



Title	Effect of notch root radius on fracture toughness of polycrystalline cubic boron nitride
Authors(s)	Carolan, Declan, Alveen, Patricia, Ivankovic, Alojz, et al.
Publication date	2011-12
Publication information	Carolan, Declan, Patricia Alveen, Alojz Ivankovic, and et al. "Effect of Notch Root Radius on Fracture Toughness of Polycrystalline Cubic Boron Nitride." Elsevier, December 2011. https://doi.org/10.1016/j.engfracmech.2011.08.003 .
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/4775
Publisher's statement	This is the author's version of a work that was accepted for publication in Engineering Fracture Mechanics. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Engineering Fracture Mechanics (78, 17, (2011)) DOI: http://dx.doi.org/10.1016/j.engfracmech.2011.08.003
Publisher's version (DOI)	10.1016/j.engfracmech.2011.08.003

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Effect of Notch Root Radius on Fracture Toughness of Polycrystalline Cubic Boron Nitride

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Abstract

The fracture toughness of five grades of polycrystalline cubic boron nitride (PCBN) has been determined using Single Edge V-Notched Beam specimens. Both coarse and fine grade materials were considered, containing CBN grain sizes of between 1 μm and 22 μm . The influence of notch root radius on the measured fracture toughness was examined. The notch root radius was found to have a major effect for materials with smaller CBN grain sizes while only a small effect was noted for the material with large CBN grain sizes. A simple analytical model was developed to explain the effect of the notch root radius on the fracture toughness and was found to agree well with experiment for all the materials tested. It was shown that the effect of notch root radius is directly linked to the size of the CBN grain. It is proposed that this effect results from the interaction between the microstructure and the stress field around the notch tip.

Keywords: Cubic Boron Nitride, fracture testing, notch root radius

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Nomenclature

α a/h ratio, ratio of initial crack length to thickness of specimen

Δa crack extension

σ remotely applied stress

σ_c critical stress

σ_{yy} stress in vicinity of notch

a initial crack length

b breadth of specimen

d grain size

h thickness of specimen

K_b measured (apparent) fracture toughness

K_I mode I stress intensity factor

K_{bi} measured (apparent) fracture toughness of test i

K_{bn} measured (apparent) fracture toughness of test n

K_{Ic} critical fracture toughness

L length of specimen

m rate of change of K_b with $R^{1/2}$, a notch sensitivity parameter

P_{in} fracture initiation load

R notch root radius

r distance from the notch tip

r_c critical distance

R_i notch root radius of test i

R_n notch root radius of reference test n

S span of three point bend test

1. Introduction

Polycrystalline Cubic Boron Nitride (PCBN) is a super hard material used in the machining of hardened steels, aerospace grade alloys and other abrasive materials [1, 2, 3]. Typical applications of these tools are characterised by high operating temperatures, abrasion and impact loading. This can lead to undesirable and premature brittle fracture of the tool. Accurate determination of the fracture toughness of PCBN under a wide range of loading rates and temperatures is therefore essential in order to evaluate the performance of the tool under these highly demanding operating conditions.

One of the major problems encountered in the fracture toughness testing of ceramics and other hard materials is the difficulty in reliably introducing reproducible sharp cracks [4]. In metals, fatigue cracks are first initiated and grown in a controlled manner. This has proved difficult to achieve without a high loss of material in both ceramics and super-hard materials as the fatigue threshold stress is very close to the fracture stress [5]. A number of techniques which have been applied include the use of Chevron Notched Beam

(CNB) samples [6], indentation micro-fracture [7], notched Brazilian disk compression test [8, 9], double torsion test [10] and Single Edge V-Notched Beam (SEVNB) with a sharpened notch introduced via a honing procedure [11, 12, 13]. This latter technique consists of introducing a relatively blunt notch via a conventional machining process and, subsequently sharpening it with a razor blade, embedded in a diamond paste, to produce a much finer notch with a very sharp root radius [14].

Damani et al. [11] and Nishida et al. [15] showed that for a dense polycrystalline ceramic, a notch root radius smaller than $10 \mu\text{m}$ can simulate a sharp crack. Kübler [16] proved empirically that measured SEVNB fracture toughness values can be considered true if the radius of curvature of the notch root is smaller than twice the characteristic length of a major microstructural feature confirming the analytical findings of Atzori and Lazarrin [17]. For PCBN, this can correspond to the CBN grain size. For values above this critical notch root radius, R_0 , the measured fracture toughness is observed to increase linearly with $R^{1/2}$ where R is the notch root radius [11]. Below this critical notch root radius, the critical fracture toughness is measured and is independent of notch root radius. Mathematically this is expressed as:

$$\begin{aligned} K_b &= K_{Ic} & R &\leq 2d \\ K_b &= K_{Ic} + m(R - 2d)^{1/2} & R &> 2d \end{aligned} \tag{1}$$

where K_b is the experimentally measured apparent fracture toughness, K_{Ic} is the material fracture toughness, R is the radius of the notch tip and d is the microstructural grain size. The slope, m , can be interpreted as the sensitivity of the material to overestimation of fracture toughness.

2. Materials and methods

Five commercially available grades of PCBN were used in the present work. The grades and their associated CBN grain sizes are given in Table 1. The binder materials in all grades examined were a variety of different ceramic phases. It is important to note that the binder composition and concentration varied from grade to grade. The material was sintered in cylindrical discs of height 4.76 mm in a high pressure high temperature chamber. Rectangular bar specimens with the dimensions shown in Table 2 were then cut from these discs using a laser. A notch was then machined in to the specimen as shown in Figure 1. A nominal notch root radius of $150\ \mu\text{m}$ was cut into both PCBN A and PCBN B, while notch root radii of 115, 200 and $400\ \mu\text{m}$ were machined into each of PCBN C, D and E.

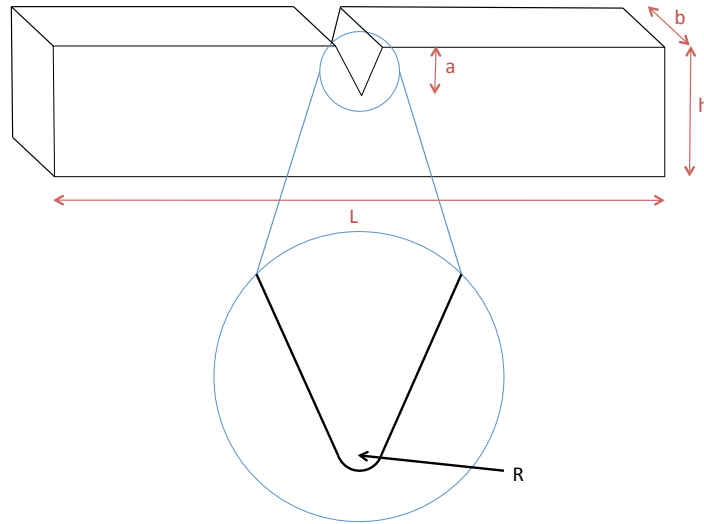


Figure 1: SEVNB test specimen geometry

From the available batch of samples for each grade of material, several

Grade	Grain size [μm]
PCBN A	22
PCBN B	1
PCBN C	1.5
PCBN D	3
PCBN E	3

Table 1: Nomenclature of PCBN grades and associated CBN grain sizes investigated in the current work

Dimension	mm
Length (L)	28.5
Span (S)	25.0
Thickness (h)	6.25
Breadth (b)	4.76
Notch Depth (a)	1.25

Table 2: Nominal dimensions of the PCBN specimens used for fracture toughness testing

specimens were chosen for notch sharpening. A reciprocating razor blade in a diamond grit slurry was used to hone out a sharp notch along the base of the machined notch. The design of the machine is similar to that outlined by Fischer et al [18]. The sharpness of the razor blade was constantly monitored and blunt razor blades were changed as necessary, approximately every 15 minutes for the duration of the operation, which typically lasted between two and four hours per specimen. On completion of the procedure each sample was cleaned in an ultrasonic bath to remove any diamond grit still embedded in the notch tip. Notch root radii (R) and initial crack lengths (a) were then measured using both optical and scanning electron microscopy. The effect of the honing procedure on the notch root radius can be seen in Figure 2. In addition to this, further samples were sectioned, polished and examined using SEM for pre-existing defects which may influence the measured fracture toughness. No major defects were noted for either of the materials examined.

Fett [19] has shown that the stress distribution around the sharper notch or small crack can be influenced by the presence of the blunter notch if $\Delta a/R < 1.5$, where Δa is the extension to the initial machined notch achieved during the honing process. This is shown clearly in Figure 2 (a). The smallest radius achieved from the honing process was $5.7 \mu\text{m}$ while the largest radius achieved was $22.6 \mu\text{m}$. The variation in honed notch root radii was attributed to the difficulty in controlling the precise position of the razor blade between microscope observations of notch depth.

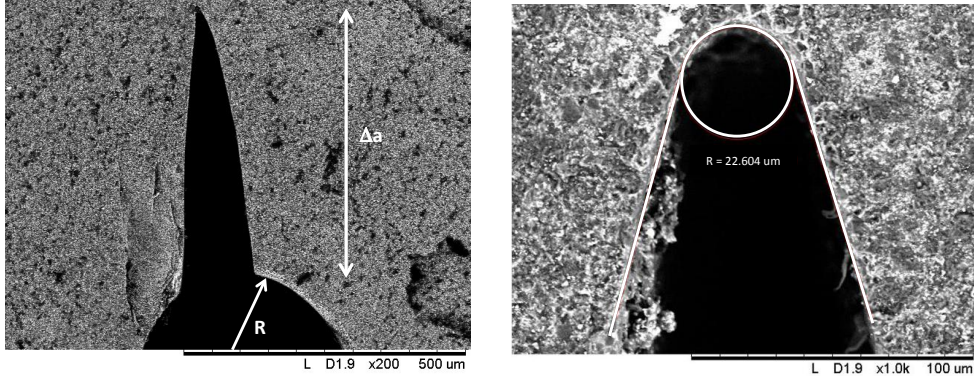
Fracture tests were performed in three point bending in a low rate tensile testing machine at room temperature. Crosshead displacement rate was kept constant at $1\text{mm}/\text{min}$. The fracture toughness was evaluated using the load

at initiation method in accordance with the British standard for measuring fracture toughness of ceramics [20]. This method is valid for low rates of loading and assumes that the peak load corresponds to the fracture load. The equation to calculate fracture toughness is given as:

$$K_{Ic} = \frac{P_{in}S}{bh^{\frac{3}{2}}}f(\alpha) \quad (2)$$

where S is the span, P_{in} is the fracture initiation load, b is breadth of specimen, h is height of specimen, $\alpha = a/h$, where a is initial crack length and f is given by Equation (3), as follows:

$$f(\alpha) = \frac{3\alpha^{\frac{1}{2}}[1.99 - \alpha(1 - \alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)]}{2(1 + 2\alpha)(1 - \alpha)^{\frac{3}{2}}} \quad (3)$$



(a) Mag. times 200

(b) Mag. times 1000

Figure 2: (a) SEM micrograph of honed notch in PCBN B showing the original notch at the bottom of the figure. Here, the notch root radius was determined to be $22.6 \mu\text{m}$. A close up of the notch tip can be seen in (b).

3. Analytical Prediction of Blunt Notch Fracture

Many, simple yet accurate criteria exist for prediction of the rupture loads of brittle, V-notched samples. An extensive review of these criteria is given by Gomez et al. [21]. In the case of PCBN the most useful estimate of the effect of notch root radius is given by considering the elastic stress σ_{yy} at a small distance from the tip of an elliptical notch of minor axis $2b$ and major axis $2a$. The radius of curvature is then $R = b^2/a$. By using the solution for stresses around an elliptical hole [22, 23]:

$$\sigma_{yy} = \sigma a^{\frac{1}{2}} \frac{2R + 2r}{(R + 2r)^{\frac{3}{2}}} \quad (4)$$

where σ is the stress remotely applied normal to the notch and r is the distance from the notch tip as outlined in Figure 3. For a sharp notch $R = 0$ and Equation (4) reduces to:

$$\sigma_{yy}(2\pi r)^{\frac{1}{2}} = \sigma(\pi a)^{\frac{1}{2}} \quad (5)$$

and the stress intensity factor for the crack tip region can be defined as:

$$K_I = \sigma_{yy}(2\pi r)^{\frac{1}{2}} = \sigma(\pi a)^{\frac{1}{2}} \quad R = 0 \quad (6)$$

As pointed out by Williams and Hodgkinson [24], a possible interpretation of the K_{Ic} fracture criterion is that $\sigma_{yy} = \sigma_c$ and $r = r_c$ at fracture. Essentially this criterion states that fracture occurs when the stress at some characteristic distance ahead of the crack tip exceeds the intrinsic strength of the material, as illustrated schematically in Figure 4. The value of σ_c and r_c should be independent of the geometry as explained by Susmel and Taylor [25] using the theory of critical distances and earlier work by Neuber [26].

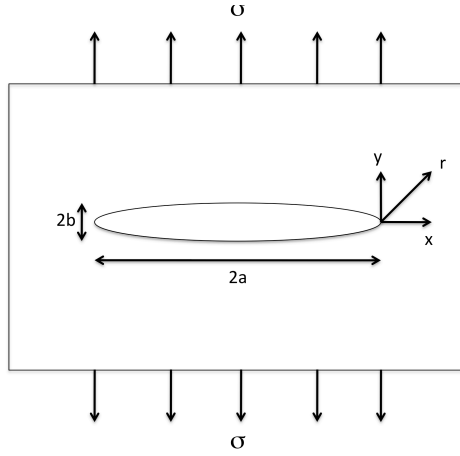


Figure 3: Elliptical hole in a plate

For a sharp crack it is not necessary to separate σ_c and r_c from the product $K_{Ic} = \sigma_c(2\pi r_c)^{1/2}$. If fracture is considered to occur from a blunt notch then from Equation (4) above:

$$K_{Ic} = \sigma_c(2\pi r_c)^{\frac{1}{2}} = \sigma(\pi a)^{\frac{1}{2}} \frac{1 + \frac{R}{r_c}}{\left(1 + \frac{R}{2r_c}\right)^{\frac{3}{2}}} \quad (7)$$

Notice that r_c now appears explicitly with R . Equation (7) is valid only for a centre cracked plate. For an edge crack it is necessary to introduce a shape factor to reflect the different boundary conditions at the free edge. In a parallel argument to that outlined by Williams and Hodgkinson [24], an apparent fracture toughness K_b for a blunt notch can be defined:

$$K_b = \sigma(\pi a)^{\frac{1}{2}} \quad (8)$$

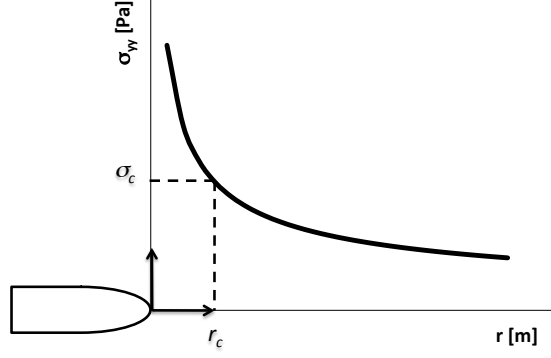


Figure 4: Schematic showing typical stress distribution ahead of a notch tip

then, following from Equation (7), K_b can be expressed as a product of K_{Ic} and a geometric function of R and r_c [21, 27]:

$$K_b = K_{Ic} \frac{\left(1 + \frac{R}{2r_c}\right)^{\frac{3}{2}}}{1 + \frac{R}{r_c}} \quad (9)$$

In the absence of prior knowledge of K_{Ic} , and r_c , it is possible to normalise any test data, i , to a reference test n as follows:

$$\left. \begin{aligned} K_{Ic} &= K_{bi} \frac{1 + \frac{R_i}{r_c}}{\left(1 + \frac{R_i}{2r_c}\right)^{\frac{3}{2}}} & R &= R_i \\ K_{Ic} &= K_{bn} \frac{1 + \frac{R_n}{r_c}}{\left(1 + \frac{R_n}{2r_c}\right)^{\frac{3}{2}}} & R &= R_n \end{aligned} \right\} \Rightarrow \frac{K_{bi}}{K_{bn}} = \left(\frac{1 + \frac{R_i}{2r_c}}{1 + \frac{R_n}{2r_c}}\right)^{\frac{3}{2}} \frac{1 + \frac{R_n}{r_c}}{1 + \frac{R_i}{r_c}} \quad (10)$$

The choice of the reference test, n , is not critical. This eliminates K_{Ic} and it remains to solve Equation 10 for r_c for each data point obtained from the experiments. The value of r_c for each experiment can be found for each experimental data point by solution of Equation (10) using an appropriate numerical procedure.

Equation (9) presented is the maximum circumferential stress criterion proposed by Ritchie et al. [27] and reviewed by Gomez et al. [21]. Gomez et al. also propose a simpler criterion, which can be written as:

$$K_b = K_{Ic} \sqrt{1 + \frac{R}{8r_c}} \quad (11)$$

Additionally, an even more sophisticated relation was proposed by Gomez and Elices [28] for analysing the apparent fracture toughness of ceramic samples with V-shaped notches where the notch angle is large. In the current work the notch opening angle is sufficiently small as not warrant the use of this more complicated relation.

A plot of Equations (9) and (11) is given in Figure 5. It can be seen in Figure 5 that while the agreement between Equations (9) and (11) is satisfactory for large values of R/R_c a significant discrepancy exists at lower values. Since many of the experimental results in the current work lie within the region of highest discrepancy, the slightly more complicated criterion expressed by Equation (9) will be used.

In the current work it will be shown that r_c can be taken a priori to be the CBN grain size. This is not the case for the analysis of other ceramic materials where the critical distance is not known beforehand.

4. Results and Discussion

A total of 46 samples were tested in the current work. The notch root radii varied from 5.7 μm to 411 μm . The relationship between measured fracture toughness and notch root radius is presented in Figure 6. Typical load displacement traces for blunt and sharp notches in the case of PCBN

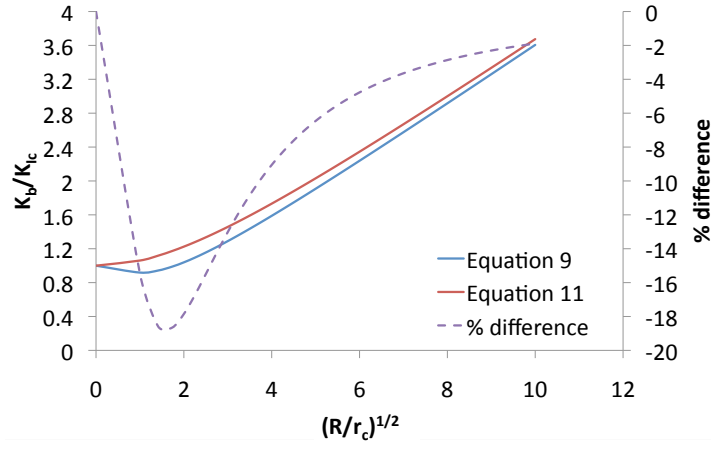
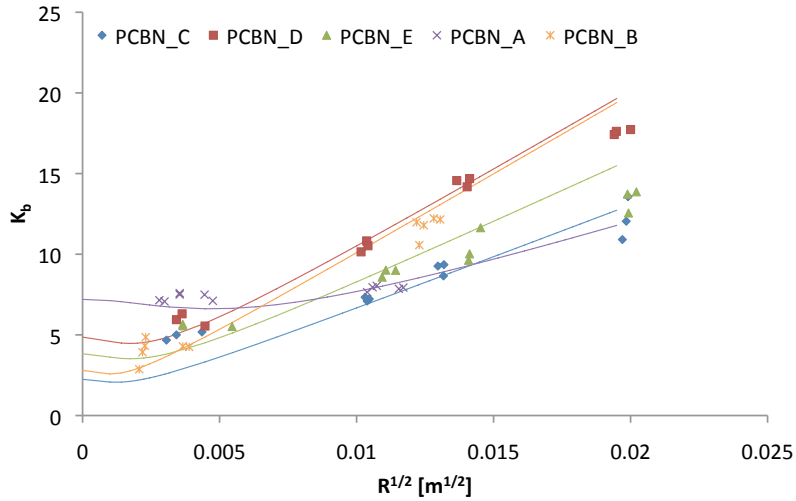
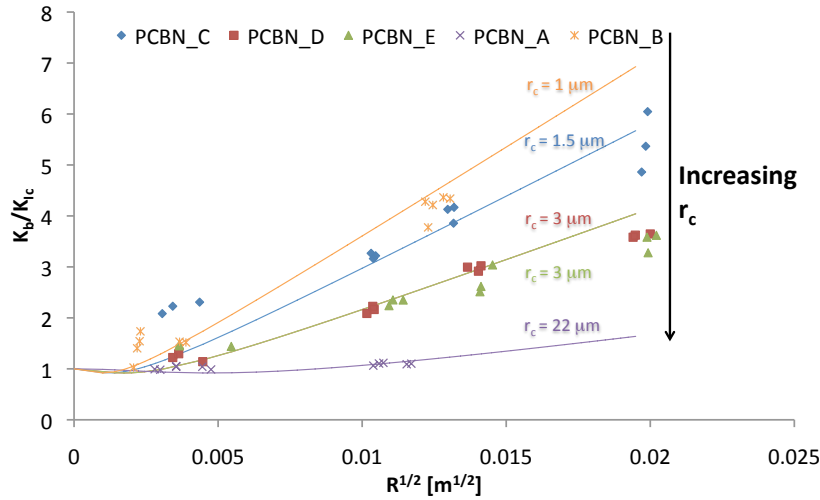


Figure 5: Maximum circumferential stress criterion (Equation 9) and simpler failure criterion proposed by Gomez et al. (Equation 11)

A and PCBN B are given in Figure 7. It should be noted that due to the extreme stiffness of the material being tested, upwards of 90% of the crosshead displacement recorded during each test was directly attributable to the compression of the loading and support jigs. Since the load at initiation fracture analysis only requires the peak load, no attempt was made to correct the load displacement traces for machine compliance. Clearly the fracture toughness of fine grained PCBN is highly dependent on the notch root radius while only a small effect of notch root radius on measured fracture toughness was observed for the coarser grained PCBN. SEM images of the fracture surfaces for the coarsest and finest grades of material for both as-machined and honed notches are given in Figures 8 and 9. A decrease in sensitivity of notch root radius to the measurement of apparent fracture toughness was noted with increase in CBN grain size. The analytical solutions plotted in Figure 6 assume that the critical distance, r_c is equal to the given CBN grain



(a) Fracture toughness of PCBN as function of the square root of notch root radius.



(b) Normalised fracture toughness of PCBN as a function of the square root of notch root radius.

Figure 6: Fracture toughness of PCBN as a function of the square root of notch root radius. A strong effect of notch root radius can be observed for fine grained PCBN while less effect was noted for the coarser grained materials. In each case the critical distance, r_c , is equal to the CBN grain size for that material.

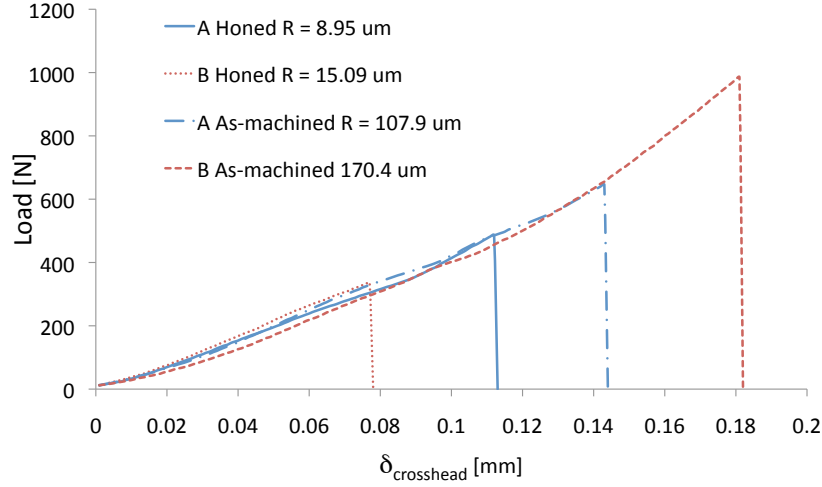
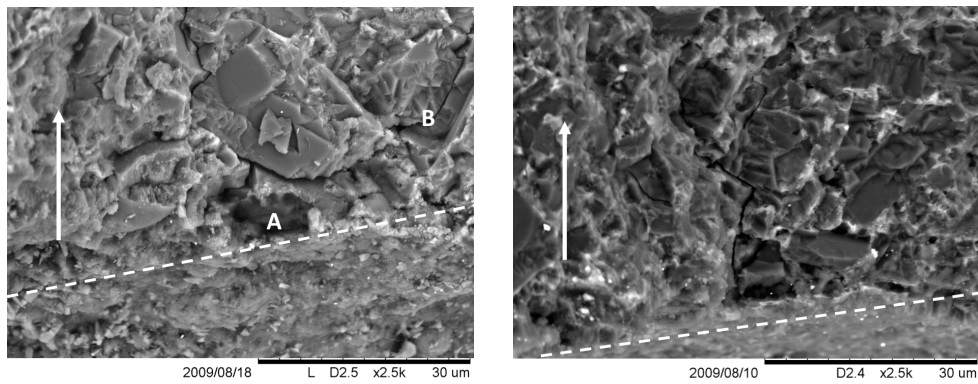


Figure 7: Typical load versus crosshead displacement traces for blunt and honed notch fracture toughness test for PCBN A and B. Crosshead displacement was 1 mm/min in all cases.

size. This shows quite good agreement with the experimental results.

Further to this, if one reconsiders Equation (9) and normalises the notch root radius with respect to the CBN grain size, all of the experimental fracture data should fall on one key curve. This is shown clearly in Figure 11 where the normalised fracture toughness, K_{Ic}/K_b is plotted with respect to normalised NRR, R/r_c . The poor agreement of PCBN C with the analytical model for the honed notches can be attributed to the quality of the honed notches. This is illustrated in Figure 10, which shows that insufficient extension of the notch was achieved during the honing process.

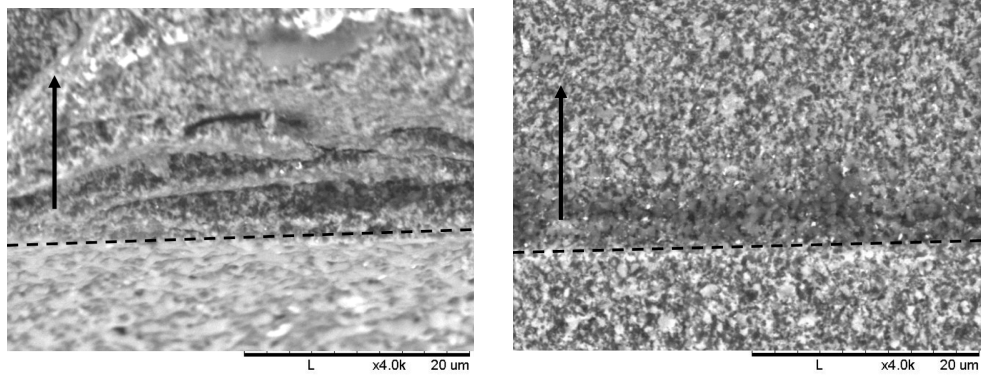
The critical fracture toughness can be estimated via the technique outlined by Equation (10). The critical fracture toughness values for each of the materials tested are given in Table 3. This shows a general decrease in



(a) As-machined notch

(b) Honed notch

Figure 8: Crack initiation region of PCBN A for (a) as-machined notch and (b) honed notch. The dashed line indicates the position of the notch tip while the arrow indicates the direction of crack propagation. There is evidence of micro-cracking in the binder surrounding the PCBN grains. Fracture is primarily inter-granular as evidenced by the voids left by grains at A and B. The fracture morphology is similar for both samples.



(a) As-machined notch

(b) Honed notch

Figure 9: Crack initiation region of PCBN B for (a) as-machined notch and (b) honed notch. The dashed line indicates the position of the notch tip while the arrow indicates the direction of crack propagation. There is considerably more damage in the notch tip region for (a) than for (b).

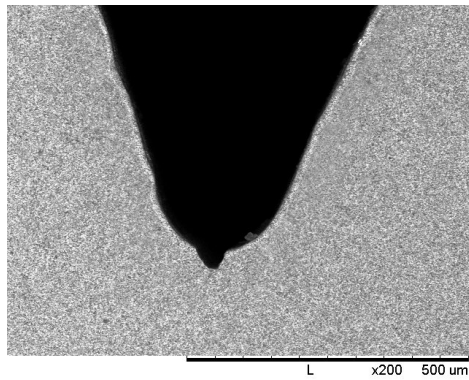


Figure 10: SEM micrograph of honed notch for PCBN C. Insufficient extension of the honed notch ahead of the blunt notch can be clearly seen.

fracture toughness with decreasing CBN grain size. However, the differences in binder volume fraction and also in binder constituents between the five grades investigated, preclude a direct comparison between each grade. It is of interest to note that the lower critical fracture toughness measured for the smaller grain size material than for the large grained material disagrees with the findings of Lammer [9], who found that the fracture toughness of polycrystalline diamond was inversely proportional to grain size.

Figure 11 plots the square root of the non-dimensional notch root radius, R/r_c versus the non-dimensional fracture toughness, K_b/K_{Ic} for Equation (9). This clearly demonstrates that the overestimation of fracture toughness from a blunt notch specimen is purely geometric in origin. Gomez et al. [21] have previously determined a master curve using Equation (11). They plot the non-dimensional notch root radius on a logarithmic scale versus non-dimensional fracture toughness. Figure 12 reproduces the master curve of Gomez et al [21], overlaying the experimental data from the current work, in colour, and the analytical solution given by Equation (9). The central black line is the solution to Equation (11) and $l_{ch} = 2\pi r_c$. Comparison of Figures 11 and 12 show the advantages of plotting the square root of non-dimensional notch root radius on the abscissa. At large values of R/r_c the curve approaches a line with slope $\sqrt{1/8}$ thus making it a relatively simple procedure to graphically interpolate the value of K_{Ic} from measurements made on blunt notches if the critical distance is known beforehand.

Table 3 also gives the best fit r_c values based on Equation 10. In each case it can be seen that the value is very close to the CBN grain size. It was not possible to pick a unique value of r_c to fit the model for PCBN A.

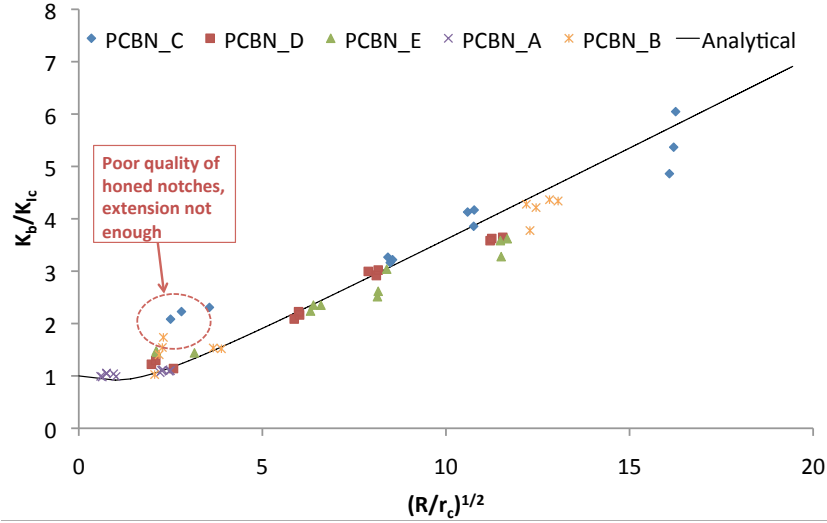


Figure 11: Master curve of non-dimensional fracture toughness versus notch root radius for PCBN material.

The large grain size (and consequently r_c) of PCBN A in comparison to the others examined means that even at large values of R , K_b is close to the theoretical critical value of K_{Ic} . A suitable plot of the relation, shown in Figure 13, as described by Equation (9) after Williams and Hodgkinson [24] explains the reason for this. The relation described in Equation (9) predicts a drop in fracture toughness below K_{Ic} for $R/r_c < 3.4$ and an approximately linear relationship of $(K_b/K_c)^2$ for increasing R/r_c . The drop in fracture toughness arises from the fixed-distance assumption of the analysis. It is necessary to assume that K_b remains constant for $R < 3.4r_c$ as the minimum value for fracture toughness in Figure 13 has no physical meaning. K_b can be reasonably represented by the bilinear approximation shown in Figure 13. The fraction on the right hand side of Equation (9) is equal to unity for $R/r_c = 0$ and $R/r_c \approx 3.4$. For values of $R/r_c > 3.4$ the curve increases

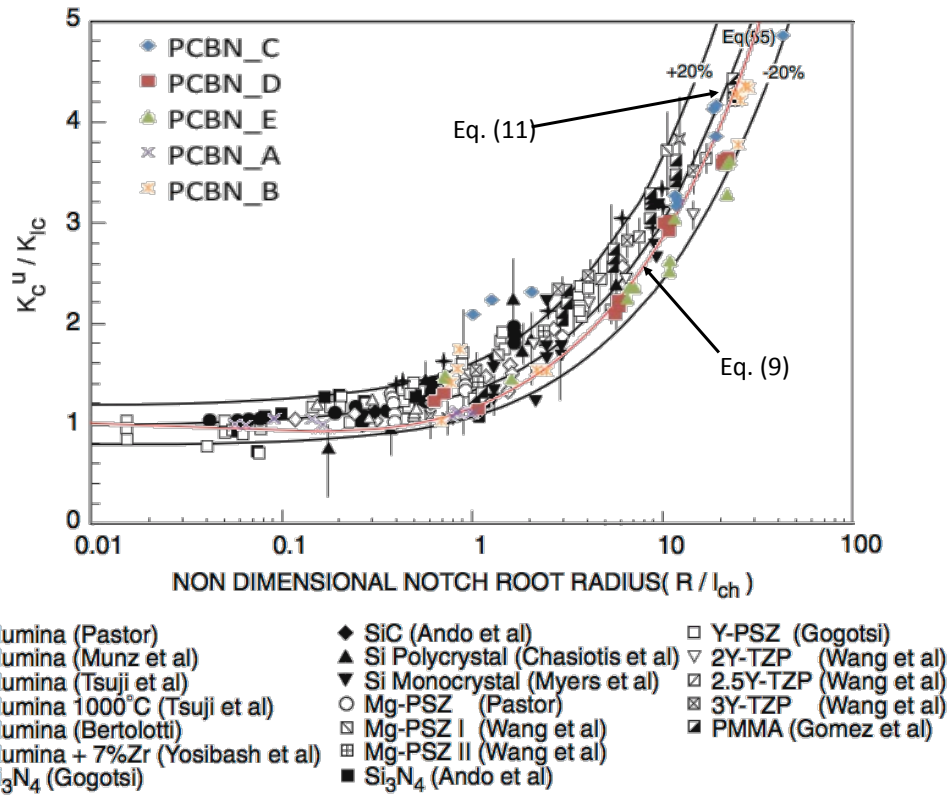


Figure 12: Gomez et al. [21] master curve with current experimental data overlaid. Very good agreement is achieved with the existing data. Appropriate references to the other experimental data can be found in [21].

monotonically tending towards a slope of $\sqrt{1/8}$ as predicted by Gomez et al. [21] using Equation (11).

This is analagous to the empirically noted increase in fracture toughness with the square of notch root radii of other authors [11, 15] and also the analytical findings of Atzori and Lazarrin [17] and Atzori et al. [29] who found that for the case of a central notch or an edge notch in an infinite plate, failure is controlled by the stress intensity factor of the crack when $R < 4r_c$ or $R < 3.2r_c$ respectively. Since the CBN grain size for PCBN A is $22 \mu\text{m}$, the available experimental data for this study falls within the region of $0.3 < R/r_c < 5.5$, which is in the region where the errors introduced by the fixed distance assumption in the model are at their greatest. However, since the grain size is relatively large a critical notch would need to have a maximum root radius of $44 \mu\text{m}$ according to Kübler [16]. It would be a trivial matter to machine a notch using conventional tooling such that it fits Küblers empirical criterion and there would be no need to analyse experimental data using the procedure outlined in this work to determine the critical fracture toughness.

Grade	K_{Ic} [MPa m ^{1/2}]	Grain size [μm]	r_c [μm]
PCBN A	7.7	22	n/a
PCBN B	2.8	1	0.97 ± 0.34
PCBN C	2.2	1.5	1.47 ± 0.56
PCBN D	4.9	3	3.15 ± 0.43
PCBN E	3.8	3	3.04 ± 0.27

Table 3: Estimated critical fracture toughness and CBN grain size of PCBN

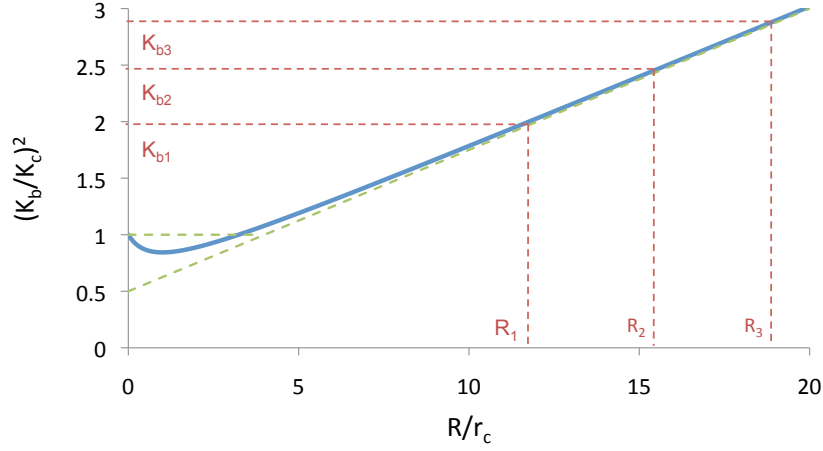


Figure 13: The effect of notch tip radius on apparent fracture toughness

This leads to a new possibility for determining the critical fracture toughness of ceramics and brittle materials. When the material being tested has critical microstructural features which are so fine that existing manufacturing techniques cannot produce a notch sharp enough to replicate a sharp crack or, if the material is particularly resistant to machining, as in the present study, it may be possible to calculate the fracture toughness via testing of blunt notched specimens. A minimum of 3 different blunt notch radii should be tested and the notch root radii should be chosen such that $R > 3.4r_c$. This is so as to avoid the errors introduced by the model at low values of R/r_c . It is important to note that for PCBN material the critical distance, r_c , can be taken beforehand to be equal to the CBN grain size. The blunt notch fracture toughness values, K_b , should all fit Equation (10) with a common value of r_c . It remains then to calculate K_{Ic} via Equation (9).

The fracture process for PCBN A is primarily inter-granular accompanied by extensive micro-cracking adjacent to the path of main crack propagation.

This micro-cracking appears to be the primary method of energy dissipation. This is evident in both as-machined and honed specimens, as shown in Figure 8. The fracture surface for the as-machined PCBN B has extensive damage on a macro scale in the initiation region, as shown in Figure 9 (a). This contrasts sharply with the fracture surface in the initiation region for the honed material shown in Figure 9 (b), which is very smooth with no obvious damage. This indicates that the notch root radius was suitably small so as to simulate a sharp crack.

The dependence on notch root radius can be further explained in terms of the material microstructure. In the case of PCBN A, the coarsest grade, the size of the CBN grain is of the same order of magnitude as the as-machined notch, as shown schematically in Figure 14 (a). There are only a small number of grains in the highly stressed region surrounding the notch tip. When a smaller notch is honed in the material, the amount of CBN grains interacting in the fracture process zone at the notch tip is not significantly affected, Figure 14 (b).

The microstructure of PCBN B, the finest CBN grade material, indicates, however, that the smaller CBN grain size may play an important role in explaining the reduction in fracture toughness from as-machined notches and honed notches. The grain size of PCBN B is an order of magnitude smaller than the as-machined notch as shown in Figure 15 (a). A honed notch with a smaller notch root radius will have significantly fewer CBN grains interacting with the fracture process zone, as shown in Figure 15 (b).

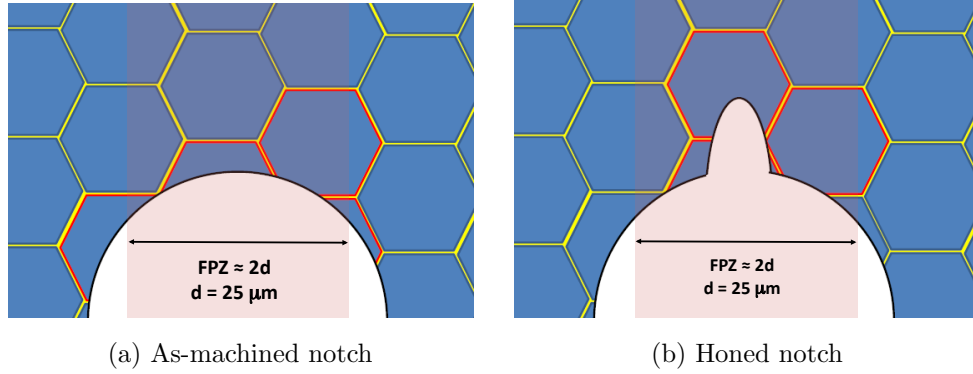


Figure 14: Schematic of microstructure of coarse grained PCBN for (a) as-machined notch and (b) honed notch showing interaction of grains and binder with the stress field in the vicinity of the notch tip.

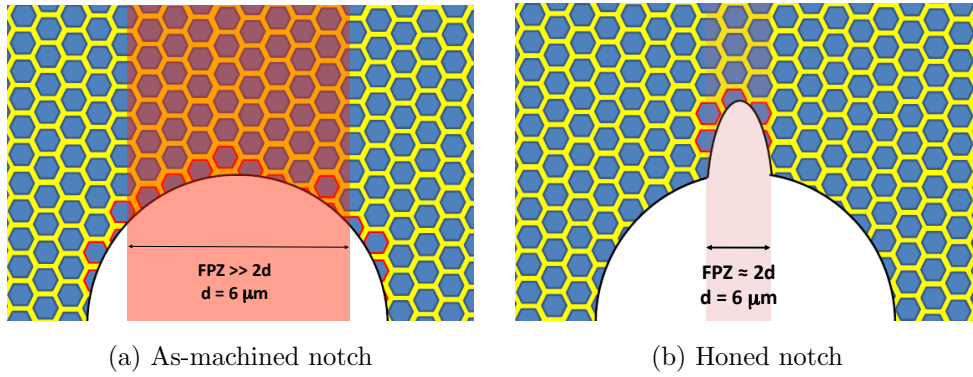


Figure 15: Schematic of microstructure of fine grained PCBN for (a) as-machined notch and (b) honed notch showing interaction of grains and binder with the stress field in the vicinity of the notch tip.

5. Conclusions

It has been shown that the measured initiation fracture toughness of polycrystalline cubic boron nitride in Single edge V-Notched Beam configuration is dependent on the notch root radius. The extent of the notch root radius dependence was observed to decrease with increasing grain size. The estimated critical fracture toughness for PCBN was found in general to be larger for coarser CBN grain microstructure. Fracture toughness values of five grades of material ranged from $2.2 \text{ MPa m}^{1/2}$, $d = 1.5 \text{ }\mu\text{m}$, to $7.7 \text{ MPa m}^{1/2}$, $d = 22 \text{ }\mu\text{m}$.

Further to this, a simple analytical model based on Inglis' classical solution for the stress distribution around an elliptical hole was found to agree well with the experimental data for a given critical distance. In addition, the best fit critical distance was found to be remarkably close to the given CBN grain size. The model was originally employed to explain the phenomenon of thermal blunting in polymer impact tests and has previously been applied to predict the failure of ceramic components with blunt notches. The agreement with PCBN materials is quite striking. This is not surprising given the definite size distribution and regularity of the CBN particles in the PCBN microstructure as opposed to the more variable microstructure one would encounter in a ceramic specimen, The model indicates that the observed change in fracture toughness can be explained solely by the change in geometry between the notch root radii of the specimens.

The dependence of the measured fracture toughness of PCBN on the notch root radius agrees with previous work on ceramics and both critical notch root radius and fracture toughness values have been determined for

this type of material. A larger notch root radius will systematically overestimate the value of fracture toughness. However, the technique currently employed for sharpening notches in PCBN is both time and labour intensive, upwards of 4 hours per sample, and does not lend itself to routine testing of large numbers of samples. The new, three blunt notch, approach proposed in this work would be of particular use for extremely fine grained materials or super hard materials which present particular difficulty in producing an adequately fine notch to satisfy the linear elastic fracture mechanics criterion. The approach would also find application in accurately determining the critical fracture toughness of a material where the relationship between r_c and the grain size of the material is not known beforehand.

6. References

- [1] Heath PJ. Properties and uses of Amborite. *Carbide and Tool Journal* 1987;19(2):12–22.
- [2] Fleming M, Wickham A. PCBN in the automotive industry. *Industrial Diamond Review* 2006;2:26–32.
- [3] Cook MW, Bossom PK. Trends and recent developments in the material manufacture and cutting tool application of polycrystalline diamond and polycrystalline cubic boron nitride. *International Journal of Refractory Metals and Hard Materials* 2000;18:147–52.
- [4] Morrell R. Fracture toughness testing for advanced technical ceramics: internationally agreed good practice. *Advances in Applied Ceramics* 2006;105(2):88–98.

- [5] Achilles RD, Bronsted P. Development of a procedure for fatigue crack growth in PCD. Proceedings of the 2nd International Industrial Diamond Conference, Rome 2007.
- [6] Amin KE. Toughness, Hardness and Wear. In: Engineered Materials Handbook Vol. 4: Ceramics and Glasses. Metals Park, OH: ASM International; 1991, 599 – 609.
- [7] D'Evelyn MP, Taniguchi T. Elastic properties of translucent polycrystalline cubic boron nitride as characterised by the dynamic resonance method. *Diamond and Related Materials* 1999;8:1522–6.
- [8] Sheity DK, Rosenfield AR, Duckworth WH. Fracture toughness of ceramics measured by a chevron-notch diametral compression test. *Journal of the American Ceramic Society* 1985;68:325–7.
- [9] Lammer A. Mechanical properties of polycrystalline diamonds. *Materials Science and Technology* 1988;4:949–55.
- [10] Lin TP, Cooper GA, Hood M. Measurement of the fracture toughness of polycrystalline diamond using the double-torsion test. *Journal of Materials Science* 1994;29:4750–6.
- [11] Damani R, Gstrein R, Danzer R. Critical notch-root radius effect in SENB-S fracture toughness testing. *Journal of the European Ceramic Society* 1996;16(7):695–702.
- [12] Gogotsi GA. Fracture toughness studies on V-notched ceramic specimens. *Strength of Materials* 2000;32:81–5.

- [13] Rocha CV, daCosta CA. Effect of notch-root radius on the fracture toughness of composite Si_3N_4 ceramics. *Journal of Materials Engineering and Performance* 2006;15(5):591–5.
- [14] Rausch G, Kuntz M, Grathwohl G. Determination of the in-situ fiber strength in ceramic-matrix composites from crack resistance evaluation using single edge notched beam test. *Journal of the American Ceramic Society* 2000;83(11):2762–8.
- [15] Nishida T, Hanaki Y, Pezzotti G. Effect of notch root radius on the fracture toughness of a fine grained alumina. *Journal of the American Ceramic Society* 1994;77:606–8.
- [16] Kübler JJ. Fracture toughness of ceramics using the SEVNB method: From a preliminary study to a test method. In: J.A. Salem GQ, Jenkins M, editors. *Fracture Resistance Testing of Monolithic and Composite Brittle Materials*. ASTM International; 2002, p. 93–106.
- [17] Atzori B, Lazarrin P. Notch sensitivity and defect sensitivity under fatigue loading: two sides of the same medal. *International Journal of Fracture* 2001;107:L3–8.
- [18] Fischer H, Waindich A, Telle R. Influence of preparation of ceramic SEVNB specimens on fracture toughness testing results. *Dental Materials* 2008;24:618–22.
- [19] Fett T. Influence of a finite notch root radius on fracture toughness. *Journal of the European Ceramic Society* 2005;25:543–7.

- [20] BSI . Advanced technical ceramics: Test methods for determination of fracture toughness of monolithic ceramics. Part 5: Single-edge Vee-notch beam (SEVNB) method. DD CEN 14425-5; British Standards Institution; 2004.
- [21] Gomez FJ, Guinea GV, Elices M. Failure criteria for linear elastic materials with U-notches. *International Journal of Fracture* 2006;141:99–113.
- [22] Williams JG. *Stress Analysis of Polymers*. London: Longmans; 1973.
- [23] Inglis CE. Stresses in a plate due to the presence of cracks and sharp corners. *Transactions of the Institute of Naval Architects* 1913;55:219–41.
- [24] Williams JG, Hodgkinson JM. Crack-blunting mechanisms in impact tests on polymers. *Proc R Soc Lond A* 1981;375:231–48.
- [25] Susmel L, Taylor D. The theory of critical distances as an alternative experimental strategy for the determination of K_{Ic} and ΔK_{th} . *Engineering Fracture Mechanics* 2010;77:1492–501.
- [26] Neuber H. *Theory of notch stresses: Principles for exact calculation of strength with reference to structural form and material*. Berlin: Springer Verlag 1958.
- [27] Ritchie RO, Knott JF, Rice JR. On the relation between critical tensile stress and fracture toughness in mild steel. *Journal of the Mechanics and Physics of Solids* 1973;21:395–410.

- [28] Gomez FJ, Elices M. Fracture loads for ceramic samples with rounded notches. *Engineering Fracture Mechanics* 2006;73:880–94.
- [29] Atzori B, Lazzarin P, Meneghetti G. Fracture mechanics and notch sensitivity. *Fatigue and Fracture of Engineering Materials and Structures* 2003;26:257–67.

7. Acknowledgements

The authors would like to acknowledge the financial support of *Element 6 Ltd*, *The Irish Research Council for Science, Engineering and Technology* and *Enterprise Ireland*.