do not accurately represent the material response of cracks growing under increasing K.

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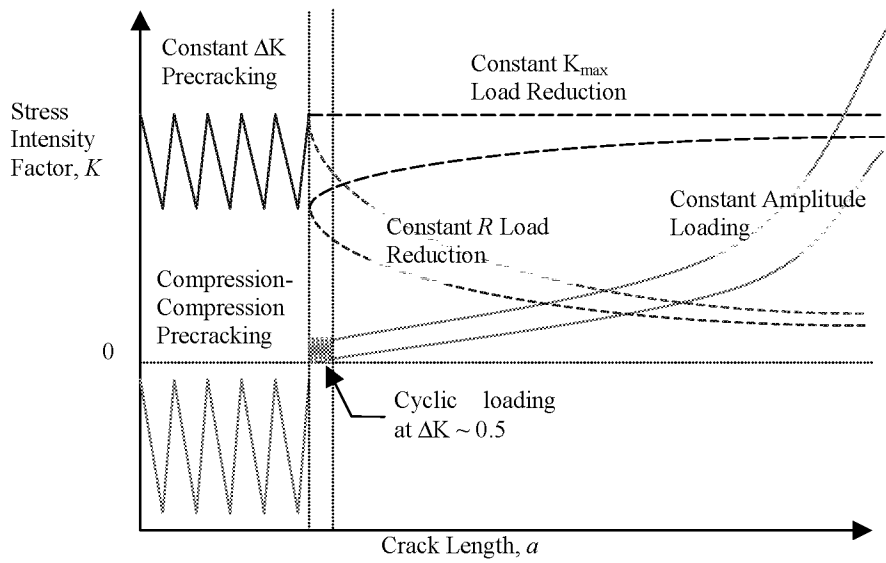
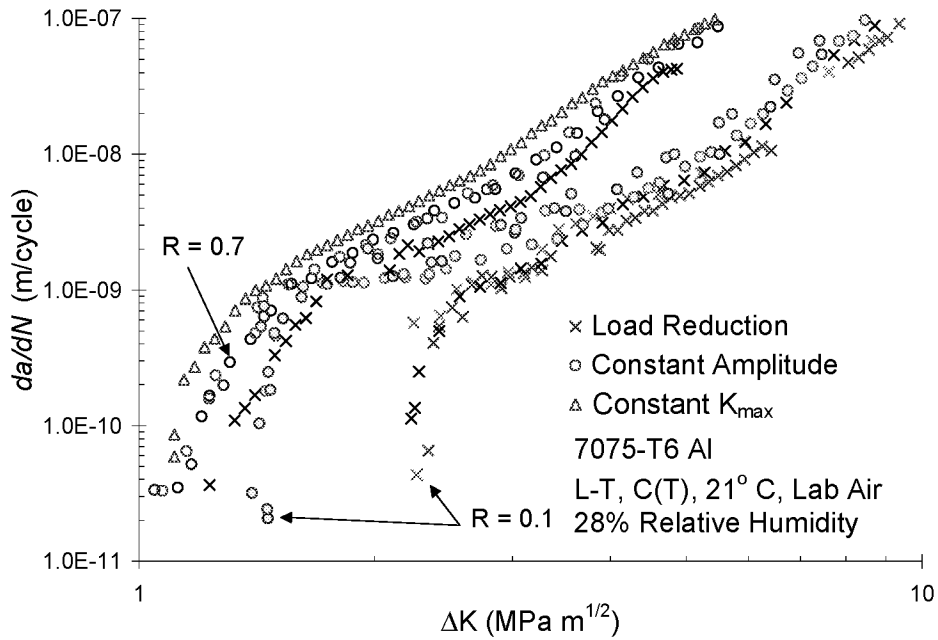FIGURE 1   Test methods for experimentally determining fatigue crack growth thresholds.

FIGURE 2   Fatigue crack growth rate data for 7075-T6 aluminum (L-T).
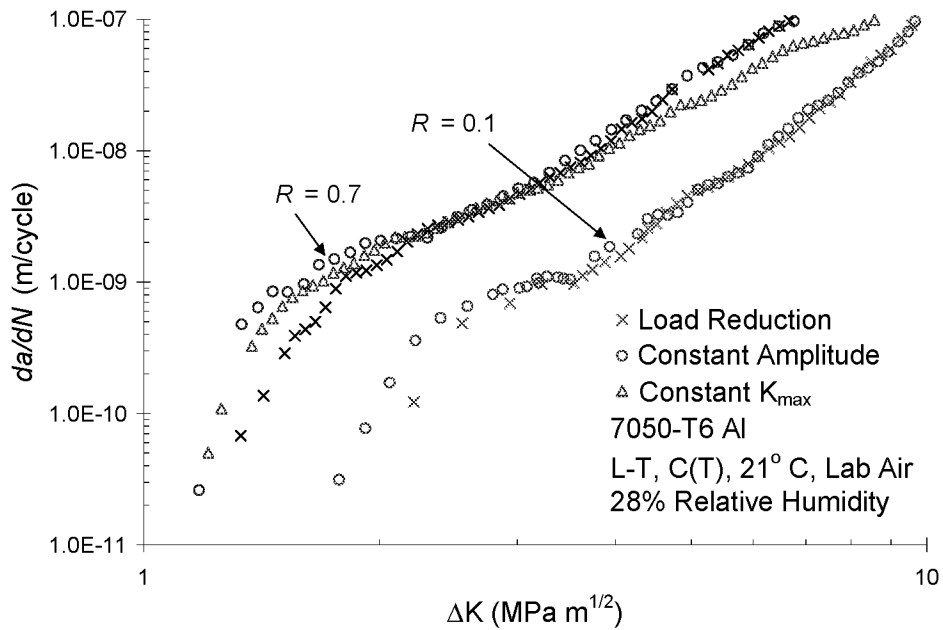
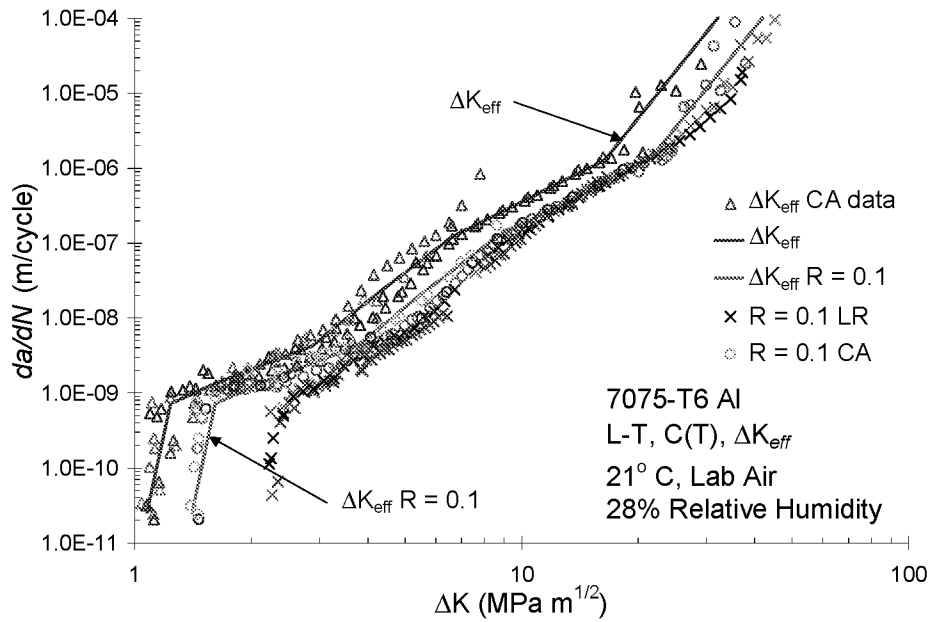FIGURE 3   Fatigue crack growth rate data for 7050-T6 aluminum (L-T).

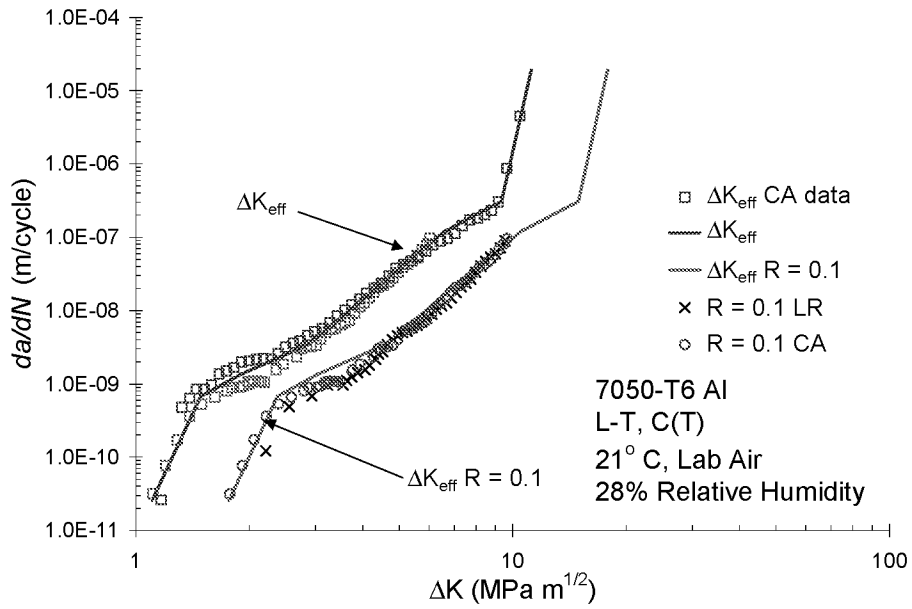FIGURE 4   Effective stress intensity factor data for 7075-T6 aluminum (L-T).

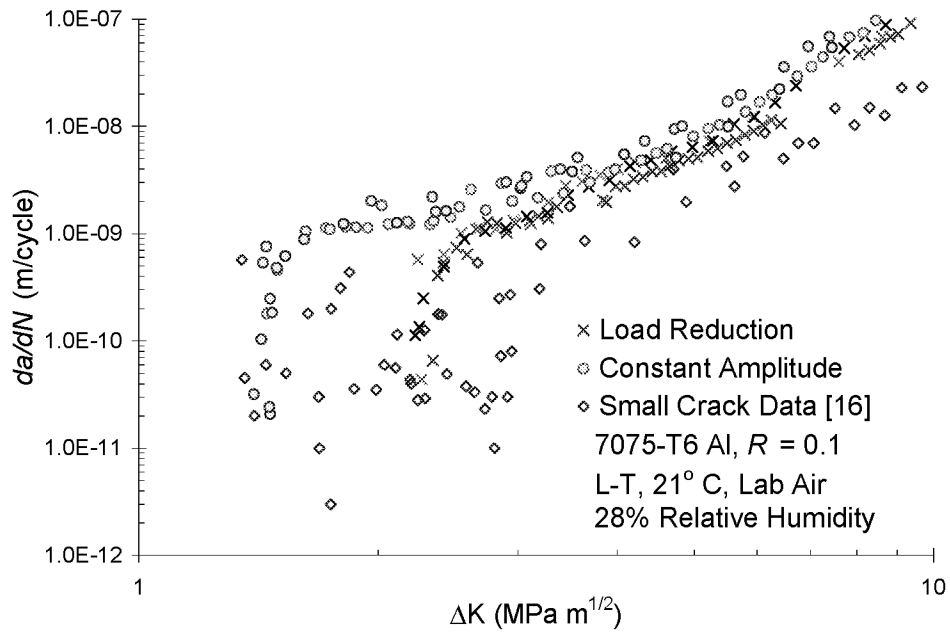FIGURE 5   Effective stress intensity factor data for 7050-T6 aluminum (L-T).

FIGURE 6   Small crack data at threshold for 7075-T6 aluminum (L-T).