Small specimen compact tension testing of ceramics

JOURNAL OF MATERIALS SCIENCE LETTERS 13 (1994) 1038–1041

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Functional ceramics are primarily optimized with respect to their functional behaviour. However, from time to time in various applications mechanical problems arise. Whether these problems are due to intrinsic material deficiencies or to processing faults is usually not known. As a first step the intrinsic behaviour of the relevant materials, e.g. the fracture toughness, K_{Ic}, is tested. Measurement of the fracture toughness of ceramics is usually done using the three-point bend (3PB) test or double cantilever beam (DCB) test. For electronic ceramics often only limited thicknesses are available and the aforementioned tests cannot be used. For materials delivered in the form of sheets a solution may be found by using the compact tension (CT) specimen. In this letter the use of this type of test is examined for ceramic materials. For a number of well-known ceramics the fracture toughness was measured using a newly designed test jig.

The original CT specimen is shown in Fig. 1. B is the specimen width, W is the loaded length, $2H$ is the total height, F is the loaded height and a is the crack length. The load is denoted by P. The specimen as modified for our purpose is shown in Fig. 2, while a schematic test jig is shown in Fig. 3.

An early expression for the stress intensity, K, valid for a limited set of dimensions, often quoted in standard texts on fracture mechanics (e.g. [1]), was given in the well-known ASTM STP's 381 and 410 [2, 3]:

$$K = (P/BW^{1/2})[29.6(a/W)^{1/2} - 185.5(a/W)^{3/2} + 655.7(a/W)^{5/2} - 1017(a/W)^{7/2} + 638.9(a/W)^{9/2}]$$

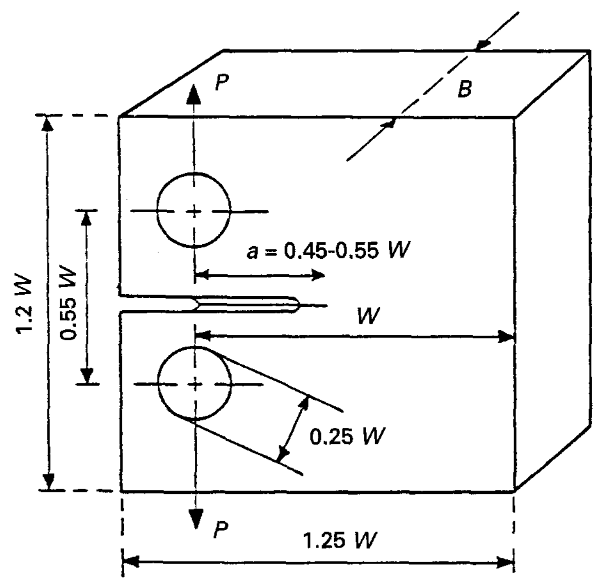

Figure 1 Original compact tension specimen.

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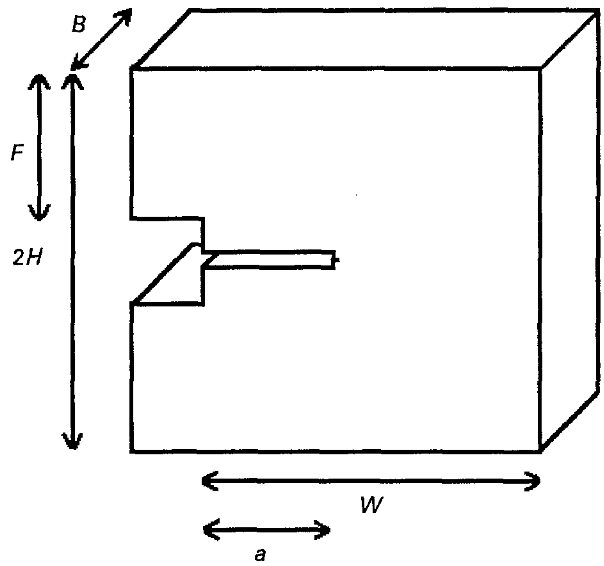

Figure 2 Modified compact tension specimen.

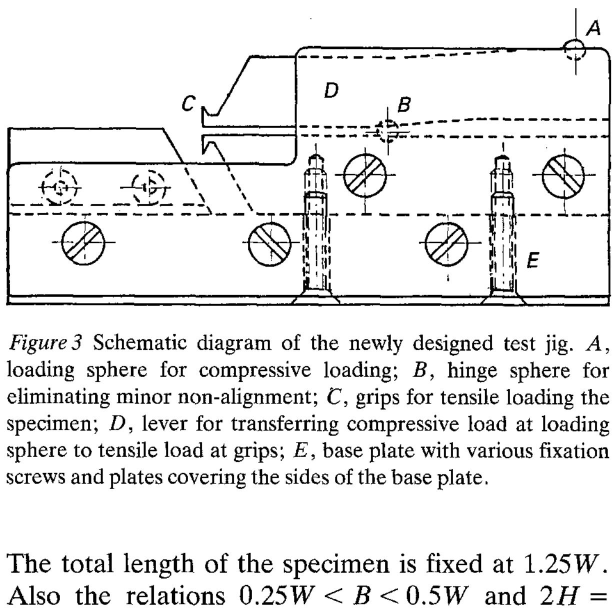

Figure 3 Schematic diagram of the newly designed test jig. A, loading sphere for compressive loading; B, hinge sphere for eliminating minor non-alignment; C, grips for tensile loading the specimen; D, lever for transferring compressive load at loading sphere to tensile load at grips; E, base plate with various fixation screws and plates covering the sides of the base plate.

The total length of the specimen is fixed at $1.25W$. Also the relations $0.25W < B < 0.5W$ and $2H = 1.2W$ should hold, while the expression is only valid for $0.45W < a < 0.55W$.

A complete set of data for the CT specimen in numerical form was given by Srawley and Gross [4]. Their information deals with loading in and out of the crack plane (F/W ratio) and the influence of the height over length ratio of the specimen (H/W ratio). The full set of data is given in Table I. In our analysis we shall neglect the influence of the loading out of the crack plane (F/W) since it is small for $a/W \geqslant 0.3$. For convenience in calculations, the data as given in Table I were least-squares fitted for each value of H/W as a polynomial in a/W for the dimensionless coefficient $Q = KB(W - a)^{3/2}/P(2W + a)$. The coefficients are given in Table II.

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TABLE I Dimensionless coefficients Q for the CT specimen [4]

		a/W						
H/W	F/W	0.2	0.3	0.4	0.5	0.6	0.7	0.8
0.4	0.3	2.063	2.010	1.837	1.634	1.459	1.351	1.315
	0.5	2.070	2.009	1.836	1.634	1.460	1.351	1.314
	1.0	2.095	2.003	1.832	1.632	1.459	1.351	1.314
0.5	0.3	1.672	1.655	1.554	1.443	1.361	1.320	1.309
	0.5	1.687	1.657	1.553	1.443	1.361	1.320	1.310
	1.0	1.742	1.661	1.549	1.440	1.360	1.320	1.310
0.6	0.3	1.451	1.466	1.419	1.364	1.327	1.312	1.312
	0.5	1.463	1.470	1.419	1.364	1.326	1.312	1.311
	1.0	1.545	1.488	1.420	1.362	1.325	1.312	1.312
0.8	0.3	1.250	1.307	1.316	1.312	1.309	1.310	1.307
	0.5	1.261	1.312	1.318	1.312	1.308	1.310	1.305
	1.0	1.368	1.352	1.329	1.314	1.308	1.310	1.305
1.0	0.3	1.190	1.258	1.287	1.299	1.305	1.311	1.278
	0.5	1.195	1.263	1.289	1.300	1.306	1.311	1.277
	1.0	1.298	1.309	1.306	1.304	1.306	1.310	1.278

The dimensionless factor Q is given by: $Q = KB(W-a)^{3/2}/P(2W+a)$. The ratio F/W indicates the relative height of the load point. Clearly, for $a/W \geqslant 0.3$ the influence of this parameter is negligible.

TABLE II Coefficients, C_i, of the polynomial expression fitted to the dimensionless coefficients $Q(a/W)$ for the CT specimen as given in Table I

H/W	C_0	C_1	C_2	C_3	C_4
0.4	1.686	4.979	−18.33	19.50	−6.363
0.5	1.575	2.638	−11.78	14.99	−6.136
0.6	1.487	1.307	−6.824	9.540	−4.242
0.8	1.287	1.099	−4.764	7.121	−3.560
1.0	1.068	2.375	−8.319	12.22	−6.401

The polynomial expression to the dimensionless factor $Q = KB(W-a)^{3/2}/P(2W+a)$ is given by $Q = \Sigma C_i(a/W)^i$

The deviations are always less than 0.6% for the complete range of a/W and less than 0.3% for the range $0.3 < a/W < 0.8$. A continuous decrease in coefficients is observed as a function of H/W, except for $H/W = 1.0$. In fact, the value of Q for $H/W = 1.0$ is constant 1.30 within 0.01. Attempts to fit these coefficients again for the various values of H/W failed using the complete range. Neglecting the data for the ratio $H/W = 1.0$, however, resulted in a proper fit. The fitted results are within 1.0% of the original values. These coefficients are presented in Table III.

Later Srawley [5] published an expression for ASTM E-399 type specimens valid for $H/W = 0.6$ only, accurate over the range $0.2 < (a/W) < 1$ within 0.5% based on this previous results and those of some others:

$$K = (P/BW^{1/2})[2 + (a/W)][0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4]/[1-(a/W)]^{3/2}$$

This expression is probably more accurate than the expressions as fitted from Table I. A comparison of the Q-values resulting from Srawley's expression and our fit shows a systematic difference for a/W values $\geqslant 0.4$ of about 1%. In view of the experimental accuracy this difference is negligible. Therefore the fit to Table I as given in Tables II and III will be used in this work throughout in view of its easier use.

A test jig was constructed in order to be able to measure small compact tension specimens (Fig. 3). The design of this jig was similar to a previously described DCB jig [6, 7]. It can be used in any universal testing machine because the jig is loaded in compression. The specimen size used was 8 mm × 9 mm × 1 mm. To check the validity of the test, specimens of materials with known fracture toughness were prepared. Materials used were silica glass (Ultrasil), alumina Wesgo A1995 and hot-pressed $BaTiO_3$. Specific details on these materials are given in Table IV.

Various values of starter crack length were used: 3.0 mm, 4.0 mm and 5.0 mm, corresponding to $a/W = 0.3$, 0.4 and 0.5, respectively. The width of the starter crack was approximately 150 μm. Side grooving was tested with two depths: 50 μm and 100 μm. At a later stage side-grooving was omitted altogether, resulting in a much easier to machine specimen. To ease the starting of the crack propagation a Vickers indentation of load 10 N was made on each side of the specimen at the notch root. A number of specimens was annealed for 24 h at a temperature of 1000 °C to remove any residual stresses present. For control, 3PB tests [8] were

TABLE III Coefficients, c_{ij}, of the polynomial expression fitted to the coefficients $C_i(H/W)$ for the CT specimen over the range $H/W = 0.4$–0.8 as given in Table II

C_i	c_{i0}	c_{i1}	c_{i2}
0	2.109	−1.101	0.09318
1	22.89	−62.39	43.95
2	−68.76	171.7	−114.6
3	58.65	−129.7	81.42
4	−12.49	18.27	−8.775

The polynomial expression of the coefficients C_i is given by $C_i = \Sigma c_{ij}(H/W)^j$

TABLE IV Material details

	SiO_2 glass[a]	$BaTiO_3$[b]	Al_2O_3[c]
Density ($g\,cm^{-3}$)	2.20	6.00	3.85
Young's modulus (GPa)	73	130	369
Poisson's ratio	0.159	0.24	0.236
Fracture toughness ($MPa\,m^{1/2}$)	0.798 (0.23)	1.08 (0.09)	4.10 (0.22)
Grain size (μm)		0.5	15

[a]From [6, 7].
[b]Data measured using the 3PB test.
[c]From [9].
The sample standard deviation is given in parentheses.

done using a specimen size of $1\text{ mm} \times 3\text{ mm} \times 15\text{ mm}$, a span size of 12 mm, a notch width of 100 μm and a relative notch depth of 0.15. Again a Vickers indentation with a load of 10 N was made for ease of crack starting.

The cross-head speed of the universal testing machine (Overload Dynamics S200) was 0.1 mm min^{-1} in all cases. All testing was done in dry nitrogen atmosphere (~200 ppmV H_2O) in order to avoid slow crack growth as much as possible.

The resulting values of the fracture toughness for side-grooved, non-annealed test materials are given in Table V. The data show a consistent behaviour as far as independence of starter crack length is concerned. Also, the effect of the depth of the side groove is small. However, the values obtained are too high as compared with the data given in Table IV. It was thought that this behaviour could possibly be due to residual stress introduced by the machining operations. Attempts were made to remove this residual stress by etching according to the procedure described previously [10]. For comparison this was also done for 3PB specimens. A non-systematic behaviour with etching depth was observed for the CT specimens. The values for the fracture toughness were heavily dependent on the amount of material etched away and are not further discussed.

It was decided to try to remove the residual stress by annealing. The alumina was chosen for this (Table VI). A value of about 3.7 $MPa\,m^{1/2}$, independent of whether grooving or indentation was present, was obtained. This value is lower than the value of 4.1 $MPa\,m^{1/2}$ reported before, possibly due to insufficient precracking of 5 N for the large 3PB specimens used at that time. In the thinner CT specimens and small 3PB specimens used here machining itself apparently provides sufficient precracking. The effect of the annealing appeared to be limited for this alumina.

Annealing for the other materials was done using indented, non-grooved specimens. The fracture toughness data for these materials are also given in Table VI. It can be concluded that a fracture toughness value is obtained, which is independent of the starter crack length and well comparable to the independently determined value by 3PB testing. The importance of removal of residual stress is thus clearly demonstrated, in particular for the CT specimens.

From the present results it can be concluded that

TABLE V Results of the fracture toughness measurements for grooved and non-annealed specimens

Material	Groove (μm)	$a/W = 0.27$	$a/W = 0.39$	$a/W = 0.51$
SiO_2	50		1.05 (0.12, 8)	
	100	1.24 (0.09, 6)	1.20 (0.11, 8)	1.22 (0.09, 6)
$BaTiO_3$	50		1.28 (0.13, 5)	
	100	1.18 (0.20, 5)	1.25 (0.04, 5)	1.36 (0.14, 6)
Al_2O_3	50		4.35 (0.20, 5)	
	100	4.15 (0.14, 6)	4.11 (0.12, 6)	4.08 (0.19, 5)

All data are given as the average value, with the sample standard deviation and the number of specimens in parentheses.

TABLE VI Results of the fracture toughness measurements for non-grooved and annealed specimens (unless otherwise indicated)

SiO_2 glass	$a/W = 0.35$	$a/W = 0.45$	$a/W = 0.56$
No groove CT	0.77 (0.07, 8)	0.78 (0.13, 7)	0.78 (0.04, 7)
3PB	0.79 (0.13, 8)		
$BaTiO_3$			$a/W = 0.56$
No groove CT			0.92 (0.08, 5)
3PB	0.96 (0.18, 6)		
Al_2O_3			$a/W = 0.56$
100 μm groove CT, NI, NA			3.70 (0.30, 6)
100 μm groove CT, I, NA			3.73 (0.23, 6)
No groove CT, I, NA			3.72 (0.13, 4)
No groove CT, I, NA			3.64 (0.26, 4)
3PB	3.40 (0.25, 6)		

All data are given as the average value, with the sample standard deviation and the number of specimens in parentheses.
I, indented; NI, not indented; A, annealed; NA, not annealed.

the CT specimen with a small size as discussed in this letter is a useful specimen type for the measurement of the fracture toughness of ceramics. The tabular data available for the compliance factor are accurately fitted by a polynomial expression. The elimination of residual stress is demonstrated to be quite important for accurate measurement of the fracture toughness.

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Received 22 December 1993
and accepted 8 March 1994