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Fracture toughness testing of small ceramic discs and plates

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Abstract

A new fracture toughness test for discs and plates is presented, which can be applied to small specimens (>5 mm diameter). A semi-elliptical surface crack is made into the centre of the top plane using a Knoop intender. Then the layer containing the plastically deformed zone is ground off and the crack is loaded in tension using the Ball-on-3-Balls test.

Applied to five different ceramic materials the results gained with the new method agree well with those of standardised methods.

Keywords: Fracture toughness; Mechanical characterisation; B3B; B3B-KIc; Surface Crack in Flexure

1. Introduction

Cylindrical disc specimens are a favourable geometry if new materials are developed or materials are prepared in laboratory scale, e.g. by uniaxial pressing or by hot pressing. Disc shaped specimens are also used for biaxial strength testing of dental materials[1] or zirconia for surgery.[2]

Apart from this, many ceramic bulk components have the shape of thin discs or plates. Examples are ceramic membranes,[3] (heat generating) resistors,[4] capacitors,[5] low temperature co-fired ceramics[6,7] (LTCC), microchips,[8,9] piezo-electric speakers,[10] watchcases and glasses[11] or armour ceramics[12,13] and much more.

Mechanical properties may depend on the processing route. Therefore it is suitable to determine these properties on real components and not on specially produced bodies. For that reason and to save costs for special specimen production it may be beneficial to use the components directly as specimens and to test mechanical properties on thin discs or plates.[14–18]

The most common biaxial test assemblies are listed in Ref. 19 and disadvantages such as unclear contact situation are discussed. The ball-on-3-balls test[20] (B3B test) was recently developed to overcome all these aspects. In this test, the plates are supported by 3 balls on one side and loaded by a fourth ball in the centre of the opposite side. Hence, the maximum tensile stress occurs at the surface of the plate directly opposite to the centre ball. Based on this idea discs and rectangular plates have also successfully been tested.[6–9,21–23] For sake of clarity, the principle of the B3B test is explained here for symmetrically loaded discs, see Fig. 1. The test piece (i.e. the disc) is defined by its radius R and thickness t. The three balls with radius R_B are in contact with each other; therefore the loading radius R_a is given by the relation $R_a = (2/\sqrt{3})\ \ R_B$.

The flexural strength is the maximum tensile stress, σ_{B3B}, in the specimen during loading, given by[19]:

$$\sigma_{B3B} = \frac{F}{t^2} f\left(\frac{R_a}{R},\quad \frac{t}{R},\quad \nu\right) \tag{1}$$

with the maximum load at failure F, the disc thickness t, and a dimensionless factor f, which depends on the geometry of the specimen and on the Poisson's ratio ν of the tested material, etc. Values for that function can be found in Ref. 24. The calculation of σ_{B3B} for discs can also easily be performed with an interactive Web-Mathematica tool on our homepage http://www.isfk.at/en/960/.

Due to the well-defined stress field and low measurement uncertainties,[25] the B3B test is a good basis for fracture toughness testing. In analogy to the standardised "Surface Crack in Flexure" (SCF) method[26,27] a semi-elliptical surface crack is

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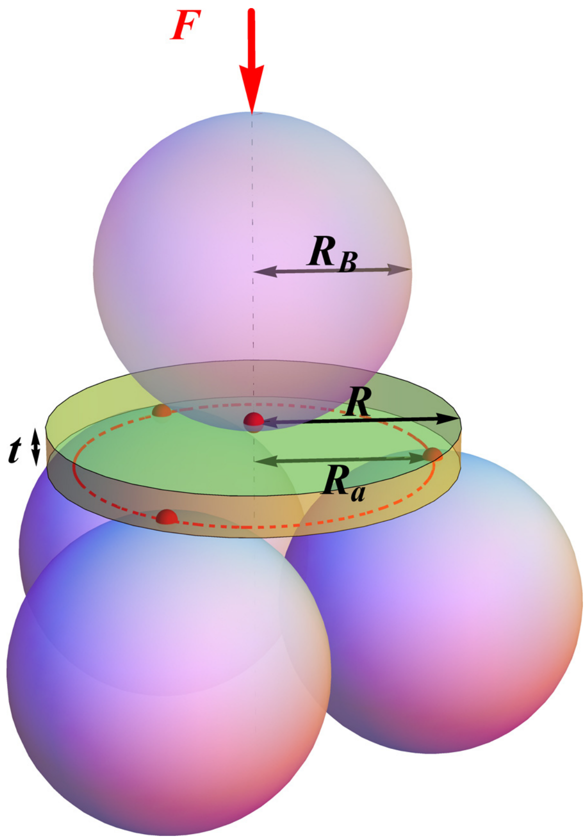

Fig. 1. Test setup of the conventional B3B strength test. In this case the test piece is a circular disc with the radius R and thickness t. The loading radius R_a is defined as the distance between the disc centre and the contact points with the supporting balls. R_a is determined by the radius of the balls R_B. The force F is applied via the centre ball, parallel to the axis of the disc (see www.isfk.at).

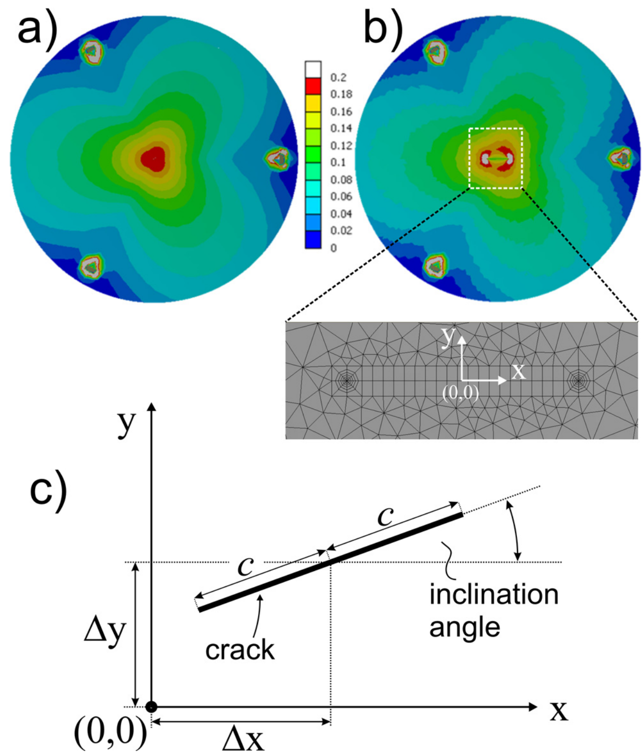

Fig. 2. View of the tensile stressed side of the B3B specimen at a load of 1 N. Plotted is the 1st principal stress in the range of 0 MPa and 0.2 MPa: (a) Stress distribution of in a disc without crack and (b) with surface crack and inset showing details of the crack mesh. (c) Sketch of possible positioning errors.

used as starter crack in the centre of the disc. This new method is further called B3B-KIc and is presented in this work.

2. Modelling the B3B test with a surface crack

In this new method a surface crack is created in the centre of the disc on the surface opposite to the loading ball (i.e. the position of the maximum stress σ_{B3B} in the conventional B3B test). This is done using a Knoop indenter analogously to the Surface Crack in Flexure (SCF) method.[26,27] Underneath of the indent the material is plastically deformed, which causes residual stresses. These stresses may conflict the measurement. To remove these residual stresses a surface layer of the plates (discs) containing the plastically deformed zone has to be ground off. Following the SCF standard[26,27] the required minimum thickness of this surface layer to be removed can be estimated; an even more accurate advice is given in Ref. 28.

The stress distribution in the conventional B3B test has a three-fold symmetry[19] (see Fig. 2a). Therefore, it is not possible to achieve a symmetrical loading of the semi-elliptical crack, even if the crack is perfectly centred in the stress field. As illustrated in Fig. 2b the stress intensity on the left and the right hand side of the crack differ. For this reason we introduce the convention that one crack tip has to be directed towards one contact point of a supporting ball, see Fig. 2b. The consequences of errors originating from this kind of positioning (Fig. 2c) are discussed later.

The crack is approximated to be perfectly semi-elliptical, where a is the crack depth and $2c$ is the full crack width at the surface (a and c correspond to the semi-axes of the ellipse). A more complete analysis of the influence of the exact crack shape on fracture toughness evaluation can be found in Ref. 28.

The fracture toughness K_{Ic} is given by to the following equation:

$$K_{Ic} = \sigma_{B3B} Y \sqrt{a\pi}, \quad (2)$$

whereas Y is the geometric factor that depends on the geometry of crack and specimen and on the Poisson's ratio of the material. The calculation of Y was performed using the commercial finite element program package ANSYS Workbench, version 13, and a J-integral formulation; for details see Ref. 29. The maximum of Y along the crack front was evaluated in the linear elastic approach. The FE model is built up parametrically. The geometric factor is a function of the following four dimensionless parameters:

$$Y = Y\left(\frac{a}{c}, \quad \frac{a}{t}, \quad \frac{t}{R_a}, \quad \nu\right) \quad (3)$$

The influence of these dimensionless parameters was evaluated for a wide range of geometries and materials