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Pre-Cracking Test-Pieces Of Brittle Materials For Fracture Toughness Measurement

Fracture toughness tests require the introduction of a sharp pre-crack into the test-piece, either by propagation from a chevron notch, or by any other suitable method. This Measurement Note reviews the primary methods that are suitable for flexural beam test-pieces of most brittle materials, including:

- single-edge straight-through pre-crack in a beam
- sharpened Vee-notch in a beam
- surface crack in a beam
- diamond-wedge induced crack in a beam
- stressing or fatiguing a notch in a beam

In selecting an appropriate method, consideration needs to be given to the objective of undertaking the toughness measurement, and whether this involves any rising crack resistance behaviour. In such cases the length of the pre-crack at the point of fracture toughness measurement needs to be considered when the method of pre-cracking is selected.

Roger Morrell

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1 Introduction

Fracture mechanics analyses for fracture tough-ness are generally reliant on the test-piece containing a sharp-tipped crack of known geometry to which a well-defined stress field is applied until the crack propagates. This essentially requires the development of a sharp pre-crack in the test-piece prior to undertaking the test.

There are exceptions to this situation for weak ceramic materials which undergo multiple localised cracking under stress, and where a critical stress intensity factor in the conventional sense cannot strictly be measured (e.g. coarse-grained refractories, intentionally open porous materials or some transformation strengthened materials).

This Measurement Note covers a range of methods for introducing a sharp, controlled pre-crack into beam test-pieces of dense, relatively brittle materials in a number of different crack geometries, including:

- a single-edge straight-through pre-crack from
- a notch or indentation
- a sharpened Vee-notch
- a small semielliptical surface flaw
- a wedge-induced edge pre-crack
- a crack from a stressed or fatigued notch

This Measurement Note discusses each of these and provides methods for undertaking them.

2 Single-Edge Pre-Cracked Beam (SEPB)

2.1 Principle

The principle of this method is to place a test-piece containing a starter notch or indentation on an anvil with a gap in it, with the notch or indentation in the centre of the gap, place a second anvil on the top of the test-piece, and apply a compressive force to the system. As the compressive force increases, the test-piece generates a localised axial tensile stress in the region between the two halves of the split anvil. When a critical force is reached, typically in the range 10 to 40 kN, a planar crack "pops in" and stops when it runs into the generally compressive stress field further into the test-piece (Figure 1). When such a test-piece is broken in four-point bending[1], the original pre-crack line can be clearly seen as an arrest mark in the fracture surface, and its length can be measured for insertion into the calculation equation for fracture toughness. The method has been used successfully for both ceramics (e.g. [1, 2]) and hardmetals (e.g. [3]).

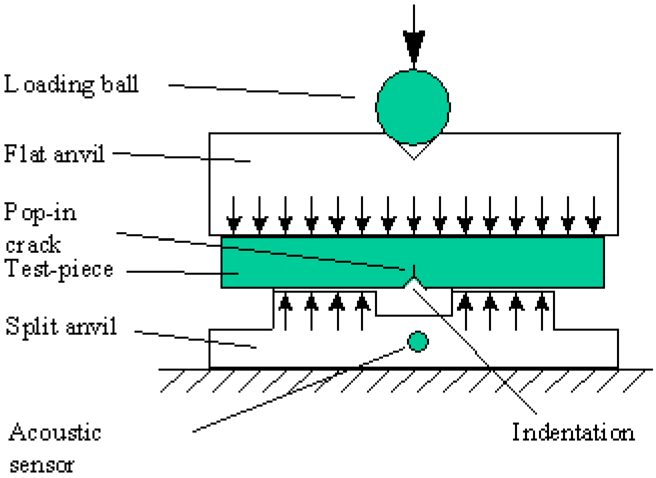

Figure 1 - Schematic of bridge pre-cracking for preparing a single-edge pre-cracked beam test-piece

2.2 Method requirements

The principal requirement is to obtain a straight-fronted pre-crack. This requires that the stress distribution during pop-in is symmetrical and preferably uniform across the width of the test-piece, which for small test-pieces is not trivial to achieve. The following requirements need to be met.

- The test-piece must have flat and parallel faces contacting the anvils. Tolerances must be better than ± 0.005 mm. The long edges should be chamfered in the same way as for flexural strength test-pieces, e.g. in accordance with CEN EN843-1. One surface has either a narrow (<100 μm), shallow (<200 μm) notch machined into it, or has one or more Vickers indentations (typically HV5 for ceramics, HV30 for hardmetals) placed so that the radial cracks emanating from the corners align across the test-piece width.

- The anvils must have flat surfaces[2] to within ± 0.005 , and the two parts of the split anvil must be coplanar to the same tolerance. Ideally the anvil is made of a material which does not deform plastically, so that no permanent deformations build up with use. If a metallic material is employed, the yield stress must exceed 500 MPa. In addition, there appears to be some advantage in the anvil material being elastically more compliant than the test-piece. Pop-in forces tend to be lower for steel anvils than for ones made from ceramic (e.g. silicon nitride) or hardmetal (e.g. tungsten carbide), a factor corroborated by finite element analysis of the process [4].

- Alignment in loading is critical. The axis of the compressive force must be central between the split anvil halves and, in the orthogonal plane, lie through the centre of the test-piece to within a very small tolerance, typically ± 0.01 mm. This requires very accurate machining of the anvil system, plus the use of guides for positioning the test-piece centrally and coaxially with the loading system. Failure to achieve such alignment results in pre-cracks which have angled fronts, i.e. exit at greatly different positions on the two side faces of the test-piece, or which are in a plane at an angle to the normal through the test-piece. Limits are being placed in standards (ASTM PS070, JIS R1607, ISO/CD15732) concerning the acceptability of pre-cracks for valid testing.

2.3 Compression jig design

A pre-cracking jig design promoted by the Japan Fine Ceramic Centre [2] and to be incorporated in an advisory Annex in the new ISO standard (ISO/CD15732) for advanced technical ceramics is shown in Figure 2. The gap in the lower anvil is treated as a variable, either by use of anvils of different gap widths, or by some means of mechanical adjustment. The groove in which the test-piece sits acts to align the test-piece, but such a geometry may restrict the ability to achieve a flat bottom to the groove since it does not permit run-out in grinding to create it. An alternative tested at NPL involves a flat anvil with added guide pieces, permitting the anvil surfaces to be machined as clean surfaces.

The top anvil and the bottom anvil must be aligned by use of a sliding cage, not shown in Figure 2, but clearly this must allow free movement without twisting and jamming. Force is applied through a ball in a conical seat in the upper surface of the top anvil in order to define the loading axis.

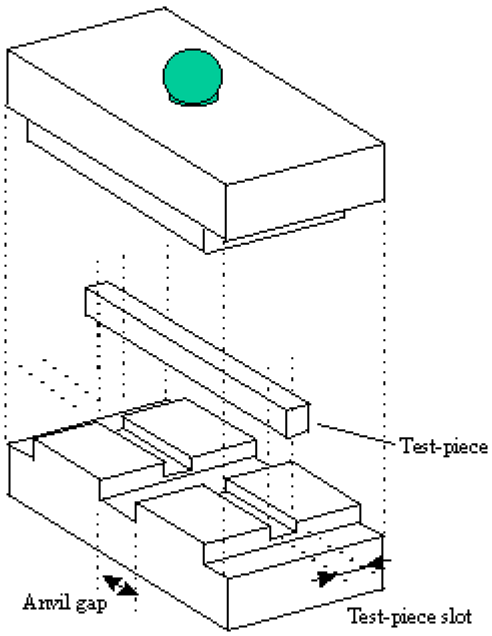

Figure 2 - Example of a pre-cracking jig for the SEPB method

2.4 Using the compression jig

Trials at NPL have shown that using such a compression jig requires skill. Great care should be taken to ensure that the anvil surfaces are kept in good condition, and that the system is properly aligned when assembled with a test-piece inside.

Detecting when pop-in occurs is most readily achieved by using an acoustic emission (AE) sensor attached to one of the anvils, since no sign-ificant load drop occurs on pop-in, and the sound may not be audible. As soon as it occurs, the test-piece can be unloaded and removed from the jig.

The target pop-in distance is between 35% and 60% of the test-piece depth ($0.35 < a/w < 0.6$, from ISO/CD15732). There are a number of variables that can be adjusted to optimise the pre-cracking procedure.

- The anvil gap can be adjusted; widening it increases the ease of pre-cracking, but also increases the pop-in depth; in general wider gaps are suited to tougher materials; a good starting points is a gap of 4 mm to 6 mm.
- If notching is used, the pre-notch depth can be made larger or smaller, or sharper by use of the razor-blade honing technique - see section 3; deeper notches are less easy to pre-crack; sharper notches are easier to pre-crack.
- If indentation is used, the indentation force can be changed; observation of the character of indentation cracking is useful; ideally, long straight radial cracks are needed, but increasing the indentation force in some materials may lead to multiple cracking rather than increasing the length of single cracks; it is generally better to use a row of three or more low-force indentations producing cracks that can link up to pop in, rather than rely on a single large indentation.
- In order to provide a slight measure of compliance, aluminium foil can be placed between the anvils and the test-piece, having the effect of reducing the force necessary for pre-cracking.

2.5 Pre-crack acceptability criteria

As noted above, the pre-crack should ideally be 35% to 60% of the test-piece depth. Unless the sides of the test-piece are polished, it is often difficult to see how long the pop-in distance is until after fracture, so it is useful to pre-crack and test them individually until experience is gained. It is also useful to prepare some additional test-pieces, because the pop-in may not give a crack of uniform length, but one canted to one side. To ensure reasonable reliability of results, ISO/CD 15732 contains the following generally accepted criteria.

- After fracture, three crack length measurements are made at positions 25, 50 and 75% of the test-piece width (Figure 3a). If the difference between the maximum and minimum length values measured exceeds 10% of the mean of all three values, then the pre-crack geometry is deemed to be invalid.

- If the angle between the pre-crack plane and the test-piece normal exceeds 10° (5° for a three-point bend test-piece), the test is similarly deemed to be invalid (Figure 3b).

2.6 Enhancing pre-crack visibility

Depending on the fracture surface morphology, it may be hard to distinguish the boundary between the pop-in crack and the propagating crack in the fracture toughness test. Angled illumination from different directions should be tried in the first instance, since subtle changes in roughness may be more readily seen and photographed. Alternatively, it may be useful, particularly on white materials, to attempt to delineate the pre-crack using a marker dye penetrant before fracturing. After applying the dye, the test-piece should be thoroughly dried before testing.

2.7 Subcritical crack growth

In materials subject to this phenomenon, such as most oxides and some non-oxide ceramics, the pre-crack may grow a little before final fracture in the toughness test. This may be detectable as a slight loss of compliance of the test-piece just before fracture. The correct toughness value should be obtained from the subcritically grown pre-crack length. The pre-crack front should be inspected for signs of growth after pop-in, sometimes visible as a slight change in direction, or a halo. The lengths measured must include the additional growth (Figure 3c).

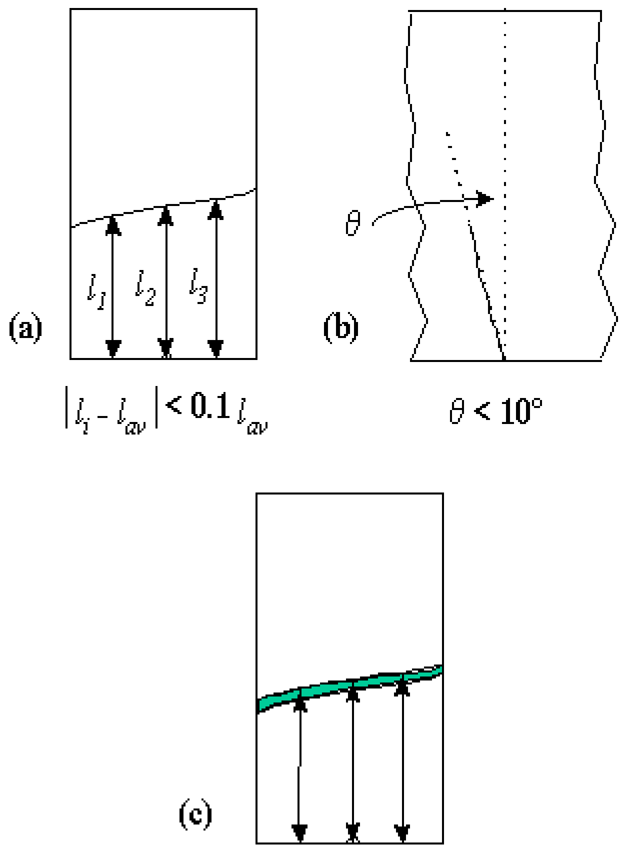

Figure 3 - Acceptable pre-crack geometry, showing criteria for (a) crack length and (b) crack plane angle, and (c) measuring crack length in the presence of subcritical growth.

3 Vee-Notched Beam (SEVNB)

3.1 Principle

A relatively recent technique is that of Vee-notching, which overcomes the problem that a round-rooted notch cannot be assumed to act as a sharp crack, especially if machining damage at the notch root induces compressive residual stresses which resist crack propagation. Vee-notching was attempted first in Japan using a specially dressed diamond-impregnated slitting wheel in which the tip radius is reduced to about 20 μm. This technique was usable [5], but expensive, since the wheel could be used only once before it blunted unacceptably. A method of overcoming this, also originating from Japan [6], but worked on in Austria [7] and Switzerland, and recently subject to an international VAMAS round robin led by EMPA, Switzerland [8], is to replace the fixed grit diamond blade with a reciprocating razor blade used with diamond paste. The razor blade self-hones in the notch while polishing away at the root and sides of the notch. With care, notch root radii as small as 2 μm can be prepared in fine-grained materials.

It is still debatable as to whether such small notch roots constitute sharp cracks for the purposes of fracture toughness determination. It has been argued [8] that if the notch root radius is smaller than the grain size, then essentially there is little distinction from a sharp crack, which forms readily once the test-piece is loaded in the test. At least, the use of fine (1 μm or finer) diamond paste for the final polishing stages will result in very little machining stress, which is one factor biasing results from machined notch tests. The recent VAMAS round robin [9] showed that for most materials the test results were very consistent and within a few percent of those for sharp-crack tests on the same materials. However, in the case of yttria partially stabilised zirconia (TZP), which has submicrometre grain size and an inherent strengthening/toughening phase transformation mechanism, slightly higher values than those for sharp crack tests are obtained. This result has in fact been correlated with notch root radius used. Nevertheless, for many conventional ceramic materials and the more-brittle hardmetals, good equivalence of results has been achieved.

3.2 Methods

The technique of notch sharpening can be performed completely manually. A set of test-pieces, say six, is glued onto a firm surface, and a starter notch typically 0.1 mm to 0.2 mm in width and 0.2 mm in depth is machined across them using a diamond wheel. This notch acts as a guide for the razor blade tip. Diamond paste, typically of 4 to 6 μm size is placed in the notch and the hand-held razor blade is reciprocated along the notch, polishing a sharp root. When this has reached a depth of about 20% of the test-piece depth, the diamond paste size is reduced, and the root sharpened further to an optimum condition. The notch root radius achieved can be checked by viewing the side of the test-pieces with an optical microscope, and measured by taking photographs at high magnification.

The manual method has some disadvantages. The end pair of the test-piece set may not be usable because the razor blade tends to rock over the set width. In addition, the hand tends to wander from the true line along the notch, and the notch tip may not develop with an optimally small radius. Also, for hard materials, it is tedious and time consuming for the operator. However, it is simple to semi-automate the technique using a horizontally reciprocating bed for the test-pieces, and a razor blade held in a vertically guided unit to which a small weight can be applied (e.g. Figure 4). Only the simplest form of construction is needed, which can be based on standard linear bearings, with the reciprocating motion achieved using a drive motor, crank and connecting rod, giving a reciprocating speed of about 1 Hz. The crucial feature is that the razor blade vertical movement is normal to the test-piece surfaces and its length is accurately aligned with the reciprocating motion such that it does not bind in the deepening notch. Another useful feature is a means of measuring vertical movement of the razor blade as notching proceeds. This gives the sum of notch depth and razor blade wear, but nevertheless is a useful guide to progress.

In use, the motion of the razor blade tends gradually to pump the diamond paste out of the notch. The blade needs to be lifted occasionally, about every five minutes, to draw paste back into the notch. Fresh paste needs to be added about every half an hour. The notch needs to be kept lubricated to avoid binding and uneven blade wear. With automation it may not even be necessary to prepare the initial guide notch.

3.3 Acceptability criteria

The notch honing process should be continued until the total notch depth is typically 15% to 25% of the test-piece depth, and the tip radius should be minimised by the use of a fine finishing grit, of size say 1 μm. The minimum root radius that can be achieved is probably related to grain size, and the popping out of whole grains during honing. Thus for medium grain size aluminas, e.g. 10 μm, the minimum experimental notch root radii are about 15 μm, but nonetheless such radii appear to be acceptable because of the easy intergranular fracture in aluminas.

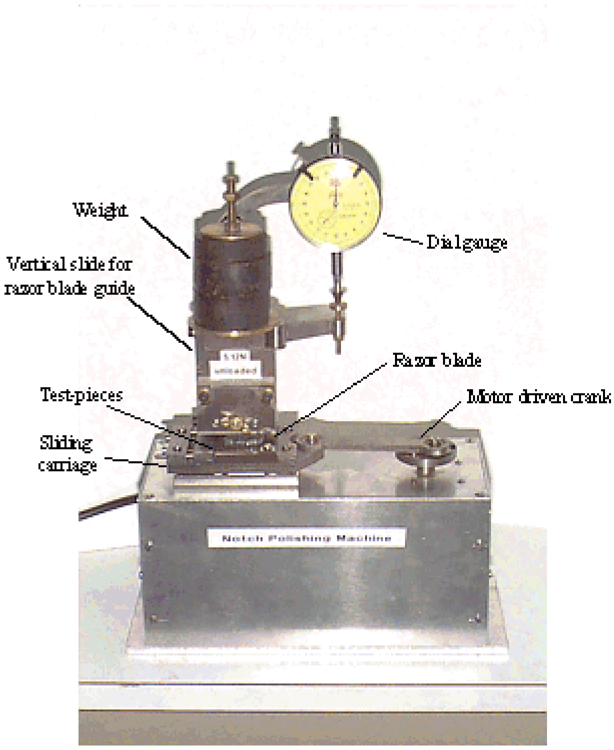

Figure 4 - Reciprocating notch honer based on a sliding table and a guided razor blade

3.4 Measuring notch length

The tip of the notch is readily identified in the microscope, both before the test on the test-piece sides, and after the test on fracture surfaces. However, as with the single-edge pre-cracked beam tests, notice should be made of any subcritical crack growth from the notch during testing, and the true notch depth plus crack length should be used for calculations of toughness.

4 Surface Crack In A Beam (SCF)

4.1 Principle

This method has been developed from Petrovic's work [9], and is now an ASTM pre-standard PS-070. Using indentation, a small semicircular crack is placed in a beam test-piece. The damage introduced by indentation is removed by machin-ing or lapping away several times the depth of the indentation to leave a nominally stress-free, pseudo-semielliptical crack in the test-piece (Figure 5a). The test-piece is then fractured, and the fracture toughness determined from the fracture force and the dimensions of the original crack using well-established equations for the stress intensity factor[3]. One virtue of the method is that the pre-crack is of similar dimensions to the naturally occurring flaws in a material.

4.2 Methods

The crucial part of the test is the indentation. To achieve this may require some experimentation on an unfamiliar material. The indentation is made preferably with a Knoop type indenter with its long axis orientated across the test-piece. A force of typically 50 N to 100 N is applied with the intention of producing a half-penny shaped radial crack under the indentation of radius about 50 µm to 100 µm. This criterion makes the test difficult to use effectively on materials which are tough, or coarse-grained, because the required shape of pre-crack may not be generated, or may not be visible on the subsequently fractured surface. However, there are some methods to improve visibility.

- If the test-piece is tilted **lengthwise** by about 0.5° before indentation (Figure 5b), the pre-crack is produced at an angle of 2° to 3° to the normal. During the subsequent fracture test, its direction reverts to normal, and the junction of the pre-crack and final fracture can then be seen more clearly as a change in fracture plane. This angular deviation introduces an insignificant error in the calculation of toughness.

- If the material is prone to producing Palmqvist type cracks, i.e. two lobes rather than a full half-penny crack, the test-piece can be tilted by 1° to 2° across its **width** (Figure 5c). This causes the up-hill lobe to be much larger than the down-hill lobe, and the former can then be used as the pre-crack. This works well for yttria partially stabilised zirconia (TZP) with the indentation force recommended to be in the range 150 N to 200 N.

The next step is the removal of the indentation damage, normally considered to run to 4.5 to 5 times the indentation depth, which can be computed as one seventh of the diagonal for a Vickers indentation, or one thirtieth of the long diagonal length of a Knoop indentation. Removal can be by a variety of methods, including hand lapping on a rotary lap, or fine grit machining, taking care not to induce significant machining stresses. Hand lapping clearly runs the risk of uneven removal across the test-piece width and of loss of cross-sectional dimensional tolerances.

4.3 Measuring the pre-crack

This requires some fractographic skills. First, the broken halves of the test-piece should be viewed together under a stereo optical microscope to check that fracture did in fact occur from the indentation flaw and not from some other pre-existing origin. Next, at higher magnification, the nature of the origin can be observed, and if appropriate photographed for measurement. However, optical microscopy has poor depth of field at the magnifications required, and it may be necessary to use the scanning electron microscope (SEM) to make observations. In this event, the type of coating applied, if any, and the accelerating voltage used can affect the image produced. It may be necessary to adjust the imaging conditions to see the pre-crack clearly. In some cases, only parts of the flaw boundary can be clearly distinguished in terms of a change in surface angle, crack propagation direction or crack surface topography. It is then necessary to use whatever observations of fracture markings can be made to construct an elliptical flaw shape, with some associated risk of error.

In fact, the computed value for toughness is not critically sensitive to measurement of either of the two elliptical axes of the flaw, because these data enter the formulation as square roots, and thus permit some leeway on flaw shape and measurement accuracies.

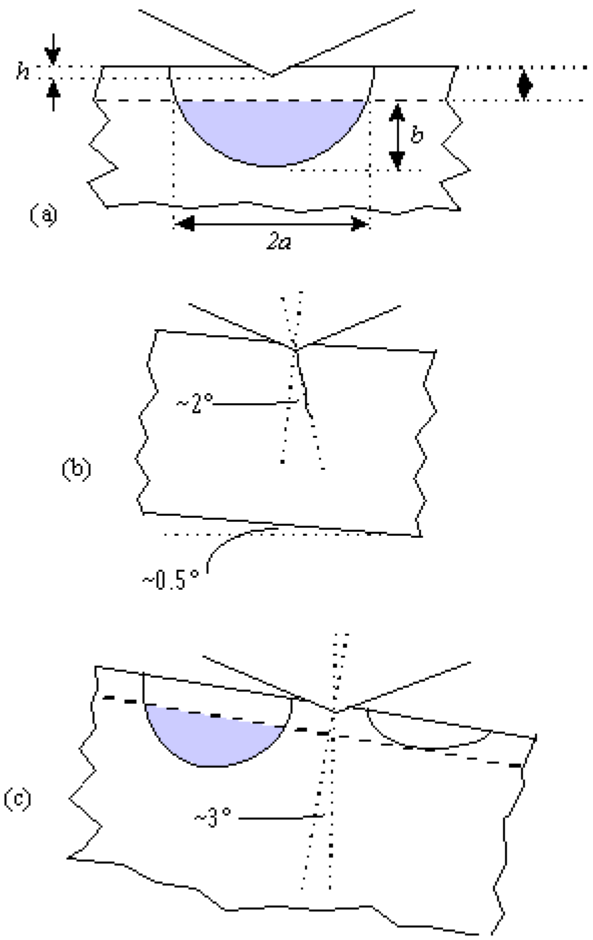

Figure 5 - Indentation for the surface flaw in flexure method: (a) normal indentation, showing depth of material removal after indentation; (b) enhancement of crack plane angle; and (c) enhancement of Palmqvist crack lobe size in tougher materials

4.4 Limitations

The technique works well if a well-defined surface flaw can be developed and measured. This is easiest for fine-grained, low-porosity materials (grain size < 3 μm, porosity < 5%) with toughness values less than 4 MPa $m^{1/2}$. For coarser grained materials, indentation cracks tend to be more irregular with directions controlled by local microstructure. The roughness of the flaw surface may be too high to see a distinct boundary. In such materials, it is advisable to increase the indentation force to make a larger flaw. Porosity may cause crushing under the indenter, rather than producing cracks. The method also seems to be impractical in most materials suffering intergranular fracture when the grain size exceeds about 10 μm. For materials of toughness greater than 4 MPa $m^{1/2}$, there is an increasing tendency for Palmqvist cracks to form. In such a case, the angled technique described above can sometimes be used to enhance one lobe at the expense of the other, but if the lobes are not deep enough, the indentation damage cannot be satisfactorily removed, leaving the flaw pre-stressed.

In terms of materials types, it is difficult to be specific about which can be tested satisfactorily, but a wide range has been cited as testable by Quinn [12]. Much depends on fractographic skills after testing. The method does not work on hardmetals because the cracks are too shallow.

5 Diamond Wedge Method (DWB)

5.1 Principle

A beam test-piece is supported on a flat anvil, and an obtuse angled diamond wedge is loaded onto the beam centre. A crack is driven into the test-piece under the tip of the wedge. After unloading, the region of damage due to indentation is removed by machining to give an essentially stress-free pre-cracked beam.

5.2 Method

This technique was developed at NPL [13] and has been used successfully on most hardmetal materials and some ceramics. The diamond wedge indenter is of polycrystalline diamond to optimise both hardness and strength, and has an obtuse angle of typically 130°. It is mounted on a stiff backing rigidly attached to the cross-head of a mechanical testing machine. The test-piece is positioned below it, with its long axis perpendicular to the apex line of the indenter. A tilting adjustment in the test-piece support anvil permits the test-piece position to be adjusted such that the apex of the diamond is exactly parallel to the test-piece upper surface. The wedge is driven downward into the test-piece (Figure 6), and the growth of a planar crack from its tip is viewed by a travelling microscope focused on one side of the test-piece. Growth is allowed to occur until the crack is 2 mm to 4 mm long in a test-piece of height 6 mm to 8 mm. The force required to do this depends on the toughness of the material, but is typically 20 kN.

Crack lengths on both sides are measured optically to check that the crack front is approximately parallel to the test-piece surface. Suitably cracked test-pieces are then machined to remove the damage zone produced by indentation, typically removing about 0.2 mm of material. Measurement after fracture is used for the true crack length for calculation purposes. For hardmetals, pre-crack faces can be stained using Murakami's reagent to make the pre-crack front more visible.

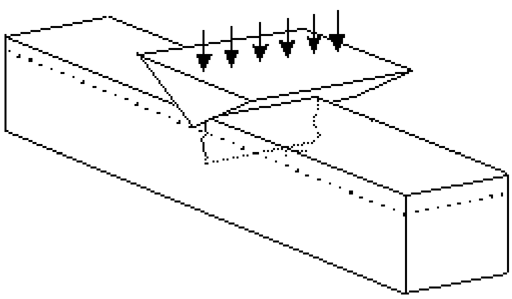

Figure 6 - Diamond wedge method

5.3 Limitations

It is believed that the technique is probably applicable only to high strength and moderate toughness materials (>3 MPa $m^{1/2}$) because other-wise there is a risk that without other mechanical constraints, test-pieces of weaker or more brittle materials may simply be split into two fragments. In higher-toughness materials (K_{Ic} > 18 MPa $m^{1/2}$), no cracking occurs under indentation because of plastic deformation. The use of sharper angled wedges has been attempted, but the test-piece tends to split unstably into two halves. The only solution for such materials appears to be to induce cracks using fatigue (see below).

6 Stressing Or Fatiguing A Notch

6.1 Principle

A number of methods have been reported for developing a sharp crack from a notch, which include those based on chevron notches, and those based on straight notches.

- A **chevron notch** comprises two angled cuts to leave a triangular shape of residual material. As this is loaded in flexure or tension, a crack grows or pops in from the tip of the triangle, and this can be grown to a sufficient length. The peak force applied during this process is itself a measure of toughness (the chevron notch beam method (CNB), e.g. ASTM PS070), but if the notch geometry is such that the test-piece can be unloaded when the crack has reached a straight-side portion of the test-piece, and then reloaded quickly, the test is equivalent to a single edge pre-cracked beam test.

- If a **straight notch** test-piece is subjected to fatigue in compression across the notch faces, a short crack will grow from the notch tip by a microstructural levering process. The test-piece can then be loaded in flexure to break it as a single-edge pre-cracked beam test.

- In tough materials, a **straight-notched** test-piece can be fatigued in flexure to grow a crack from the notch tip. The method relies on a stiff fatigue machine operating under displacement control to avoid machine compliance causing catastrophic fracture.

6.2 Methods

6.2.1 Flexural stressing of a chevron notch

The chevron method requires the machining of a chevron of about 45° semi-angle with the two cuts coplanar, leaving typically half the test-piece height uncut[4]. Ideally the notch tip should be as sharp as possible, produced by a diamond Vee-tipped blade, or a wire saw, or possibly even the razor-blade honing method. Using a stiff testing machine (in which machine compliance is small enough that it does not drive the crack unstably), the test-piece is slowly loaded in flexure until a load drop is seen. By inspection, loading can continue until the crack front passes the ends of the chevron notch into the straight sided portion of the test-piece. It is then unloaded, and reloaded more quickly to perform the fracture toughness test as in an SEPB test[5]. The effective crack length needs to be determined from a change in appearance of the crack surfaces after fracture. The unloading often produces a delineation of this event, but if not, the pre-crack must be dye penetrated to delineate the crack front, as described for the SEPB method above.

This method appears to be suitable for most ceramic materials, even those which fail to give controlled growth during crack initiation from the notch tip. Such behaviour would normally invalidate the conventional chevron notch fracture toughness test, but if the crack can be stopped the test-piece can then be validly tested using essentially the SEPB method.

6.2.2 Compression fatigue of a straight-through notch

A notch is placed in a test-piece with flat and parallel end faces, which is then subjected to axial cyclic compression to high loads between flat and parallel hard platens. The cyclic stress concen-tration at the notch tip causes a crack to initiate and grow during cycling, primarily it is thought by a residual stress wedging process when the compressive force is removed. The developed crack is quite short, a few 10's of micrometres, but is said to be adequate for the purposes of fracture toughness measurement in tough materials such as hardmetals [14].

7 Selection Of Method

7.1 Technical aspects

The choice of method depends firstly on whether it is feasible for the material in question, and secondly on whether the crack length produced is thought to be an important factor in determining a toughness value. In medium and coarse-grained materials, and in materials in which there is deliberate microstructural reinforcement via the incorporation of whiskers, platelets, or internally grown elongated grains, fracture toughness is a function of crack length. This is usually interpreted as incomplete separation of the opposing faces of the crack, which thus exert some residual forces during crack propagation, increasing the apparent toughness. This results in a rising crack resistance curve, a so-called "R-curve", as the crack lengthens. In materials showing this behaviour, the toughness may depend on the pre-crack length, with short cracks produced by, say, the surface crack method giving a lower result than a single edge planar pre-crack propagated a distance of a millimetre or more. It is recommended that, where possible, the shortest pre-crack length is used, such that the values obtained represent a minimum toughness, rather than a value that is a function of the experimental set-up. In fact, this is a key advantage of the razor blade honed Vee-notch method, because the notch faces are traction-free, and the crack length (excluding the notch length) is probably about that of a single grain.

7.2 Economic aspects

Pre-cracking, however it is done, incurs some cost and time. As a guide, Table 1 gives an approximate breakdown of the cost of specialist jigs and fixtures, the types of ancillary apparatus needed (much of which may already be in a well-equipped laboratory), the time required to pre-crack a test-piece, and the time involved in analysing the fractured test-piece, particularly measuring the size and shape of the pre-crack from fracture surfaces. Data are based on the preparation of a batch of six test-pieces by an adequately skilled operator. The cost of test-pieces is similar for all the methods, except for the compression fatigue method because additionally the test-piece ends must be machined flat, parallel and square to the length. Clearly, there will be some variations owing to rates of machining of test-piece surfaces or notches, depending on material hardness.

Table 1 - Comparison of skill levels, costs and time for pre-cracking

Method	**Skill level**	**Typical cost of special jigging**	**Other facilities needed**	**Set-up time**	**Time to pre-crack, per test-piece***	**Post-test evaluation time, per test-piece**	**Typical success rate**
Pre-cracked beam (SEPB)	High	£2000	Hardness tester or diamond saw AE detection Optical microscope	1 h	0.3 h	0.3 h	50 - 90%
Vee-notched beam (SEVNB)	Medium	£1000	Optical microscope	0.5 h	1 - 2 h	0.2 h	100%
Surface crack in flexure (SCF)	High	Low	Hardness tester SEM	0.5 h	0.5 h	1 h	Material dependent***
Pre-cracked beam using diamond wedge (DWB)	Medium	£1000	Optical microscope	0.5 h	0.5 h	0.3 h	80-100% on hardmetals 50-80% on hard ceramics
Chevron notched beam(CNB)	Medium	Low	Diamond saw Optical microscope	0.2 h	0.5 - 1 h	none	Material dependent***
Fatigued	Medium	Low	Diamond saw Fatigue test machine with	0.2 h	>> 1 h	0.2 h	Material

notch (FN)**			suitable hard-faced compression jig				dependent***

* Based on pre-cracking a batch of six

** Test-piece ends need to be flat and parallel

*** Method may not be applicable to some materials:

SCF: 80% to 100% on materials with grain size < 3 μm, typically 50% with grain size 3 μm to 10 μm, usually impossible for coarser grain sizes.

CNB: Depends on crack initiation from chevron tip, giving either controlled or uncontrolled growth. Risks of uncontrolled growth can be reduced by pre-cracking the notch tip using indentation, impact, thermal shock.

FN: Depends on factors associated with modulus, grain size, hardness and ductility.

Footnotes

1. Four-point bending is preferable to three-point bending in most flexural testing because the conditions at the crack tip are better defined by not being in a steep lateral stress gradient. In three-point bending, the crack tip may not be directly under the loading roller, and thus the applied force required to extend the crack is greater than for a correctly aligned case, and the toughness is over-estimated.

2. It has been proposed in the German DIN committee that the top anvil can usefully have a cylindrical surface with its axis parallel to the length of the test-piece. It is said that this may improve the force alignment in pre-cracking by loading down the centre-line of the test-piece, rather than contacting its entire top surface.

3. This is distinct from the indent/strength (IS) method [10] in which, following indentation, the residual stresses are not removed, but a correction factor is used to account for them in the calculation of toughness. The method has the advantage that the flaw size does not have to be measured, but relies on many assumptions concerning indentation theory, and is thus not well-based from a fracture mechanics viewpoint.

4. This is in contrast to the developing requirements for the chevron notch toughness test in which only a triangular ligament of material is left. This latter geometry is unsuitable for producing a pre-crack for the SEPB method.

5. Rates of loading for these two operations will depend on the material and its susceptibility to subcritical crack growth, and on the test-piece size and loading span. No general guidelines can be given.

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For further information contact:

R Morrell
Centre for Materials Measurement and Technology
Tel: 020 8943 6381
Fax: 020 8943 2989
Email: Roger.Morrell@npl.co.uk
Experts Link to Expert

National Physical Laboratory
Queens Road
Teddington
Middlesex
United Kingdom
TW11 0LW

Tel: 020 8977 3222
Fax: 020 8943 6458
Email: materials@npl.co.uk

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