FATIGUE CRACK PROPAGATION IN ALUMINA UNDER CYCLIC COMPRESSIVE LOADS

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The influence of the load ratio and the peak compressive stress on the fatigue crack growth of notched plates of polycrystalline alumina under far field cyclic compressive loads has been studied. The rate of crack growth increases with the load ratio and with the peak compressive load. The fracture toughness of specimens pre-fatigued by cyclic compressive loads has been determined by three point bending. The values obtained by this method **are** smaller than those obtained in notched virgin specimens and by the Vickers indentation method. The results are discussed in terms of tensile residual stress fields created by the cyclic compressive loads at the tip of the notch.

INTRODUCTION

Mechanical fatigue effects in ceramics have not received the attention that one would expect from such a broad field of potential research. The reason is that in many ceramics there is the competing effect of static fatigue (stress corrosion) which is not always easily separated from intrinsecal mechanical fatigue effects produced by cyclic loads. On the other hand, the lack of significant plasticity at the crack tip, makes crack propagation not possible in these materials by the same mechanisms which operate for metals.

In the present work we have studied the behaviour of notched plates of polycrystalline alumina subjected to cyclic compressive loads. Suresh and co-workers (1-3) have shown that in this case mode I crack growth takes place either in vacuo or in a moist air environment.

Here, we shall concentrate on the effect of the load ratio and the peak compressive stress on crack growth. In addition, some of the pre-fatigued specimens were

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fractured by three point bending in order to obtain the fracture toughness.

EXPERIMENTAL PROCEDURE

The alumina studied was polycrystalline aluminium oxide of 99.5% purity supplied by Ceraten, Madrid, Spain. The main impurity content in weight % is given by: SiO_2, 0.164; Fe_2O_3, 0.051; TiO_2, 0.04; CaO, 0.036; MgO, 0.072; Na_2O, 0.133; K_2O, 0.026. The flexural strength at room temperature was 415 MPa and it was measured by four point bending (outer span, 40 mm, inner span, 20 mm) in specimens with dimensions 3x4x45 mm.

For the fatigue compression-compression tests, single edged notched specimens were machined with the following dimensions: 3x11x20 mm and also 3x6.5x20 mm in the case of the specimens which were subsequently fractured in three point bending (span 19 mm). A notch was produced by means of a diamond wheel with a depth of about 2 mm and a root radius of about 0.25 mm.

The fatigue tests were carried out in a servohydraulic fatigue testing machine by applying sinusoidal loads at a frequency between 10 and 30 Hz at room temperature. The specimens were loaded through compression platens with a spherical seat in order to obtain good alignment with the specimens surfaces. The extension of the fatigue crack from the notch root was monitored by means of a zoom stereo microscope.

In order to determine the fracture toughness, three different types of tests were performed. After pre-fatiguing under far field cyclic compressive-compressive stresses during about 50.000 cycles, the specimens were fractured by three point bending at room temperature under load control by increasing the load at a constant rate of 2.5 N/s. The results are compared with those obtained in specimens not subjected to cyclic compressive loads and with those obtained by the Vickers indentation method by using a maximum load of 100 N.

RESULTS AND DISCUSSION

A crack appeared at the root of the notch after a number of cycles under cyclic compressive-compressive stresses, at both specimen surfaces (Fig.1). Usually, the number of cycles to nucleate the crack and also its length at each specimen side surface was not the same. The crack extension plotted in Fig.2 corresponds only to that observed on the surface where the extension was larger.

The crack extension was very sensible to the maximum compressive stress for a constant load ratio of 8 (Fig.2). Thus, for σ_{min}= -500 MPa, the crack appeared during the first cycles and the specimen fractured after only 300 cycles. By contrast, for σ_{min} = -300 MPa, the crack could not be seen at the notch tip after some thousands of cycles and its progression was very slow and it stopped after about 10^6 cycles.

The influence of R on the crack extension is also revealed in Fig.1, where it can be noticed that in the case of σ_{min} = -500 MPa the crack extension for R=2 is much smaller than for R=8. In the case of σ_{min} =- 300 MPa and R=2 (not plotted in Fig.1), no crack was nucleated at the notch tip after $4x10^5$ cycles, while a crack was formed and propagated for R= 8 under the same peak compressive stress.

From the appearance of the fracture surfaces it was possible to differentiate that part caused by fatigue from that originated by quasi-static fracture. However, in the specimens fatigued at low compressive stresses and subsequently fractured by three point bending, no crack was detected at the side surfaces of the specimen, and also the fracture surfaces did not show clear evidence of significant crack extension by fatigue. The results obtained for the fracture toughness in three point bend specimens are shown in Table 1 by using the stress intensity factor proposed by Srawley (4) and the crack lengths were taken equal to the length of the notch plus the radius of the notch tip for the pre-fatigued specimens. On the other hand, the fracture toughness obtained by the Vickers indentation method was 3.2 MPa $m^{1/2}$ (average of 10 measurements). It can be noticed that the value of K_{Ic} in pre-fatigued specimens was always smaller than that obtained in virgin specimens.

The observations presented here are very similar to those reported by Ewart and Suresh (1) on fatigue crack

TABLE 1 - K_{Ic} obtained in three point bending in notched specimens pre-fatigued by cyclic compressive loads (*) and without pre-fatiguing.

Specimen	ACT-1*	ACT-2*	ACT-3*	ACT-4	ACT-5	ACT-6
K_{Ic}/MPa $m^{1/2}$	2.90	2.87	2.96	4.45	5.09	4.69

growth in notched plates of polycrystalline alumina of approximately the same purity and by Sabadell and Anglada (4) in alumina of 92% purity. As shown by Suresh and co-workers (1-3), the phenomenon of Mode I stable crack growth at the notch root under cyclic compressive stresses is formally similar to that which occurs in metals, although the underlying mechanisms are very different. A common characteristic feature to both class of materials is the existence of a local zone of damage in front of the notch root which is surrounded by material elastically strained in compression. In brittle materials, this zone is caused by microcracking mainly along grain boundaries. Brockenbrough and Suresh (2) have shown that large residual tensile stresses are induced in the vicinity of the notch tip when randomly oriented microcracks inside this zone do not close upon unloading from the maximum nominal compressive stress. This residual stress seems to be the principal driving force for Mode I crack growth in ceramics fatigued in cyclic compression. According to Ewart and Suresh (1), the early compression cycles cause appreciable damage in the form of microcracking at the root of the notch, but the coalescence of microcracks to form a macroscopic Mode I fatigue crack is normally achieved during many thousands of cycles. This model can also qualitatively explain the general trends of our results. The fact that crack extension increases with the amount of unloading is because higher tensile residual stresses may be produced as the stress increases to higher values (less negative) from the peak compression load applied in each cycle.

The presence of debris particles on the fatigue fracture surfaces should induce crack closure effects. This would explain the fact that fatigue crack growth decreases with the number of cycles. Evidence in favour of this interpretation is the observed increase in the fatigue crack extension when the specimens are cleaned by ultrasounds (1,4).

From a quantitative point of view, it is possible to compare our results with the predictions of a model recently proposed by Brockenbrough and Suresh (2). They used the results of Budiansky and O'Connell (5) for the loss in **stiffness** caused by randomly oriented penny shaped cracks. The unloading response of the brittle solid is governed by the density of microcracks which close upon unloading from the maximum compressive stress. The numerical calculation carried out showed that the tensile stress generated at the notch tip process zone exceeds the tensile fracture strength over a distance approximately equal to the length of crack extension observed. A result of this calculation is that the transition from compression to tensile stresses at the notch tip during unloading occurs at values that are about 25% of the more compressive stress. That is, in terms of R, no fatigue crack propagation should occur for values of R lower than 4. The fact that crack growth is observed for R=2 and σ_{min} =-500 MPa, seems to indicate that the onset of tensile residual stresses at the notch tip is not a linear function of the peak compressive stress.

The values of K_{Ic} obtained in the different specimens pre-fatigued by cyclic compressive loads are very consistent and are slightly smaller than those obtained by the Vickers indentation method, but significantly smaller than the values found in non-fatigued notched specimens. This seems to indicate that pre-fatiguing by cyclic compressive loads may be used as a new technique for the determination of K_{Ic} as suggested by Suresh et al (7). The reason for the small values encountered may be caused by the tensile residual stresses created by the cyclic loads.

ACKNOWLEDGEMENT

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REFERENCES

(1) L. Ewart and S. Suresh, J. Mater. Sci. **22** (1987) 1173.

(2) J. R. Brockenbrough and S. Suresh, J. Mech. Phys. Solids, **35** (1987) 721.

(3) S. Suresh and J. R. Brockenbrough, Acta Metall., **36** (1988) 1455.

(4) J. E. Srawley, Int. J. Fract., **12** (1976) 475.

(5) J.M. Sabadell and M. Anglada, J. Mater. Sci. Lett., in print.

(6) B. Budiansky and J. O'Connell, Int. J. Solids Struct., **12** (1976) 81.

(7) S. Suresh, L. Ewart, M. Maden, W.S. Slaughter and M. Nguyen, J. Mater. Sci. **22** (1987) 1271.

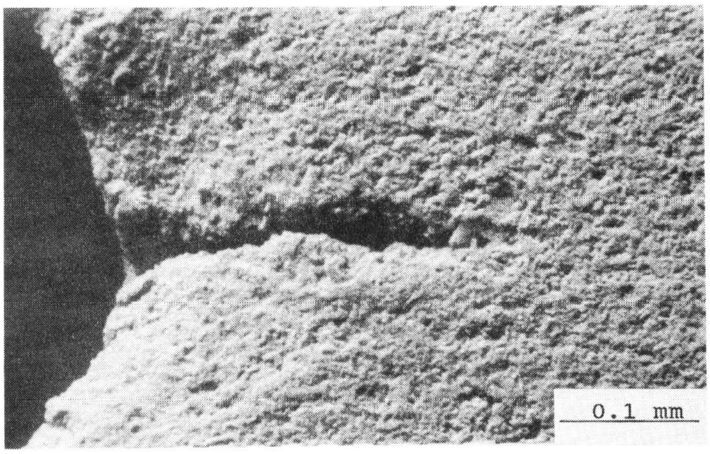

Figure 1 Fatigue crack at the tip of the notch.

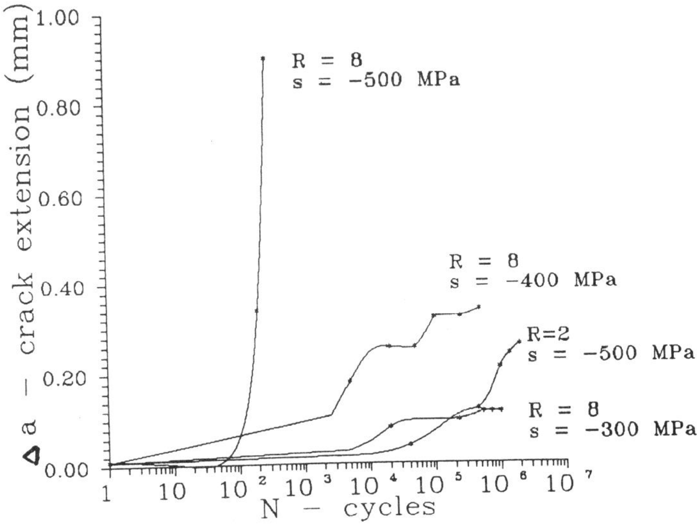

Figure 2 Crack extension as a function of the number of cycles for different peak compression stresses and load ratios.