EFFECTS OF NON-UNIFORM STRESS FIELDS ON FATIGUE CRACK GROWTH IN ZIRCONIA-CERIA ALLOYS

D.C. Cardona*, P. Bowen* and C.J. Beevers*

The growth of short and long cracks under cyclic loading has been studied in zirconia-ceria alloys. Short cracks grow at much lower stress intensity ranges than long through thickness cracks. This behaviour has been modelled by the use of an assumed residual stress distribution, and it would appear that crack growth resistance is controlled by the thickness of the transformation bands.

INTRODUCTION

Much effort has been directed recently to the study of potential toughening mechanisms in brittle solids. Several origins of non-linear behaviour in monolithic ceramics and composites have been identified Ruhle and Evans (1), and a consequence of such behaviour is the possibility of stable crack growth under monotonic and cyclic loading. Indeed, in general terms, there should be greater potential to identify subtle toughening phenomena more clearly under cyclic loading conditions where crack advance is inherently less catastrophic than under incremental monotonic loading. This paper considers the growth of fatigue cracks in uniform and non-uniform stress fields in partially stabilised zirconia (PSZ) containing 12 wt.% ceria. Previous papers Cardona and Beevers (2,3) have demonstrated both short and long fatigue crack behaviour in this material. In particular, the growth of self-initiated and short cracks has been studied and the influence of pores and transformation bands on crack paths observed. Short cracks have been shown to propagate at much lower stress intensities than long cracks and these observations are discussed in more detail.

* School of Metallurgy and Materials/IRC in Materials for High Performance Applications, University of Birmingham.

EXPERIMENTAL

The material used in this study was a partially stabilised zirconia containing 12 wt.% ceria produced by sintering homogeneously mixed sub-micron powders at 1500°C. This resulted in sintered compacts of 98.6% theoretical density, a grain size of 3.8 μm and greater than 90% tetragonal phase (less than 10% monoclinic phase). Bend testpieces were cut from the sintered discs using a diamond saw, ground and polished to 0.25 μm. Short or self-initiated crack growth studies were performed on testpieces of size 33 (length) by 13 (top-surface thickness) x 3 mm (width). To facilitate long crack growth, testpieces of size 50 x 5 x 10 mm were pre-notched to a depth of 1.5 mm (i.e. a/W = 0.15 mm) using a diamond wheel of 150 μm thickness. Pre-cracks were then introduced using reversed compression bending (details are given in Cardona and Beevers (3)), to a depth of between 40 and 320 μm.

In both short and long crack growth studies, bend tests were carried out using Amsler vibrophore electromagnetic resonant fatigue testing machines at 80 Hz and a mean stress ratio of 0.1. Three-point bending was utilised while for the latter studies pure bending was used. In all cases tests were performed under increasing stress-intensity conditions. Cellulose acetate replication techniques were used to monitor crack growth. The resolution of the technique is ±1 μm. The technique also allowed transformation bands to be observed and measured on the replicated surfaces. Maximum crack depths of 1200 μm ahead of the notch were observed in long crack studies, while maximum surface crack lengths of 310 μm were observed in the short crack work.

RESULTS

Mechanical Testing

Fatigue crack growth rate resistance curves are shown in Figure 1, for both short and long fatigue cracks. Despite some scatter it can be seen clearly that short cracks grow at much lower values of stress intensity range, ΔK. Load increases were required to maintain crack growth in all specimens as the crack depth increased. The stress intensity range shown for the short cracks corresponds to the surface position (the cracks appear to grow in a semi-circular manner Cardona (4) and therefore the values of ΔK at the surface will be larger than that at the depth position by a factor of 1.117). Crack replication has confirmed that the long cracks grow through thickness. Also shown in Figure 1 is the effect of an uniform residual compressive stress distribution of 350 MPa extending to a distance of 233 μm ahead of the notch root in the long crack studies. This distance is that over which local stresses ahead of the notch root alone exceed the stress for transformation (320 MPa) The effective ΔK has been calculated using point loading methods developed originally by Westergaard (5) and used recently Bowen and Knott (6) and is considered in detail elsewhere, Bowen, Cardona and Beevers (7). This value of residual stress approximates to the minimum rupture strength of the material, and therefore it is appropriate to consider reduced levels of compressive stress, Figure 2, where maximum values of applied stress intensity, K_{max} have been plotted versus distance of crack ahead of the notch.

In this region it is sensible to consider that the crack is growing within the stress field of the notch. Also shown in Figure 2 are the actual values of K_{max} calculated using finite geometry compliance tables for pure bending, for a crack length equal to the notch depth plus the fatigue crack depth. The point loading methods are rigorous for the case of a semi-infinite edge crack in tension (6) and therefore the solution for this case is also given in the Figure. Although the solutions given in this Figure are necessarily approximate, they suggest that the effect of including point loading of the crack with the stresses local to the notch cannot rationalise the results given in Figure 1, for crack depths of greater than 10 μm ahead of the notch root. Moreover, crack growth resistance curves measured for long pre-cracks of 320 μm produced in compression show no significant differences to those measured for smaller pre-cracks. Nevertheless, if the compressive residual stress fields used in Figure 2 can be justified from phase transformation dilatations, then this form provides an explanation for the retardation and arrest of cracks with increased crack size at least within the region local to the notch. It also suggests a way in which the short and long crack data could be rationalised if more potent residual stresses acted on the long crack.

Replication studies and optical measurements

Phase transformations were evident on smooth specimens at applied stresses of approximately 320 MPa. This was confirmed optically in all cases, but an indication of transformation was always heard audibly. Note that this transformation stress is close to the rupture strength of this condition. Optical micrographs of replicas are shown in Figure 3 and Figure 4 for the short and long cracks respectively. Note that the lengths and widths of the transformation zones can be measured, and in the case of the long crack (Figure 4) are uniform over much of the crack depth. The surface stress intensity range in Figure 3, is 4.1 MPam$^{1/2}$, with a length of transformation zone ahead of the crack tip of 65 μm, and maximum transformation thickness of approximately 14 μm. In Figure 4, the stress intensity range is 10.8 MPam$^{1/2}$, and both the length of the transformation band ahead of the crack tip and its thickness have increased to 664 μm and 176 μm. Replication studies at maximum and minimum loads have also demonstrated that conventional microstructural associated crack closure is not observed in general, except very close to the crack-tips.

DISCUSSION

From the combination of crack growth rate resistance curves, assumed residual stress distributions and replication studies, the mechanics of crack growth can be elucidated. The phase transformation appears to take place over a region where local stresses exceed 320 MPa. This is seen in plane testpieces, and can also be supported by a simple analysis ahead of the short crack, Figure 3. Using $K = \sigma(2\pi r)^{1/2}$ where r is the distance ahead of the crack tip, for an applied surface K_{max} = 4.56 MPam$^{1/2}$, local stresses ≥ 320 MPa are exceeded for 32 μm ahead of the crack-tip, in reasonable agreement with the experimentally observed value of 65 μm, further details are given elsewhere (7). In the long crack testpieces, the notch tip stress field introduces a benign residual stress distribution ahead of the growing crack-tip, such that a stress intensity range of much greater values, ≥8 $MPam^{1/2}$ is needed to overcome this stress field. As the crack grows, the high local stresses from the crack-tip field (≥ 320 MPa) encourage further phase transformations to occur (to greater distances than that defined originally by the notch root) and consequent increases in favourable compressive residual stresses result. Therefore increases in load are required additionally once more to promote growth in a step-wise manner. The mechanism is supported by the observed increase in transformation band thickness from 14 μm (ΔK = 4.11 $MPam^{1/2}$) to 176 μm (ΔK = 10.8 $MPam^{1/2}$). Transformation toughening modelling equations can be modified from the monotonic case (1) to predict an effective ΔK of 14.5 $MPam^{1/2}$ for the long crack data, from the observations of short crack behaviour (7). These predictions are in good qualitative agreement with the experimentally observed values, Figure 1, and provide a clear physical basis for the difference between short and long crack behaviour. Full details of this study are reported elsewhere (7). It would appear that there is little contribution to the increased crack growth resistance in the long crack case from either microcracking (which is often observed for this condition) or crack closure.

CONCLUSIONS

Short cracks in zirconia-12 wt.% ceria alloys under fatigue loading grow at much lower stress intensity ranges than long through-thickness cracks.

It would appear that crack growth resistance is controlled by the thickness of the transformation bands, and this has been modelled qualitatively by the use of residual stress distributions.

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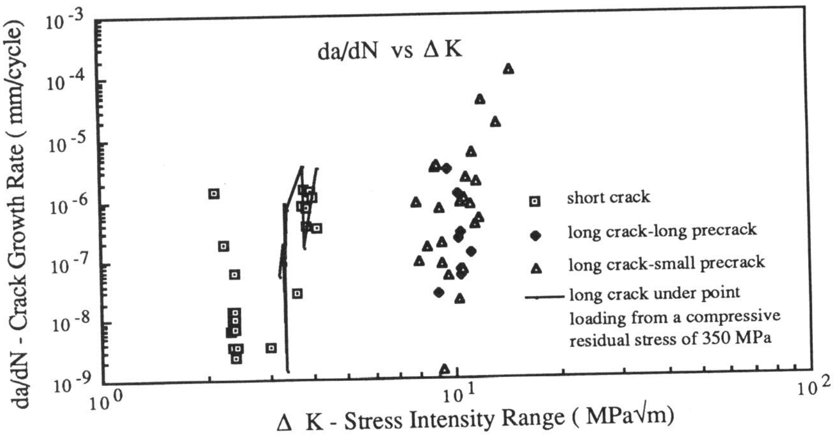

Figure 1 Fatigue crack growth rates versus stress intensity range

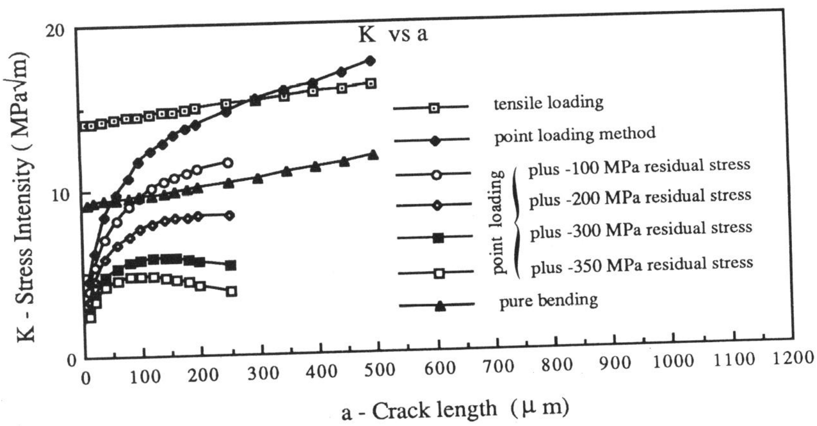

Figure 2 Stress intensity versus crack length ahead of the notch

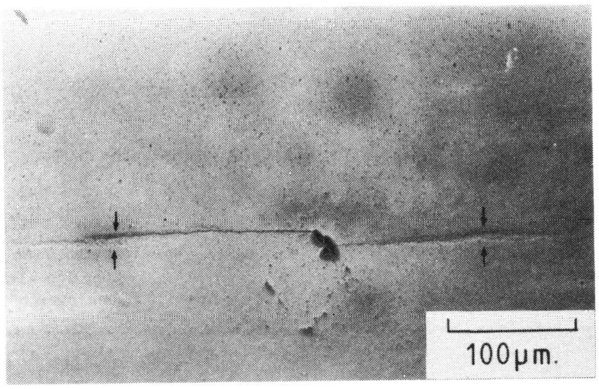

Figure 3 Short fatigue crack (the width of the transformation band is arrowed).

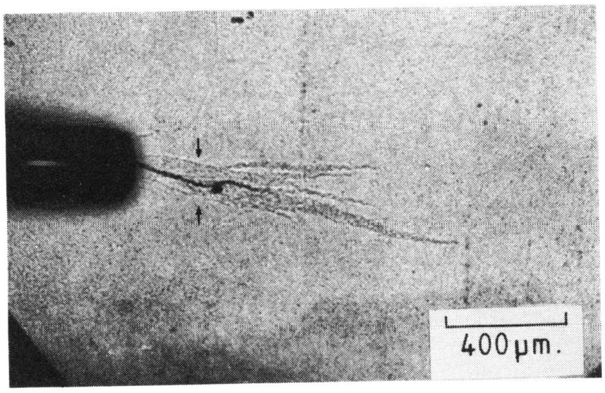

Figure 4 Long fatigue crack (the width of the transformation band is arrowed).