DETERMINATION OF TRUE FRACTURE TOUGHNESS OF POLYCRYSTALLINE ADVANCED CERAMICS AT A RANGE OF LOADING RATES

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Abstract - Polycrystalline advanced ceramics represent synthetic product constituted of hard carbide or other tough material particles bonded together by a metallic binder. Superior wear and corrosion resistance, high temperature stability, low thermal expansion and many more extreme properties give significance to these materials for their use in ferrous materials machining and industrial applications such as construction and mining, automotive and agriculture, oil and gas drilling etc. 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. At present, their fracture properties data are quite scarce in the literature. Fracture of polycrystalline advanced ceramics in mode I loading across the range of loading rates was studied using notched three point bending specimens with two different average grain size and the predictions of the linear elastic fracture mechanics theory. Dependency on the notch root radius was analysed experimentally obtaining apparent and true fracture toughness as well as their interdependence. This dependency was confirmed analytically using predictions by the theory of critical distances. The resulting true fracture toughness showed certain deviation to apparent fracture toughness, which is more pronounced for smaller grain size compacts.

Index Terms - Fracture toughness, Notch root radius dependency, Polycrystalline advanced ceramics, Theory of critical distances

INTRODUCTION

Polycrystalline advanced ceramics represent synthetic product constituted of hard carbide or other tough material particles bonded together by a metallic binder. Superior wear and corrosion resistance, high temperature stability, low thermal expansion and many more extreme properties give significance to these materials for their use in ferrous materials machining and industrial applications such as construction and mining, automotive and agriculture, oil and gas drilling etc. 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. As their fracture properties data are quite scarce in the literature at present, there is emerging need to undertake comprehensive research of the material behaviour at a range of loading rates corresponding to their real operating conditions. On one hand, the current situation offers great opportunities for testing and improvement of these materials, but on the other hand, it is quite difficult to measure the properties of these materials at elevated loading regimes. Based on relative qualities and advantages of different methods of fracture toughness testing [1], single edge notch beam (SENB) proved to be the most adequate for this kind of research. It is also well known that the fracture toughness data from the indentation method are inaccurate for this material. Deviations of up to 48% from the true fracture toughness value have been reported in the literature for ceramic materials [2]. On the other hand, SENB method required very little specialised testing apparatus and specialist skills, which makes it relatively cheap and applicable in most standard fracture laboratories. Also according to [1], amongst all of alternatives, the SENB method was found to provide the most reproducible results and therefore was chosen for this investigation.

II. MATERIALS AND METHODS

A. Materials

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. These grades of material will be referred to as grade A and grade B and contain average grains of 6 and 30 μm, respectively. The test specimens had the following average dimensions: (b) 2.98 mm x (h) 6.22 mm x (l) 28.5 mm.

The need for small-sized specimens arises for several reasons, but mainly due to the high cost of the material. A schematic of the test specimen is given in Fig.1. The depths of the notches were nominally (a) 1.25 mm with the notch angle 45°.

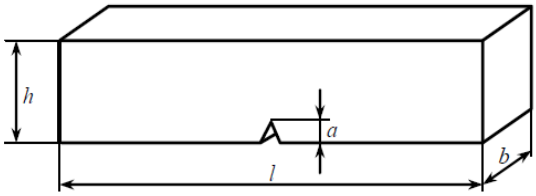


Fig.1 Sample geometry

The specimens were positioned on a three-point bend (TPB) fixture with a span (S) of 24.8 mm and two supporting rollers with a radius of 3 mm. The load was applied by a stainless steel striker fitted with a loading

roller with the same radius of 3 mm. All rollers were made from Inconel alloy 600 (Ni72/Cr16/Fe8) which retains its stiffness at elevated temperatures, should the need arises for elevated temperature tests at a later stage of the research. Tests were carried out at a range of loading rates: 1 mm/min and 100 mm/min on a standard screw driven testing machine, and 0.3 m/s, 1 m/s and 5 m/s on an instrumented drop-weight tower.

B. Experimental tests

The low-rate three point bend flexural tests were performed using a standard screw-driven Hounsfield tensile testing machine [3],[4]. The load versus crosshead displacement at the loading point is recorded automatically by the testing machine in low rate tests. Although there might be some complications in defining the fracture initiation, the quasi-static testing rates generally allow the measurement of the loads and energies in a straightforward manner using the load cell reading. The fracture initiation corresponds to the peak load point after which the load drops suddenly.

For improved accuracy, for tests at 100 mm/min and above, specimens were instrumented with strain gauges bonded as close to the crack tip as possible, in order to determine the initiation load, and therefore fracture toughness, directly from the strain values measured by the gauge. After wiring, each specimen was connected to the Vishay 2310B Signal Conditioning Amplifier to amplify the strain gauge signal. A 100MHz Handyscope HS3 was used to allow the strain signal to be captured by a laptop computer. The strain gauges were calibrated as a function of the applied load at quasi-static rates. Having determined the load-strain calibration curves, the strain gauge readings from the actual fracture tests could be used to determine the fracture load and hence fracture toughness in the high rate tests.

High rate tests were carried out on a Zwick-Roell drop-weight tower. In these tests the point of initiation cannot be accurately detected from the load signals measured by the machine load cell at high rates. Various dynamic effects occur in the impact test and therefore it is very difficult to determine the initiation time from the load-time curve obtained by the machine load cell, as peaks in this curve are due to the dynamics of the system and are not necessarily related to the crack initiation. Also, the measured striker load will be different to the crack tip load. This means that expensive instrumentation of the specimen is necessary and the load-time trace from the crack-tip strain gauge must be used for high rate tests [5]. Deflection of the specimens results in a change in voltage across the strain gauges, which varies linearly with both force and displacement, and which is directly proportional to the force. The other uncertainty is in the determination of the fracture initiation time, as it is rather difficult to ascertain the point where the striker makes contact with the specimen or where the load rise begins. For this purpose, a trigger line is used along the top face of the specimen to accurately determine the crack initiation time. A schematic diagram of the basic trigger circuitry is given in Fig.2.

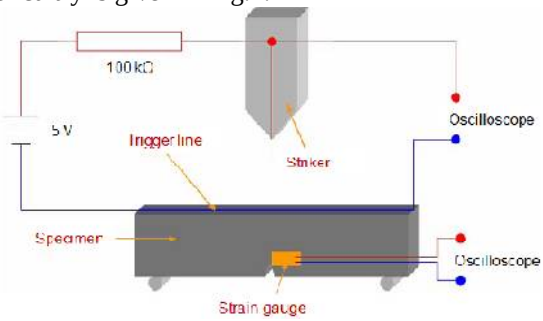


Fig.2. Basic trigger circuitry

III. NOTCH ROOT RADIUS DEPENDENCY

Sets of at least 3 and no more than 5 tests have been conducted at each of 5 loading rates in the three-point bending configuration and the fracture toughness was determined by the load at initiation method according to ASTM E1820-01 fracture standard [3],[4]:

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

Where $\alpha = a/h$, P_{in} is the breaking load and $f(\alpha)$ is a fitting function given by:

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

Test results [6] revealed the apparent fracture toughness of grade A material to remain generally constant at quasi-static rates, and then to decrease with a further increase in the loading rate above 100 mm/min. The apparent fracture toughness of the grade B material remains relatively constant at quasi-static and intermediate rates up to 0.3 m/s, and then sharply drops at higher rates.

The experimentally determined fracture toughness is very sensitive to the notch root radius and it is therefore of fundamental importance to sharpen the notch of the test specimens in order to determine the 'true' fracture toughness value. It is commonly presented in the literature that, if the notches are too wide, i.e. the notch-root radius ρ is too large, the values of fracture toughness will be systematically determined too high. Only below some critical value of notch-root radius ρ_0 will the values of fracture toughness remain constant and correct. Indeed, such behaviour is to be expected if the differences in stress distribution in front of a notch and in front of an infinitely sharp crack are considered. Thus, by treating the notch as a blunt crack and by considering the true role of small cracks at the notch tip, an explanation for this critical notch root radius effect becomes evident. These small cracks can be assumed to be in-plane material flaws, or machining damage, statistically distributed along the notch front.

Having a blunt notch, the calculated fracture toughness values would be higher than the true fracture toughness. How much higher depends on the magnitude of the effect of the notch and the size of the starting defect. Generally, the wider the notch the more force is required and the higher the value of fracture toughness determined. If, however, the notch is sharp enough, the stress intensity at the tip of the small crack does not greatly differ from that supposed to be obtained by an equivalent long crack. Thus a correct value (within the scatter) of fracture toughness should be measured.

In the samples used, a notch of a certain depth was machined by laser and then sharpened using sharp monocrystalline diamond blades. The notch root of every specimen was examined under scanning electron microscope and the radius ρ was measured. The root radius of the blunt machined notches was of the order of 156±5 μm with an original notch depth a of about 1.24 mm. After sharpening, the notch root radius was in the range of 15.4–34.8 μm, with a notch depth of 1.42–1.50 mm. A comparison of the machined and sharpened notches is shown in Fig.3.

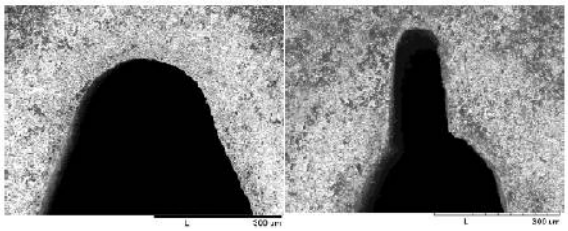


Fig.3. Blunt and sharpened notch of tested specimens

It can be seen that the sharp crack tip is not positioned precisely in the pre-machined notch. This could result in a difference between the measured fracture toughness and the true fractured toughness of the material and also be a source of the scatter in the experimental results. However, the position of the sharp crack tip is fairly close to the centre of the pre-machined notch (up to 30 μm off-centred) and very similar for all considered specimens. Therefore it was not believed that this would cause any significant scatter.

IV. RESULTS AND DISCUSSION

Samples were tested in standard three-point bending in the Hounsfield tensile testing machine at room temperature and the same range of loading rates, using the procedure outlined above.Following the guidelines from the literature [7] regarding the limiting notch root radius of $\rho_0 = 2d_g$, where d_g is the grain size of the material, the true fracture toughness for the tested material can be obtained. Predictions are also made by the point method (PM) and the line method (LM) of the theory of critical distances (TCD) [8]-[10]. An estimate of the notch root radius effect can be made by considering the elastic stressσ_{yy} around the elliptical notch on an infinite plate at a small distance from the tip. The usual solution for stressesaround an elliptical hole gives [11]:

$$\sigma_{yy} = \sigma\sqrt{a}\frac{2\rho+2r}{(\rho+2r)^{3/2}} \quad (3)$$

where ρ is the tip radius, and r is distance from the notch tip. For the sharp notch caseρ = 0 and the solution reduces to:

$$\sigma_{yy} = \sigma\sqrt{a}/\sqrt{2r} \quad (4)$$

The normal stress component in mode I loading for a givenlocation in the immediate vicinity of the crack tip (r,θ) in a linear elastic material is:

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left[1 + \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] \quad (5)$$

On the crack plane θ = 0 we may define the stress intensity factorK_I for the crack tip regionas:

$$K_I = \sigma_{yy}\sqrt{2\pi r} = \sigma\sqrt{\pi a} \quad (6)$$

According to Irwin's fracture condition [12], at the instant of fracture $K_I = K_{Ic}$, $\sigma_{yy} = \sigma_c$and $r = r_c$. Under the assumption that the same criterion applies when the fractureoriginates from a blunt notch, then we have:

$$K_{Ic} = \sigma_c\sqrt{2\pi r_c} = \sigma\sqrt{\pi a}\frac{1+\rho/r_c}{(1+\rho/2r_c)^{3/2}} \quad (7)$$

and if an "apparent" fracture toughness of a blunt notch of arbitrary tip radius ρ is defined as $K_{Ib} = \sigma\sqrt{\pi a}$, the previous equation can be written as:

$$\frac{K_{Ib}}{K_{Ic}} = \frac{(1+\rho/2r_c)^{3/2}}{1+\rho/r_c} \quad (8)$$

As the true fracture toughness K_{Ic} and r_c are constant, we get thefollowing type of behaviour:

$$K_{Ib} \sim \rho^{1/2} \quad (9)$$

The fracture toughness is linearly proportional to the square root of the notch root radius.

Experimental results are presented in Fig.4 and Fig.5 for quasistatic loading rate of 1 mm/min.Although the exact critical distance value r_c is unknown prior to the test and possibly differs for different materials, it is assumed here to be of the order of the grain size.

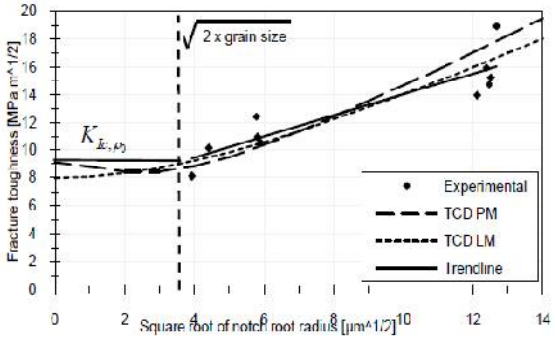


Fig.4. True fracture toughness of grade A specimens at 1 mm/min

Comparison of apparent and true fracture toughness for both grades of material at a full range of the loading rates used in this analysis is presented in Fig.6 and Fig.7.

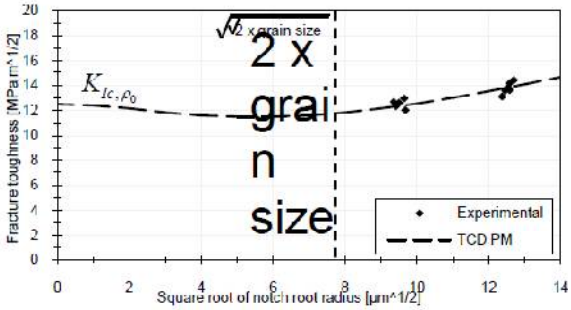


Fig. 5. True fracture toughness of grade B specimens at 1 mm/min

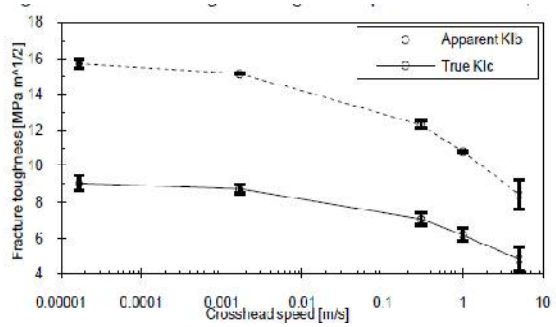


Fig.6 Apparent and true fracture toughness of grade A as function of crosshead speed

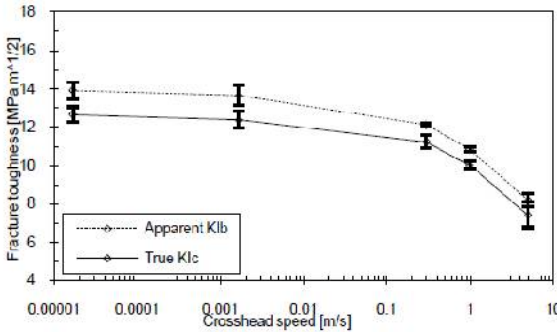


Fig.7 Apparent and true fracture toughness of grade B as function of crosshead speed

Polycrystalline advanced ceramics with a coarse grain size of 30 µm was shown to be much less sensitive to the notch root radius than fine grained material. There is very little difference between the true and the apparent fracture toughness which suggests that the difference would be even smaller and quite negligible for coarser grain materials.

It can be seen that the fracture toughness obtained theoretically using the geometrical approach with an assumed critical distance r_c compares well with what has been observed experimentally. The procedure outlined above shows that, if the notch tip of a certain material cannot be prepared sufficiently sharply, e.g. if a fine-grained ceramic material is tested or the material is sufficiently hard that sharpening is unreasonably time-consuming, the theoretical (true) fracture toughness value can be easily estimated by mathematical methods, greatly reducing the costs.

CONCLUSIONS

Fracture of polycrystalline advanced ceramics in mode I loading across the range of loading rates was studied using notched three point bending specimens. The aim of the analysis was to provide reproducible results of the true fracture toughness which is the material property, compared to the apparent fracture toughness depending on the notch geometry of the specimen. This true fracture toughness is of extreme importance for behaviour prediction in actual operation, compared to the apparent fracture toughness obtainable in laboratory conditions.Two different average grain sizes were used in this analysis with the predictions of the linear elastic fracture mechanics theory. Dependency on the notch root radius was analysed experimentally obtaining apparent and true fracture toughness as well as their interdependence. This dependency was confirmed analytically using predictions by the theory of critical distances. The resulting true fracture toughness showed certain deviation to apparent fracture toughness, dropping consistently at all loading regimes, which is more pronounced as the average grain size in the compact is decreasing. The true fracture toughness determined in this analysis is the material constant and can be used in simulations of realistic geometries.

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