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# Comparison of the sandwiched beam (SB) and opposite roller loading (ORL) techniques for the pre-cracking of brittle materials

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**Abstract**

The "sandwiched beam" (SB) and "opposite roller loading" (ORL) methodologies suitable to introduce sharp through-thickness cracks in brittle materials are critically reviewed and compared in this work. In both cases a sharp crack is obtained in a notched specimen by means of a suitable loading. In the SB technique the specimen is placed between two support bars and bent in a 3- or 4-point configuration. The ORL procedure is based on the symmetrical loading by four rollers which induces a local tensile stress. Results show that both techniques are successfully usable on brittle materials: in both cases suitable specimens are obtained for fracture toughness measurements. The crack length can be reasonably controlled and varies in a wide range. The SB procedure typically provides cracks with $\alpha \cong 0.5$, while shorter cracks are obtained by the ORL technique. Fracture toughness is measured on specimens prepared using the two techniques. The obtained values result in good agreement with literature data.


*Keywords:* Cracks; Fracture; Fracture toughness; Mechanical properties; Test methods

## 1. Introduction

The fracture toughness, $K_{Ic}$, represents a fundamental parameter for the description of the mechanical behaviour of brittle materials. Several methodologies have been proposed in the past for the measurement of $K_{Ic}$. Unfortunately, there is not an universally accepted technique and different approaches often lead to different $K_{Ic}$ values for the same material.[1–10] The fundamental task in each technique generally consists in the production of the starting crack. It is usually difficult to introduce a sharp crack, with controlled geometry and low crack opening displacement, which can be easily obtainable and measurable with low cost and common instrumentation. Methods have been proposed where a notch is introduced by a saw blade, such as the single edge notched beam (SENB) and the chevron notch (CN) techniques.[1–3,9] Unfortunately, in both cases either the crack is not sharp or the sample preparation and the test itself are extremely complex. Similar problems are encountered in the case of double torsion (DT) or double cantilever beam (DCB) procedures.[1–3] Indentation techniques are quite simple and can be used on small samples.[1,8] Nevertheless, results are seldom in agreement with data obtained using "long crack" techniques because of the indentation residual stress field and the high COD of the crack.[7] Alternatively, one can relate to cracks propagated from indentations, as in the case of the "bridging" technique.[10] Nevertheless, the procedure to obtain such cracks is not reliable and not suitable for all materials, as it often requires several trial-an-error tests.

In this paper two innovative pre-cracking method are revised and analysed. The theoretical fundamentals are initially exposed. The methods are then applied to some brittle materials and their relative advantages are discussed.

## 2. Theory

The SB technique is based on the bending of a sandwich as represented in Fig. 1.[11,12] The sample is initially notched to a depth $a$ (Fig. 2). The symbol $a$ is used here

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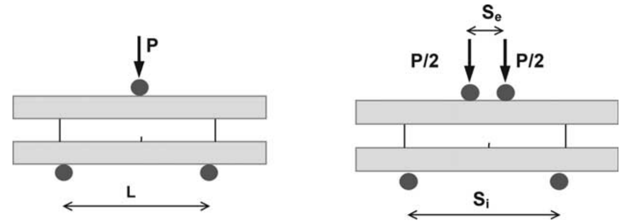


Fig. 1. Schematic of the sandwich in 3- and 4-point flexure configuration.

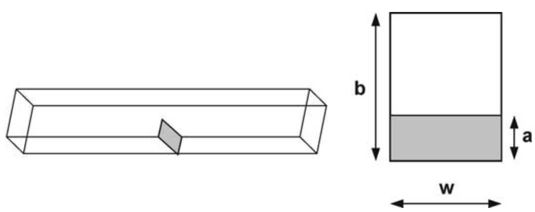


Fig. 2. Side view and section of a notched specimen for SB and ORL tests.

both for the initial notch and for the final crack length. The specimen is placed between two supporting bars and loaded in flexure up to a maximum load, $P$. A sharp crack propagates from the notch tip and extends in a stable manner, reaching a final length which depends on the maximum applied load.[11,12] The flexure of the sandwich has been analytically studied[11,12] in order to determine the applied stress intensity factor at the notch tip, both in 3- and 4-point bending. The result has been accomplished neglecting the friction between the specimen and the support beams, so that the stress field in the system can be totally defined by the maximum bending moment $M_s$ acting on the system:

$$M_S = \mathrm{Pd}/4 \quad (1)$$

where $d$ depends on the spans $L$ (3-point) or $S_e$ and $S_i$ (4-point). It has also been supposed that all three bars have the same curvature during the flexure. This assumption allows to express the flexural stiffness EI of the ‘‘sandwich’’ as the sum of the flexural stiffnesses of the single elements:

$$(\mathrm{EI})_S = (\mathrm{EI})_n + (\mathrm{EI})_b \quad (2)$$

where the subscripts $S$, $n$ and $b$ refer to the flexural stiffness of the sandwich, of the notched specimen and of the supporting bars, respectively.

The bending moment $M_n$ acting on the notched specimen is therefore proportional to its stiffness:

$$M_n = M_S(\mathrm{EI})_n/(\mathrm{EI})_S \quad (3)$$

and the flexure of the notched specimen can be considered as due to an apparent load $P_n$ defined as:

$$P_n = P(\mathrm{EI})_n/(\mathrm{EI})_S \quad (4)$$

The initial crack has been considered sharp in order to relate the stress intensification in the specimen to the apparent load $P_n$ by a simple equation[13] where b and w represent the specimen dimensions as defined in Fig. 2 and $f(\alpha)$ is a function of the ratio $\alpha = a/w$:

$$K_I = \frac{P_n d}{bw^{1.5}} f(\alpha) \quad (5)$$

Eq. (5) can then be rewritten as a function of the applied load $P$:

$$K_I = \frac{Pd}{bw^{1.5}} f(\alpha) g(\alpha) \quad (6)$$

where $g(\alpha)$ is defined by the relation:

$$g(\alpha) = (\mathrm{EI})_n/(\mathrm{EI})_S \quad (7)$$

The stiffness of the notched bar has been previously evaluated as:[12]

$$(\mathrm{EI})_n = \left[\frac{1}{(\mathrm{EI})_0} + \frac{96(1-\nu^2)}{\mathrm{E}bw^2\eta} h(\alpha)\right]^{-1} \quad (8)$$

where $\nu$ is Poisson’s ratio and $\eta$ is a function of the system geometry defined as

$$\eta = L/96 \quad (9a)$$

$$\eta = \frac{S_e^2 - 2S_e S_i + 4S_i^2}{48(S_e - S_i)} \quad (9b)$$

for 3- and 4-point bending, respectively, and

$$h(\alpha) = \int_0^{\alpha} f^2(t)\,\mathrm{d}t \quad (10)$$

Fig. 3 represents a plot of $K_I$ as a function of the crack length, $a$, through the ratio $\alpha = a/w$, for different values of the applied load $P$. The major feature of the

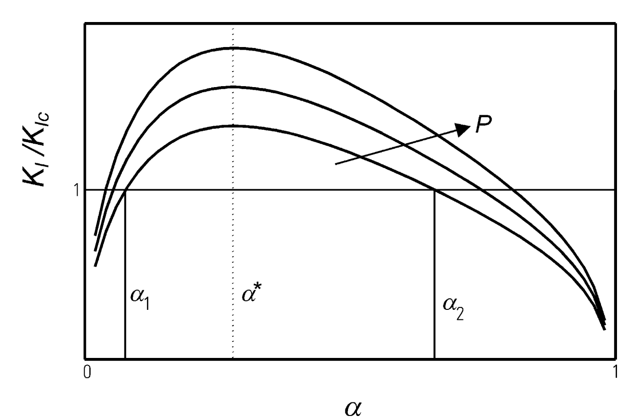


Fig. 3. Dependence of the applied $K_I$ on the relative crack length $\alpha$ and on the applied load $P$ in a 3-point bending SB test.

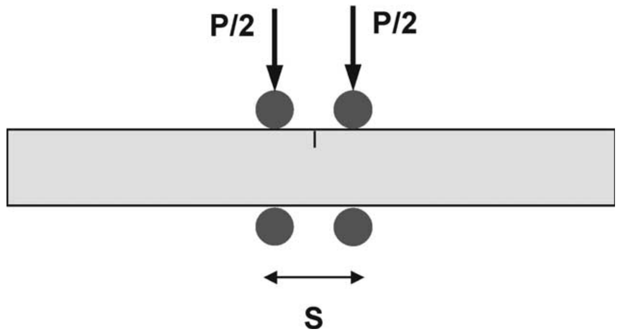


Fig. 4. Schematic of the ORL configuration for pre-cracking a notched specimen.

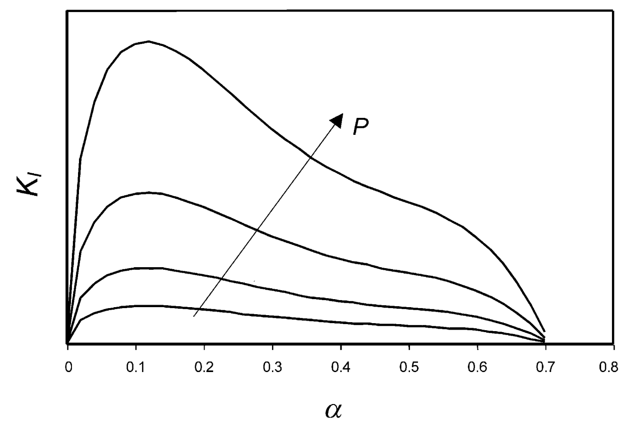


Fig. 5. $K_I$ as a function of the relative crack length ($\alpha = a/w$) for the ORL test.

plot is that $K_I$ is a decreasing function of $a$ for crack length in excess to $\alpha^*$, this being a critical crack size depending on the specimen geometry, the support bars stiffness and the loading configuration. This condition expresses the possibility of stable crack growth. Therefore, with reference to Fig. 3, when a sample with a notch $\alpha_1$ is loaded in the sandwich configuration and $K_{Ic}$ is reached, the crack propagates in an unstable manner to reach $\alpha_2$. Conversely, for notches with length larger than $\alpha^*$ the propagation is stable, as the slope of the curve is negative for $\alpha > \alpha^*$. The curves defining $K_I$ in the SB test depend on the flexural stiffness of the supporting bars and on the spans: this allows to modify $\alpha^*$ by changing the testing conditions.

The ORL procedure has been recently proposed by Fett et al.[14] In this case the loading rollers are placed symmetrically in order to obtain identical spans, as schematized in Fig. 4.

From a macroscopic point of view, the specimen is not loaded in flexure. Nevertheless, in the central region, where the notch is introduced, a tensile stress field originates, due to the loading rolls. This configuration has been analytically studied and a simple fitting equation, which expresses $K_I$ as a function of the crack length has been obtained for the specific case when the roller span, $S$, is equal to the specimen thickness, $w$:[14]

$$K_{Ic} = \frac{2P}{b\sqrt{w}}\left(0.905\alpha^{0.5} - 3.359\alpha^{1.5} + 3.875\alpha^{2.5} + 1.4425\alpha^{3.5} - 3.873\alpha^{4.5}\right) \tag{11}$$

In this case $K_I$ depends on the applied load, the specimen dimensions and the crack length.

Eq. (11) is plotted in Fig. 5 for different load values. The curves are similar to those obtained for the SB technique and similar considerations about the stable crack growth are still valid for ORL tests. It is important to point out that on average the maximum point of the $K_I$ curve is more shifted to the left for ORL test configuration, indicating that the crack is stable for lower crack lengths. The theoretical observations indicate that shorter cracks can be obtained with the ORL procedure than with the SB technique.

## 3. Experimental procedure

SB and ORL tests were performed on different brittle materials (alumina, hot pressed silicon nitride, sintered silicon carbide, yttria-partially stabilized zirconia, a SiC whiskers reinforced alumina composite and soda-lime silica glass). The ceramic materials were available in form of bars and could be tested without further machining. Glass specimens were cut from plates and polished with 45-μm grit abrasive paper. The most important properties of the materials are summarized in Table 1.

Table 1
Microstructural and mechanical properties of the tested materials

| | Grain size (μm) | Microstructure | Young's modulus (GPa) | Fracture toughness (MPa $m^{0.5}$) |
|---|---|---|---|---|
| Glass | / | Amorphous | 70 [17] | 0.75 [17] |
| $Al_2O_3$ | 5 | 10% Intergranular glassy phase, some elongated grains | 247±4 | 3.4±0.5 |
| $Si_3N_4$ | <1 [16] | Some elongated grains | 320 [16] | 5.4 [16] |
| SiC | 7 [16] | Equiaxic | 427 [16] | 2.1–3.5 [16] |
| $ZrO_2$ | 0.45 [15] | Equiaxic | 211 [15] | 5.3 [15] |
| $Al_2O_3$–$SiC_w$ | <1 | Equiaxic ($Al_2O_3$) + whiskers (SiC) | 390±8 | 7.2±0.6 |

Table 2
Experimental parameters for SB tests

| Material | Specimen dimensions ($mm^3$) | $EI_b$ ($10^6$ N $m^4$) | $S_i$ (mm) | $S_o$ (mm) |
|---|---|---|---|---|
| Glass | 3×5×50 | 156 | 4 | 20 |
| Composite | 3.5×4.5×50 | 156 | 4 | 20 |
| Other | 3×4×50 | 156 | 4 | 20 |

The mechanical properties of the composite and alumina reported in Table 1 were measured by the acoustic resonance technique[15] (Young's modulus) and an indentation technique[8] (fracture toughness).

For SB tests a notch was introduced by a low speed saw using a 0.3 mm thick diamond blade. The notch was manually sharpened with a razor blade and diamond paste, according to the procedure described by Kübler.[16] The length of the notch was chosen around the maximum of the $K_I$ curve ($\alpha = \alpha^*$ in Fig. 3), that is to say about 30% of the specimen thickness. This condition should allow to obtain the shortest cracks.

Hard metal bars were used as supporting beams resulting in a total stiffness ($EI_b$) being 156 kN $m^2$. The tests were performed in 4-point bending configuration, as shown in Table 2.

The load applied to the sandwich was gradually increased until a sharp crack propagated from the notch tip. The cracks were measured by an optical microscope. In the ceramic materials they were decorated with penetrating dye to make successive measurement easier.[8]

For ORL tests the specimen were notched with the procedure previously described for SB tests. In this case the length of the notch was in the range 8–12% of the specimen thickness. The rolls span was equal to 4 mm (equal to the specimen thickness), in agreement with the validity requirements of the model. During the loading process a thin strip of paper was placed between the specimen and the rollers in order to avoid high local cracking in the part of the specimen in direct contact with the rollers. The loading of the specimen was carried out similarly to SB tests. The crack was measured in the same way as well.

Bending fracture tests were then performed on the cracked specimens for the measurement of fracture toughness according to the ASTM standard procedure.[9]

## 4. Results and discussion

The application of the present techniques allowed the introduction of sharp, through thickness cracks in bars. Examples of SB and ORL cracks obtained on various materials are provided in Figs. 6 and 7. The cracks satisfy the geometrical requirements defined by the ASTM standard procedure to measure fracture toughness:[9] the crack length in different points of the specimen section

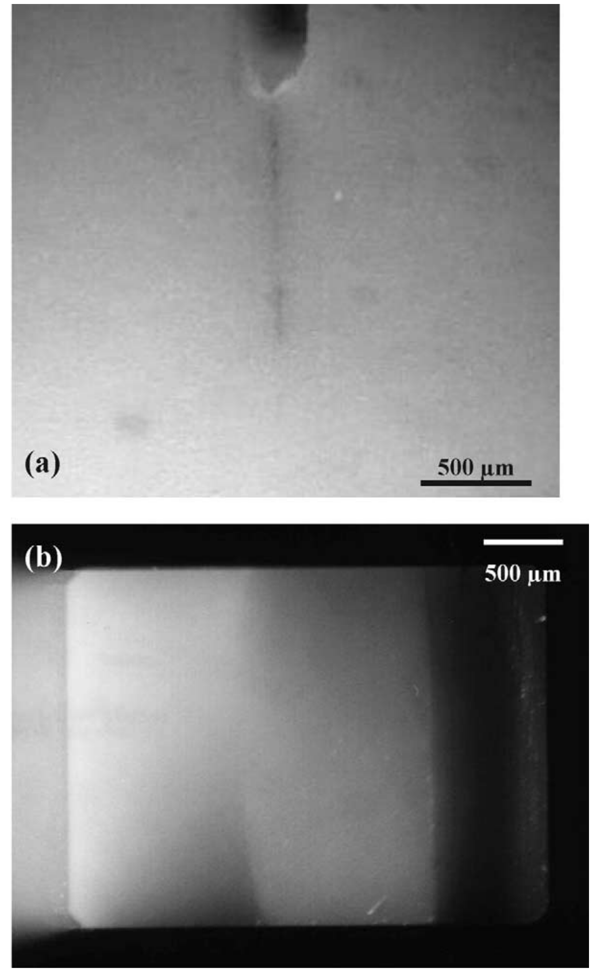


Fig. 6. Specimens pre-cracked by the SB technique. (a) Side surface of an alumina specimen, showing the starting notch and the sharp crack; the crack was coloured with red dye to enhance contrast; (b) fracture surface of a $ZrO_2$ specimen; the initial notch is on the right.

is constant, it does not exceed 70% of the specimen thickness and lays on a plane perpendicular to the specimen faces. On average, cracks obtained by SB tests are longer than expected from Fig. 3 and their extension exceeds half the thickness of the specimen. By using the ORL procedure very short cracks have been obtained. Both procedures have been successfully applied on the considered ceramics and glass and none of the different kind of material presented any particular problem.

The experimental data are summarized in Tables 3 and 4, for SB and ORL tests, respectively. The ''theoretical load'' indicates the load required for sharp crack propagation according to the analytical model (Fig. 3) and the ''maximum load'' is the highest load applied to the specimen during the test. The expected crack length is indicated as ''theoretical crack'' while ''final crack'' represents the final crack length. Both theoretical and final crack length are scaled to the specimen width, in order to compare results for specimens with different geometry more easily.

The propagation load is higher than expected from theoretical calculations, both for SB and ORL tests. This accounts for the fact that the obtained cracks are longer than expected: in fact with a higher load the crack grows in an unstable manner within a wider range, as it can be deduced from Fig. 3.

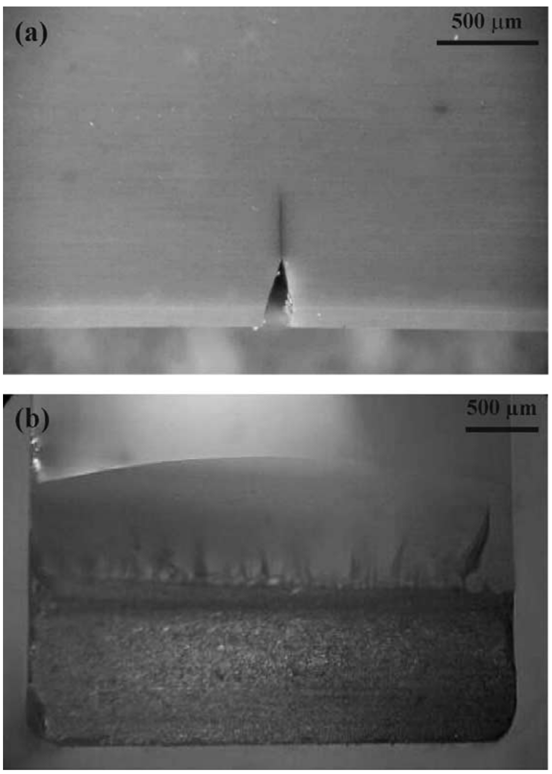


Fig. 7. Specimens pre-cracked by ORL procedure. (a) Side surface of a silicon nitride specimen, showing the starting notch and the sharp crack; the crack was coloured with red dye to enhance contrast; (b) fracture surface of a glass specimen; the initial notch is on the bottom.

Table 3
Experimental results for "sandwiched beam" tests

| | Theoretical load (N) | Maximum load (N) | Theoretical crack length (%) | Final crack length (%) |
|---|---|---|---|---|
| Glass | 2900–3100 | 4570 | 35–40 | 62 |
| $Al_2O_3$ | 2200–2400 | 2950 | 45–55 | 52 |
| SiC | 900–1000 | 1539 | 50–60 | 65 |
| $Si_3N_4$ | 2500–2600 | 5650 | 50–60 | 61 |
| $ZrO_2$ | 3700–3800 | 6500 | 50–60 | 68 |
| $Al_2O_3$–$SiC_w$ | 2300–2400 | 3250 | 60–70 | 58 |

Table 4
Experimental results for "opposite roller loading" tests

| | Theoretical load (N) | Maximum load (N) | Theoretical crack length (%) | Final crack length (%) |
|---|---|---|---|---|
| Glass | 300–500 | 2130 | 20–25 | 36 |
| $Al_2O_3$ | 1600–1800 | 5570 | 20–25 | 25 |
| $Si_3N_4$ | 2600–2800 | 7833 | 20–25 | 23 |

One of the most evident reasons that justifies the necessity of higher loads for the crack propagation is that the initial crack is not sharp, as supposed in the theoretical analysis. If the notch is blunt, the stress intensification is not so effective and it is necessary to increase the load to obtain critical stress condition in the specimen. This consideration is valid both for SB and ORL tests.

For the SB configuration, other facts can account for the disagreement between theoretical and experimental data. In the elaboration of the model, the friction between the specimen and the support bars has been neglected, while it is reasonable to think that friction forces act in the same direction of the tensile stresses upon bending, this modifying the total effective stress on the notch.

The hypothesis that the curvature of the beams in the "sandwich" is the same is also an approximation whose quantitative consequences are not easily definable. If the curvature of each beam is not the same, the stress on the notched specimen is different from what calculated: it will be higher if the specimen's curvature is greater, lower if the curvature is smaller.

Despite the approximations, the model can indeed provide useful indications for the experimental tests. In the graph reported in Fig. 8 the theoretical load required for the crack propagation is compared to the experimental value, both for SB and for ORL tests. It is clear that the two series are related and a linear relation can be identified. The greater the theoretical load, the greater the experimental value. This suggests that the disagreement previously pointed out does not depend on the material or on its toughness. A scale factor (Table 5) can be calculated for each procedure from the slope of the fitting line. Such scale factor can be used to calculate the real load required to propagate the sharp notch, from the load values supplied by the models.

SB and ORL cracked specimens were used for fracture toughness measurements. Results are shown in Table 6. All data are in good agreement with literature values (Table 1).[1–3,17]

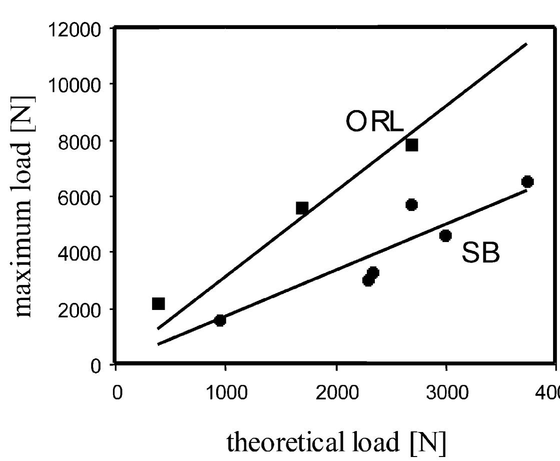


Fig. 8. Load required for crack propagation in SB and ORL tests: comparison between theoretical and experimental values.

Table 5
Scale factor between propagation load to theoretical value (from Fig. 8)

| | SB tests | ORL tests |
|---|---|---|
| Linear fitting through the axis origin | 3.04 | 1.65 |

Table 6
Fracture toughness values measured on SB and ORL cracked specimens (all values are expressed in MPa $m^{0.5}$)

| | SB | ORL |
|---|---|---|
| Glass | 0.76±0.02 | 0.76±0.02 |
| $Al_2O_3$ [A] | 3.4±0.3 | |
| SiC | 2.7±0.1 | |
| $Si_3N_4$ | | 5.6±0.2 |
| $ZrO_2$ | 5.3±0.3 | |
| $Al_2O_3$–$SiC_w$ | 7.6±0.5 | |

## 5. Conclusions

Both SB and ORL procedures allow to introduce sharp, through-thickness cracks in brittle materials. They are low-cost techniques, as small samples are needed, the notch preparation is quite simple and the necessary instrumentation is common in typical materials science and technology laboratories. The final cracks have definite geometry and are easy to be measured.

The load required to propagate the sharp crack can be evaluated on the basis of theoretical considerations from the sample geometry, the loading conditions and an empirical constant.

Fracture tests on SB and ORL cracked specimen furnished $K_{Ic}$ values in good agreement with literature data.

## References

1. Lawn, B. R., *Fracture of Brittle Solids*, 2nd edn. Cambridge University Press, Cambridge, 1993.
2. Watchman, J. B., *Mechanical Properties of Ceramics*. J. Wiley and Sons, New York, 1996.
3. Munz, D. and Fett, T., *Ceramics*. Springer-Verlag, Berlin, 1999.
4. Lemaitre, P. and Piller, R., Comparison of the fracture toughness of alumina measured by three different methods. *J. Mater. Sci. Lett.*, 1988, **7**, 772–774.
5. Kurth, R., Lawlor, B. F., Stockman, Y. J. and Steinbrech, R. W., Toughness determination from stable growth of long and short cracks in $Si_3N_4$ ceramics. In *Fracture Mechanics of Ceramics*, ed. R. C. Bradt *et al.* Plenum Press, New York, 1996, pp. 151–162.
6. Quinn, G., Kübler, J. and Gettings, R., Fractography and the surface crack in flexure (SCF) method for evaluating fracture toughness of ceramics. In *Fractography of Glasses and Ceramics III*, Ceramic Transactions, Vol. 64, ed. J. R. Varner, V. C. Fréchette and G. D. Quinn. *J. Am. Ceram. Soc.*, 1996, pp. 107–144.
7. Smith, S. M. and Scattergood, R. O., Determination of short-crack toughness curves. *J. Am. Ceram. Soc.*, 1996, **79**(1), 129–136.
8. Sglavo, V. M. and Pancheri, P., Crack Decorating Technique for Fracture Toughness Measurements in Alumina. *J. Eur. Ceram. Soc.*, 1997, **17**(14), 1697–1706.
9. ASTM Norm 1421–01a, Standard test method for determination of fracture toughness of advanced ceramics at ambient temperature. In *Annual Book of ASTM Standards, Vol. 15.01*. American Society for Testing and Materials, Philadelphia, PA, 2001.
10. Nose, T. and Fujii, T., Evaluation of fracture toughness for ceramic materials by a single-edge precracked beam method. *J. Am. Ceram. Soc.*, 1988, **71**(5), 328–333.
11. Sglavo, V. M., Bosetti, P., Trentini, E. and Ceschini, M., Sandwiched-beam procedure for pre-cracking brittle materials. *J. Am. Ceram. Soc.*, 1999, **82**(8), 2269–2272.
12. Pancheri, P., Bosetti, P., Dal Maschio, R. and Sglavo, V. M., Production of sharp cracks in ceramic materials by three-point bending of sandwiched specimens. *Eng. Fract. Mech.*, 1998, **59**(4), 447–456.
13. Srawley, J. E., Wide range stress intensity factor expression for ASTM E399 standard fracture toughness specimens. *Int. J. Fract.*, 1976, **12**, 475–576.
14. Fett, T., Munz, D. and Thun, G., A toughness test device with opposite roller loading. *Eng. Fract. Mech.*, 2001, **68**(1), 29–38.
15. ASTM norm C 1198–91, Standard test method for dynamic young's modulus, Shear modulus and Poisson's ratio for advanced ceramics by sonic resonance materials. In *Annual Book of ASTM Standards, Vol. 15.01*. American Society for Testing and Materials, Philadelphia, PA, 1991.
16. Kübler, J., Fracture Touhgness of Ceramics using the SEVNB Method; Round Robin (VAMAS Report No. 37). ESIS Document D2–99, 1999.
17. *Engineered Materials Handbook—Ceramics and Glasses, Vol. 4*. ASM International Handbook Committee, USA, 1991.