CRACK INITIATION UNDER COMPRESSION FATIGUE IN TOUGH CERAMICS

Jesús Solís, Carlos Lapetra and Jaime Domínguez *

A procedure for initiation of cracks by cyclic compression in ZrO_2 partially stabilized with Y_2O_3 is presented. Single edge-notched specimens were used. The antecedents and foundation of the method are described, particularly as regards the appearance of residual stresses in notch tips. The loads to be applied were calculated by numerical analysis of stresses in the vicinity of the notches. Results obtained by using various notch geometries and loading processes are reported.

INTRODUCTION

The engineering uses of ceramics have arisen growing interest in the last few years. However, extensive application of ceramics has so far been hindered by their fragility, which has been countered by the development of new, tougher ceramic materials (Evans and Heuer [1]).

Some of the new materials have been found to be vulnerable to cyclic loading. The most frequent failure in this context is caused by fatigue. Steffen et al. [4] found that the fatigue limit of smooth specimens of some tough ceramics is roughly equal to one-half their tensile strength. Cyclic loading may result in steady crack growth. Unlike in metals, crack growth in ceramics is of intergranular type. As with metals, the growth rate depends on the stress intensity factor, but the exponent of ΔK is usually much greater. Likewise, some materials have threshold stress levels ΔK_{TH} (roughly one-half of K_{IC}) below which no growth occurs. Cracks of microstructural dimensions may grow at ΔK values well below the threshold.

Crack growth rates are usually determined by using three or four-point bend configurations with pre-cracked notched specimens or, less

* Department of Mechanical Engineering, ETSII, University of Sevilla.

frequently, compact specimens. The dimensions of the initial crack should be larger than microstructural dimensions by at least one order of magnitude and large enough to ensure that the crack front is beyond the notch stress field.

Pre-cracking can be done in various ways. Occasionally, the notched specimen is subjected to cyclic loading to produce cyclic tensile stresses until a crack develops (Dauskardt and Ritchie [3]). As soon as the crack appears, loads are decreased so as to avoid failure. Then, growth is furthered until it surpasses the notch stress field by using appropriate loads. This method has one serious shortcoming: the fact that unstable growth starts before a crack is detected results in the development of abundant undesirable fractures.

One other procedure for crack generation was developed by Warren and Johannesson [4] and is known as the "bridge indentation" method. A smooth rectangular specimen, precraked at the centre of the top surface by means of diamond indentation, resting on the opposite surface, is loaded normally to this surface. It gives rise to stresses that result in longitudinal stress at the centre of the indented surface; this causes the crack to progress towards the resting surface. As the crack progresses, the tensile stresses with which the crack-tip meets decrease gradually and become compressive stresses or so small tensile that they fail to stop further crack increase. This method is being successfully applied in recent times.

Ewart and Suresh [5,6] developed a compression fatigue method that allows for more accurate control of the final pre-cracking length. It involves applying cyclic compression loads to a notched specimen so as to generate maximum stresses —even greater than the unconstrained compression fracture stress— at the edge of the notch. This gives rise to a crack that grows steadily from the root of the notch normally to the maximum principal stress. The crack grows in a residual tensile stress field and its growth rate decreases with increasing distance from the notch until it eventually stops.

In this work we analyse this procedure for compression fatigue initiation of cracks in the root of notches in polycrystalline ZrO_2 partially stabilized with 4% (mol) Y_2O_3 specimens.

COMPRESSION CRACK GROWTH

When compression stresses at the edge of the notch exceed the unrestricted fracture stress, the appearance of intergranular microcracks disrupts the linear behaviour in such a way that the slope of the stress-strain curve starts to diminish [6]. As the specimen is unloaded, the material recovers roughly linearly, yet the slope is greater than the secant modulus corresponding to the maximum compression stress. This gives rise to residual tensile stresses close to the notch root, the magnitude of which will depend on the above-mentioned slope, which in turn decreases with increasing distance from the edge.

The microcracks resulting from compression are under the influence of the residual tensile stress field during the unloading process, so they grow integranularly on application of a cyclic compression load. Such growth is steady as a result of the crystals through which it progresses acting as natural barriers. Changes in the orientation of the microcracks and the different residual stresses between grains, due to thermal contraction anisotropy, eventually bring each cycle to a standstill.

As the crack departs from the notch tip, the amount of microcracks resulting from loading and residual tensile stresses decrease. All this diminishes the growth rate until the process is eventually halted.

The crack front generates a relatively weak stress and strain field, hence damage to the material is also scarcely significant. Hence pre-cracked specimens can be used to determine toughness and in fatigue crack growth tests (Suresh et al. [7]; Davidson et al. [8]).

MATERIAL AND METHODS

Figure 1 shows the geometry of the specimens and the loading direction. We used 0.4 and 0.7 mm wide notches to determine the effect of this parameter and the stress level on the final crack length.

Notches were made by using 0.4 and 0.7 mm thick diamond discs, which provided nearly flat notch roots and rounded apices (Fig. 2). They were rounded in order to ensure that maximum stresses built up in the notch tips.

Tests were carried out on a push-pull servohydraulic testing machine that was controlled numerically. In order to avoid flexural defects due to misalignment or non-parallel surfaces, the compression load was applied by interposing two spherical-seated bearing blocks. The centre of their spherical surfaces was made to coincide with that of the specimen surfaces to within 0.05 mm.

The maximum nominal stresses applied to the different specimens were between 165 and 210 MPa, with a minimum to maximum stress ratio R = 10. The stress concentration factors of the notches were 31.3 and 25.4 for the specimens with 0.4 and 0.7 mm wide notches, respectively.

RESULTS AND DISCUSSION

We tested various specimens. The geometry of two of them (with 0.4 mm thick notches) departed somewhat from the other specimens (Fig. 2). The geometry of the notch roots was such that the maximum stress occurred in the arched zones rather than at the centre. Figure 2 also shows the changes in von Mises stresses at the central plane of the notches and at a plane tilted by 45°. Stated values correspond to the elastic solution.

No crack was observed in either specimen after 300,000 cycles involving a maximum nominal stress of 152 MPa and R = 10. Increasing the maximum stress to 175 MPa resulted in the simultaneous appearance of two cracks on both sides of the notch tip in the zones of maximum stress, as can be seen in Fig. 3, which shows the variation of the crack lengths across one side after the initial 300,000 cycles with no growth.

A compression load will cause any existing crack in the stress field of the notch to eventually close without relaxation of the stresses on the rest of the zone. Inasmuch as residual tensile stresses are of local nature, two cracks at a distance of the same order as the notch radius will not interact and the longer will not cause the shorter to unload. All this results in their growing independently of each other.

We also tested specimens with semicircular notch tips of 0.35 and 0.2 mm radii (three of each type), with a stress ratio R = 10. The 0.35 mm specimens were initially loaded with low stresses that were gradually increased after a reasonable number of cycles in order to control growth. Each specimen required a different stress level for cracks to develop —the differences were up to 20%. Likewise, the crack length at which growth stopped under a given load varied considerably from specimen to specimen, which can be ascribed to a random behaviour of the material, alignment differences and geometric randomness. This last factor is particularly affected by changes in the notch root shapes due to wear of the radius generating tool.

Crack growth was monitored more closely in the specimens with 0.2 mm notch radius by using cyclic loads of constant amplitude throughout the tests. Figure 4 shows the length changes in the cracks on both sides of the specimens, together with the maximum nominal stress of the cycles. As can be seen, the growth rate decreased as the cracks progressed to zones of smaller stresses. Also, the crack length varied from side to side —to a greater or lesser extent— in all instances. This can be ascribed to virtually the same reasons as before, viz. random growth, geometric differences between the notches on the two sides and load misalignment, which, however small, can have a significant effect.

CONCLUSIONS

This work is a first step to a reliable determination of fatigue features of tough ceramics by using pre-cracked specimens. The results obtained in its application allow us to draw the following conclusions:

— Bearing surfaces should be parallel and loads carefully aligned so as to ensure that cracks grow to simmilar lengths on both sides of the specimen. By using a smaller spherical-seated bearing block, moments resulting from a given centring error will also be smaller.

— Obtaining regular semicircular notches is mandatory; otherwise, high stress levels may result in the appearance of more than one crack.

— Inasmuch as the final crack must be long enough to ensure that its tip is beyond the influence of the notch, the geometry and load level to be used must be carefully selected.

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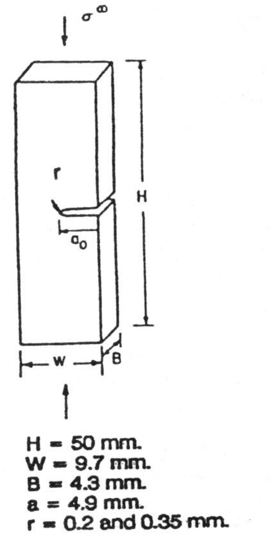

Figure 1 Geometry of the specimens used.

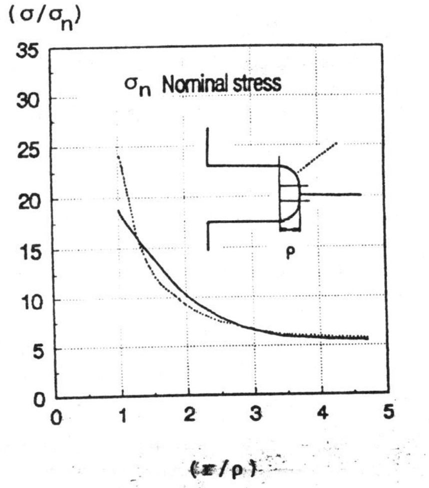

Figure 2 Stress distribution at notch edge.

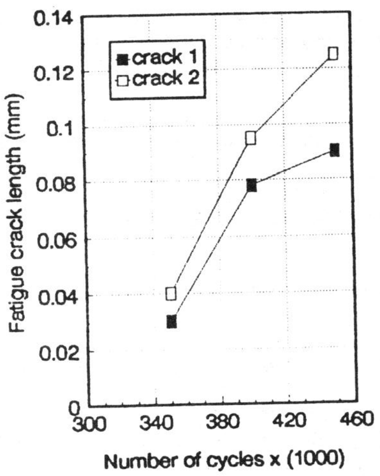

Figure 3 Growth of two cracks in one side.

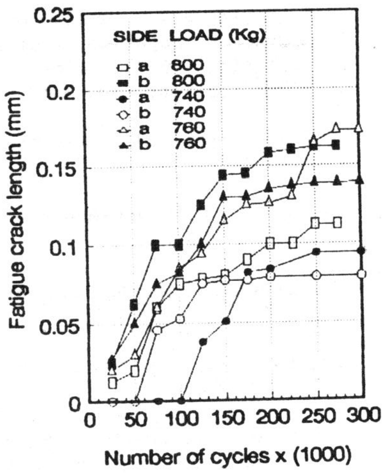

Figure 4 Crack growth in three specimens.