Journal of the European Ceramic Society **16** (1996) 1021–1025

S0955-2219(96)00021-0
0955-2219/96/$15.00

Controlled Crack Growth in Ceramics: The DCB Specimen Loaded with Pure Moments

Bent F. Sørensen,[a] Philippe Brethe[b] & Peder Skov-Hansen[a]

[a]Materials Department, Risø National Laboratory, DK-4000 Roskilde, Denmark
[b]Ecole Nationale Supériere de Céramique Industrielle, Limoges, France

(Received 3 November 1995; revised version received 13 December 1995; accepted 3 January 1996)

Abstract

The energy release rate of a double cantilever beam (DCB) loaded with pure bending moments is independent of crack length, allowing stable crack growth in even truly brittle materials. The method is thus suitable for measuring fracture toughness and R*-curve behaviour of ceramics. This paper describes the development of a new test configuration and reports the testing results from two ceramics: one with constant fracture toughness and one possessing* R*-curve behaviour due to phase transformation. Stable crack growth was obtained for both materials. © 1996 Elsevier Science Limited.*

1 Introduction

Generally, the fracture toughness of technical ceramics is low. This limits the number of applications in which ceramics can be used. In order to enhance the fracture toughness, energy-absorbing mechanisms must be built into the microstructure. Typically, the effect of the toughening mechanism increases as the crack grows, leading to rising crack growth resistance (*R*-curve behaviour). In parallel with the development of tougher ceramics, it is equally important to develop experimental methods that allow controlled (stable) crack growth, such that the *R*-curve behaviour can be properly measured.

Many of the fracture mechanics tests methods that work well for metals are not suited for controlled crack growth in ceramics because the test configurations are unstable in nature; i.e. for a fixed external load, the energy release rate $\mathcal{G}$ increases with crack length. Then, controlled crack growth is only possible when the tests are performed on servo-hydraulic test machines controlled by the crack opening displacement (feedback from a clip-on extensometer), such that the specimen is rapidly unloaded as soon as crack growth takes place. It is difficult to perform such experiments in ceramic.[1] Typically, it is only possible to control the crack growth for a few millimetres before the crack extends unstably.[2]

Chevron-notched specimens give stable crack growth,[3] but cannot be used for characterizing *R*-curve behaviour since the crack extension varies along the crack front (in order to be able to measure *R*-curve behaviour properly, the crack front should be straight, such that the full crack width experiences the same state of toughening). It is possible to obtain controlled crack growth of straight through the thickness cracks in ceramics by controlling the crack opening displacement utilizing the Poisson's effect of a rod loaded in compression.[4] The calculation of $\mathcal{G}$, however, is sensitive to the accuracy with which the Poisson's ratio of the rod is known, and $\mathcal{G}$ depends on the crack length. Stable crack growth can also be obtained by compressing a square specimen with a circular hole in the centre.[5] However, machining a pre-crack from the circular hole is quite difficult. Also, the energy release rate depends on the stiffness of the support areas and varies with crack length. Another method utilizes torsion moments on a double cantilever beam (DCB) specimen.[6] For this method the energy release rate is independent of crack length. However, the crack front is not straight through the width. Therefore the measured resistance may, at least in the initial stages of crack extension, represent an averaged value. After completion of this work we discovered an older paper by Freiman *et al.*,[7] which describes a loading arrangement for loading a DCB specimen with pure bending moments. This method also gives an energy release rate that is independent of crack length. The moments were applied by forces acting through wires at external beams bonded perpendicular to the DCB arms. However, if rigid supports are used[8] instead of the wire arrangement,[7] then the external beams slide over the support points as the DCB specimen opens, so that the test becomes sensitive to friction.

In this paper a novel arrangement is proposed for loading a DCB specimen with pure bending

moments. Using a special fixture which moves with the beams of the DCB, the problems of bonding are avoided. The bending moments are created by loading the DCB specimen by compressive forces. The potential of the method is demonstrated by the characterization of two ceramics: one with and one without R-curve behaviour.

2 Analysis of Test Configuration

2.1 Conditions for stable crack growth

A material's resistance to crack growth $\mathcal{R}$ may increase during crack extension, i.e. $\mathcal{R} = \mathcal{R}(\Delta a)$, where Δa is the crack extension. Denoting the decrease in the potential energy (per unit width of the specimen) of the system by $\mathcal{G}$ (the energy release rate), the Griffith criterion for crack growth can be formulated as follows. Crack growth takes place when the decrease in the potential energy during an incremental crack growth equals or exceeds the energy consumed in the fracture process: $\mathcal{G} \geq \mathcal{R}$. Crack growth is stable if $d\mathcal{G}/da < d\mathcal{R}/da$ and unstable if $d\mathcal{G}/da > d\mathcal{R}/da$.

2.2 Fracture mechanics analysis of the DCB loaded with pure moments

The DCB specimen consists of two slender beams each with the thickness H and width B. The crack growth takes place in the mid-plane between the beams, such that the crack growth is in pure mode I. Each beam end is loaded with a bending moment M [Fig. 1(a)]. The plane strain energy release rate can be found by taking the J-integral[9] along the boundaries of the specimen, giving

$$\mathcal{G} = 12(1 - \nu^2)\frac{M^2}{EB^2H^3} \tag{1}$$

where E and ν denote Young's modulus and Poisson's ratio. Since $\mathcal{G}$ is independent of the crack length a, it follows that $\partial\mathcal{G}/\partial a = 0$ (constant moment). If

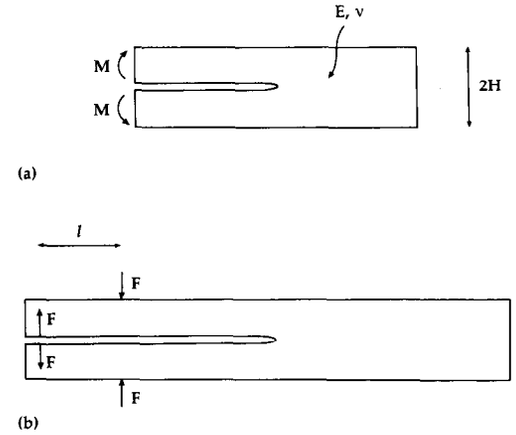

Fig. 1. The geometry and loading of the DCB: (a) loaded by pure bending moments; (b) loaded with compressive forces creating pure moments in the inner parts of the beams.

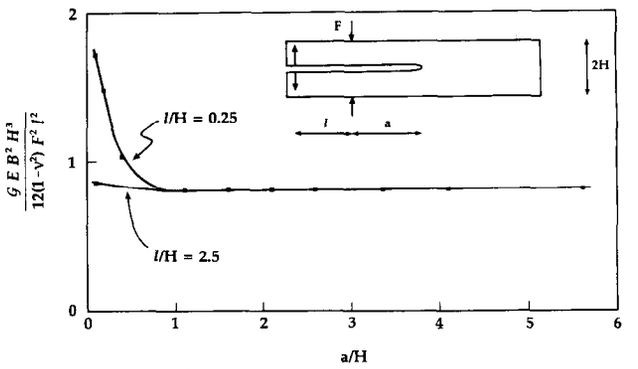

Fig. 2. The computed value of the energy release rate (normalized by the value calculated by simple beam theory) as a function of the distance a from loading point B to the crack tip. $\mathcal{G}$ approaches a constant value for $a/H \geq 1$.

the test is performed in displacement control then $d\mathcal{G}/da = \partial\mathcal{G}/\partial a$ (constant rotation) < 0, such that crack growth is stable even in materials with constant fracture toughness $d\mathcal{R}/da = 0$. This is the prime advantage of the DCB loaded with pure moments.

In our design the bending moments are created by applying two compressive forces, separated by a distance l, to each beam [Fig. 1(b)] such that the moment is

$$M = Fl \tag{2}$$

where F is the magnitude of the force. In order to assess how far away the forces should be from the crack tip, the stress distribution of the specimen was analysed using the finite element method (FEM).[10] A typical mesh consisted of 1698 eight-noded, isoparametric, plane strain elements and 5321 nodes. Singular elements were used at the crack tip. The energy release rate, calculated by a virtual crack extension technique, is shown in Fig. 2 as a function of the distance a from the crack tip to the nearest loading point for two different moment arms ($l/H = 0{\cdot}25$ and $l/H = 2{\cdot}5$). It is seen that $\mathcal{G}$ is essentially independent of a for $l/H = 2{\cdot}5$. For $l/H = 0{\cdot}25$, the steady-state value of $\mathcal{G}$ is attained when $a/H \geq 1$. For small values of a/H and l/H the stress field from the forces acting at the crack face is directly affecting the stress field near the crack tip. Therefore, $l/H = 2{\cdot}5$ was chosen in the current design.

3 Experimental Method

3.1 Practical design of test specimen

For practical reasons, modifications are required to the idealized specimen geometry. A slot must be introduced at the inner part of the beam ends to give room for the brads. Also, a side groove must be introduced in order to guide the direction of the crack. Grooves can be made to both sides of the specimen to ensure symmetrical deformation.

3.2 Description of fixture

In order to apply the moments to the beams without inducing wedging forces or friction, a fixture utilizing a wire and rollers was developed (Fig. 3). The wire runs via two transverse rollers, mounted at the top and bottom grips of a standard tensile machine such that the forces in the wire at the front and rear sides of the fixture are identical. If the friction from the rollers is neglected and the gravity forces on the fixture are small (the weight of each fixture part is 570 g), then the force in the wire has the same magnitude everywhere, and it follows that each beam is loaded with a pure moment

$$M = P(2R + d) \tag{3}$$

where P is the applied force, R is the radius of the rollers and d is the horizontal distance between the centre of the rollers (Fig. 3). The moment is transferred to the specimen by two brads (separated by the distance l), welded to the fixture. Note that the specimen and fixture parts are free to move up and down without inducing any forces in the wires; only a rotation does. The uncracked end is supported from the sides and the bottom (snug fit only), in order to ensure that the specimen does not rotate (e.g. due to gravity forces).

3.3 Test procedure

The experiment should be performed under displacement control (i.e. under a constant crosshead speed) to obtain stable crack growth. An extensometer can be mounted at the end of the specimen (point A, Fig. 3) to detect crack growth. Acoustic emission can also be used for detecting crack growth. The crack length is recorded prior to loading. The load P is increased until crack growth is detected, whereafter the specimen is unloaded, and the new crack length is measured. Then the load can be increased again until further crack growth has taken place, etc. The load at the onset of crack growth can be converted into a moment M [eqn (3)] and the critical energy release rate $\mathcal{G}_{Ic}$ can be calculated from eqn (1). The crack growth resistance can then be calculated from

$$\mathcal{R}(\Delta a) = \mathcal{G}_{Ic}(\Delta a)\frac{B}{b} \tag{4}$$

where b is the remaining ligament of side-grooved specimens (i.e. the beam width B minus the side groove depth), since the changes in strain energy occur over the full width B, while fracture energy is only consumed over the width b.

The crack extension Δa can be measured by several means. A face of the specimen can be polished, allowing the crack length to be measured by optical microscopy. The crack is easy to see, if it is coloured by a penetrating ink. Alternatively, a surface replica can be taken and the crack extension can be determined later. This is a precise and efficient method. These two methods rely on the crack extension at the surface. A third method is to determine the crack length by means of the changes in specimen compliance: the end-opening of the specimen (two times the deflection of a single beam) can be found from simple beam theory to be (plane strain)

$$\delta_A = 4(1 - \nu^2)\frac{2R + d}{B}\frac{P}{EH^3}(3a^2 + 2l^2 + 6la) \tag{5}$$

where l is the horizontal distance between the loading points A and B (see Fig. 3), and a is the crack length (the horizontal distance from B to the crack tip).

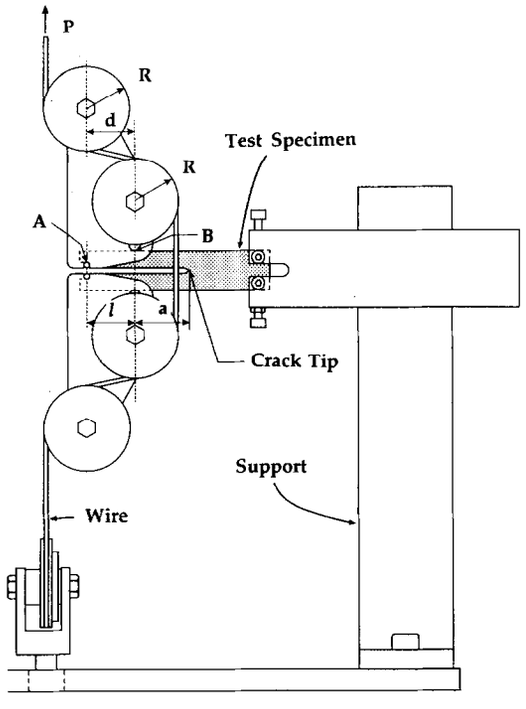

Fig. 3. Schematic illustration of the loading fixture.

4 Example of Stable Crack Growth in Ceramics

4.1 Processing of ceramics

CeO_2-stabilized ZrO_2 ceramics that may experience R-curve behaviour due to phase transformation (tetragonal to monoclinic crystal phase) were studied. Powders from two different companies (TZ-12CE from Tosoh Co., Japan and Z-65 from Ceramatec, USA) were used. The test specimens were made by slip casting. After pre-sintering (1 h at 1000°C), the slots for the brads, the side groove and a 1 mm thick notch were cut. A 0·1 mm thin slit (approximately 3 mm in length) was made at the end of the crack by a new razor blade. The specimens were sintered at 1500°C for 2 h. The linear shrinkage was nearly 20%. The specimens were nominally 100 mm long, with B = 5 mm, b = 2·5 mm and

H = 10 mm. The average grain size of both materials was approximately 2 μm.

4.2 Testing and results

Prior to the fracture mechanics testing, the elastic properties were determined by strain-gauge measurements on four beams loaded in four-point bending. This gave E = 187 GPa and ν = 0·30.

The fracture mechanics experiments were conducted using an Instron 1115 spindle-driven test machine at a constant crosshead speed of 0·2 mm min^{-1}. Acoustic emission (Spartan AT, Physical Acoustic Corporation) was used to monitor crack growth. Replicas (Struers Transcopy) were used to document crack extension. To start the measurements from a truly sharp crack, each specimen was pre-cracked in the following manner. The specimen was inserted in the fixture, and loaded until crack growth was detected. Then the specimen was unloaded and annealed at 1000°C for 30 min to reverse the transformation that might have occurred in connection with the crack initiation.[2] The specimens were tested in the procedure described above.

The measured crack growth resistance for typical specimens is shown in Fig. 4. For the Tosoh ceramic the R-curve is essentially flat (constant fracture toughness). The R-curve behaviour of the Ceramatec ceramic is much more pronounced. The full R-curve of this material has, as far as we are aware, not been measured before. The initial part of the R-curve has been measured by single-edge-notch-bend specimens by Yu and Shetty[2] (up to 1·5 mm crack extension, where unstable crack growth took place; i.e. before the steady-state level was attained). Their results are superimposed in Fig. 4. The agreement between their and our measurements is very good. One of our specimens of Ceramatec ceramic was annealed after 6 mm crack growth in order to reverse the transformation. This specimen was then used to measure the R-curve behaviour again. The measured R-curves coincide completely, suggesting a complete reverse transformation during the heat treatment. Such behaviour has also been demonstrated by Yu and Shetty.[2]

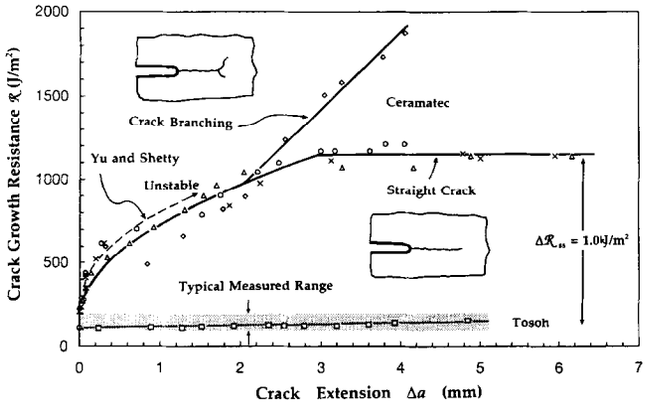

Fig. 4. The measured crack growth resistance $\mathcal{R}$ as a function of crack extension Δa for two ceramic materials. The Ceramatec material experienced a pronounced R-curve behaviour. Note that crack branching leads to erroneous measurements. The Tosoh ceramic showed no R-curve effect; it appears to have a constant fracture toughness.

As indicated in Fig. 4, for one of the specimens the crack branched and kinked away from the intended mode I crack direction after a growth of 2 mm. The crack branching was identified from the replicas and resulted in a higher apparent crack growth resistance (only growth of a single straight crack is valid for measurements of mode I R-curve behaviour).

4.3 Discussion

Under steady-state conditions, the J-integral taken along the external boundaries [Eqn (1)] can be split into parts associated with the unloading in the wake of the crack and the energy release rate at the crack tip.[11] Assuming that the critical energy release rate at the crack tip remains the same during crack growth, the increase in the global energy release rate [Eqn (1)] is predicted to be[12]

$$\Delta\mathcal{R}_{ss} = 2 f h \sigma_c \epsilon^T \tag{6}$$

where f is the volume fraction of transforming particles within the transformation zone, h is the transformation zone height, σ_c is the critical transformation stress and ϵ^T is the transformation strain.

The transformation zone height h of the Ceramatec material was measured to be approximately 100 μm, similar to the measurements of Yu and Shetty.[2] The critical transformation stress σ_c is assumed to be approximately the yield stress, which is 200 MPa.[2] Assuming an average transformation fraction of 0·4 (Yu and Shetty[2] report f = 0·8 at the fracture surface and ϵ^T = 0·05) gives a prediction of $\Delta\mathcal{R}_{ss}$ = 0·8 kJ m^{-2}. From the experimental data (Fig. 4) $\Delta\mathcal{R}_{ss}$ is found to be 1·0 kJ m^{-2}. Thus, the agreement between experimental results and the prediction is satisfying.

5 Conclusions

A fracture mechanics testing technique, the DCB specimen loaded with pure bending moments, was developed and used to characterize the crack growth resistance of two ceramics. One of the materials experiences R-curve behaviour due to phase transformation. For this material the full R-curve was measured. The other material had a constant fracture toughness. Stable crack growth was obtained in both materials.

Acknowledgements

This work was supported by the Risø Engineering Science Centre for Structural Characterization and

modelling of Materials. The work of P.B. was performed when he was staying at Risø, during which time he was supported by the European Commett organization. The Ceramatec powder was kindly provided by Professor D. K. Shetty.

References

1. Nielsen, B. N., Thomsen, N. B. & Karihaloo, B. L., in *Proceedings of the 4th International Conference on Experimental Mechanics*, 20–24 August 1990, Lyngby, Denmark, p. 674.
2. Yu, C. S. & Shetty, D. K., *J. Mater. Sci.*, **25** (1990) 2025.
3. Blum, J. I., *Eng. Fract. Mech.*, **7** (1975) 593.
4. Calomino, A. M. & Brewer, D. N., *J. Am. Ceram. Soc.*, **75** (1992) 206.
5. Tirosh, J., Altus, E. & Yifrach, T., *Int. J. Fract.*, **58** (1992) 211.
6. Vekinis, G., Ashby, M. F. & Beaumont, P. W. R., *Acta Metall. Mater.*, **38** (1990) 1151.
7. Freiman, S. W., Mulville, D. R. & Mast, P. W., *J. Mater. Sci.*, **8** (1973) 1527.
8. Sohn, K.-S., Lee, S. & Baik, S., *J. Am. Ceram. Soc.*, **78** (1995) 1401.
9. Rice, J. R., *J. Appl. Mech.*, **35** (1968) 379.
10. SOLVIA 90, Solvia Engineering AB, Västerås, S-72214, Sweden.
11. Budiansky, B., Hutchinson, J. W. & Lambropoulos, J. C., *Int. J. Solids Struct.*, **19** (1983) 337.
12. Evans, A. G. & Cannon, R. M., *Acta Metall.*, **34** (1986) 761.