FATIGUE CRACK GROWTH IN TRANSFORMATION TOUGHENING CERAMICS

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ABSTRACT

The influence of crack tip shielding during fatigue crack growth in transformation toughening ceramics is studied. It is shown that a unified description of fatigue during the development of crack tip shielding and at different levels of transformation can be obtained through a generalized Paris power-law by normalizing the crack tip stress intensity factor by the steady-state toughening. This procedure also captures the experimentally observed decreasing crack growth rate at early stages of fatigue. The application of this approach to the determination of endurance limits for these ceramics is outlined.

KEYWORDS: Fatigue, transformation-toughening-ceramics, small and large crack rates, endurance limit, overloading

INTRODUCTION

Evidence of the susceptibility of zirconia toughened ceramics to mechanical degradation under cyclic tensile loading has been provided by a number of studies (see e.g. Dauskardt et al., 1987; Swain & Zelizko, 1988). Similar to metals the crack growth rate dc/dN for long cracks follows the well-known Paris power-law dependence on the applied stress intensity range, $\Delta K^{appl} = K^{appl}_{max} - K^{appl}_{min}$. Using the steady-state shielding value, K^{ss} to calculate the effective stress intensity range at the crack tip, $\Delta K^{tip} = K^{appl}_{max} - K^{ss}$, Dauskardt et al. (1990) showed that long crack data for materials of different toughnesses fell close to a universal curve of the form

$$\frac{dc}{dN} = A\left(\Delta K^{tip}\right)^n, \qquad (1)$$

where A and n are material parameters.

A more recent study by Steffen et al. (1991) showed a different behaviour for small cracks. It revealed a negative dependency of the crack growth rate on the applied stress intensity range for small (250 μm) naturally occurring surface cracks. Furthermore, small cracks were observed to grow at stress intensity levels below the long crack fatigue threshold, at which fatigue cracks are presumed dormant in damage tolerant design. The small crack behaviour is therefore of serious concern to fatigue life prediction procedures, where the use of long crack data could lead to a nonconservative design. It was also shown schematically in that paper that the crack growth rates for long cracks fell within the region of small crack behaviour, when plotted against the maximum effective stress intensity factor, K^{tip}. Again the steady-state shielding was used to calculate K^{tip}.

The presentation in this paper suggests that a relation similar to eqn (1) can be used for the fatigue behaviour of small, as well as long cracks by computing the shielding effect as the crack grows rather than using the steady-state value to calculate K^{tip}.

TRANSFORMATION TOUGHENING DURING FATIGUE CRACK GROWTH

The model of a single surface crack in a transforming ceramic is illustrated in Fig. 1 (see Andreasen et al., 1995). The crack, C, is subjected to an oscillating far-field load, with a peak value of σ^∞, normal to its faces resulting in a pure mode I opening of the crack. At the tip of the crack a transformation zone with the boundary, S develops when the load is applied. Full transformation is assumed to occur when the mean stress reaches a critical value, σ_m^c.

It is also assumed that the transformation is accompanied by a purely dilatational strain inside the transformation zone, and the transformation is assumed to be irreversible leaving a transformation zone wake behind as the crack grows. The dilatation is described through the parameter $\omega = Ec\theta_p^T(1+\nu)/[(1-\nu)\sigma_m^c]$, where c is the volume fraction of transformable particles and θ_p^T is their volumetric strain.

Obviously the model does not take the cyclic nature of the loading into consideration when the transformation zone is determined, but it is assumed that the zone shape develops during peak loading. Raman spectroscopy and surface uplift measurements made under monotonic and cyclic loading by Dauskardt et al. (1990) support the contention that the transformation zone shape and size are not significantly affected by the cyclic character of the loading.

The amount of transformation toughening is determined as the ratio of the applied stress intensity factor K^{appl} to the crack-tip stress intensity factor K^{tip}. An example is shown in Fig. 2 as a function of crack advance normalized with the characteristic length $L = 9[K_c(1+\nu)/\sigma_m^c]^2/(2\pi)$ for $\omega = 10$ and two values of initial crack length c_0 and normalized load $\sigma_0 = \sigma^\infty(1+\nu)/\sigma_m^c$. During constant stress amplitude fatigue crack growth both the applied stress intensity factor and the shielding effect due to transformation rise. At the early stage of crack growth the shielding effect rises faster than the applied stress intensity factor. As the crack grows further the applied stress intensity factor starts to catch up as the crack length increases, leading to a peak in the ratio K^{appl}/K^{tip}. Thereafter this ratio approaches a constant (steady-state) value. The steady-state toughening ratio K^{appl}/K^{tip} for $\omega = 10$ varies between 1.56 and 1.58. This value is within 5% of the steady-state toughening value of 1.63 obtained for quasi-static crack growth (Amazigo & Budiansky, 1988).

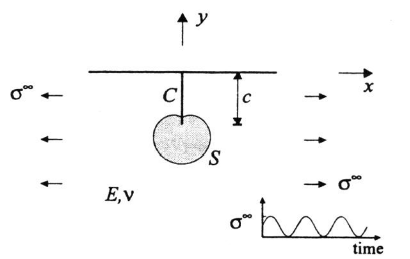

Figure 1: A Surface crack model for fatigue crack growth

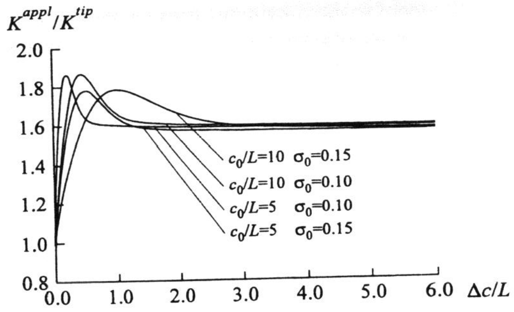

Figure 2: Transformation toughening during fatigue crack growth for $\omega = 10$

An example of resulting transformation zone shape is given in Fig. 3, with the steady-state transformation zone shape obtained for quasi-static crack growth shown by the dashed curve for comparison. Though the difference in scaling between the x- and y-axes tends to exaggerate the difference between the two transformation zone shapes, it is clear they are distinctly dissimilar. In view of the large differences in zone shapes, one should not be lulled into concluding that the value of toughening obtained via quasi-static crack growth will always be close to the steady-state value obtained from the present analysis. The differences in toughening values mentioned above may very well reflect the different shapes of the associated transformation zones.

In analogy with eqn (1) the crack growth law is formulated as

$$\frac{dc}{dN} = B\left(\frac{K^{tip}}{K_c}\right)^n \tag{2}$$

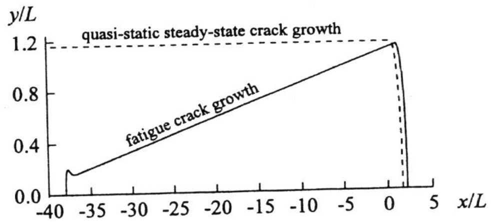

Figure 3: Transformation zone shape for $\omega = 10$, $\sigma_0 = 0.15$, and $c_0/L = 10$

where $K^{tip} = K^{appl} - K_s$ denotes the maximum stress intensity factor at the crack tip in a loading cycle, K_s representing the shielding effect due to transformation. Taking the logarithm of eqn (2) gives

$$\log \frac{K^{tip}}{K_c} = \frac{1}{n}\left(\log \frac{dc}{dN} - \log B\right) \quad (3)$$

where the logarithmic crack growth rate $\log(dc/dN)$ is seen to be linearly related to $\log(K^{tip}/K_c)$. When $\log(K^{tip}/K_c)$ is plotted against the applied stress intensity factor, results as shown in Fig. 4(a) are obtained. For $\omega = 10$ and 15 the initial crack growth rates quickly decline to a minimum but increase thereafter and follow the normal power law for long cracks. The initial drop in K^{tip} is a consequence of the peak shielding illustrated by the results in Fig. 2.

For $\omega = 20$, the initial decline is sufficient for the crack-tip stress intensity factor to drop to zero, which for this example happens at a crack growth increment of $\Delta c/L = 0.126$. The shift in the power-law region between the curves for $\omega = 10$ and 15 in Figs. 4(a) is due to different amounts of transformation toughening.

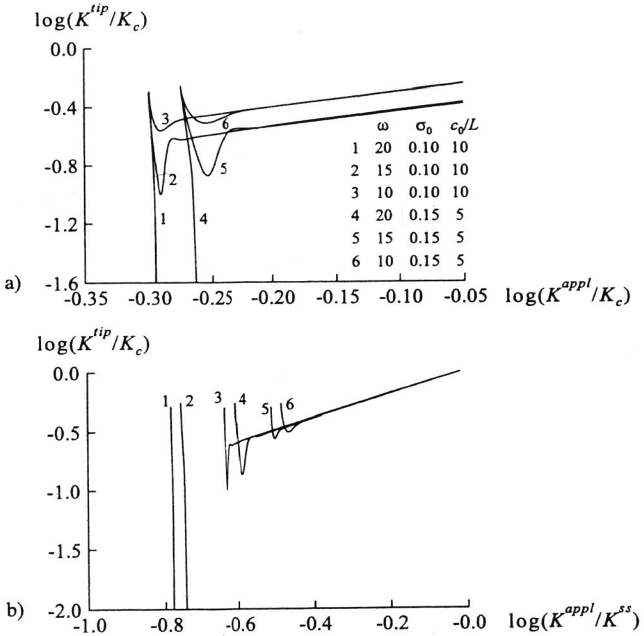

Figure 4: Fatigue crack growth rates against the applied stress intensity factor normalized by (a) intrinsic toughness and (b) steady-state toughness

The results for crack growth rates from Figs. 4(a) can be unified by normalizing the applied stress intensity factor by the steady-state toughening from quasi-static crack growth K^{ss}, rather than by the intrinsic toughness K_c. The normalized curves are shown in Fig. 4(b). The crack growth rate curves in Fig. 4(b) that reach the power-law region are simulated until unstable crack growth appears with $K^{tip} = K_c$. These curves fall within a very narrow band, thereby showing that replacement of the steady-state toughening from fatigue crack growth with values from quasi-static crack growth is a good approximation.

From the results presented above, it would appear that the power-law

$$\frac{dc}{dN} = C\left(\frac{K^{tip}}{K^{ss}}\right)^n \quad (4)$$

is valid for both the initially small and the subsequently long crack stages of fatigue crack growth in transformation toughening ceramics.

CRACK ARREST AND IMPROVED ENDURANCE LIMIT BY OVERLOADING

In the results discussed above the possibility of crack arrest at limited crack growth was exemplified in Fig. 4 for $\omega = 20$. A more detailed investigation of this phenomenon was given in Møller and Karihaloo (1995). In the sequel the enhancement of crack arrest by overloading is studied, as well as its influence upon the endurance limit (see Møller et al. 1996).

The effective stress intensity factor at the crack tip is plotted in Fig. 5 as a function of crack advance for different normalized applied stresses and fixed values of $\omega = 15$ and normalized initial crack length, $c_0/L = 5$. All the curves generally follow the same pattern at different levels of K^{tip} depending on the applied load. Initially, there is a drop in K^{tip}, as the shielding increases due to the formation of a transformation zone in the wake of the crack tip. At a finite crack advance, K^{tip} reaches a minimum and a monotonic increase in K^{appl} overrides the increasing shielding. For a sufficiently high transformation strength ω, K^{tip} will drop to zero before the minimum is reached and thereby cause crack arrest. For

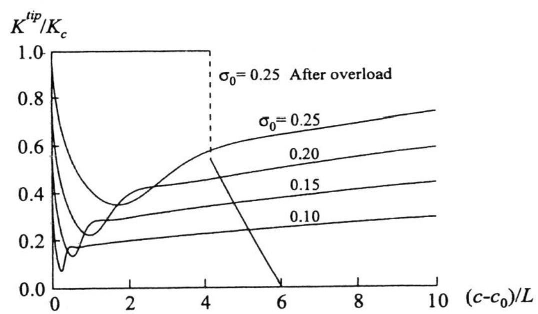

Figure 5: Effective stress intensity factor as a function of crack advance for a single surface crack with $\omega = 15$, $c_0/L = 5$ and $\sigma_0 = 0.10, 0.15, 0.20, 0.25$, and $\sigma_0 = 0.25$ after an initial overload at $\sigma_0^o = 0.3455$

$\omega = 15$ however, after the minimum, a monotonically increasing K^{tip} eventually leads to failure, as K^{tip}/K_c reaches unity at a finite crack advance. This is qualitatively consistent with the known R-curve behaviour.

The above curves are compared with the curve for an identical crack which is initially overloaded to $\sigma_0^o = 0.3455$, which is equal to the ultimate strength of this composition, before being loaded at the constant value $\sigma_0 = 0.25$. The crack is grown as in an R-curve analysis under an overload (i.e. it is allowed to grow quasi-statically under monotonically increasing load while K^{tip}/K_c is maintained at unity, see Andraesen and Karihaloo, 1994). Subsequently the load is lowered to $\sigma_0 = 0.25$ to simulate fatigue crack growth. The overload has a significant effect on the behaviour of K^{tip} after the load has been reduced leading to a quick arrest of the crack; without the overload K^{tip} would only experience a small drop at the load level $\sigma_0 = 0.25$ and the crack would eventually lead to failure.

The beneficial effect of an initial overload is well-known from metals, e.g. in the proof testing of high pressure vessels. In transformation toughened ceramics the effect can be theoretically explained by the development of the transformation zone. The initial overload causes crack advance and formation of a large transformation zone wake. During the subsequent low level fatigue loading the crack merely grows into the initial zone without any additional transformation zone being formed in front of it. In this way, there is an overall increase in the amount of transformed material behind the crack tip. Since it is the transformation zone in the wake that provides the bulk of the shielding (i.e. a decrease in K^{tip}), whereas the transformation zone in front of the crack tip has the opposite effect, the overload generally improves the fatigue behaviour of a transformation toughened material.

For a given overload level σ_0^o, only TTC components containing cracks smaller than a certain length, c_0^s would survive the overload. This corresponds to a conventional proof test for screening out components not capable of sustaining the proof load.

An analysis of shorter cracks with the same transformation strength and subjected to the same overload surprisingly showed (Fig. 6) a decreasing endurance limit with decreasing initial crack length. The longest critical crack in a proof test is therefore not the worst case crack length in the post-overload fatigue crack growth. However, the endurance limit approaches a minimum value asymptotically as the crack length decreases. The minimum value is reached (to within the numerical accuracy) for an initial crack length $c_0/L \approx 2$

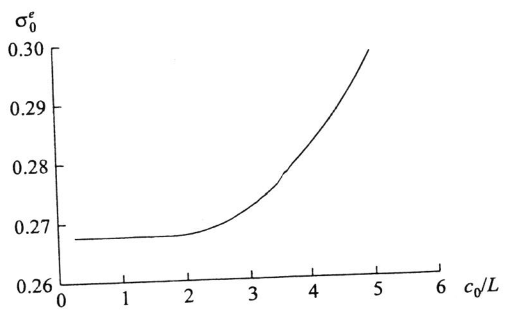

Figure 6: Endurance limit as a function initial crack length with $\omega = 15$ and $\sigma_0^o = 0.3455$

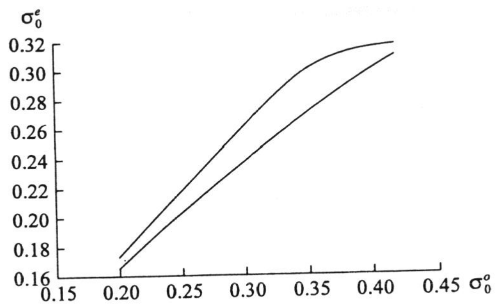

Figure 7: Minimum and maximum endurance limits as a function of overload level with $\omega = 15$

which did not grow during overloading. It should also be noted that crack arrest for $\omega = 15$ is not possible without overload, irrespective of the initial crack length and applied load. The proof test could therefore play an important role in the improvement of the fatigue performance of TTC, especially of ceramics with low transformation strength.

Figure 7 shows the normalized minimum and maximum endurance limits as a function of the applied overload level for $\omega = 15$. The minimum limit is of course the most relevant from a practical point of view, if the crack size distribution is not known. Both limits increase monotonically with the applied overload level.

The maximum achievable endurance limit is bounded by the maximum value of σ_0^o that can be allowed without causing global transformation in the component (i.e. the applied mean stress equals the critical mean stress for transformation, $\sigma_0^o = \sigma_m^c$). For instance, the critical mean stress is reached globally when $\sigma_0^o = 0.433$ for a TTC with $\nu = 0.3$.

The minimum endurance limit is plotted in Fig. 8 as a function of the applied overload

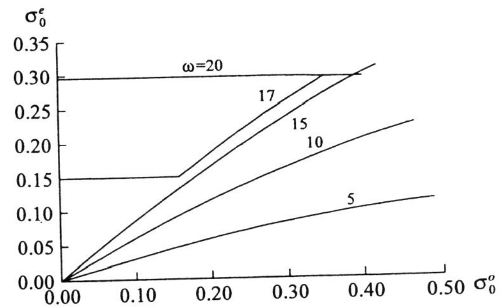

Figure 8: Minimum endurance limit as a function of overload, for $\omega = 5, 10, 15, 17, 20$

for different values of ω. The curves for $\omega = 5, 10$ follow the same pattern as for $\omega = 15$ in Fig. 7. In the range $\omega = 15.5 - 19.5$, there exists a lower bound on the overload level below which crack arrest occurs without any overload, as for $\omega = 17$ in the figure. For higher values of ω no significant change in the endurance limit due to initial overloads is detected.

If the transformation strength is known, a proof test can be designed from the above results to achieve a prescribed endurance limit. The statistical crack size distribution however dictates how many or how few components will survive the proof test. It has been shown above how initial overloads can be exploited to improve the endurance limit of transformation toughened ceramics. Most importantly, it was demonstrated that an overload will facilitate crack arrest in a low transformation strength material which would otherwise be prone to cyclic fatigue degradation and eventual failure.

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