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FATIGUE RELIABILITY PREDICTIONS FOR CRACK BRIDGING MATERIALS

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ABSTRACT

Many modern materials are reliant on crack bridging to achieve adequate fracture resistance. As they are used in more cyclic loading applications, there is a need to make accurate fatigue reliability predictions. In bridging materials, the fatigue threshold, or stress intensity range below which fatigue cracks will not propagate, increases with crack extension in a manner similar to the fracture resistance. Thus, fatigue thresholds can be plotted versus crack extension as a *fatigue threshold R-curve*. The fatigue threshold *R*-curve was measured for a 99.5% pure polycrystalline alumina. Crack growth was initiated from razor micro-notches ($\rho < 10$ μm) in compact tension specimens at a loading frequency of 25 Hz and a load ratio of $R = 0.1$. The fatigue threshold was determined as a function of crack size by 1) decreasing the cyclic load until the crack growth rate slowed to less than 10^{-10} m/cycle and 2) using varying initial crack length and load combinations to get varying final crack sizes. Using the measured fatigue threshold *R*-curve and fracture mechanics weight functions, the bridging stress profile, considered a true material property, was calculated. The accuracy of the bridging stress profile was verified by direct measurement of the bridging stresses using x-ray fluorescence spectroscopy. From the bridging stress profile, the fatigue threshold *R*-curve was calculated for more technically relevant crack geometries, such as a semi-elliptical surface crack. Finally, fatigue endurance strength predictions were made as a function of initial flaw size using the calculated fatigue threshold *R*-curve for a semi-elliptical surface crack.

INTRODUCTION

Demand for high-performance, high-temperature structural materials has lead to extensive research on methods to improve the fracture resistance of brittle and semi-brittle materials such as ceramics and intermetallics. Furthermore, it is well known that microstructures that promote crack bridging have better crack growth resistance properties and exhibit increased toughness with crack growth (i.e., *R*-curve behavior).[1] For example, titanium aluminide alloys, which are being implemented in the low-pressure turbine section of the next generation of some turbine engines,[2] are commonly toughened by crack bridging.[3, 4]

Fracture toughness for a specific loading mode is measured by stress intensity factor (K), given in Eq. 1, which is a function of the sample geometric factor (Y), the applied stress (σ), and the crack length (a).

$$K = Y\sigma\sqrt{\pi a} \qquad (1)$$

In bridging materials, some of the load is transferred to bridges spanning the wake of the crack, reducing the stress intensity at the crack tip by an amount K_{br}. As the crack length increases, more bridges are formed increasing the crack growth resistance by further reducing the stress intensity at the crack tip.

Applications for many advanced materials toughened by crack bridging can be found in the aerospace industry, where components are also commonly subjected to cyclic loading. Crack bridging materials are generally susceptible to fatigue failure. Under cyclic loading, the bridges that serve to increase cracking resistance can be destroyed. Fatigue reliability prediction of such materials is tricky due to inherent short crack fatigue effects at crack sizes smaller than the fully developed bridging zone.[5-8]

Short cracks can propagate at loads below the presumed long-crack fatigue threshold.[9-11] As short cracks grow, they will either arrest or begin to exhibit long-crack behavior. For bridging materials, a long crack has a fully developed, steady state bridging zone where the bridges are being created and destroyed at a roughly equal rate and growth rates are independent of crack length. As a result, the fatigue threshold, or stress intensity range below which fatigue cracks will not propagate, increases with crack extension in a like manner to the fracture resistance.[12-14] Accordingly, the fatigue threshold can be plotted versus crack length, similar to a fracture toughness *R*-curve, in what is called a *fatigue threshold R-curve*. The purpose of this research is to develop a new methodology to characterize the fatigue behavior of and make fatigue reliability predictions for materials toughened by crack bridging using fatigue threshold *R*-curves. An outline of this methodology and experiments are below.

MATERIAL

Fatigue experiments were conducted on a 99.5% pure commercial polycrystalline alumina, Coors AD995. This is considered an ideal model material because 1) the several millimeters long bridging zone gives short crack fatigue effects at relatively large crack sizes [5] and 2) the lack of plasticity makes the competing effect of crack closure negligible. There is also a large amount of fracture, fatigue, and strength data for this alumina available in the literature. Crack bridging in alumina is due to a predominance of intergranular microfracture along a weaker, glassy phase at the grain boundaries which leaves interlocked and serrated grains in the wake of the crack.[15-17] A micrograph of the microstructure can be seen in Fig. 1.

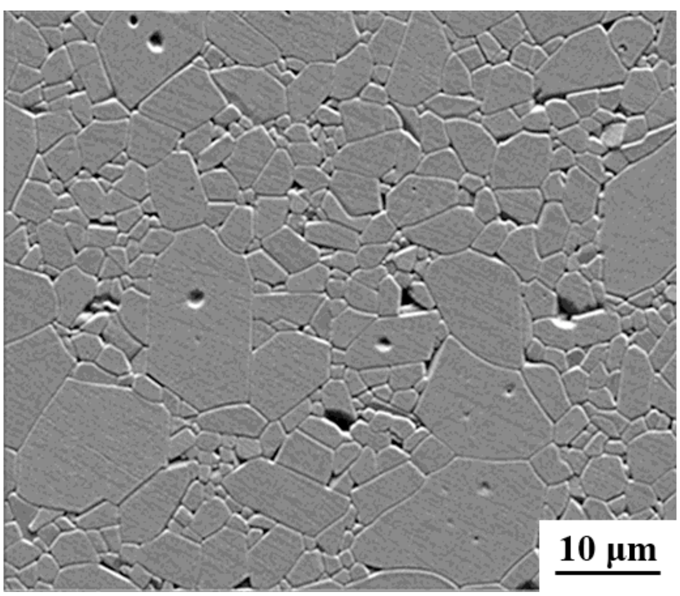

FIGURE 1. SCANNING ELECTRON MICROGRAPH OF THERMALLY ETCHED SURFACE OF POLYCRYSTALLINE ALUMINA USED IN THIS STUDY, COORSTEK AD995.

FATIGUE EXPERIMENTS

Fatigue thresholds were measured and plotted versus crack extension in what is known as a fatigue threshold R-curve. Crack growth was initiated in compact tension specimens from razor micro-notches having root radii of ρ < 10 μm. Once the crack length exceeded 10 μm, notch effects were assumed to be negligible.[18] Specimens were fatigued at a loading frequency of ν = 25 Hz and a load ratio of $R = K_{min}/K_{max} = 0.1$, where K_{min} and K_{max} are the stress intensities calculated via Eq. 1 using the minimum and maximum force during the loading cycle, respectively. Crack length was monitored using back face strain compliance methods.[19] The fatigue threshold was determined as a function of crack size by decreasing the cyclic load at a constant *K*-gradient until the crack growth rate slowed to less than 10^{-10} m/cycle.[20] Varying initial crack lengths and load combinations yielded a range of final crack lengths. The measured fatigue threshold *R*-curve is plotted in Fig. 2.

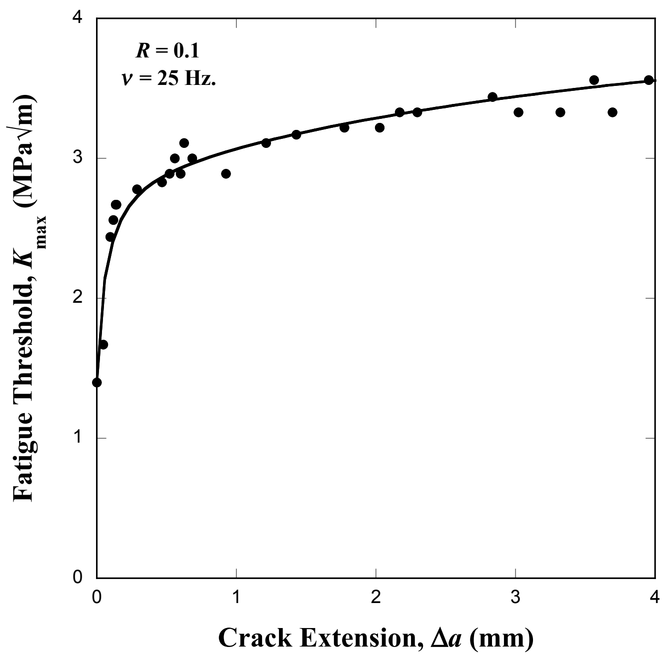

FIGURE 2. MEASURED FATIGUE THRESHOLD *R*-CURVE

BRIDGING STRESS PROFILES

R-curves and fatigue threshold *R*-curves are not material properties. They depend on sample geometry, loading type, and crack propagation conditions.[15] However, *R*-curves caused by bridging effects can be described by the relationship between the bridging stress and the crack opening displacement, and this bridging stress profile is considered a material property. Using the measured fatigue threshold *R*-curve and fracture mechanics weight functions, the bridging stress profile, considered a true material property, was calculated using the methods outlined in Ref. [21] and is shown in Fig. 3(a).

It is not feasible to measure fatigue threshold *R*-curves for materials which have very small bridging zones (e.g., <100 μm) making short crack fatigue experiments prohibitively difficult. However, for these materials it can be possible to directly measure the bridging stresses.[22] To demonstrate the equivalence of the techniques for alumina, bridging stresses were measured using optical fluorescence spectroscopy, where stresses are related to shifts in the characteristic optical fluorescence lines produced by the Cr^{3+} impurities in the alumina matrix.[23] The measured and the calculated bridging stress profiles, shown together in Fig. 3(b), were in very good agreement.

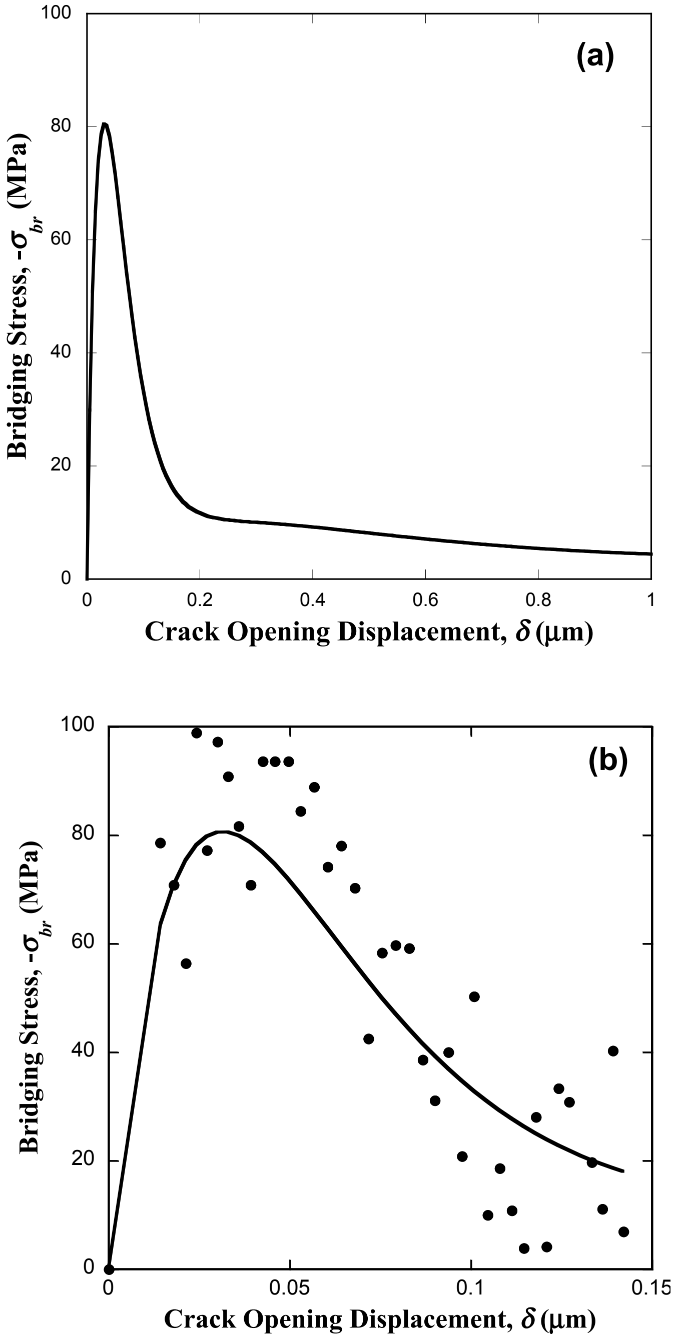

FIGURE 3. (a) CALCULATED BRIDGING STRESS PROFILE (SOLID LINE) FOR AD995 WITH (b) MEASURED BRIDGING STRESSES (SOLID CIRCLES)

From the bridging stress profile, the fatigue threshold R-curve was calculated for more technically relevant crack geometries of a semi-elliptical surface crack, again using the methods of Reference [21]. The newly calculated fatigue threshold R-curve for a semi-elliptical surface crack is shown with the measured R-curve for a compact tension specimen in Fig. 4.

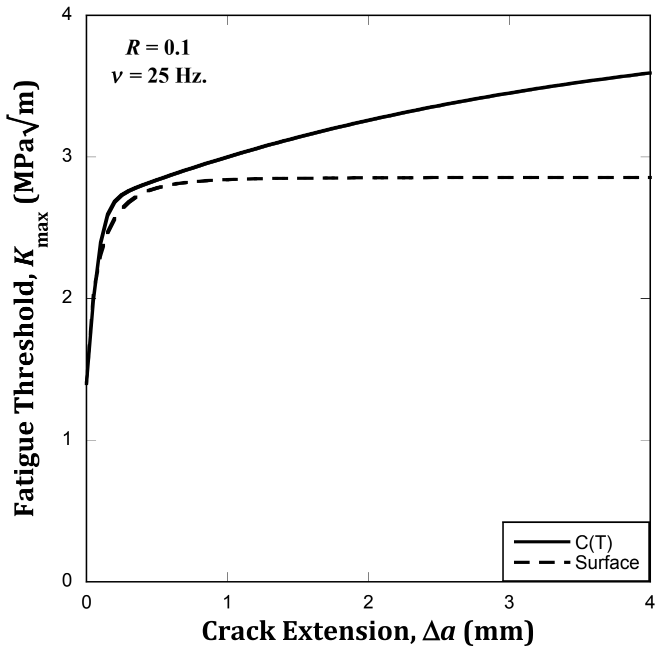

FIGURE 4. CALCULATED *R*-CURVE FOR SEMI-ELLIPTICAL SURFACE CRACK PLOTTED WITH MEASURED *R*-CURVE FOR A COMPACT TENSION SPECIMEN

ENDURANCE STRENGTH PREDICTIONS

Fatigue endurance strength predictions were made as a function of initial flaw size using the calculated fatigue threshold R-curve and the following relations:[14]

$$\Delta K_{app} = Y \Delta\sigma_{app}\sqrt{\pi a_i} = \Delta K_{TH}\left(\Delta a\right) \tag{2}$$

$$\frac{d\Delta K_{app}}{d\Delta a} = \frac{d\Delta K_{TH}\left(\Delta a\right)}{d\Delta a} \tag{3}$$

The applied stress intensity equation can be plotted with the fatigue threshold R-curve, offset by the initial flaw size, as shown in Fig. 5. The load that results in the two curves being equal and tangent at a point according to Eqs. 2-3 gives the fatigue endurance strength for that given initial flaw size. The fatigue endurance strength predictions for AD995 are shown in Fig. 6.

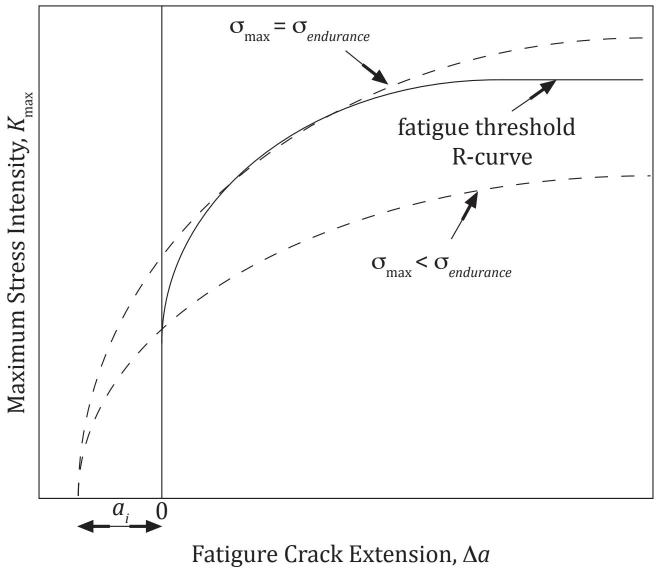

FIGURE 5. SCHEMATIC FOR DETERMINING THE FATIGUE ENDURANCE STRENGTH FOR A GIVEN INITIAL FLAW SIZE

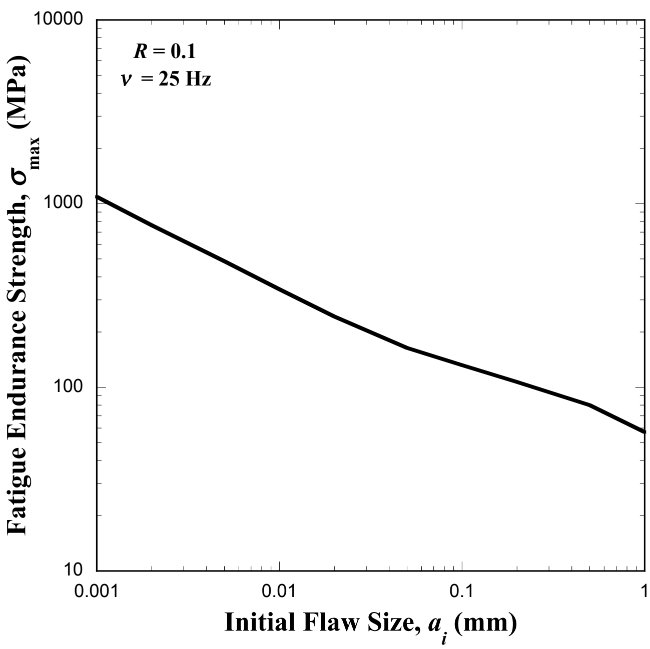

FIGURE 6. ENDURANCE STRENGTH PREDICTIONS

FUTURE WORK

Current work is focused on verifying the predictions in Figure 6. Moreover, it is expected that this methodology will be extendable to cover a wide range of materials toughened by crack bridging, including semi-brittle intermetallics, fiber reinforced composites, laminates, etc. The current research is being done on bridging ceramics, where lack of crack-tip plasticity make crack closure effects negligible. In addition to alumina, silicon nitride is also being studied,[14] which has a much smaller bridging zone that makes direct short crack experiments impractical. Future work also includes the study of titanium aluminide, a material of interest for turbine applications which has the added complexity of crack closure effects.

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