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Effect of loading rate on the fracture toughness and failure mechanisms of polycrystalline diamond (PCD)

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ABSTRACT

Quasi-static and dynamic fracture toughness tests are performed on four grades of PCD to evaluate the effect of rate and identify dominant failure mechanisms. The results indicate that the presence of the secondary phase cobalt has a significant negative influence on the fracture toughness of PCD grades at high rates of loading. An apparent rate insensitivity was exhibited for coarse grain specimen, where appreciable amounts of secondary phase cobalt were removed, or leached from the crack-tip region. The beneficial effect of cobalt removal on dynamic toughness was observed to be dependent on grain size, with fine grain microstructures exhibiting a similar negative rate sensitivity to corresponding non-leached grades. SEM analysis was used to evaluate the resulting fracture surfaces of both static and dynamic fractured specimens. The effect of rate on the prevailing fracture mode was analysed using a dynamic fracture mechanics approach.

1. Introduction

During rock drilling operations, PCD tools engage with highly inhomogeneous rock formations, which subject the cutter edge to dynamically unstable drilling [1]. Under these extreme operational conditions, impact related fractures are frequent, and costly. Material response under dynamic conditions is often dramatically different compared to that under quasi-static loading, and with this in mind research on this topic is of great importance on a commercial level.

Previous studies into the dynamic properties of PCD are limited, with the majority of literature focused on the high rate abrasive resistance of PCD for machining of advanced metal matrix composites [2,3]. Considering fracture toughness evaluation, research has been traditionally restricted to the static regime using Brazilian disk and double torsion testing methods [4,5]. More recent work however, has adopted high rate bending tests using a drop-weight tower [6], and the dynamic impact fatigue fracture of PCD compacts has also been investigated [7]. Despite these studies, there remains a limited body of knowledge in this area compared to traditional ceramic cutting tools, and thus, the investigation of the dynamic fracture toughness of PCD is vital for the evaluation and design of improved material grades.

Under dynamic loading conditions, the critical value of SIF can be separated as three independent properties: crack initiation toughness, crack propagation toughness, and crack arrest toughness. Among these, it is the dynamic crack initiation toughness that is of most interest for brittle materials. In comparison with static fracture toughness, no standard methodology yet exists for the determination of the dynamic fracture toughness. The major challenges facing dynamic fracture characterisation are the effects of stress wave propagation, and inertial forces on the crack-tip driving force [8]. Traditionally, dynamic techniques have focused on extending the quasi-static ASTM standards into the dynamic loading regime, using high-rate bending experiments performed on a Charpy pendulum [9,10], and drop-weight towers [11,12]. However, bend tests performed using these techniques are prone to high frequency oscillations that can be difficult to delineate from the critical data [13]. Early work by Böhme and Kalthoff [11], demonstrated that the SIF at the crack-tip did not correspond to that calculated by the far-field loading conditions for polymer specimens in three-point bending. This research highlighted that under dynamic conditions, far-field load signals can be misleading since the actual crack-tip conditions are heavily influenced by dynamic effects. The use of the quasi-static analysis is not valid under such conditions unless certain precautions are considered.

Recent trends in dynamic testing have moved away from traditional impact testers towards the use of modified Kolsky bars for fracture testing [14–16]. Unlike striker impact tests, the Kolsky bar apparatus dynamically loads the specimen through stress wave propagation. Early developments by Tanaka et al. [17], and Homma et al. [18], established the measurement of dynamic toughness through stress wave loading based on calculation of the loading history using one-dimensional

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stress-wave theory. Since then, numerous experimental techniques and iterations of the Kolsky bar set-up have been explored [14–16,20]. Tokoyama and Kishida [14] proposed a novel three-point bend Kolsky bar set up to determine dynamic toughness, coupling the standard quasi-static equations with finite element analysis. Rittel et al. [15] calculated the dynamic fracture toughness of mild steel using a hybrid experimental-numerical method as outlined by Bui et al. [19]. Based on this approach, the authors introduced a path independent dynamic H-integral relating the SIF to the externally applied loads and displacements. These parameters were determined experimentally along with the specimen time to fracture for evaluation of the critical dynamic SIF. Analytical approaches coupled with quasi-static analysis have also been explored. Of particular note is Bacon et al. [16] who used a two-point measurement technique to evaluate the loading, and load-point displacement over extended time periods for determining the dynamic toughness for PMMA. More recently, Weerasooriya et al. [20] introduced a method for monitoring stress equilibrium over the entire specimen through direct measurement of the axial forces using quartz crystal force transducers. Through precise control of the loading conditions, dynamic equilibrium was established in a ceramic specimen and the quasi-static equations could be related to the far-field conditions for toughness determination. Despite the advances in the evolution of dynamic methods, the transient effects caused by specimen inertia and stress wave propagation impose compelling challenges for current and future testing of advanced ceramics.

2. Experimental procedures

Fracture tests were performed on Single-Edge Notched Beam (SENB) PCD specimens with dimensions $14 \times 5 \times 2$ mm. Four grades of PCD with variable grain size and cobalt content are examined. Due to the extreme hardness of PCD, it is difficult to introduce a sharp crack without completely fracturing the test specimen. This is because the fracture stress is very close to that of the threshold fatigue stress required to produce a sharp crack, as is observed in many advanced ceramics. Consequently, blunt notches were introduced into the specimen using electrical discharge machining (EDM). The apparent fracture toughness, K_b of the blunt notches was then converted to an estimated critical fracture toughness K_IC by applying the method described by us previously in [21] and given by the equation.

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

where R is the radius of the blunt notch and and r_c is a microstructural length parameter, determined experimentally. The best estimate values of r_c were taken form [21] and are 10 μm and 4 μm for PCD30 and PCD4 respectively.

2.1. Low rate tests

Fracture tests were conducted in a three-point bend configuration, shown in Fig. 1. Stress was applied at a constant cross-head displacement of 1 mm/min and at room temperature, using a screw driven tensile testing machine, the *Hounsfield H50KS*. The fracture toughness of the specimens has been evaluated using the load at initiation method in accordance with the British Standard (BS EN ISO 15732) for fracture toughness testing of ceramics [22]. In the absence of a sufficiently sharp crack the standardised evaluation will yield an measured fracture toughness, K_b, as per Eq. (2):

$$K_b = \frac{P_{in} s}{b h^{\frac{3}{2}}} . f(\alpha) \quad (2)$$

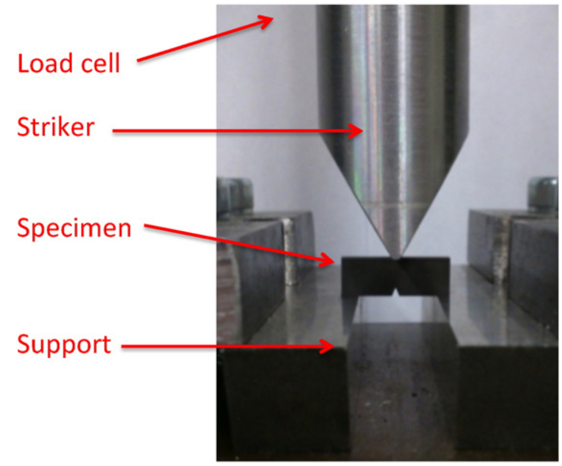

Fig. 1. Static Fracture toughness test rig.

where s is the span, P_{in} is the maximum breaking load, $\alpha = a/h$, where a is initial crack length, and f is a fitting function given by Eq. (3):

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

While the evaluation procedure follows that set out by [22], due to a number of practical limitations, the test set-up, and specimen geometry deviate from the standards. Firstly, due to limitations in the manufacture of PCD, specimen dimensions are smaller than those recommended, and as mentioned above, blunt notches were introduced as a pre-crack into all specimens. The introduction of notches with finite geometries lead to a systematic overestimation of the true material fracture toughness. Finally, the supporting anvils were altered as it was not feasible to maintain a sufficient span length without using rollers with very small radii. Small rollers such as these would be at risk of crushing, and so, flat high strength steel was used as supports. Due to the extreme stiffness of PCD, and the small specimen dimensions, the strain prior to fracture will be small, and thus, the influence on the overall dynamics of the test will likewise be small.

2.2. High rate tests

To facilitate the testing of ceramic materials with limited dimensions, tests are conducted using a bespoke miniature Kolsky bar, as schematically depicted in Fig. 2. The incident and striker bars are manufactured from tungsten carbide, and the strain signals are recorded by diametrically opposite strain gauges located at the midpoint along the incident bar.

The incident bar is loaded axially by a projectile which is fired from a gas gun. Upon impact with the leading edge of the incident bar, a compressive longitudinal stress wave is generated which propagates down the length of the bar. It is of the upmost importance that the impact between the projectile and incident bar be a perfectly planar one. This ensures a trapezoidal wave will be generated and avoids any spurious wave reflections during propagation which can greatly influence the analysis. When the wave reaches the interface between the incident bar and the material being tested, a portion of the wave is transmitted through the interface into the test specimen. The transmitted wave loads the test specimen, and causes the dynamic fracture event. The remaining portion of the wave is reflected at the interface and travels back down the bar as a stress wave in tension. Strain gauges at the midpoint of the bar are placed to measure the incident pulse generated by the impacting striker, and the reflected pulse from the incident bar-specimen interface. The duration of the incident wave can be well