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Effective Crack-Propagation Resistance Under Monotonic And Cyclic Loading

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ABSTRACT: Crack propagation under monotonic and cyclic loading was investigated in alumina-epoxy composite specimens, produced via a multi-step infiltration technique. Under monotonic loading, an increase in effective fracture toughness was observed, which was attributed to the development of a bridging zone behind the crack-tip. A similar increase in crack propagation resistance was observed under cyclic loading, though this was more difficult to quantify. This was achieved approximately using an adjustment based on the Paris-law relation. This adjustment approach is described in this paper, and is also applied to fatigue results for graded composite specimens, in which the increase in crack-growth resistance with crack-extension is accompanied by a spatial variation in intrinsic and extrinsic crack-growth resistance.

1 INTRODUCTION

In many homogeneous materials under monotonic loading, the development of a bridging zone leads to crack-extension toughening. The value for stress intensity factor (SIF) at the crack-tip, K_{tip}, is less than the applied SIF, $K_{app}(a)$, due to crack-extension dependent shielding effects, $K_{br}(\Delta a)$. For fracture, K_{tip} must be equal to intrinsic fracture toughness, K_0, so the required value of K_{app} increases with crack propagation. This equates to an increase in effective fracture toughness:

$$K_c^{eff}(\Delta a) = K_0 + K_{br}(\Delta a). \quad (1)$$

Crack extension effects are also likely to influence resistance to crack propagation under cyclic loading [Ritchie, 1999]. This is more complicated than under monotonic loading, due to progressive fatigue degradation of the bridging zone, and introduces a dependence on propagation-rate as well as on crack-extension, ie. $K_c^{eff}(\Delta a, {}^{da}/_{dN})$, where ${}^{da}/_{dN}$ is the crack extension per cycle. The traditional approach for quantifying fatigue behaviour by presenting crack propagation rates as a function of SIF amplitude therefore becomes insufficient when R-curve effects are present.

This issue is pertinent to functionally graded materials (FGMs). As FGMs are typically composites, extrinsic fracture phenomena, such as crack-bridging, are likely to influence the propagation of cracks within them, and the influence of such phenomena will vary across the graded region [Cai and Bao, 1998]. For crack propagation in a graded composite structure with property variation in the x-direction, the applied SIF, intrinsic fracture toughness and the crack-tip shielding will all depend on crack-tip position [Tilbrook *et al.*, 2004a].

In this paper, the results of crack propagation experiments on alumina-epoxy composites under monotonic and cyclic loading are presented and analysed. A novel approach is described for approximately analysing cyclic fatigue results using an adjustment based on the Paris law relation. This analysis is demonstrated for homogeneous composite specimens and is also applied to a previously investigated graded composite specimen [Tilbrook *et al.*, 2004b].

2 METHODS & MODELLING

The alumina-epoxy composite system was chosen for the large disparity in elastic properties (E_{Al} = 390 GPa, E_{Ep} = 3.4 GPa) and failure strains (ε_{Al} <1%, ε_{Ep} > 3%). Specimens were prepared by infiltrating alumina slip into pieces of open-celled polyurethane foam compressed to required density [Neubrand *et al.*, 2002]. After drying, the foam was burnt out and the alumina sintered. The resulting porous ceramic bodies were infiltrated with epoxy resin. After curing, specimens were machined to size (45x3x6 mm^3) and polished with diamond paste. Microstructural characterisation was conducted with optical microscopy and elastic properties were measured using the impulse excitation technique [Tilbrook *et al.*, 2004c]. The scale and morphology of the composite microstructure reflected that of the original polyurethane foam.

Stable crack propagation from notches (~2mm long) sharpened using a razor blade technique was investigated under monotonic and cyclic four-point bend loading, using an Instron 1185 in displacement-control for fracture and an MTS 810 in load-control for fatigue (frequency = 8Hz, load ratio, R = 0.1). Applied loading was varied throughout fatigue tests in such a manner as to ensure that crack growth rates varied non-systematically with crack extension. Crack growth was monitored via a microscope and digital camera. SIF values were calculated from applied load, specimen dimensions and crack length.

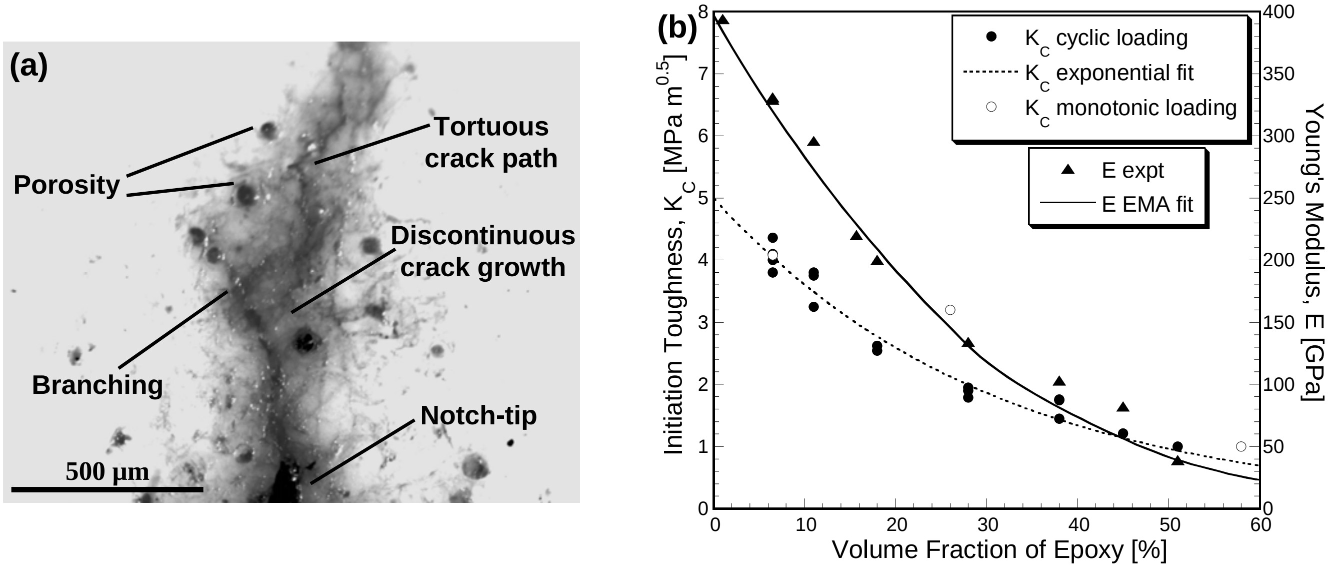

Figure 1: Crack growth in homogeneous composites. (a) Optical micrograph showing crack propagation path. Evidence of discontinuous crack growth and surface porosity may be observed. (b) Effect of composition on initiation toughness, K_C, under monotonic and cyclic ($K_C = K_{max}$, R = 0.1) loading, and on Young's modulus, E, measured via impulse excitation.

3 RESULTS & ANALYSIS

Crack propagation occurred in a discontinuous manner, as illustrated in Figure 1(a), which was attributed to the brittle nature of both phases and the relatively coarse composite structure. Figure 1(b) shows that an increase in epoxy content caused a decrease in the maximum SIF required to initiate crack growth (ie. crack initiation toughness) under monotonic and cyclic loading, and a decrease in effective Young's modulus [Tilbrook et al., 2004c]. This is attributed to the significantly lower stiffness and higher susceptibility to fatigue degradation of the epoxy phase.

An increase in fracture toughness with crack extension, under monotonic loading, was observed, as shown in Figure 2(a). This was attributed to crack-bridging by intact epoxy ligaments, due to the significantly higher failure strain of the epoxy phase. Figure 2(b) shows that, under cyclic loading, crack propagation appeared to follow the Paris law, $(^{da}/_{dN}) = A(\Delta K)^m$, with some scatter. During fatigue testing, the applied SIF amplitude was varied so that the correlation between crack growth rates and crack extension would be negligible, and that any transient effects would be non-systematic and would contribute to noise in the data. This was achieved by varying the applied SIF amplitude, within the range resulting in crack growth, numerous times throughout the crack propagation.

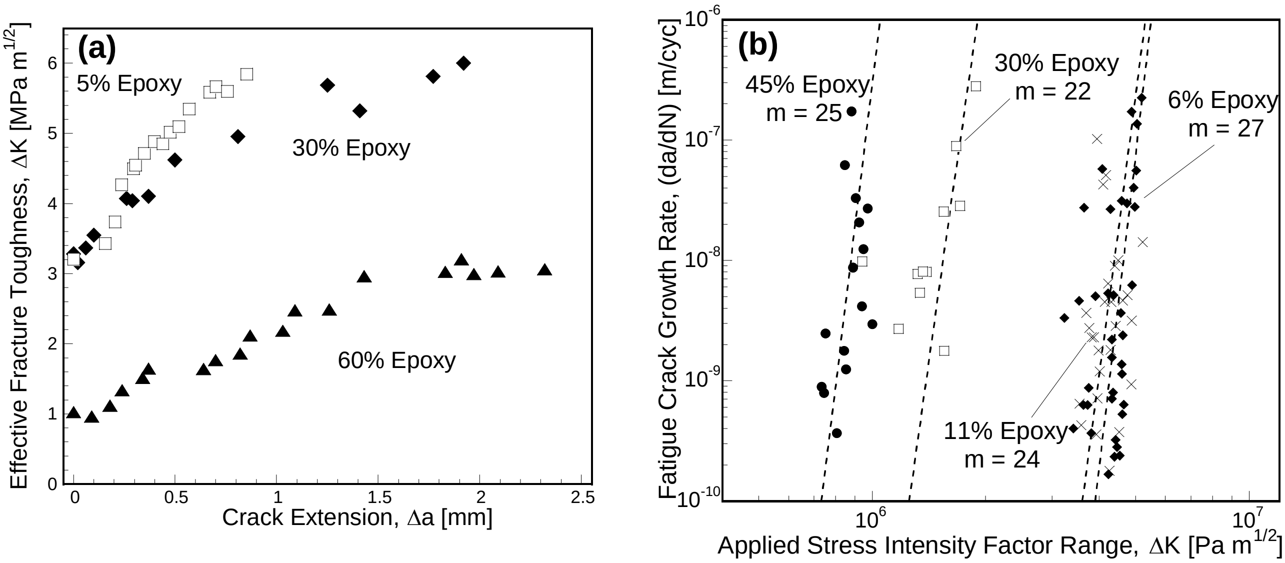

Figure 2: Crack propagation in homogeneous composites (a) R-curves for homogeneous specimens under monotonic loading. (b) Fatigue crack growth rates for several different compositions, showing Paris law behaviour.

It was observed that the SIF amplitude required for crack growth generally increased with crack extension. It is believed this, and some of the scatter in Figure 2(b), are due to the effect of crack-extension toughening on fatigue crack growth rate [Tilbrook *et al.*, 2004b]. Assuming this is the case, and that these effects may be extracted from the fatigue data, the following analysis is proposed.

The underlying assumption is that, for a given composition, the mechanisms of crack advance at the crack-tip, and accordingly the value of the Paris-law exponent, do not vary with crack-extension. The Paris law may be rearranged to form an expression equal to the Paris law coefficient, A, which is assumed constant for a given specimen:

$$A = (\Delta K)^{-m}\left(\frac{da}{dN}\right) \qquad (2)$$

This suggests that the measured values, ΔK^{meas} and $({}^{da}/_{dN})^{(meas)}$, for SIF amplitude and crack growth rate could be related to adjusted values, ΔK^{adj} and $({}^{da}/_{dN})^{adj}$:

$$\left(\Delta K^{meas}\right)^{-m}\left(\frac{da}{dN}\right)^{(meas)} = \left(\Delta K^{(adj)}\right)^{-m}\left(\frac{da}{dN}\right)^{(adj)} \qquad (3)$$

Measured ΔK values that resulted in differing crack-growth rates may be compared, by estimating the adjusted values that correspond to a standard adjusted crack growth rate, $({}^{da}/_{dN})^{adj} = ({}^{da}/_{dN})^{std}$:

$$\Delta K^{adj} = \Delta K^{meas}\sqrt[m]{\frac{\left({}^{da}/_{dN}\right)^{(std)}}{\left({}^{da}/_{dN}\right)^{(meas)}}} \qquad (4)$$

In this work, the value for $({}^{da}/_{dN})^{std}$ was arbitrarily chosen as 10^{-7} m/cycle. Essentially, this adjustment represents an estimate, assuming that the Paris law is applicable, of the SIF amplitude value which would have resulted in crack extension at the standard rate. The adjusted SIF was interpreted as a measure of fatigue crack propagation resistance, K_{CF}, ie. $\Delta K^{adj} = K_{CF}$. This adjustment method does not provide absolute results, rather it provides an *approximate* way of quantifying the *relative* variation in fatigue crack-propagation resistance. The variation in adjusted SIF with crack extension is shown in Figure 3(a) for several alumina-epoxy composite specimens. A systematic increase in fatigue resistance with crack extension is observed, comparable with the

R-curves in Figure 2(a). It appears that the crack-extension effects are less significant under cyclic than monotonic loading, which is consistent with the susceptibility to fatigue degradation of the epoxy phase. Furthermore, an increase in epoxy volume fraction results in a decrease in the bridging effect, both absolutely and relatively, which may also be explained in terms of the inferior toughness and fatigue resistance of the epoxy phase.

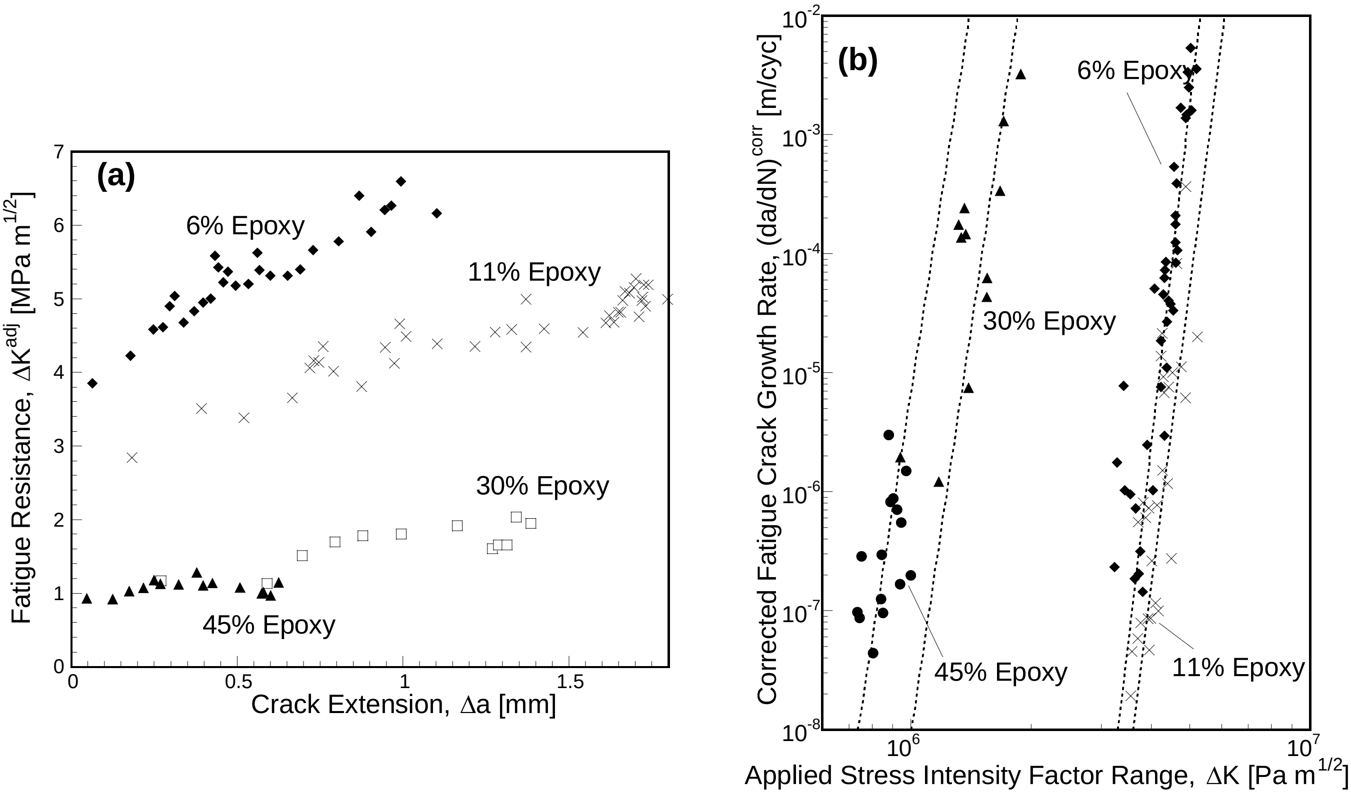

Figure 3: (a) Variation of effective fatigue crack propagation resistance, ie. adjusted SIF as in Equation (4), with crack length for a range of compositions. (b) Fatigue crack growth rate results from Figure 2(b) corrected to remove crack extension effect, as in Eq. (7).

Applying a fit to the fatigue resistance curve, the effective fatigue resistance, $K_{CF}(\Delta a)$, may be predicted at a given crack extension, Δa. Rearranging Equation (3) and making the substitution $\Delta K^{adj} = K_{CF}(\Delta a)$ yields:

$$\left(\frac{da}{dN}\right)^{(std)}\left(\frac{\Delta K^{meas}}{K_{CF}(\Delta a)}\right)^{m} = \left(\frac{da}{dN}\right)^{(meas)} \qquad (5)$$

A form of the Paris law similar to this, in which the applied SIF amplitude is normalised by fracture toughness, has been used to quantify fatigue behaviour in grain-bridging ceramics [Gilbert *et al.*, 1997]. Expanding the logarithms of each side in Equation (5), and writing $\left({}^{da}/_{dN}\right)^{std}$ as a constant, A':

$$\log\left(\frac{da}{dN}\right)^{(meas)} = \log(A') + m\log\left(\Delta K^{meas}\right) - m\log\left(K_{CF}(\Delta a)\right) \qquad (6)$$

This implies that each measurement of fatigue crack growth rate may be corrected, removing the dependence on crack-extension:

$$\log\left(\frac{da}{dN}\right)^{(corr)} = \log\left(\frac{da}{dN}\right)^{(meas)} + m\log\left(K_{CF}\right) = \log(A') + m\log\left(\Delta K^{meas}\right) \qquad (7)$$

Figure 3(b) demonstrates that applying this correction to the data improves the linearity of the data significantly, which confirms that much of scatter was attributable to R-curve effects.

4 APPLICATION TO GRADED SPECIMENS

The fatigue data analysis method has also proved useful in application to step-graded alumina-epoxy composite specimens. The analysis is demonstrated here for a specimen investigated previously, with the relevant experimental and computational simulation procedures given elsewhere [Tilbrook *et al.*, 2004b, 2004d]. A step-graded specimen, produced by a similar method to the homogeneous composites described above, is illustrated in Figure 4(a). Significant crack deflection is observed, which was attributed to elastic property asymmetry around the notch. Accordingly, cracks traversed the gradient region, thereby experiencing a variation in composition and properties at the crack-tip.

Figure 4(b) shows the effective crack-propagation resistance profile for the crack in a stepped gradient, in which stable propagation occurred across two compositional steps. A steady increase in effective crack propagation resistance was observed and attributed to the development of a bridging zone behind the crack-tip. As the crack moved from one step to the next, the effective fatigue resistance, ΔK^{adj}, and relative stress intensity, K/P, both decreased suddenly. The decrease in resistance was more dominant, so the crack advanced significantly and a reduction in applied loading was required in order to avoid unstable crack growth. After crossing the interface, the crack propagation resistance began to increase again, corresponding to further development of the bridging zone.

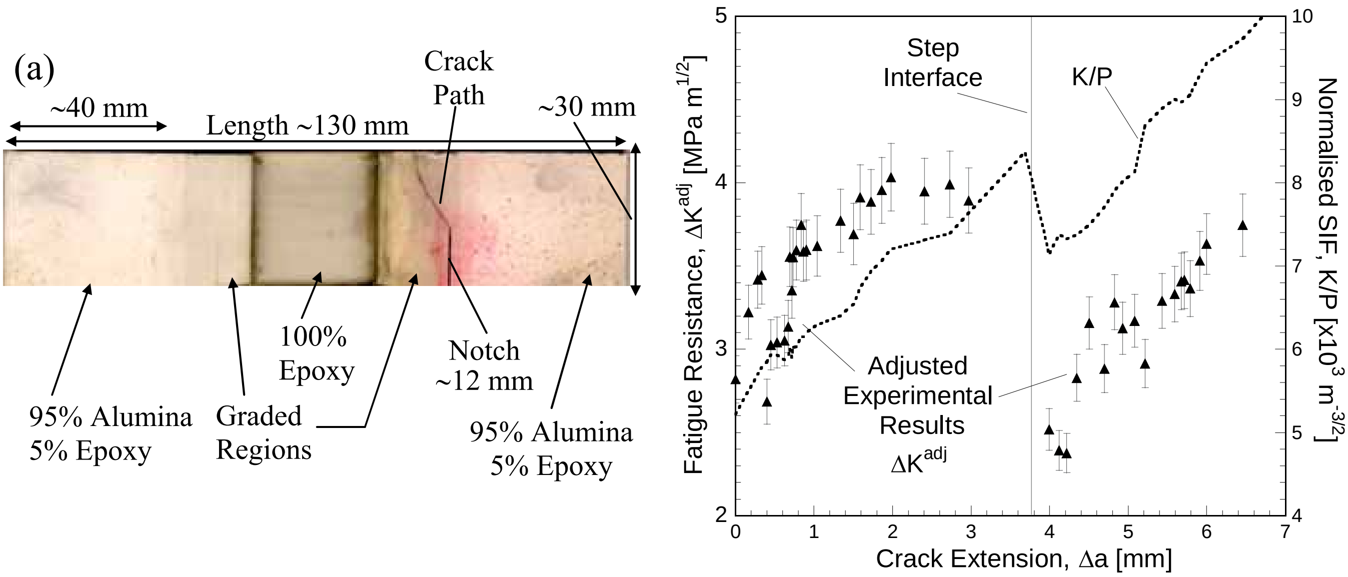

Figure 4: Graded alumina-epoxy specimens, investigated by Tilbrook *et al.* [2004b]. (a) Graded specimen showing dimensions and crack rpopagation path. (b) Load profiles for fatigue crack propagation (a) across an interface between compositional steps.

It is apparent that the variation in effective crack-propagation resistance in graded materials results from a competition between (1) crack-extension effects, which tend to increase resistance, and (2) spatial variation in intrinsic and extrinsic contributions to crack-propagation resistance. The adjustment method developed in this work for homogeneous composites provides a useful approach for analysing this phenomenon in graded composites.

5 CONCLUSIONS

Crack propagation in homogeneous and graded alumina-epoxy composites, under monotonic and cyclic loading, was investigated via experiments and FE simulations, and several conclusions were reached:

1. Crack-extension toughening effects in homogeneous specimens were observed under monotonic loading and also, by adjusting SIF amplitude values, detected under cyclic loading.
2. The adjustment of SIF amplitudes provides a useful approach for quantifying the relative increase in crack propagation resistance with crack-extension, under cyclic loading, for homogeneous and graded materials.
3. Compositional variation experienced by cracks propagating in graded specimens led to a decrease in crack propagation resistance, which occurred suddenly at step-interfaces in the specimens studied.

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