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Toughness measurement on ball specimens. Part II: Experimental procedure and measurement uncertainties

Stefan Strobl [a,b,*], Tanja Lube [b], Oskar Schöppl [c]

[a] *Materials Center Leoben Forschung GmbH, Roseggerstraße 12, 8700 Leoben, Austria*[1]

[b] *Institut für Struktur- und Funktionskeramik, Montanuniversitaet Leoben, Peter-Tunner-Straße 5, 8700 Leoben, Austria*[2]

[c] *Research & Development Office, SKF Österreich AG, Seitenstettner Straße 15, 4401 Steyr, Austria*[3]

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Abstract

The “Surface Crack in Flexure” method is widely used for fracture toughness (K_{Ic}) determination of ceramics. In part I of the paper we developed the theoretical fundamentals to apply this procedure to ceramic balls by using the stress application as developed for the so-called “Notched ball test”. The new test (SCF-NB) can be used to test spherical components without the need to cut out special specimens such as bending bars. In this work the practical part is presented including suggestions for crack introduction and specimen preparation and possible measurement errors are discussed. It is concluded that a measurement error less than ±5% is possible.

Experiments on balls and bars made from the same silicon nitride ceramic indicate that SCF-NB delivers the same K_{Ic}-values as standardised measurements on bars. Additionally, K_{Ic}-values obtained for silicon carbide, alumina and zirconia ceramics are presented. They coincide with K_{Ic}-data from the literature.

Keywords: Rolling elements; Notched ball test; Fracture toughness; Hybrid bearings; Silicon nitride

1. Introduction

For most of all established methods for fracture toughness determination, the specimen geometry is standardised. Prismatic flexural beams with a cross section of 3 mm × 4 mm and >40 mm in length are used in the Single Edge V-Notch Beam (SEVNB),[1] the Chevron Notch (CN)[2] or the Surface Crack in Flexure (SCF)[3] method.

The task in the present work is to measure the toughness of balls without cutting special specimens out of the balls. For that we follow the basic ideas of the SCF method,[3] where a well-defined crack is made by an indent (Knoop) into surface of a prismatic beam. Then the beam is loaded in flexure until failure occurs. From the crack geometry and the failure stress the critical stress intensity factor (fracture toughness) can be determined. One of the most important advantages of SCF method is that the start defect is a real crack and not a relatively sharp notch, which is required for the validity of linear elastic fracture mechanics (LEFM).[4] A difficulty of the SCF method is that the indentation causes a plastically deformed zone, which provokes internal stresses. This can adulterate the testing results. Therefore the plastically deformed material has to be removed – e.g. by grinding – in order to avoid a preloading of the crack tip by residual stresses and to receive a fully closed and unloaded crack in order to follow the assumptions made for the evaluation of the experiments. Standards recommend to grind-off a layer having the thickness of 1/6 of the long indentation diagonal. An alternative suggestion for the grinding depth is given in,[5] which additionally ensures that the critical point (where the stress intensity factor becomes a maximum) is not at the surface but at the deepest point of the crack where the determination of the stress intensity factor is more precise. Therefore this situation (critical point at the deepest position) is preferred. This grinding depth is approximately 1/3 of the long indentation diagonal

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* Corresponding author at: Institut für Struktur- und Funktionskeramik, Montanuniversitaet Leoben, Peter-Tunner-Straße 5, 8700 Leoben, Austria.
Tel.: +43 3842 402 4113; fax: +43 3842 402 4102.

E-mail addresses: stefan.strobl@mcl.at, stefan.strobl85@gmail.com (S. Strobl).

[1] mclburo@mcl.at, http://www.mcl.at.

[2] isfk@unileoben.ac.at, http://www.isfk.at.

[3] oskar.schoeppl@skf.com, http://www.skf.at.

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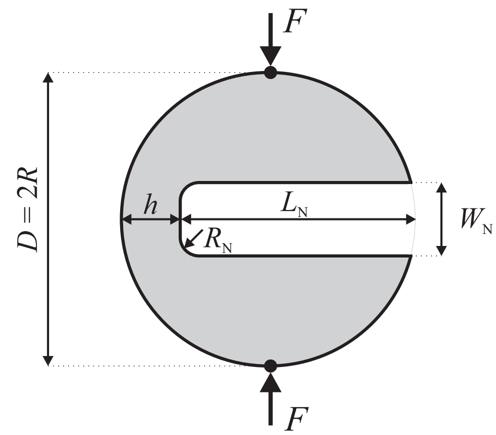

Fig. 1. Specimen in the notched ball test. The notch is defined by the length L_N, the width W_N and the fillet radius R_N of the notch. In the equatorial plane remains a ligament having the shape of a segment of a circle with the thickness $h = D - L_N$.

(more precisely it depends on the crack length before grinding and other additional parameters, see in Ref. 5).

The measurement of the crack shape is not straight forward since the crack's visibility may dependent on the material itself. The measured quantities are influenced by the operator[6] as well as by the available devices (such as optical microscopy or SEM).[7] The SCF standard[3] contains some advices to facilitate the crack size measurement on the fracture surface. From them only fluorescent penetration dye (FPD) was used in this work. There are further methods to enhance the visibility of the crack and its detection, such as tilted indentation,[3] non-fluorescent penetration dyes[8] or decoration with lead acetate[9,10] which are not discussed in the framework of this paper.

In the literature on the SCF testing, the geometric factor defined by Newman and Raju in the late seventies of the last century is used.[11,12] In these papers an FE-analysis of the stress field is made. But in that time, the computers were relatively slow and a coarse FE mesh had to be used to keep the calculation time manageable. In a recent paper it has been shown, that – in extreme cases – this can cause errors up to 40% of the determined value[5] (remark: the formula in the SCF-standard based on the work of Newman and Raju[11,12] is fixed to a Poisson's ratio of 0.3 and a perfect semi-ellipse). Therefore a more precise solution for the geometric factor of the surface crack has been proposed, which is used for the data evaluation in this paper (see part I [13]).

In the new test a crack is introduced into the surface of a ball with an indenter. Then the plastically deformed material is ground-off and traction forces are applied to the crack using the principles of the notched ball test (NBT).[14–18] In the NBT a notch is cut in the equatorial plane of the ball and afterwards the notch is squeezed together by introducing point loads at the poles perpendicular to the notch (see Fig. 1). This produces a very well defined stress field (note: the NBT has been standardised recently [14]). Tensile stresses occur at the surface opposite the notch root. This stress field (maximum tensile stress σ_{NBT}) is almost uniaxial, simple to calculate and almost insensitive regarding

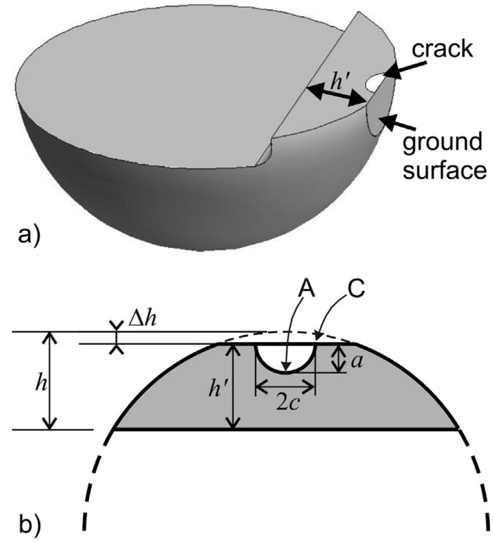

Fig. 2. Geometric situation in the fracture toughness test for balls. Shown is a half model of a notched ball with a semi-elliptical crack (white). The plastically deformed material is still removed (e.g. by grinding). The remaining ligament thickness is $h' = h - \Delta h$. Also shown are the positions A and C, where the crack may start growing.

measurement uncertainties caused by small geometry deviation and the testing setup. Furthermore, the specimen preparation is highly flexible. The needed parameters to describe the geometry of the notched ball specimen are illustrated in Fig. 1. All together, these are good preconditions for toughness testing. For the SCF test applied to balls we use the notation SCF-NB.

The theoretical background and the equations necessary to evaluate the experiments in this work are described in detail in the first part of this paper,[13] but are shortly summarised in the following: for the creation of the start defect a Knoop hardness impression is used in analogy to the standardised SCF method to introduce an approximately semi-elliptical crack into the specimen surface, where the maximum tensile stress occurs (i.e. apex of the notched ball specimen).

The removal of residual stresses by grinding-off the deformed material applied to the notched ball specimen causes a change in the specimen geometry and thus an altered stress field at the position of the crack (see Fig. 2). This has to be taken into account in the data evaluation: the maximum tensile stress in the NBT, σ_{NBT}, has to be multiplied with a correction factor, f_{Sigma}, to get the stress in the specimen after removing the plastic deformed zone: $\sigma \to f_{Sigma} \cdot \sigma_{NBT}$.

The fracture toughness, K_{Ic}, is determined by the fracture stress, $f_{Sigma} \cdot \sigma_{NBT}$, the typical crack size, a, and the geometric factor, Y. The maximum of the geometric factor Y_{MAX} along the crack front is used for K_{Ic} calculation. Note that the value and position of the maximum depends on the geometry of the notch and of the crack and can either be at the deepest point of the crack (position A, see Fig. 2) or at the intersection of the crack with the surface (position C, see Fig. 2).

$$K_{Ic} = \sigma Y \sqrt{a\pi} = (\sigma_{NBT} f_{Sigma}) Y_{MAX} \sqrt{a\pi} \quad (1)$$