Fracture Properties of PCBN as a function of loading rate and temperature

D. Carolan[1,a], M. Petrovic[1], A. Ivankovic[1], N.Murphy[1]
[1]University College Dublin, Dublin, Ireland
[a] declan.carolan@ucd.ie

Keywords: PCBN, fracture, high rate,

Abstract. Polycrystalline Cubic Boron Nitride (PCBN) is a super-hard material used in some of the most demanding material removal operations today. These include turning of hardened steels, as well as the machining of highly abrasive alloys. In these applications the tools are subjected to high operating temperatures, abrasive and impact loading. This can lead to the brittle fracture of the tool. Accurate determination of the fracture toughness and mechanical properties of PCBN under a wide range of operating conditions is therefore essential in order to evaluate the performance of the tool under these highly demanding conditions. For this study, a laboratory scale three point bend test rig has been used for the fracture tests. The fracture toughness of two different grades of PCBN are measured at a range of loading rates and temperatures corresponding to the actual in-service conditions. The results show the measured properties of these materials vary with both loading rate and temperature. The fracture surfaces of the specimens are examined using scanning electron microscopy to determine dominant fracture mechanisms.

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 [1]. PCBN is preferred over polycrystalline diamond (PCD) for the machining of ferrous materials, as it is chemically stable in the presence of iron. PCBN cutting tools are composed of a mass of CBN particles of the order of 1-25 microns sintered with a variety of ceramic and metal phases. The advantage a polycrystalline material offers over a single crystal material is 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 both loading rate and temperature are considered.

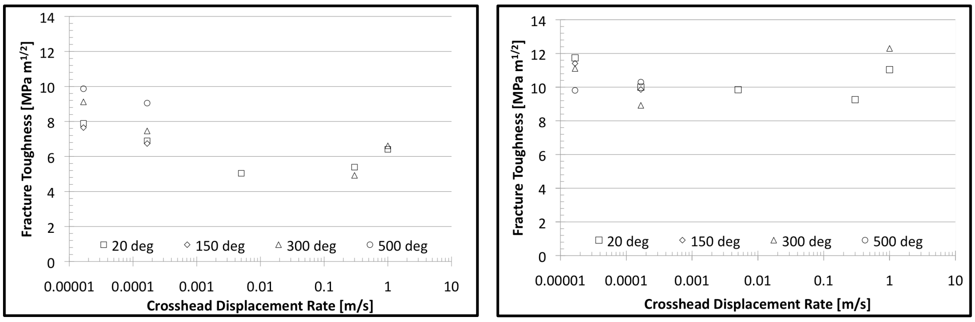
Materials and Methods

In this study the fracture properties of two grades of PCBN were analysed over a range of loading rates and temperatures, from 1 mm/min to 1 m/s and from 20^{o} C to 750^{o} C. The first grade of PCBN investigated, denoted PCBN A, has a CBN grain size of 25 microns whereas the second grade, denoted PCBN B, has a CBN grain size of 2 microns.

High temperature testing was carried out in a custom built heating unit. Details of both specimen geometry and the heating unit have been previously described by us[2, 3]. Fracture was evaluated using both the load to initiation method [4] and the time to fracture method [5]. At low rates the initiation load was recorded directly via a remote load cell. At higher rates the load was recorded via a small strain gauge placed close to the crack tip. This also recorded the fracture initiation time required for the time to fracture method.

Results

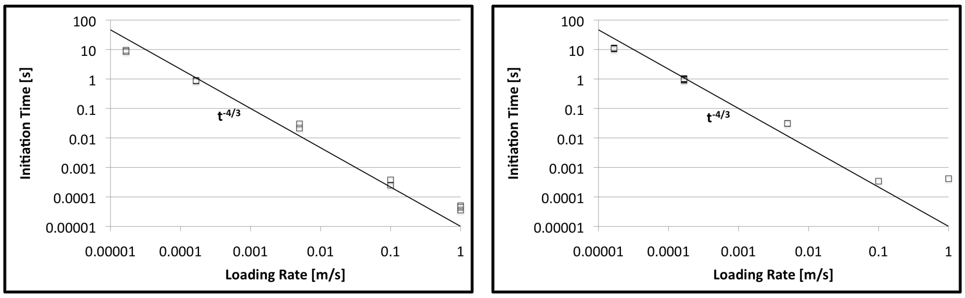
Rate Effects: A total of 125 fracture tests were performed at a variety of loading rate and temperature combinations. A plot of calculated fracture toughness using the load at initiation method versus variation in crosshead displacement rate is shown in Figure 1. It should be noted that for these extremely stiff materials that the actual local loading rate is significantly less than the applied crosshead displacement rate. It is readily apparent that at low rates the fracture toughness increases with temperature while the measured fracture toughness in general decreases with increasing rate at all temperatures except at 1 m/s where an increase in fracture toughness is recorded for both materials.



(a) *(b)*

Figure 1: Fracture toughness versus rate at different temperatures for (a) PCBN A and (b) PCBN B

Fracture times for both materials at room temperature are shown in Figure 2. The values, especially at lower rates, fall along a line with a slope of approximately -4/3. This is good agreement with a prediction from the Carslaw-Jaeger thermal decohesion model [6] particularly for rates lower than 1 m/s, which predicts this -4/3 slope.



(a) *(b)*

Figure 2: Fracture time versus impact velocity at room temperature for (a) PCBN A and (b) PCBN B

Temperature Effects: The change in fracture properties versus temperature for a crosshead displacement rate of 1 mm/min is presented in Figure 3.The fracture toughness for PCBN A changes with temperature reaching a maximum value at around 500^o C. As can be seen from the graph, there is little dependency on fracture toughness with temperature for PCBN B up to 500^o C. At temperatures above this there is a marked increase in the measured fracture toughness.

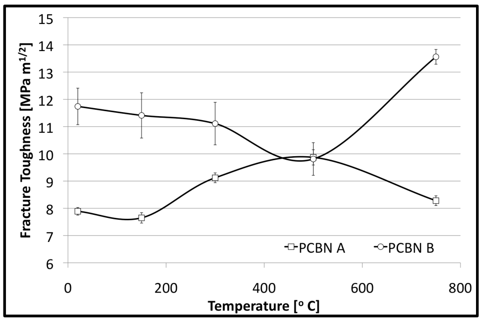
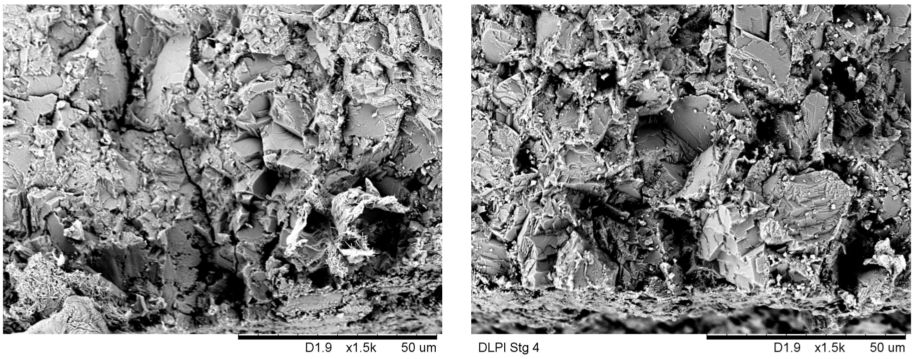


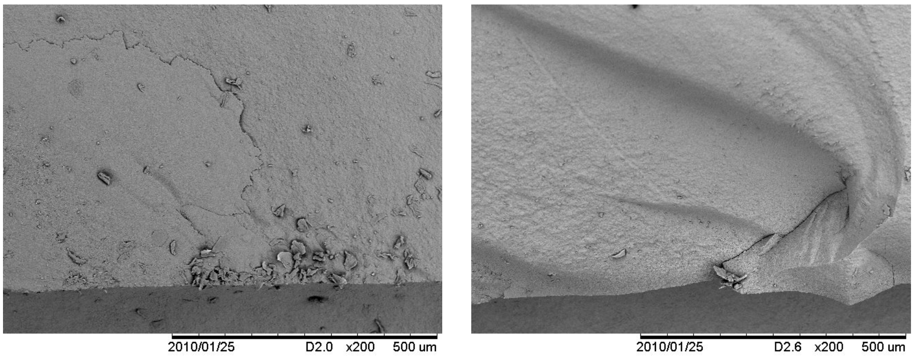
Figure 3: Measured fracture toughness versus test temperature for crosshead displacement rate of 1 mm/min

Microscopy Analysis: Scanning Electron Microscopy was carried out on selected fracture surfaces in order to determine the dominant fracture mechanisms at each rate-temperature combination. Figures 4 and 5 show the difference in fracture behaviour for PCBN A and PCBN B respectively. In all cases the fracture propagates from the bottom of the image.



(a) *(b)*

Figure 4: SEM Micrographs of fracture surface for PCBN A tested at (a) 1 mm/min, 20^o C and (b) 1 mm/min, 500^o C



(a) *(b)*

Figure 5:SEM Micrographs of fracture surface for PCBN B tested at (a) 1 mm/min, 20^o C and (b) 1 mm/min, 750^o C

Discussion and Conclusions

The characteristic slope of -4/3 obtained from the Carslaw-Jaeger model can be explained from thermal considerations. At high impact velocities adiabatic conditions may exist at the crack tip. The heat generated by the fracture process is trapped in a small zone ahead of the crack tip. This results in a temperature rise ahead of the crack tip. This indicates that the fracture of both grades of PCBN could be governed by thermal phenomena. At higher rates the prediction breaks down for PCBN B. This suggests that a different process becomes dominant in this region. There is relatively little difference between the fracture surfaces of PCBN A at low or high temperatures. The fracture is found to be predominantly inter-granular accompanied by extensive micro-cracking perpendicular to the principal plane of crack propagation. The fractographs for PCBN B are topographically quite different indicating that a different fracture process has taken place at the test temperatures shown. Since the effects of rate and temperature are coupled, this is a further indication that a non-thermally dominated fracture process governs the fracture behaviour of PCBN B at high rates.

It has been shown that the measured fracture toughness of two grades of PCBN varies with both loading rate and temperature. A good fit with a well known thermal decohesion model implies that for the large CBN grain material the fracture process is thermally dominated for all rate temperature combinations tested. The smaller grain material does not fit the model well at higher rates. It is suggested that at these rates the temperature rise at the crack tip is sufficient to cause a microstructural change in the fracture process zone ahead of the crack tip. Low rate fracture tests conducted at extremely high temperatures seem to support this. Future work will concentrate on determining the temperature rise and detecting any microstructural changes that may occur.

References

[1] Fleming, M.A., Bossom, P.K., 2000. PCBN – performance goals for the 21st century, Industrial Diamond Review

[2] Carolan, D., Petrovic, M., Ivankovic, A., Murphy, N., 2009. Key Engineering Materials 417, 669-672

[3] Carolan, D., Petrovic, M., Ivankovic, A., 2009. Mechanical and Fracture Properties of PCBN as a function of rate and temperature. In: Proceedings of the 6th ICCSM, Dubrovnik, Croatia.

[4] Advanced Technical Ceramics – Test methods for determination of fracture toughness of monolithic ceramics, Part 5, Single-edge vee notch beam (SEVNB) method (CEN 14425-5:2004). British Standards Institute

[5] Kalthoff, J.F. 1985. On the measurement of dynamic fracture toughness – a review of recent work. International Journal of Fracture 27, 277–298

[6] Carslaw, H.S., Jaeger, J.G., 1959. Conduction of heat in solids (2nd Ed.) London: Oxford University Press

Acknowledgements

The authors gratefully acknowledge the support of *Enterprise Ireland, IRCSET* and *Element 6 Ltd., Shannon, Ireland.*