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Mechanical properties of silicon nitride rolling elements in dependence of size and shape

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Abstract

Silicon nitride rolling elements for hybrid bearings (rollers, two sizes of balls and plate material as a reference) made from the same material lot and using the same sintering route are investigated in regard to their microstructure and their mechanical properties. For the first time, a direct comparison of the surface strength of the components as well as of their fracture toughness is enabled by recently developed testing methods for balls and rollers.

It was found that the microstructure of these material variants influences the fracture toughness up to about 10%. In addition, due to the different surface finish, the surface strength of the different rolling elements (made of the same material) is very different. The differences may reach up to 100% and more.

Keywords: Mechanical characterization; Strength testing; Fracture toughness; Silicon nitride; Ceramic rolling elements

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1. Introduction

Silicon nitride rolling elements for hybrid rolling bearings (according to ISO 5593: amendment 1[1]) are well established on the market and in International Standardisation (see ISO 26602[2]). Such hybrid bearings are used in many applications, more recent ones can be found in railway industry and renewable energy business such as windmill generators.[3,4] Beside silicon nitride balls, which have the biggest share on silicon nitride rolling element types used for hybrid bearings, also other ceramic rolling element types like silicon nitride cylindrical rollers, spherical rollers etc. are growing in quantities. Depending on the size and shape of the silicon nitride rolling element, different processes for blank forming out from the ceramic powder are used in industry. Ball blanks in the small diameter range up to about 8 mm ball diameter can be compacted from powder granulates by dry pressing (uniaxial pressing) and/or cold isostatic pressing (CIP) or even by rolling granulation out of powder nuclei.[5,6] Larger ball blanks are mainly formed by CIP. Sometimes green machining is done afterwards.

Cylindrical rollers are typically shaped by dry pressing or CIP depending on the size and/or length to diameter ratio. Most of the other roller types like spherical roller blanks or CARB (Compact Aligning Roller Bearing) are done by CIP and green machining as the quantities are typically low and tooling costs would be too high.

The above described different powder compaction routes may lead – according to the authors experience and to literature[7–10] – to different microstructures and therefore to different mechanical properties

An important property of rolling elements is their tensile strength (more precisely their surface strength, since the surface is close to the highest loaded region of the rolling elements in application). The tensile strength of components

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made from brittle materials can be described by the Griffith/Irwin criterion[11–14]:

$$K \geq K_{Ic}, \tag{1}$$

where K_{Ic} is the fracture toughness and $K = \sigma Y \sqrt{a\pi}$ is the stress intensity factor, which describes the stress field at the tip of the crack with the length a. The geometric factor Y accounts for the geometry of component, crack and stress field. Details can be found in Refs. 11, 12, 14. The tensile stress σ acts perpendicular to the crack faces (mode I loading) and pulls them apart. Note that the fracture toughness is a material property, which depends on details of the microstructure (and therefore also on details of the processing[15]). The stress intensity factor depends on the length of the fracture initiating (micro) crack. Such cracks can also be caused by the machining of the components. Therefore the tensile strength of ceramic rolling elements will depend on details of the materials processing and on details of the machining of the components, even when using the same material grade from the same manufacturer. It should be noted that the strength of ceramic rolling elements can also be influenced by handling defects and residual stresses.[16]

ISO 26602[2] gives a reference to tensile strength values obtained by bending tests.[17,18] These bending bars are typically cut out of plates manufactured in a different way to the silicon nitride rolling elements used in bearings. This means, the strength of the rolling elements in the application does not necessarily correlate with the values determined on bending bars.

Some techniques have been developed in the past to test the surface strength of typical rolling elements directly on the component, i.e. the “Notched Ball Test” (NBT) for balls[19–22] and the “Notched Roller Test” (NRT) for rollers.[23] The NBT was recently standardised in ÖNORM M 6341,[24] where the specimen preparation (notching procedure) and the testing setup is defined. In the NBT a long narrow notch is cut in the equatorial plane of the ball. The ball is then loaded in compression perpendicular to the notch, which causes tensile stresses in the outer surface region of the ball opposite to the notch. Production and testing of the notched roller specimens work analogously. With this approach of strength testing of the original components not only a material comparison can be conducted, but also the influence of the surface finish of the rolling elements and of the handling (before testing) can be evaluated.[25] It has to be noted that – for the NBT as well as for the NRT – a specimen preparation and testing routine has been elaborated, which guarantees that the test surface remains untouched, which is important for the integrity of the surface strength results.

As stated before the fracture toughness is strongly related to the materials microstructure. Therefore it is also important to determine K_{Ic} directly on the component. There exist several standardised methods[26–32] for the determination of K_{Ic} in ceramic bending bars but not for components or specimen geometries clearly deviating from bars. Recently, a new method was published for K_{Ic} determination of small ceramic balls[33,34] based on a combination of the NBT and the “Surface Crack in Flexure” (SCF) method. A Knoop indenter is used to introduce a surface crack into the balls surface which is then used as well defined starting crack in the subsequent NBT to determine the fracture toughness. Analogously, the SCF method can be adopted for small discs. This is described in Ref. 35. Therefore it is possible to test the fracture toughness on small disc specimens, which are directly machined out from small balls and rollers.

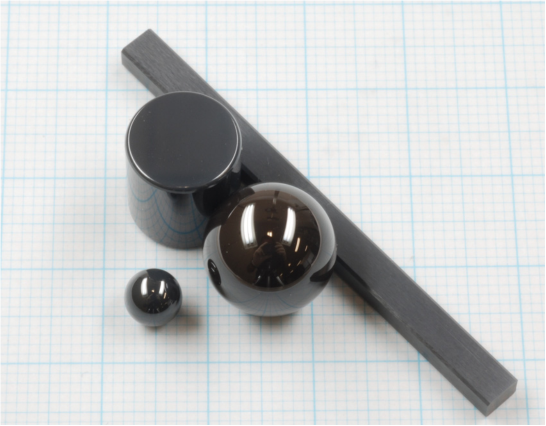

Fig. 1. Overview of samples used in this study. All delivered specimens were made from the same powder mixture and using nominally the same sintering conditions: 5.55 mm balls, 12.7 mm balls and rollers (diameter: 11 mm, length: 12 mm). The bending bars with a cross section of $3 \times 4\,\text{mm}^2$ and ~40 mm in length were machined out from plate material.

The primary aim of this study is to analyse the strength of the rolling elements and to evaluate if the standardised material strength (observed in 4 point bending) reflects the component strength, i.e. the influences of the specific surface finish and the fracture toughness of the rolling elements.

Secondary, the differences in the microstructure originating from the shaping process are analysed and a correlation of quantitative microstructural parameters with the mechanical properties such as hardness or fracture toughness is investigated.

2. Experimental procedure and results

2.1. Investigated materials, density, microstructure

The investigated material is a commercial silicon nitride ceramic, typically used for rolling contact applications.[2] Finished rolling elements and plates were provided for our investigations by our industrial partner SKF: “small balls” (diameter $D = 5.55$ mm), “big balls” ($D = 12.7$ mm), rollers ($D = 11$ mm and length $L = 12$ mm) and plates ($52 \times 42 \times 4.2\,\text{mm}^3$), see Table 1 and Fig. 1. Only limited information on the details of the components’ processing is available: all of the elements are made from the same material lot, i.e. the same initial powder and the same sintering route was used, but presumably, the shaping step was different. Since the microstructure may depend on details of the production route the materials of the four differently produced elements (specimens)[7–10] are called in the following “*material variants*”.

The chemical composition of the variants was measured with X-ray fluorescence spectroscopy: approximately 3 wt.% Al_2O_3,