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Fracture-toughness/notch-sensitivity correlation for metal- and ceramic-based fibrous composites

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ABSTRACT

The fracture toughness of a material is given by the critical stress intensity factor K_{IC} used in linear fracture mechanics to evaluate the ultimate load on a structural element containing a crack-like defect. However, K_{IC} can hardly be applicable to the failure analysis of elements made of fibrous composites. Hence, an apparent value of the critical stress intensity factor, K^*, for composites are normally experimentally measured to evaluate only the damage tolerance of composite materials. The measurements of the ratio of the flexural strength of specimens with and without a notch (σ_N/σ_0) serve the same purpose. The analysis of K^* and σ_N/σ_0 data obtained by testing various oxide/molybdenum composites as well as those for oxide/oxide and C-fibre/SiC-matrix composites published recently along with older data for boron/aluminium reveals a linear correlation between these two characteristics of composites.

1. Introduction

Fracture toughness, given by the critical stress intensity factor (K_{IC}), is a property of structural materials, which determines the material applicability in heavily loaded structural elements. If the value of K_{IC} is measured accurately for a particular metal alloy, the failure load of a structural element containing a crack-like defect can be calculated.

In the middle of the last century, a new chapter in the history of structural materials began with fibrous composites because inherently brittle solids could now be used. This became possible as a number of toughing mechanisms in fibrous composites of all types were discovered and studied (see [1,2] for a review of the mechanisms). At the crack tip, most of these mechanisms generate a fracture zone that is much larger than the Orowan plastic zone. This prevents the application of linear fracture mechanics based on the Griffith-Orowan model and the determination of the exact solutions of corresponding elasticity problems to characterize composites.

Studies on high-toughness ceramic matrix composites often focus only on evaluating the damage tolerance of the materials by measuring K_{IC} and/or the ratio of the values of the strength of specimens with and without a notch (i.e., damaged and non-damaged objects, respectively). Some examples of such an approach can be found in Refs. [3,4]. Another approach to the problem is based on the calculation of the area under the load/displacement curve obtained by loading a specimen with a notch and taking this value as a measure of the work of fractures [4,5].

In the present paper, a composite specimen with a notch is considered, for the first approximation, as a “black box” without a microstructure. Loading the specimen yields a value K^*, which we call the apparent critical stress intensity factor. Strength σ_N of the notched specimen is calculated by assuming no stress concentration. Next, the specimens of the same material but without notches are tested to determine the strength σ_0, and then, the ratio σ_N/σ_0 is calculated. Similar experiments were performed previously in [4,5]. Nevertheless, no attempts have been made to correlate σ_N/σ_0 and K^*. This is done in the present study by analysing both recent results obtained by the author's team (Section 2) and data found in previous published reports (Section 3).

2. Oxide/molybdenum composites: fracture toughness and notch sensitivity

In this section, two types of the composites are considered: (i) oxide-fibre/molybdenum-matrix composites and (ii) molybdenum-fibre/Al_2O_3-$Y_3Al_5O_{12}$-matrix composites. The oxides in the first type of the composites are single crystalline yttrium-aluminium garnet $Y_3Al_5O_{12}$ (YAG) and perovskite $YAlO_3$ (YAP),

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alumina-YAG eutectic, Al_2O_3-$Y_3Al_5O_{12}$-$Ca_xAl_yO_z$, and mullite-ZrO_2 eutectic. Both types of composites can now be considered as important high-temperature materials because recent findings have indicated the possibility of decreasing the oxidation rate of molybdenum, which is used as the matrix material for composites containing oxide fibres containing a chemical element forming a molybdate on the composite surface [6,7,8].

3. Oxide-fibre/molybdenum-matrix composites

A systematic study of the fracture toughness and notch sensitivity in the present work was done on the composites obtained by the Internal Crystallization Method (ICM) [9,10]. This method is based on infiltrating a molybdenum carcass containing continuous cylindrical channels with a fibre material melt and crystallizing the fibres in the channels. The melting points of the oxides used are about 2000 °C, so molybdenum recrystallizes during the fabrication process; this makes the molybdenum matrix brittle.

K^* was measured by testing single-edge notched bend (SENB) specimens shown schematically in Fig. 1(a) similar to those developed for metal alloys according to ASTM-399. Note that the bending moment is applied in such a way that the neutral axis is vertical with respect to the composite microstructure, as shown in Fig. 1(b). The values of K^* were calculated using the approximation recommended by ASTM-399:

$$K^* = \frac{3QLc^{1/2}}{2h^2w} Y\left(\frac{c}{h}\right), \tag{1}$$

where

$$Y = \left[1.96 - 2.75\frac{c}{h} + 13.66\left(\frac{c}{h}\right)^2 - 23.98\left(\frac{c}{h}\right)^3 + 25.22\left(\frac{c}{h}\right)^4\right]$$

Here, L is the distance between the supports, c is the notch length, h and w are the height and width of the specimen, respectively. In the present study, these are $L \approx 60$ mm, $h \approx 15$ mm, $w \approx 5$ mm, $c \approx (0.45-0.55)h$. The maximum load is denoted Q. The notch tip radius R is about 0.15 mm.

Typical load/displacement curves are presented in Fig. 2. Such curves also yield strength σ_N of a notched specimen calculated without taking into account the stress concentration at the notch tip.

A SENB specimen after testing was cut into six sub-specimens as shown Fig. 1(c) and four sub-specimens selected randomly were tested at 20 °C by a three-point bending to find the strength σ_0 of specimens without notches. The bending moment was applied to a part of the sub-specimens in such a way as the neutral axis is horizontal with respect to the composite microstructure shown in Fig. 1(b)), and the other part of the specimen was tested with the bending moment changed by 90° (i.e., the orientation corresponds to that used in tests to measure K^*). Then, the ratio σ_N/σ_0 versus K^* was plotted for the composite systems reinforcing fibres Al_2O_3-$Y_3Al_5O_{12}$, $Y_3Al_5O_{12}$, $YAlO_3$, Mullite-ZrO_2, Al_2O_3-$Y_3Al_5O_{12}$-$Ca_xAl_yO_z$; see Fig. 3).

The large scatter of strength values is rather usual for the composites under consideration. However, it should be noted that composite specimens were obtained at various crystallizations rates of the fibres, from 10 to 250 mm/min. Fig. 4 shows that the crystallization rate essentially affects mechanical properties. Some fibres such as $YAlO_3$ (Fig. 4(b)) are obtained in the preliminary experiments, so their microstructure changes with the crystallization rate and along the specimen length. Hence, a wide distribution of the composite strength values is obtained. A more detailed discussion on the fibre microstructure and its effect on the fibre strength is outside the scope of this paper and will be presented elsewhere.

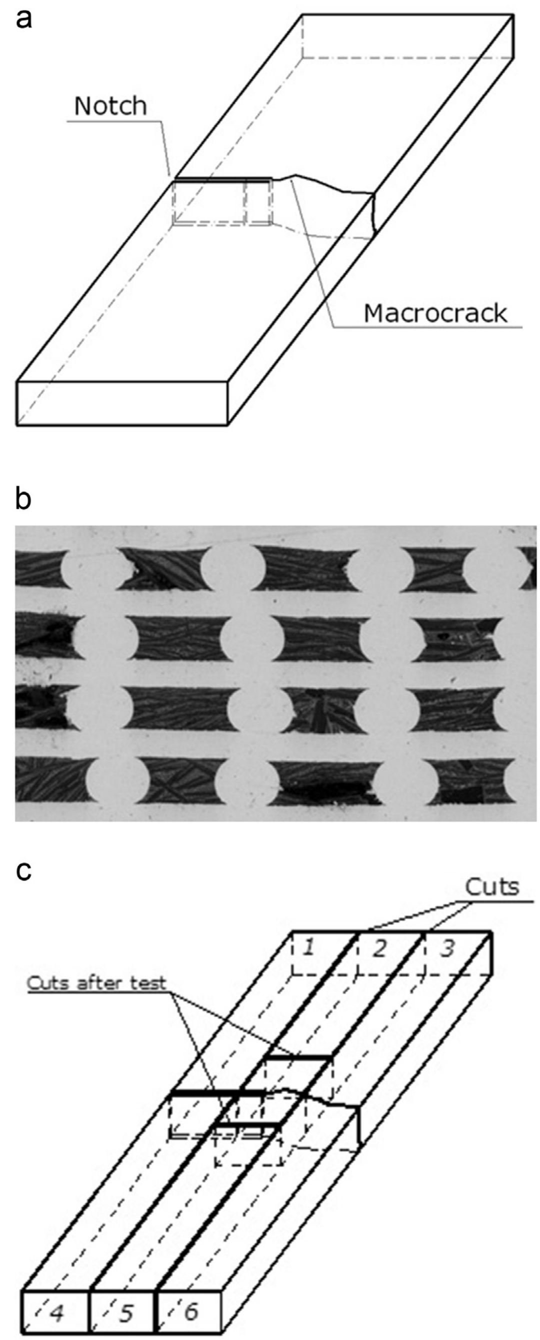

Fig. 1. (a) Specimen for measuring the apparent value of the critical stress intensity factor and the strength of the notched specimen (b) SEM image of a specimen cross-section of the composite obtained by the internal crystallization method. The average cross-section size of the fibers is ~0.1 mm; (c) Schematic of cutting the specimen shown on the left side into six sub-specimens for measuring the composite strength of specimens without the notches. The crystallization of the fibers starts from the specimen marked as 1 and proceeds to 4, also 2 to 5, 3 to 6.

The correlation coefficient is calculated by the well-known Pearson formula:

$$r(K^*, s^*) = \frac{E\left[(K^* - E(K^*))(s^* - E(s^*))\right]}{SD(K^*)SD(s^*)} \tag{2}$$

where $s^* = \sigma_N/\sigma_0$, $E(X)$ is the expectation of X, and $SD(X)$ is the