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The variation in fatigue crack closure behavior across the thickness of aluminum alloy specimens was investigated. The specimen geometries examined in this study were the middle crack tension M(T) and compact tension C(T). The fatigue crack closure behavior was determined using remote displacement and strain gages, near tip strain gages, and fatigue striations. A hybrid experimental/numerical method was also used to infer the crack opening loads. The results of this study indicate a variation in crack opening load, in terms of the ratio of opening load to maximum load, of 0.2 in the specimen interior to 0.4-0.5 at the surface.

INTRODUCTION

Many of the crack growth analyses of fatigue cracks have been made with the assumption that the crack front is straight. In reality this is rarely the case, with even the simplest geometries exhibiting a curved crack front. In many cases, such as constant amplitude loading, this curvature is essentially trivial because the crack rapidly assumes a nearly "steady state" shape. For other conditions, such as overloads and variable amplitude loading, the crack front curvature becomes more pronounced as the crack growth behavior is affected by the complex interaction between the stress intensity factor and fatigue crack closure variations through-the-thickness.

Experimental evidence of a through-the-thickness variation in fatigue crack closure behavior was observed by Pitoniak et al (1) in their experiments with polymethylmethacrylate (PMMA), a transparent polymer. The through-the-thickness fatigue crack closure behavior of polymers was further illustrated in work by Ray et al (2-3) and Troha et al (4). A method of obtaining a detailed description of the through-the-thickness variation in fatigue crack closure behavior of metals

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using fatigue striations was developed by Sunder et al (5) based on the work of Pelloux et al (6). Anandan and Sunder (7-8) used this method to obtain a detailed description of the through-the-thickness crack opening loads for cracks propagating from a notch root.

The purpose of this study was to examine the through-the-thickness variation in fatigue crack closure behavior of 2024-T351 aluminum alloy. The fatigue crack closure behavior of this alloy was examined experimentally using the "standard" remote displacement and strain gages, near-tip strain gages, and a fatigue striation method. A hybrid experimental/numerical method was also used to infer the crack opening load. The fatigue crack growth tests were conducted under constant stress amplitude (ΔS) loading for material characterization and constant stress intensity factor range (ΔK) loading for fatigue crack closure behavior measurement.

CRACK OPENING LOAD MEASUREMENT TECHNIQUES

The fatigue crack closure behavior was experimentally described through the measurement of the crack opening load. The crack opening loads were measured with near-tip strain gages, fatigue striations, backface strain gages (C(T) only), and crack opening displacement (COD) gages (M(T) only). The material used in this study was 9.5mm thick 2024-T351 aluminum. The M(T) and C(T) specimens were tested under a constant stress intensity factor range of ΔK=13.8 MPa $m^{1/2}$ and a stress ratio of R=0.1. One M(T) specimen was tested with a 1.6 overload. The surface crack lengths were measured optically and the ΔK was maintained, to within ±2%, through load shedding. The details of the experiments and crack opening load measurement techniques are provided in References 9-10.

The crack opening loads were determined from backface strain gages and COD gages by recording the load and strain (or displacement) for a complete loading-unloading cycle. The backface strain (or displacement) against load curve should (for relatively low loads) be linear for a specimen that has a crack that is always open. The presence of fatigue crack closure causes the initial portion of the signal to be non-linear, as part of the load is required to relieve the residual compressive stresses on the crack surfaces due to closure. The opening load was found by identifying the load at which the signal became linear. The reduced displacement (or strain), as defined to be the difference between the actual displacement and a line fit through the linear portion of the upper unloading curve, was used to magnify the non-linearity in the measured displacement (or strain) curve to aid in identifying the crack opening load.

The crack opening loads were determined from near-tip strain gages in a manner similar to that described above. The near-tip strain gage technique used a small strain gage placed 0.5mm below and behind the crack tip and oriented to measure strain perpendicular to the direction of loading. A strain gage oriented in this manner produced the load/strain behavior shown in Figure 1. The two knees in the curve were hypothesized to represent the loads at which the crack surfaces separated in the interior (lower change) and at the surface (upper change).

A technique based on the work of Sunder et al (5) was used to determine the fatigue crack closure behavior from fatigue striations. The method used a special loading sequence to mark the fatigue surface with uniquely spaced fatigue striations at different crack lengths during the test. The surface was marked by applying a special loading sequence consisting of 20 cycles. The cycles in the sequence had a constant maximum load and minimum loads which increased with each succeeding cycle. The space between fatigue striations should remain constant, corresponding to a constant effective stress intensity factor range, as long as the minimum load was below the crack opening load. The space between fatigue striations should decrease, corresponding to a decreasing effective stress intensity factor range, when the minimum load rose above the crack opening load. The crack opening load was obtained by determining at which cycle the spacing between fatigue striations began to decrease. The fatigue striations were examined at several locations through-the-thickness of the specimen to obtain the variation in crack opening load.

HYBRID EXPERIMENTAL/NUMERICAL CRACK OPENING CALCULATION

A hybrid experimental/numerical method was developed to infer the crack opening load behavior at any location through-the-thickness from a measurement of crack growth rate and a calculated stress intensity factor range at that location on the crack front. The method relies on the assumption that the material crack growth behavior can be uniquely described by a relationship between crack growth rate and the effective stress intensity factor range. This crack growth relationship was approximated from high stress ratio (R=0.5) constant stress amplitude tests. For the 2024-T351 alloy, the cracks were assumed to always be open for stress ratios above R=0.5, thus the effective stress intensity factor range was equal to the applied stress intensity factor range. The crack growth rate data were represented well by a simple power law (Equation 1) for the stress intensity ranges of interest.

$$\frac{da}{dN} = 3.95\times10^{-10}(\Delta K_{eff})^{2.8} \qquad (1)$$

The effective stress intensity factor range at any point along the crack front ($\Delta K_{eff}(z)$) was determined by measuring the crack growth rate at that location on the crack front from the fatigue fracture surface, and substituting the rate into Equation 1. The stress intensity factor range for that location ($\Delta K(z)$) was determined using a 3-D finite element analysis for a curved, through-the-thickness crack. The crack shape used in the analysis was obtained from examination of the fatigue fracture surfaces. With the information on $\Delta K_{eff}(z)$ and $\Delta K(z)$, the opening load could be calculated from the customary definition of $\Delta K_{eff}(z)$ given by Equation 2.

$$\Delta K_{eff}(z) = \frac{\Delta K(z)}{(1 - R)}\left(1 - \frac{P_{open}(z)}{P_{max}}\right) \qquad (2)$$

RESULTS AND DISCUSSIONS

Crack opening loads determined experimentally and inferred for the same conditions using the hybrid experimental/numerical calculation technique are shown in Figures 2-3 for the M(T) and C(T) specimens, respectively. The solid symbols represent the upper and lower knees of the near-tip strain gage signal. In Figure 2, the symbols on the left ($2z/B=-1$) correspond to the M(T) specimen with the overload and the symbols on the right ($2z/B=1$) correspond to the M(T) specimen without the overload. The symbols were located on the surface where the measurement was made, even though the lower knee is thought to represent the crack opening behavior of the interior. The small dashed line in Figures 2 and 3 represents the constant value of crack opening load determined from COD in the case of the M(T) specimen and backface strain in the case of the C(T) specimen.

The C(T) and M(T) specimens had crack opening loads around 0.4-0.5 at the surface and 0.2 in the interior, with the C(T) specimens having slightly higher crack opening loads, as shown in Figures 2 and 3. After crack growth of 0.4 mm following a 1.6 overload, the M(T) specimen had a crack opening load (P_{open}/P_{max}) of 0.6 at the surface and around 0.3 in the interior, as shown in Figure 2. The lower knee of the near-tip strain gage signals showed good agreement with the crack opening loads determined from the striations in the specimen interior. The hybrid experimental/numerical calculation showed good agreement with the crack opening loads determined from the striations throughout the specimen and the calculated surface crack opening loads agreed with the upper knee of the near-tip strain gage signals.

The hybrid experimental/numerical calculation was also used to infer the crack opening load for a surface crack in a transparent polymer material subjected to pure bending. The crack opening load through-the-thickness was obtained by Ray et al (3) through optical interference. The comparison of the experimental measurements and the hybrid calculation in Figure 4 indicates that the transparent polymer behaves in a qualitatively similar manner as the aluminum alloy. The large dashed line represents the minimum applied fatigue load. The load was dropped to zero, for one cycle, during the optical interference measurements to determine crack opening loads below the minimum load. The hybrid technique cannot infer crack opening loads below the applied minimum load, but the location at which the inferred opening load exceed the minimum fatigue load ($\approx 30°$) agrees quite well with the optical interference measurements.

CONCLUDING REMARKS

The results of this study indicate that fatigue crack closure behavior varies along the crack fronts of through-thickness and surface cracks in the materials examined. Crack opening loads determined by the fatigue striation method, a near-tip strain gage method, and a hybrid experimental/numerical calculation were consistent with each other.

SYMBOLS USED

B	= specimen thickness (m)	R	= stress ratio
P	= applied load (KN)	z	= distance from mid-plane (m)
P_{open}	= crack opening load (KN)	P_{max}	= maximum applied load (KN)
ΔS	= stress range (MPa)	da/dN	= crack growth rate (m/cycle)
ΔK_{eff}	= effective stress intensity factor range (MPa $m^{1/2}$)	ΔK	= stress intensity factor range (MPa $m^{1/2}$)

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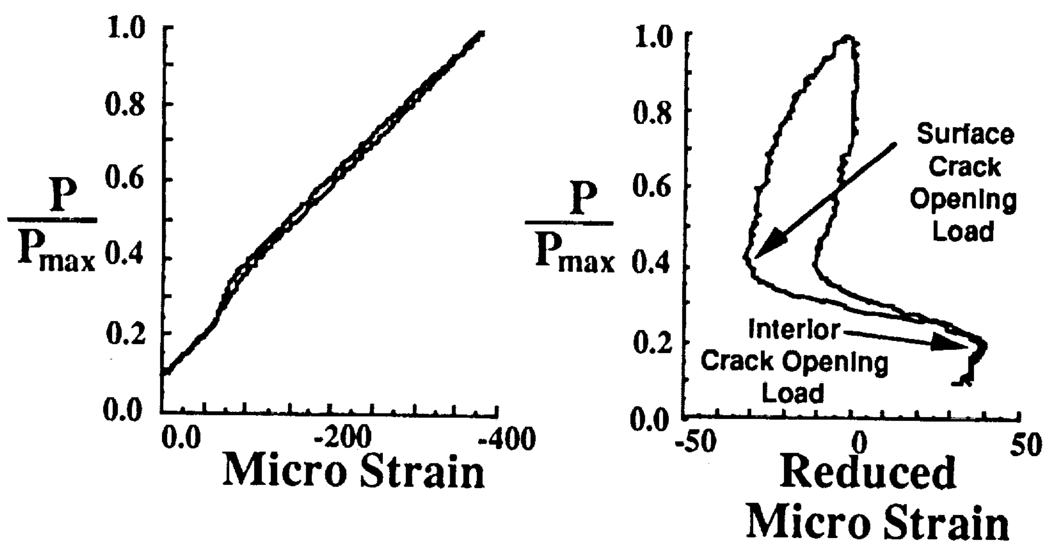
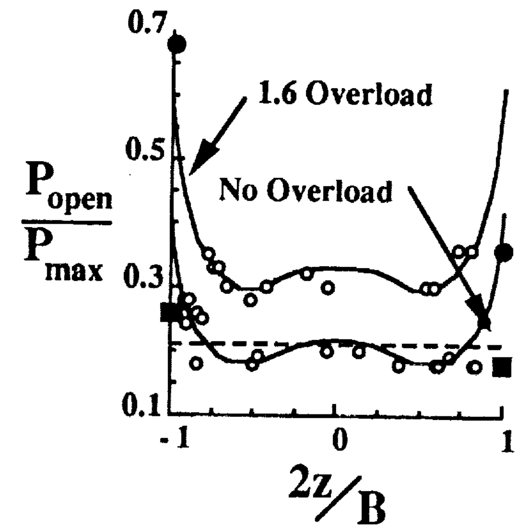


Figure 1. Load-strain and load-reduced strain behavior for a near tip strain gage.



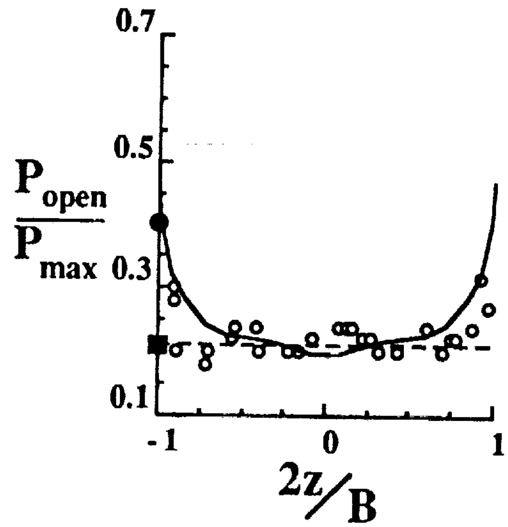


Figure 2. Experimental and calculated crack opening loads for a M(T) specimen subjected to constant ΔK loading with and without a 1.6 overload.

Figure 3. Experimental and calculated crack opening loads for a C(T) specimen subjected to constant ΔK loading.

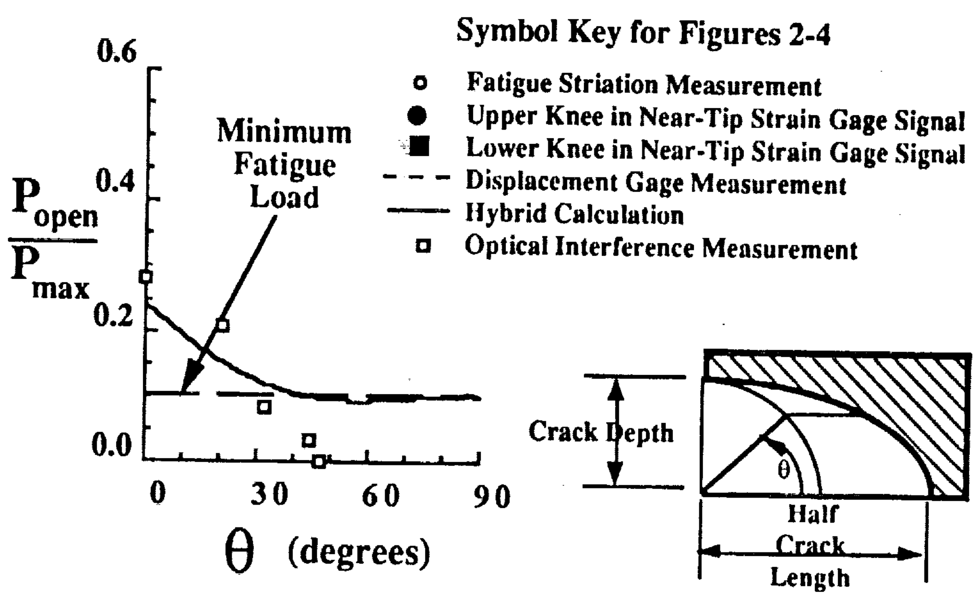


Figure 4 Experimental and calculated crack opening loads for a surface crack in a transparent polymer subjected to pure bending.

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16. Abstract

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