Fracture Properties of PCBN as a function of loading rate

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Abstract. Polycrystalline Cubic Boron Nitride (PCBN) is a superhard material which is used in machining of hardened steels and other abrasive and aerospace grade alloys. In these applications the tools are subjected to high operating temperatures, abrasive and impact loading. Impact loading can lead to the sudden fracture and hence failure of the tool. In this work the static and dynamic fracture toughness of PCBN is determined via a combined experimental-numerical approach. The results show that the fracture toughness of PCBN varies with loading rate.

Introduction

The main application area for PCBN tooling is in the machining of hard steels (>45 HRC), aerospace alloys and both grey and hard cast irons. PCBN is preferred over polycrystalline diamond (PCD) for the machining of ferrous materials as it is chemically stable in the presence of iron. PCBN, as used for cutting tools, is a sintered mass of CBN particles of the order of 1-10 microns with a variety of ceramic and metal phases. The advantage a polycrystalline material offers over a single crystal material is the greater toughness due to the random orientation of the crystalline cleavage planes in the sintered mass. However failure due to fracture and chipping is still a major problem in the industry today. In order to improve the fracture toughness of these materials it is firstly necessary to fully characterize the fracture properties and understand the fracture behaviour of the material under a wide range of operating conditions. In this work, the effects of loading rate are considered.

Materials and Methods

Fracture tests were performed on PCBN Single Edge V-notched Bend (SEVNB) specimens. The specimens were loaded in a three point bending configuration in both a low rate tensile test machine and a high rate drop tower. The fracture toughness of PCBN was evaluated at 3 loading rates, 1 mm/min, 10 mm/min and 1 m/s. The fracture toughness, K_{Ic}, for low rate tests was evaluated using the load at initiation method. The main assumption of this analysis is that linear elastic fracture mechanics (LEFM) can provide a realistic description of the stress field at initiation.

Low Rate Fracture. The accuracy of the analysis depends on the precise determination of the instant of crack initiation on a load time trace. At low rates this is a trivial procedure as the fracture load can be taken to be the peak load which is a distinctive point in accordance with the DD CEN 14425:5 test standard [1]. The standard equation to calculate fracture toughness is then:-

$$K_{Ic} = \frac{P_{in} S}{b h^{1.5}} f(\alpha). \tag{1}$$

where S is the span (24.8 mm), 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 a fitting function given by Eq. 2:-

$$f(\alpha) = \frac{3\alpha^{0.5}[1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)]}{2(1+2\alpha)(1-\alpha)^{1.5}}. \tag{2}$$

High Rate Fracture. Determination of the crack initiation load at the higher dynamic rates is rather more complicated due to inertia and stress wave propagation effects. Hence, at the initation of fracture, the fracture load does not necessarily coincide with the peak load on the load time trace obtained by the machine loadcell. Kalthoff et al. [2] showed that the dynamic effects at the crack tip were significantly smaller than the load measured at the striker contact point. It follows that there exists a unique relationship between the dynamic fracture toughness of a material and the time to fracture initiation. A measurement of fracture time is then all that is necessary to calculate the dynamic fracture toughness. To this end, a minute strain gauge (TSG) was bonded close to the crack tip for all high rate tests. A trigger line is bonded to the top of the specimen which allowed precise determination of the point at which the striker contacts the specimen. Details of the trigger system are shown in Fig. 1. The strain was recorded on a 100 MHz signal conditioning amplifier, while the load was recorded by the by a 25 MHz amplifier.

A numerical model based on transient 2-D Finite Volume (FV) discretisation as outlined in Rager et al. [3] was employed to simulate the test. The model allows an input for the striker stiffness, which is very important when working with materials as stiff as PCBN. This is because the less stiff striker will elastically deform on impact and the local velocity of the striker at the contact point with the specimen will be less than the prescribed velocity. Hence, the measured striker load will be different to the crack tip load. An approximation for the contact stiffness was obtained by calculating the stiffness of the striker approximated as simple geometric shapes. The axial strain at the node where the TSG is located is also monitored by the model. This is then compared to the experimental strain measured at that point.

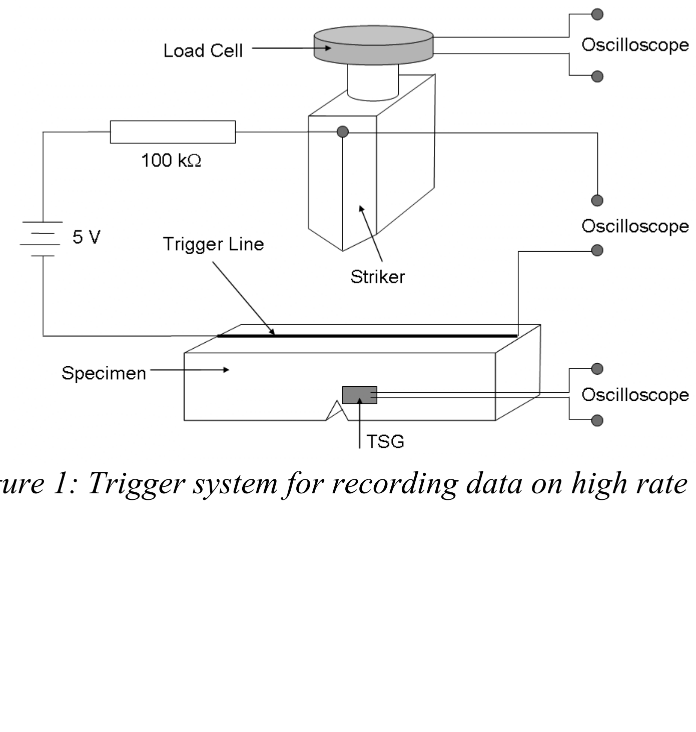


Figure 1: Trigger system for recording data on high rate tests

Results

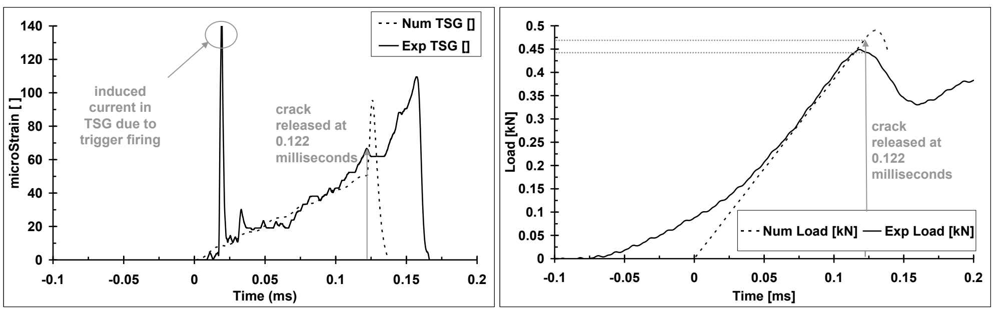
Low Rate Fracture Tests. Five repeats of each test were conducted at 1 mm/min and 10 mm/min. The results show a decrease in fracture toughness with increased loading rate. The results are shown in Table 1.

	K_{Ic} *[MPa m$^{0.5}$]*
1 mm/min	7.89±0.14
10 mm/min	6.88±0.07

Table 1: Low rate fracture toughness results

High Rate Fracture Tests. The results of the model experiment and numerical simulation are presented in Fig. 3. In Fig. 3(a) the strain output from the strain gauge is plotted against time. From this trace it is possible to select the crack initiation time as 0.122 ms as indicated. This was selected after comparing the strain output to multiple to several simulations with different assumed crack speeds and crack initiation times. The subsequent increase in measured strain after propagation until 0.150 ms is due to the increase in kinetic energy of the system as the crack propagates. The numerical output plotted is the strain output at the node closest to the position of the strain gauge during the experiment. The initial spike of strain at 0.02 ms is due to an induced current in the TSG which occurs when the trigger voltage drops to zero.

In Fig. 3(b) the experimental and numerical striker load is plotted against time. The agreement between the results is quite good once the anvil strikers have settled into place correctly. This occurs at a load of around 200 N. The measured striker load is less than the computed load. This indicates that the approximation of the striker stiffness overestimates the actual contact stiffness. The experimental and numerical loads at initiation are 445 N and 474 N. Inserting these values into Eq. 1 above, fracture toughness is calculated via the static analysis as 5.47 MPa m$^{0.5}$ and 5.85 MPa m$^{0.5}$ respectively. This compares well with the value determined from the numerical analysis at 0.122 ms of 5.59 MPa m$^{0.5}$. It is important to note that the inertial effects at 1 m/s are still relatively small prior to the onset of fracture. An examination of the strain energy and kinetic energy in the system versus time reveals this. At higher loading rates these values will diverge as the amount of kinetic energy in the system increases. A further two samples were tested and the fracture toughness was calculated numerically from the initiation time. Initiation times were remarkably consistent and the fracture toughness of this grade of PCBN at 1m/s was measured at 5.58±0.2 MPa m$^{0.5}$ for three repeats.



(a) *(b)*

Figure 3: (a) Experimental and Numerical TSG output (b) Experimental and Numerical Load

A plot of K_{Ic} versus time is given in Fig. 4. This clearly illustrates the decrease in fracture toughness with increased loading rate.

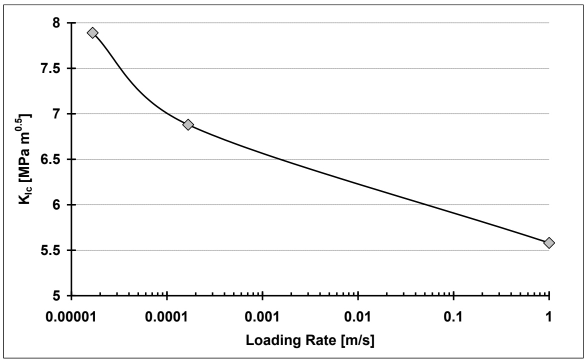


Figure 4 : Decrease in K_{Ic} with increased loading rate

Discussion and Conclusions

It has been shown that the fracture toughness of PCBN decreases with increased loading rate. The determination of the onset of fracture at quasi-static rates is a trivial process. At dynamic rates, however determination of the crack initiation is a more difficult matter. To this end a combine experimental-numerical approach ahs been used. A FV numerical model of the impact test yields good agreement with the experimental data obtained at 1 m/s. The contact stiffness, which incorporates both machine and striker stiffness in the experiment is found to be a very important parameter in determining the initiation time of the experiment. This is especially important in testing PCBN as the contact stiffness is generally an order of magnitude lower than the stiffness of the material being tested and the measured striker load will not coincide with the actual load at the crack tip. Future work will concentrate on measuring the dynamic fracture properties at ever higher rates.

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