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Abstract

Due to a coarse grain structure, crack lengths in precracked spinel specimens could not be measured optically, so the crack lengths and fracture toughness were estimated by strain gage measurements. An expression was developed via finite element analysis to correlate the measured strain with crack length in four-point flexure. The fracture toughness estimated by the strain gaged samples and another standardized method were in agreement.

Introduction

Three techniques for measuring the fracture toughness of ceramics were standardized by the American Society for Testing and Materials (ASTM) (Refs. 1 to 3): the chevron-notched beam (VB), the single edged precracked beam (SEPB), and the surface crack in flexure. One issue concerning the techniques is the measurement of crack length, which has been identified as a major source of error in fatigue and fracture testing of metallic materials (Ref. 4). In ceramics, crack length measurement can be particularly difficult for a number of reasons: the small specimens typically used; the semi-opaque nature of many glass-based ceramics; the lack of plastic deformation at the crack tip which results in poor definition of the crack front; and high elastic modulus and low fracture toughness that result in small crack opening displacements. Ceramics with coarse grain structure, such as ZnSe, alumina and $MgAlO_4$ (spinel), present an additional difficulty because the crack front is difficult to delineate from the grain boundaries.

A simple and sensitive technique that can be used to estimate crack length and extension in SEPB specimens is the back-face strain gage (BFSG), as illustrated in Figure 1. BFS was previously used with metallic compact-tension specimens (Ref. 5), and in fine gain, opaque ceramics (Ref. 6). An additional benefit of strain gaging specimens is the ability to easily monitor the stability of the test, which is a requirement for the chevron-notch method.

This communication illustrates how BFS was employed to measure crack length and fracture toughness in a transparent, coarse grain spinel.

Finite Element Analysis

A two dimensional, plane strain finite element analysis (FEA) was performed to determine the BFS as a function of normalized crack length (a/W) for the four-point flexure specimen. The FEA results from several specimen heights were combined by writing the BFS as:

$$\varepsilon_{BF} = \varepsilon_N \frac{P(S_o - S_i)}{EBW^2} \tag{1}$$

where P is the applied force, S_i and S_o are the inner and outer spans, E is the elastic modulus, B is the thickness, W is the height, a is the crack length, and ε_N is the normalized strain taken as a function of normalized crack length. The normalized crack length as a function of absolute normalized BFS as determined from the FEA is shown in Figure 2. For $a/W = 0$, $\varepsilon_N = 3/2$, which corresponds to that of an uncrack beam. The BFS is more sensitive to crack length changes for normalized lengths greater than $a/W = 0.3$.
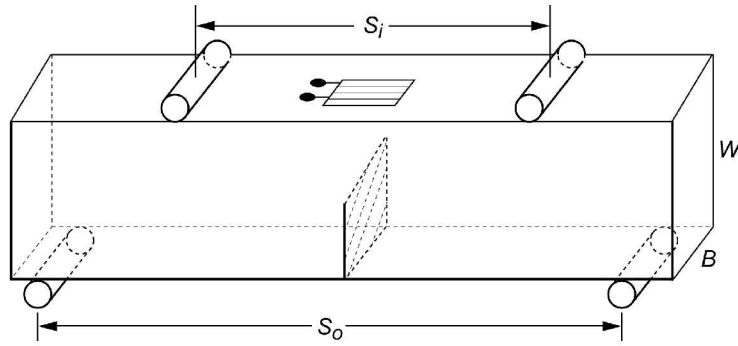
Figure 1.—Strain gage mounted on the back-face of a four-point flexure specimen.
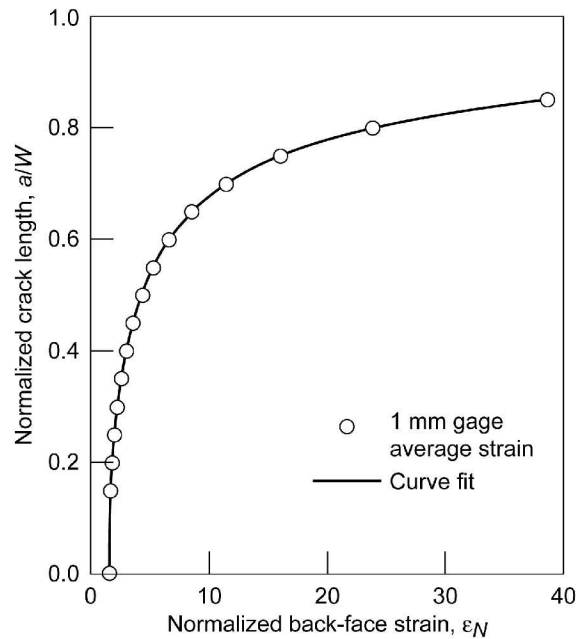

Figure 2.—Normalized crack length as a function of the absolute value of normalized back-face strain.

The FEA BFS results were fit via least squares regression:

$$a/W = \frac{-0.0732199 + 0.7643304 Ln|\varepsilon_N| - 1.4386992\left(Ln|\varepsilon_N|\right)^2}{1 - 2.1294083 Ln|\varepsilon_N| - 0.8732785\left(Ln|\varepsilon_N|\right)^2 - 0.0197908\left(Ln|\varepsilon_N|\right)^3} \quad (2)$$

with the strain taken in absolute terms. Equation (2) resulted in correlation better than $r^2 = 0.999$.

Equation (2) requires knowledge of ε_N to determine a/W. This can be estimated from the compliance observed (ε/P) prior to stable crack extension, as shown in Figure 3. Then the mode I stress intensity factor at any point during the test can be estimated from Equation (3), where $F(a/W)$ is the appropriate stress intensity factor coefficient (Ref. 3):

$$K_I = \frac{P(S_o - S_i)}{BW^{3/2}} F(a/W). \quad (3)$$

For fracture toughness measurements (K_{Ipb}), the maximum load observed and the initial crack length are employed in Equation (3).
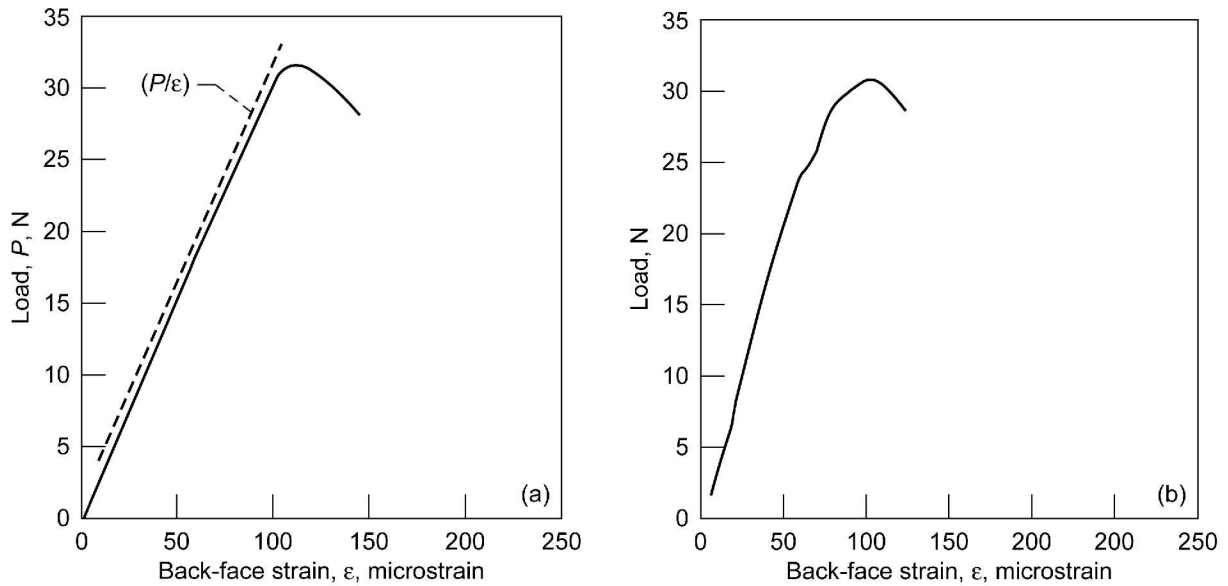
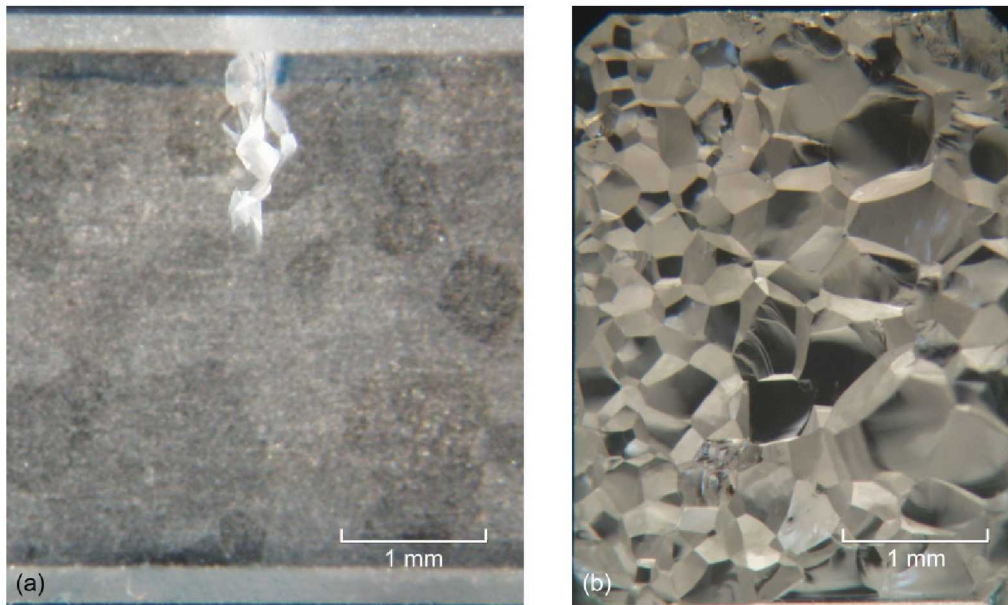Figure 3.—Load as a function of BFS for spinel. (a) SEPB specimen. (b) VB specimen.

Figure 4.—(a) Precracked spinel specimen. (b) Post-fracture surface.

Experimental Application

During recent testing of a transparent spinel ($MgAlO_4$), crack length could not be measured to the operational requirements of ASTM C1421. The coarse structure and poor crack front definition, even with indicial illumination, can be seen in Figure 4. Thus BFS was employed to estimate the effective crack length and thereby estimate the fracture toughness K_{Ipb}.

Precracking of 3.0 by 4.0 mm^2 cross-sections was performed using a 4 mm bridge span with three, 5 kg Vickers indentations. A 1 mm strain gage was employed, and the precracked beams loaded between 20 and 40 mm spans at a rate of 0.2 mm/min in air or dry nitrogen. Chevron-notched tests were also conducted using the same spans and a 1 mm strain gage. Example P-BFS curves are shown in Figure 3

for SEPB and VB tests, and the results are summarized in Table 1. Good agreement occurs between the techniques. The elastic constants in Table 1 were determined in accordance with ASTM C1259 (Ref. 7).

TABLE 1.—FRACTURE TOUGHNESS AND ELASTIC CONSTANTS

	Fracture toughness ($MPa\sqrt{m}$)		Poisson's ratio, v	Elastic modulus, E (GPa)
Configuration	Air (75°F, ~60% RH)	Dry N_2		
SEPB	1.32 ±0.05	1.52 ± 0.07	0.26	265 ± 4
VB	1.48 ± 0.14	1.58 ± 0.08		

Conclusion

Back-face strain is a simple, inexpensive method for monitoring crack length in ceramic flexure specimens when the usual optical techniques are inadequate. The fracture toughness of a transparent spinel, as measured with BFS applied to the SEPB specimen, was comparable to that measured using the chevron-notch in flexure. Monitoring BFS in chevron-notched specimens is also very useful, as the stability is clearly determined.

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