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Toughness measurement on ball specimens. Part I: Theoretical analysis

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Abstract

A new toughness test for ball-shaped specimens is presented. In analogy to the "Surface Crack in Flexure"-method the fracture toughness is determined by making a semi-elliptical surface crack with a Knoop indenter into the surface of the specimen. In our case the specimen is a notched ball with an indent opposite to the notch. The recently developed "Notched Ball Test" produces a well defined and almost uniaxial stress field.

The stress intensity factor of the crack in the notched ball is determined with FE methods in a parametric study in the practical range of the notch geometries, crack shapes and other parameters. The results correlate well with established calculations based on the Newman–Raju model.

The new test is regarded as a component test for bearing balls and offers new possibilities for material selection and characterisation. An experimental evaluation on several ceramic materials will be presented in a consecutive paper.

Keywords: Fracture; Mechanical properties; Toughness and toughening; Si_3N_4; Notched Ball Test

1. Introduction

Structural ceramics, especially silicon nitride (Si_3N_4), are distinguished due to their special properties: low wear rates, high stiffness, low density, electrical insulation and high corrosion resistance. For this reason they are advantageous for highly loaded structural applications or when special properties (due to additional requirements) are needed. An important application with a rapidly growing market are hybrid bearings (ceramic rolling elements and metal races), which are used for high operation speeds (e.g. racing), current generators (e.g. in wind turbines) or in the chemical industry.[1,2] Key elements of the bearings are the ceramic rolling elements, which should have to comply with highest requirements. But relevant standards for the proper determination of the mechanical properties of roller elements are missing.

Mechanical properties of ceramics depend to a large fraction on their microstructure, which is strongly influenced by processing conditions. Therefore proper mechanical tests should be made on specimens cut out of the components, or – even better – on components themselves. The strength depends on the flaw populations occurring in the component which are – in general – different in the volume and at the surface. In roller bearing applications the highest tensile stresses occur at (and near) the surface of the rolling elements and surface flaws are of outmost significance for the strength of rolling elements. Therefore the highest loaded area in mechanical testing of bearing balls should be situated at the surface of the balls.

These conditions are fulfilled in the case of the Notched Ball Test (NBT)[3–6] for the strength measurement of balls, which has recently been developed by several of the authors. A slim notch is cut into the equatorial plane of a sphere and the testing force is applied on the poles perpendicular to the notch. In that way an almost uniaxial tensile stress field is generated in the surface near area opposite the notch, which is used for the determination of the strength of the Notched Ball (NB) specimen. Therefore the NBT is very sensitive to surface flaws and relevant for determining the strength of ceramic balls. Note that a similar test, the C-Sphere Test,[7] was proposed earlier, where the notch is not slim but wide and must have a precise shape. The quality of bearing balls is strongly related to a high toughness, which should also be measured at specimens cut out of the balls or on the balls themselves. In industry toughness measurements on

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bearing balls are commonly made with indentation methods (i.e. "Indentation Fracture"-method[8–12] due to their ease of use. It has been recognised in the last years that the toughness values measured with indentation methods depend on the size and shape of the plastic deformation zone around the indent, which may vary from material to material. Therefore the resulting "Indentation Fracture Resistance" (IFR) is only a rough estimate of fracture toughness and has to be calibrated for each material and indentation load.

Standardised fracture toughness testing methods normally use standard beams, which contain a well defined crack and which are loaded and broken in 4-point bending. The fracture toughness K_C is determined by application of the Irwin failure criterion: $K = K_C$, where K is the stress intensity factor (SIF). Note that K and K_C mean pure Mode I configuration (i.e. crack opening). In the following the authors disclaim to use indices because the other loading Modes are not discussed. The critical stress intensity factor can be determined using the fracture load and with information on beam and crack geometry.

A prominent example is the "Single Edge V-Notched Beam" (SEVNB) method,[13] in which, a slim notch is introduced in a bending beam using a razor blade. In that way straight notches with a tip radius of at least 3 μm can be produced. For materials having a mean grain size of several micrometers or greater, this is an accurate approximation of a crack[14,15] but for fine grained materials sharper cracks would be beneficial for a precise toughness measurement.

Very sharp cracks are used in the "Surface Crack in Flexure" (SCF) method.[16,17] A Knoop hardness indent is made on the tensile loaded side of a rectangular bending bar. Thus, an almost semi-elliptical and very sharp crack is introduced in the surface. The size of the remaining Knoop crack is determined by fractographic means, which may need some fractographic experience.

In comparison the SEVNB method is easier to apply and less time consuming but the SCF-method is more appropriate for materials with a very fine grain structure.

To measure the fracture toughness of ceramic balls, bending bars can machined out of balls, if the balls have minimum diameter, say 20–25 mm, but most of the produced rolling elements are smaller. So a simple toughness test for ball shaped components is needed. In this work we will focus on an extension of the SCF method on NB specimens.

2. The SCF-method applied to notched ball specimens

2.1. The Notched Ball Test for strength measurement

Recently, the "Notched Ball Test" (NBT) was established at the Institut für Struktur- und Funktionskeramik at Montanuniversitaet Leoben to measure the strength of ceramic balls, see Fig. 1. With a commercial diamond disc, a notch is cut into the equatorial plane of the ball (depth ca. 80% of the diameter) and the load F is applied at the poles (point 3) using a conventional testing machine. Then the notch is squeezed together and high tensile stresses occur in the surface region of the ball opposite to

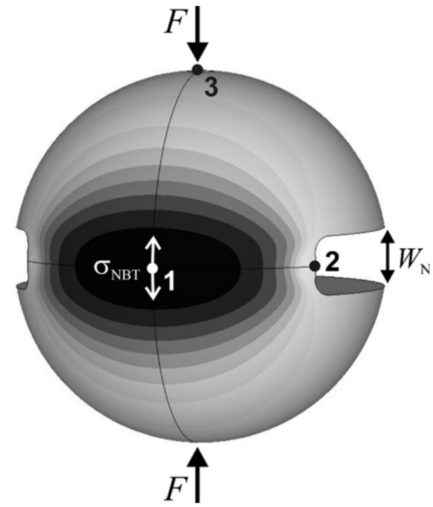

Fig. 1. Stress distribution of a notched ball (NB) specimen. The ball is loaded in compression with the force F perpendicular to the notch. This causes tensile stresses in the outer surface region of the ball opposite to the notch with a maximum stress σ_{NBT} at position 1. W_N is the notch width.
Adapted from [6].

the notch root (the maximum stress σ_{NBT} is located at position 1, furthermore called peak stress).

The stress field in the NB only depends on the ball diameter D (ball radius R), the notch length L_N, the notch width W_N, the fillet radius R_N of the notch at the notch base, and on the Poisson's ratio ν of the tested material. The geometric parameters are defined in Figs. 1 and 2.

To generalize the results the definition of the following dimensionless geometric parameters is convenient: the relative notch length $\lambda = L_N/D$, the relative width of the notch $\omega = W_N/D$, the relative radius of the fillet of the notch base $\rho = R_N/W_N$.

The peak stress σ_{NBT} can be calculated using Eq. (1), with h as the ligament thickness and f_N as dimensionless factor, which depends on the relative notch geometry (λ, ω, ρ) and the Poisson's ratio ν, and which, in the parameter range used for tests,

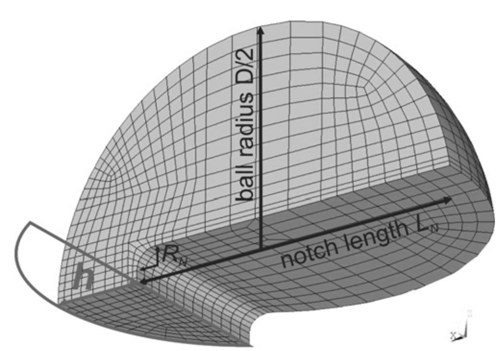

Fig. 2. The stress field in the specimen depends on the ball diameter D, the notch length L_N, the notch width W_N and the fillet radius R_N of the notch. The dimensionless geometric parameters are the relative notch length $\lambda = L_N/D$, the relative width of the notch $\omega = W_N/D$, the relative radius of the fillet of the notch base $\rho = R_N/W_N$. In the equatorial plane remains a ligament having the shape of a segment of a circle with the thickness $h = D - L_N$.