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EFFECTS OF CRACK TIP STRESS RELAXATION ON SUBCRITICAL CRACK GROWTH IN SILICATE GLASSES: THRESHOLD AND STOCHASTICITY

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Abstract

Silicate glass is a non-equilibrium material and as such evolves over time to reduce internal energy through thermally activated structural rearrangement. This statement is perhaps especially true in the highly stressed region around a crack tip. At the atomistic scale, structural changes to accommodate crack growth or to mediate stress relaxation become indistinguishable. Here, we present a simple expression for static fatigue threshold using slow crack growth power law parameters and a structural relaxation time scale. Using subcritical crack growth data from the literature and measured threshold data, this model is demonstrated for soda lime silicate glass. In addition, we discuss the impact of crack tip relaxation on statistical lifetime prediction and evolution of flaw populations.

1. Introduction

Subcritical crack growth (SCG) is a process by which a crack advances at a stress intensity that is less than the fracture toughness, $K_I < K_{Ic}$. From a kinetics perspective we can view this process as crack propagation via thermally activated propagation events. As the crack is opened, a positive energy release offsets the activation energy to a bond breaking event, and the crack propagates faster at larger K_I. At high enough K_I enough energy is released during a propagation event that the system is no longer in a metastable state, and we have critical fracture. At large stress intensity approaching critical fracture, the crack tip is moving quickly enough through the material that we can consider the material as having an equilibrium, fixed structural arrangement. In other words, the characteristic time for fracture events is much less than the characteristic time for structural rearrangements, $t_{frac} \ll t_{struct}$.

At lower stress intensity, however, we may need to consider crack propagation mechanisms and structural evolution mechanisms in a unified context. In equilibrium systems such as a crystal lattice, $t_{struct} \to \infty$, and we can neglect structural evolution in many cases. Although silicate glasses at room temperature are relatively stable and typically only evolve over long time scales, the high strain energy density near a crack tip can offset the activation energy for structural changes, and it is not unreasonable that we must consider the effect of crack tip stress relaxation on a moving crack. This assumption is particularly true when considering the very slow crack velocities necessary for lifetime prediction at decades or longer time scales or for very small cracks. We note that for a crack in a non-equilibrium material we expect there to be a stress intensity, K_{th}, which satisfies $t_{frac} = t_{struct}$. This relation acts as a transition between fracture dominated evolution ($t_{frac} < t_{struct}$), a regime where the crack propagates faster than the structure relaxes, and relaxation dominated evolution ($t_{frac} > t_{struct}$). We interpret K_{th} as a threshold stress intensity for SCG in silicate glass.

2. Results

In order to perform a prediction for SCG threshold, we first note that $K_I = Y\sigma\sqrt{a}$. We assume for the time being a far-field stress σ that is constant in time, and we note that $\dot{K}_I = Y\sigma\dot{a}/2\sqrt{a}$. We also assume a power-law relation between crack velocity and stress intensity, $\dot{a} = A(K_I/K_{Ic})^n$. We add a term to the K_I evolution expression for linear relaxation with time constant β, and after some minor manipulation we find the non-dimensionalized coupled evolution expressions for stress intensity and crack length

$$\frac{d\kappa}{d\tau} = \frac{\gamma\kappa^{n+1}}{2\alpha} - \kappa$$

$$\frac{d\alpha}{d\tau} = \gamma\kappa^n$$

where we have defined the non-dimensional quantities $\kappa = K_I/K_{Ic}$, $\alpha = a/\delta$, $\tau = \beta t$, and $\gamma = A/\delta\beta$, where δ is a characteristic length. K_{th} can be found by setting $d\kappa/d\tau = 0$, and we find the threshold stress intensity

$$K_{th} = \left(\frac{2\alpha}{\gamma}\right)^{1/n} K_{Ic} = \left(\frac{2a\beta}{A}\right)^{1/n} K_{Ic}.$$

We then need to deterimine the relaxation constant β. We demonstrate two different strategies. First, we express both SCG in vacuum and stress relaxation in glass as anArrhenius processes. We propose that since both phenomena are mediated by atomic configurational changes to reduce internal energy, the mechanisms must be related. We can then express β in terms of parameters for SCG in vacuum. Second, we combine the above evolution expressions with Weibull statistics characterizing beginning-of-life flaw populations and fit the resulting flaw population evolution to measured static fatigue data. A comparison is made between the β value obtained using the two methods. Finally, we briefly discuss the impact of structural relaxation and static fatigue threshold on flaw population evolution. Notably, a significant portion of the the flaws may be sub-threshold in many cases, such that only the strength-limiting flaws are actually evolving. The impact of this statement on strength variation and time-to-failure prediction is discussed.

3. Conclusions

A simple expression has been proposed to predict SCG threshold in terms of SCG power law parameters, fracture toughness, and a structural relaxation time scale. This has been demonstrated for silicate glass materials using relaxation time scales determined using two different methods. The effects of SCG threshold and crack tip structural relaxation on the evolution of flaw population and statistical predicition of strength and lifetime is also discussed.

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