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# Dynamic fracture toughness determination of polycrystalline advanced ceramics using the crack closure integral method

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ABSTRACT

The development of ultra-hard cutting tool materials such as cubic boron nitride and ceramics exhibiting excellent wear resistance, chemical stability and hardness at high temperatures have enabled much higher cutting speeds and dry machining. In order to achieve high performance cutting, it is necessary to know the true properties of the cutting tool materials in real operating conditions as well as mechanisms of their failure. The aim of this paper is to determine the properties of certain types of polycrystalline advanced ceramics at a range of loading rates, including dynamics involved in these processes. In order to determine the dynamic fracture toughness of two grades of the material, a crack closure integral method was applied, showing some discrepancy to the static values at high loading rates.



## 1. Introduction

Polycrystalline advanced ceramics are pressure-sintered ceramic materials in a metal matrix aimed to provide exceptional strength combined with resistance to wear and corrosion in cutting applications. These materials are highly resistant to impact, have high temperature strength and exceptional resistance to thermal shock, enabling much higher cutting speeds and dry machining. Behaviour of these materials is of extreme importance considering the nature and costs of these materials, in order to be able to prevent their fracture in operation. In order to achieve high performance cutting, seeking to minimize production times while maximizing product quality, it is necessary to know true properties of the cutting tool materials in real operating conditions as well as mechanisms of their failure.

Published fracture data for sintered polycrystalline advanced ceramics compacts is relatively scarce and somewhat limited in nature. Values are mostly confined to properties determined at low loading rates. However, these properties are rather irrelevant when investigating the fracture of these materials under typical working conditions. In addition, the costs involved in research of this kind are very high, which is main reason why a systematic study of this kind has not been performed to date.

Valuable indicator of fracture properties in these materials is a fracture toughness, a quantitative way of expressing a material's resistance to brittle fracture when a crack is present. Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for many design applications. The linear-elastic fracture toughness of a material is determined from the stress intensity factor at which a thin crack in the material begins to grow.

## 2. Materials and methods

Two grades of polycrystalline advanced ceramics have been used in this study containing different mean grain sizes and amounts of metallic binder employed in the structure. The grades used in this analysis contain tungsten-carbide (WC) and cobalt (Co) as the main elements, although small additions or trace levels of other elements can also be found as added to optimize their properties. These grades of material will be referred to as fine grade (FG) and coarse grade (CG), containing average grains of 6 and 30 μm, respectively. The test specimens had the following average dimensions: FG specimens were ($b$) 4.73 mm x ($h$) 6.25 mm x ($l$) 28.5 mm (thicker specimens) and CG specimens were ($b$) 2.98 mm x ($h$) 6.25 mm x ($l$) 28.5 mm (thinner specimens). The need for small-sized specimens arises for several reasons, but mainly due to the high cost of the material. Single edge V notched beam (SEVNB)

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specimens had the depths of the notches nominally ($a$) 1.25 mm with the notch angle 45°.

Fracture tests were performed loading the specimens in a three point bending configuration in both a low rate tensile test machine and a high rate drop weight tower, as described earlier in Carolan et al. (2010). The standard equation to calculate fracture toughness is then applied according to ASTM standard test method (Morrell, 2006; ASTM, 2001):

$$K_{Ic} = (P_{in}S / bh^{1.5})\, f(\alpha) \quad (1)$$

where, $\alpha = a/h$, $P_{in}$ is the breaking load and f($\alpha$) is a fitting function of $\alpha$ as outlined in Petrovic et al. (2011). Results obtained by experimental testing were earlier presented in Petrovic and Kljuno (2017).

## 3. Dynamic fracture toughness

Previously determined data correspond to apparent fracture toughness obtained by static formula. In order to predict a real behaviour of the material in operation, it is however necessary to take into account dynamic effects at high loading rates included in dynamic fracture toughness $K_{Id}$.

A transient numerical finite volume stress analysis was applied to the TPB specimen model. Only half of the specimen was considered due to symmetry with the dimensions 14.25 mm x 6.25 mm and the notch depth of 1.25 mm (Fig. 1). Both thick FG specimens with 4.73 mm thickness and thin CG specimens with 2.98 mm thickness were considered in this analysis.

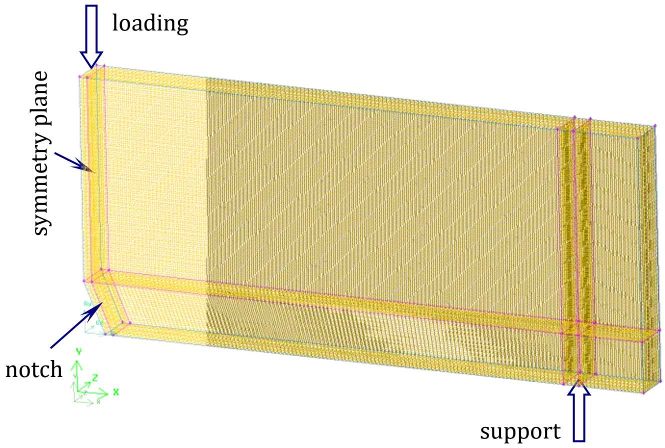


**Fig. 1:** Three point bend specimen model

The experiment analyzed is a displacement controlled test with a constant applied velocity. Space discretization was performed using a single-block structured computational mesh consisting of quadrilateral cells of 0.05 mm x 0.05 mm in size. A time step of 1 ns was used. The numerical strain output at the location of the crack tip strain gauge was compared to the corresponding experimental strain signal and this was used to determine the time at which fracture initiation occurred in the numerical model. The dynamic fracture toughness was determined according to the crack closure integral method (Murthy, 1988), which can be expressed as follows:

$$G_{\mathrm{Id}} = 2 \lim_{\Delta a \to 0} \frac{1}{b\,\Delta a}\left(\frac{1}{2}\int_0^{\Delta a} b\sigma_{yy} u\, dx\right) \quad (2)$$

where, $G_{Id}$ is the apparent fracture energy, $\Delta a$ is crack increment, $b$ is the thickness of the specimen, $\sigma_{yy}$ is the stress normal to the crack plane, $u$ is the opening displacement of a point along the crack face and the factor of 2 accounts for the two fracture surfaces. The dynamic fracture toughness can then be determined according to:

$$K_{Id} = [(G_{in}E / (1 - v^2)]^{\frac{1}{2}} \quad (3)$$

where, $E$ is the Young's modulus experimentally determined for both material grades (Petrovic et al., 2012) and $v$ is the Poisson's ratio. For the loading and supporting rollers the material properties of Inconel 600 were used ($E$ = 214 GPa, $v$ = 0.324).

An example of comparison of numerical prediction and experimental strain signal is given in Fig. 2. As can be seen, quite good agreement was obtained.

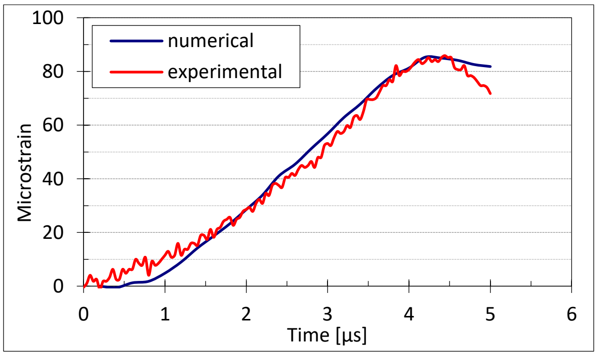


**Fig. 2:** Experimental and numerical strain signals at 5 m/s loading rate for coarse grain specimen

## 4. Results and discussion

The determined dynamic fracture toughness $K_{Id}$ values of thick FG and thin CG specimens at room temperature are presented in Fig. 3 and compared with the corresponding $K_{Ic}$ values calculated using Eq. 1. The same property is presented as a function of local strain rate in Fig. 4. It is important to note that the local strain rate is calculated from experimental/numerical strain signals, which is sufficient to give ballpark figure of the strain rate values at the crack tip.

Some discrepancy can be noted for higher loading rates, as expected, but still below 12%. Here $K_{Id}$ values of FG and CG should not be compared as they are obtained for two materials of different quality (thick FG and thin CG), but it is of interest to compare the static and dynamic values for each of these materials separately. The rate sensitivity appears to be greater for thin CG than for thick FG samples.

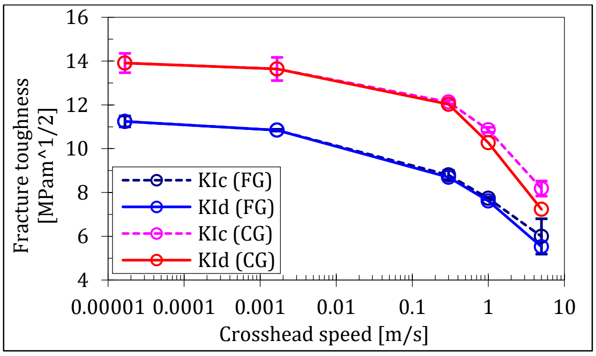


**Fig. 3:** Dynamic fracture toughness of polycrystalline advanced ceramics as a function of crosshead speed compared to the corresponding value using Eq. 1

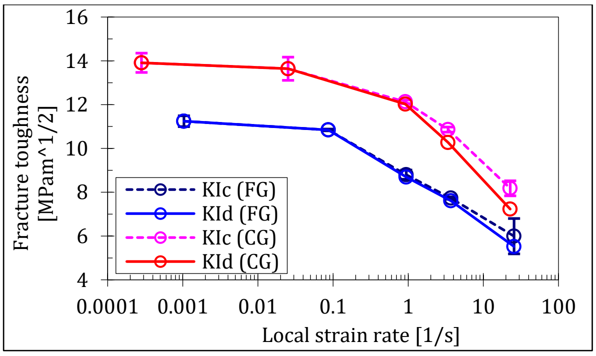


**Fig. 4:** Dynamic fracture toughness of polycrystalline advanced ceramics as a function of local strain rate

## 5. Conclusion

Polycrystalline advanced ceramics are finding increased application in industry, where brittle fracture can often render the tool unfit for purpose. In practical applications, the replacement of the tool is a time-consuming and costly exercise. The true characterization of their fracture properties is therefore of fundamental importance for the classification of existing materials and the development of improved grades in the future. The present paper has presented an analysis of the dynamic fracture toughness of polycrystalline advanced ceramics specimens subjected to a range of loading rates and its comparison to previously obtained static values. This leads to a prediction of the real behaviour of the material in operation.

Based on the analysis performed, a few important conclusions can be made. The fracture toughness of polycrystalline advanced ceramics layers is strongly dependent on the starting grain size of material particles. The dynamic fracture toughness, the same as the static parameter, appears to be higher for coarser grain size material. For loading rates less than about 0.3 m/s the dynamic fracture toughness of each grade is relatively rate independent and nearly equal to the static fracture toughness. Above these rates both static and dynamic fracture toughness decrease sharply with increase in the loading rate. Moreover, dynamic fracture toughness has more pronounced decrement rate above 1 m/s for FG and 0.3 m/s for CG material. Dynamic effects are therefore more pronounced in coarse grain material, which is in line with a thermal decohesion model validity observed in Petrovic and Kljuno (2017). These findings disclosed greater vulnerability of CG material to fracture at higher rates due to adiabatic effects. However, the discrepancy between static and dynamic fracture toughness is still below 12% for both grades of the material.

The undertaken study leads to improvement of understanding of polycrystalline advanced ceramics behaviour and thereafter allows recommendations to be made for the improved design of the material itself and of the corresponding manufacturing processes.

## List of symbols

| | |
|---|---|
| $a$ | initial crack length [mm] |
| $b$ | breadth of specimen [mm] |
| $E$ | Young's modulus [GPa] |
| $G_{Id}$ | apparent fracture energy [N/m] |
| $h$ | height of specimen [mm] |
| $K_{Ic}$ | fracture toughness [MPa m$^{1/2}$] |
| $K_{Id}$ | dynamic fracture toughness [MPa m$^{1/2}$] |
| $l$ | length of specimen [mm] |
| $P_{in}$ | fracture initiation load [N] |
| $S$ | span of three-point bend test [mm] |
| $u$ | opening displacement of a point along crack face [μm] |
| $v_l$ | local loading rate [m/s] |
| $\alpha$ | initial crack length to specimen height ratio |
| $\Delta a$ | crack increment [μm] |
| $\sigma_{yy}$ | stress normal to the crack plane [MPa] |
| $\nu$ | Poisson's ratio |

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