

A new test to determine the tensile strength of brittle balls—The notched ball test

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Abstract

A new strength test for ceramic spheres (balls) is presented. A long narrow notch is cut in the equatorial plane of the ball and the ball is then loaded in compression perpendicular to the notch. This causes tensile stresses in the outer surface region of the ball opposite to the notch, which are analysed carefully with finite element (FE) methods. The tensile stress amplitude depends on the bending moment in the notch ligament – given by the applied force – and on details of the notch geometry. The stress state in the highly stressed surface is almost uniaxial showing only a slight influence of Poisson's ratio. Numerical solutions for balls with quite different notch geometries are given.

Strength tests have been performed on commercial silicon nitride balls of 5 mm diameter. Two sets of specimens having notches of different length have been tested. Although the typical fracture loads in both sets of data are quite different, the tensile strengths are closely similar. This indicates the validity of the data evaluations. Experimental details are discussed and an analysis of the experimental uncertainties on the test results is made. For balls with 5 mm the uncertainties are estimated to be less than $\pm 3\%$ (of the measured value). For balls having a diameter of 10 mm or more the uncertainties are less than $\pm 1\%$.

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1. Introduction

Silicon nitride ceramic balls have been used in high-performance, highly stressed bearing races for the last decade.¹ Compared with steel, silicon nitride has higher hardness, Young's modulus, wear and corrosion resistance, and a lower density, which are very beneficial for bearing applications. If used in electric power generation the high electrical resistance of silicon nitride makes electrical isolation via the bearing possible.² However, ceramic materials are more brittle than steels; therefore information on the strength of the balls is essential, but simple strength testing methods for balls are missing up till now.

Standard specifications exist for determining the properties of silicon nitrides for bearing balls,^{3,4} but these require the strength of a candidate material to be determined using the usual four-point flexure test^{5–7} on $3\text{ mm} \times 4\text{ mm} \times >45\text{ mm}$ test-

pieces which generally have to be cut from specially prepared plate material fabricated in an identical manner, rather than from finished balls. For large balls (having a diameter of say 15 mm or larger) it is possible to machine bending specimens out of the balls in order to perform three- or four-point bending tests,⁸ but this procedure is very costly. The surface of the specimens has to be prepared very carefully to avoid unrepresentative machining damage. Inevitably, in testing these specimens in bending the uniaxial tensile strength of the material is measured in materials originating from the interior of the balls with concomitant machining damage, but it should be noted that in bearing balls high tensile stresses only occur at and near their polished surface.

Disc shaped specimens can also be cut from the balls. Testing can be done by some kind of biaxial disc testing, e.g. using the ring-on-ring^{9,10} or the ball-on-three-balls test.^{11,12} This test can also be applied to specimens having only a few millimetres diameter. Again, specimen preparation is time consuming and costly, and as with the beam bending tests the interior of the ball material is tested. The preparation of the tensile loaded surface requires even more care than that of beam bending specimens, since under a biaxial stress state surface cracks of any direction

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are possible fracture origins (in the case of uniaxial bending tests, cracks parallel to the stress direction are harmless).^{13–15}

These classical methods of ceramic material testing thus do not reflect actual ball properties. Some work has been done to test whole balls by squeezing them together. This can be done by squeezing one ball between two plates, by positioning two balls one on top of the other and then squeezing them between plates, or even by positioning three balls on top of each other and then squeezing them between plates.¹⁶ The first variety of this test is expected not to be very reliable; significant tensile stresses only occur in a ring shaped zone around the contact area between the plates and the ball (i.e. Hertzian stresses^{17,18}). The highly stressed zone is very close to the area where the load is transferred from the fixture into the ball. Therefore the actual amplitude of the highest tensile stresses is sensitive to the details of the contact zone, e.g. some plastic deformation of the plates, the friction between the ball surface and the plates, surface roughness, or even some surface contamination. The loading situation is better defined in the second variety of this test, where the contact situation between the two balls is symmetrical and therefore free from friction effects. (Remark: by using spherical seats on the ends of the pistons the contact situation between the ball and piston is harmless with respect to failure initiation.) Therefore this type of test should be reliable if fracture starts near the middle plane. In the case of three balls, the situation for the ball in the middle is well defined on both contact regions and test results are significant, and reliable if fracture starts in the ring shaped near surface regions around the contact planes of the middle ball. This can be recognised by fractographic analysis of the broken pieces. However, the interpretation of the test results is still a little unclear. Recently, it has been claimed that this test does not determine the strength of the balls but is controlled by toughness and plasticity of the ball material,^{8,19} and a similar conclusion was found recently for the contact loading of ceramic tools for metal forming.²⁰

In this paper, a new strength test – the notched ball test – is proposed. A long and narrow notch is cut along the equatorial plane of the ball. The ball is loaded in compression along the axis perpendicular to this plane. High tensile stresses occur in the outer surface region of the ball opposite the notch root (in the ligament).⁸ These stresses are used to determine the strength of the ball. Fracture starts from defects which exist in this region. It is important to note, that in this area the notched ball still has its original surface. Therefore notched ball test results are also a measure for the quality of the balls, i.e. of the ball surface preparation.

A similar test – the C-sphere test – was proposed in 2007 by Wereszczak et al.²¹ In their test they used a wide notch with a fixed geometry; the notch length is 3/4 of the diameter, the notch width is equal to half of the diameter and the shape of the notch root is a semicircle. This notch geometry is used to maximise the effective surface of the specimen. But this wide notch is difficult and expensive to machine precisely. In our notched ball test a narrower notch is used, having a typical width between 5 and 20% of the diameter and a typical length of 75–90% of the diameter. The exact geometry of the notch root (e.g. half circle, rectangular, etc.) can be determined after machining and

is used for the determination of the stress field. These notches can be machined using simple commercially available grinding wheels.

2. Analysis of the stress field in the notched ball specimen

2.1. Overview

In this section, the stress field of ideally notched balls is described. All examples shown here are based on spheres with a diameter of $D=5$ mm and for a material with Poisson's ratio $\nu=0.27$ corresponding to that of the Si_3N_4 balls tested experimentally. However, the results can be generalised by scaling with the diameter of the spheres and a simple formula to calculate peak stresses given by the applied force will be derived (similar to the evaluation of a bending test). The general feature of this type of notched ball test is a narrow notch cut into a sphere along the equatorial plane. A schematic sketch of the testing arrangement and the definitions of the geometric parameters are given in Figs. 1 and 2.

A finite element (FE) model has been programmed within the framework of ANSYS® classic, version 11SP1.²² The whole model is built up parametrically by programming an input code with the programming language APDL (APDL: Ansys Parametric Design Language²³), and uses pure hexahedra elements. Highly stressed regions are meshed with smaller elements (i.e. the region within and around the ligament behind the notch base), while other parts of minor interest and low stress gradients have larger elements (see Fig. 2).

The middle plane of the notch (i.e. plane of symmetry) is defined to be the X – Y plane. The base of the notch root is parallel to the Y -axis. The force is applied parallel to the Z -axis at the poles of the sphere, see arrows in Fig. 1. The X – Z plane is also a plane of symmetry; therefore only a 1/4 model is needed to describe the problem (for the case of the ideal arrangement).

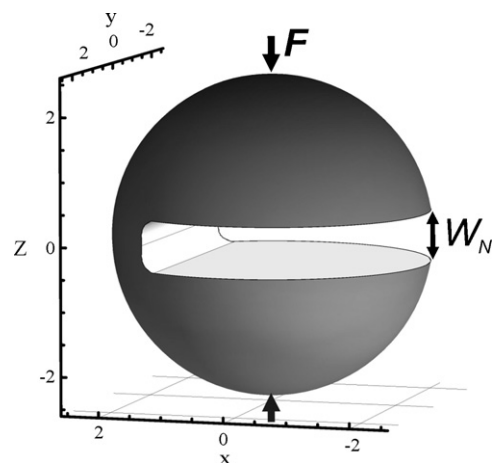


Fig. 1. Sketch of the testing arrangement: the notched ball ($D=2R=5$ mm) is loaded perpendicular to the equator plane at the poles, see arrows. The axes shown define the Cartesian coordinate system used. The origin is the center of the ball. W_N is the width of the notch. The other geometric parameters are described in Fig. 2.

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