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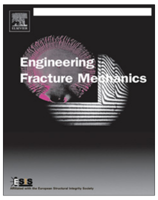

Fracture toughness evaluation of polycrystalline diamond as a function of microstructure

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ABSTRACT

The fracture toughness of polycrystalline diamond has been investigated with reference to the microstructure. The physical interpretation of the critical distance is examined, and it is illustrated that this becomes increasingly difficult to define for larger grain sizes. Consequently, the minimum notch root radius becomes an important parameter governing the accuracy of toughness for blunt notched specimens. A higher than expected toughness was observed for fine grain specimens, illustrating the influence of the combination of both intrinsic and extrinsic fracture mechanisms on the overall toughness. Finally, the process of cobalt removal was found to reduce toughness compared to conventional grades.

1. Introduction

Polycrystalline diamond (PCD) is a super-hard material that possesses favourable properties over conventional cutting tools such as high hardness, abrasive resistance and high thermal conductivity. Given these superior characteristics, it is used in a wide variety of demanding cutting operations, including machining of advanced aerospace alloys, and drilling in the petroleum and mining industry [1]. During in-service operations PCD tools are subjected to high temperature abrasions, and multiple interrupted impacts. Despite their exceptional mechanical properties, PCD tools are susceptible to failure through fracture and chipping due to their relatively low fracture toughness.

In previous studies fracture toughness evaluation has focused on diametral compression of thin discs with chevron notches [2,3]. Based on this approach, Meiss and Rai [3] evaluated the fracture toughness of PCD as a function of grain size. Here, the authors found that coarse grain PCD with a low secondary phase content, exhibited a higher toughness compared to fine grain specimen with a greater percentage second phase. Evaluating PCD using a single-edge V-notch beam (SEVNB) test with honed notches of 10 μm, Morrell et al. [4] determined the fracture toughness to be approximately 10 MPa $\sqrt{m}$. This value is similar to that reported by Petrovic et al. [5] for coarse grain PCD with blunt notches, where fracture toughness was evaluated as function of rate and temperature. Despite these studies, there remains a limited body of work concerning the static fracture toughness of PCD, and in particular the effect of notch root radius and microstructure on the measured value. To improve the fracture toughness of PCD, it is first necessary to accurately analyse the underlying failure mechanics, and define the structure–property relationship linking fracture initiation and microstructure. Griffith was the first to do this, the classical Griffith relation links material strength and toughness to a critical flaw size [6]. Over the years many authors including Evans [7] and Krstic [8,9] have demonstrated the relationship of the critical length scale to the material grains size

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Nomenclature

E	Young's modulus
G_{Ic}	critical strain energy release rate
K_{Ic}	critical fracture toughness
K_b	apparent fracture toughness
P_{in}	fracture load
L	characteristic length scale
R	notch root
a	initial crack length
b	sample breadth
h	sample height
s	support span
r_c	critical distance
α	ratio of initial crack/notch length to sample height (a/h)
σ_{max}	cohesive strength

in the presence of thermoelastic stresses. They show that the critical grain size is often not equal to the grain size. For many engineering materials the Theory of Critical Distances (TCD) is an effective and simple theory to predict the failure in a variety of complex components [10].

Based on a theory for predicting fatigue failure in metallic components [11,12], Tanaka [13] presented a theoretical relationship linking the microstructure of a material to its toughness and strength based on a characteristic length. Later, Lazzarin and Tovo [14], and Taylor [15], developed the same relationship and presented supporting experimental evidence for various metals. The effect of a microstructure on the experimentally measured fracture toughness of materials has been extensively investigated by a number of researchers, most notably Taylor [10,15–18] and Gomez and Elices [19], who have shown that the characteristic length scale can be related back to the microstructure for a wide range materials, such as ceramics, polymers, metals and composites. More recently, Carolan et al. [20] related the characteristic length scale to the grain size for polycrystalline cubic boron nitride (PCBN), and proposed an experimental approach to determine the critical fracture toughness of superhard materials with blunt notches.

The current work investigates to role of microstructure, in particular grain size, and the influence of cobalt removal, on the fracture toughness of PCD. The experimental analysis illustrates that for increasing grain sizes the physical interpretation of the characteristic length becomes difficult to interpret for PCD, and that the accuracy of the critical toughness depends on the minimum notch root radius.

2. Material and methods

In the current work a number of PCD grades, with grain sizes of 4 μm and 30 μm, and varying cobalt content of 6.5–10% are examined. Details of all grades and their associated grain size and cobalt content are given in Table 1. Those materials with the subscript *BL* refer to PCD grades that have undergone *leaching*. Chemical leaching is used to remove the cobalt from interstitial regions within the microstructure of PCD to improve the high temperature wear performance of these grades [21]. The process of leaching is extremely difficult, and time consuming, in particular for finer grained microstructures. The complex network of interpenetrating grains formed by finer grains resist infiltration of the leaching agents, such that residual cobalt remains in the leached specimen. Furthermore, it is often very time consuming to achieve appreciable levels of leaching and so, is it not unusual that only regions directly adjacent to the working surface of PCD are leached. To this end, the cobalt percentages quoted in Table 1 for the leached variations do not represent to overall percentage of the grades, but rather the percentage cobalt in the leached regions close to the specimen free surfaces.

Table 1
PCD grades with associated grain size and cobalt content.

Grade	Grain size (μm)	Cobalt (%)
PCD30A	30	8.5
PCD30B	30	7.5
PCD30C	30	6.5
PCD30B$_{BL}$	30	0
PCD30C$_{BL}$	30	0
PCD4A	4	10
PCD4A$_{BL}$	4	0