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Characterization and modelling of the degradation of silicon nitride balls with surface missing-material defects under lubricated rolling contact conditions

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ABSTRACT

Hybrid bearings in which ceramic rolling elements are used in combination with hardened steel rings outperform the conventional full-steel bearings in some demanding applications where high speed, high temperature, electric current, and thin-film or medium lubrication are involved. Despite the continued effort and progress made to improve the toughness, ceramics are regarded as brittle solids that can suffer in general from lack of damage tolerance in the form of sensitivity to pre-existing features that are seen as being potentially harmful. Under specific conditions, these imperfections may become critical for the reliability of hybrid bearings.

This paper reports on a study of the degradation of silicon nitride ceramic balls, caused by surface missing-material (MM) defects under lubricated rolling contact conditions. Rolling contact fatigue test is conducted on the ceramic balls containing artificial defects of different configuration and sizes. Numerical simulation by means of finite element analysis indicates that the lubricant entrapped inside the MM cavity will be pressurized under rolling contact. The hydraulic pressure of the entrapped lubricant can result in significant tensile stress at the corner of the cavity that may cause crack initiation, initial crack propagation, and eventual spalling of the ball surface. Such a degradation mechanism is confirmed by the characteristics of the fatigue damage observed from the tested balls. Based on the understanding of the failure mechanism, a model based on the nonlocal approach to crack initiation at a V-notch is developed to describe the damage tolerance of the silicon nitride balls with the MM defects of specific geometry with respect to the rolling contact load. The prediction of the tolerance limits agrees well with the endurance limits of the silicon nitride balls tested under lubricated rolling contact conditions.

This research has contributed to a fundamental understanding on what type and size of the MM defects can be tolerated in hybrid bearings in relation to used application running conditions.

1. Introduction

Substitution of modern, high-performance ceramics such as the hot iso-statically pressed silicon nitride for conventional metallic alloys in machine components is becoming an increasingly attractive option for those applications where the system performance is constrained by the harsh operating conditions. This is largely owing to the distinguished performance of ceramics such as wear resistance resulting from the high hardness and low friction coefficient, corrosion resistance, electrical insulation, and good dimensional stability due to high stiffness and low thermal expansion coefficient. However, ceramics can suffer in general from lack of damage tolerance in the form of sensitivity to pre-existing defects. An important characteristic of ceramics is the so-called strength differential effect (SDE), i.e. the tensile strength being lower than the compressive strength, a phenomenon that is also common for high-strength metallic alloys [1]. In other words, the ceramic materials are strong under compression but weak or fragile under tension. Despite the continued effort and progress made to improve the toughness [2–4], ceramics are regarded as brittle solids that are prone to cracking upon tension or impact, and are rather susceptible to premature failure in the form of fatigue crack propagation under cyclic tensile stress [5–9].

Hybrid bearings in which ceramic rolling elements are used in combination with hardened steel rings outperform the conventional full-steel bearings in some demanding applications where high speed, high temperature, electric current, and thin-film or medium lubrication are involved [10,11]. There are, however, some technological and economic factors that imped the implementation of the hybrid bearings. Ceramics are highly sensitive to potential pre-existing defects like voids,

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material inhomogeneities, and surface cracks or defects which may be caused by manufacturing pressing faults or result from blunt impact loads. Under specific conditions, these defects may degrade the ceramic rolling elements and lead to failure of the bearing. To reduce the risk of failure, ceramic rolling elements with visible surface defects are usually rejected. Rejection of defect ceramic balls, on the other hand, would increase the cost of the products. Therefore, determination of the tolerance of ceramic rolling elements for specific defects is critical for the cost-effective production and secured reliability of the hybrid bearings used in specific applications.

Rolling contact fatigue performance of ceramics have been investigated from different perspectives. Kida et al. [12] studied experimentally the shearing-mode fatigue crack growth in silicon nitride. Gilde et al. [13] and Burrier [14] researched the effects of the material microstructure on the rolling contact fatigue performance of silicon nitride balls. Vieillard [15] characterized the propagation of subsurface cracks in silicon nitride balls tested in rolling contact fatigue conditions. Realising the high susceptibility to fatigue damage by cyclic tensile stress, Zhou et al.[16] proposed a fatigue life model for silicon nitride balls based on the superficial tensile stress induced by the Hertzian contact. Pattabhiraman et al. [17] presented a sensitivity study of the effects of the size of a pre-existing crack and the fatigue threshold on the rolling contact fatigue failure probability of silicon nitride bearings. Surface crack defects, in particular the ring or cone cracks introduced by impact between two ceramic balls, have been extensively studied and reported in the literature [18–25].

Another type of defect often found on the surface of newly manufactured ceramic balls is the so-called surface missing-material (MM). The MM defects can result from the partial material pull-outs during machining of clustered coarse secondary phase or grains in the silicon nitride matrix, inclusions or can be associated with the star features caused by the manufacturing diamond coarse grit that indent the surface while lapping, or large pre-existing pores by extension. Fig. 1 shows the natural MM defects on the surface of a silicon nitride ball. The MM defects usually appear like circular holes on the ceramic ball surface, as shown in Fig. 1a. Though the depth profile indicates rough surfaces of the cavity (Fig. 1b), a MM defect can be reasonably represented by some simple configurations like cylindrical or conic holes. Compared to the ring crack defects, very few publications about surface MM defects are found in the literature, except for a recent study by Awan et al. [26,27]. There has been some published work [28–31] on the artificial defects in the form of drilled holes on the steel components in rolling contact fatigue, in order to simulate the effects of stringer-type inclusions in steels. Two types of cracks were found to develop from the holes, namely, the horizontal cracks and vertical cracks. FE simulation indicated that the vertical cracks were associated with the tensile residual stress resulting the plastic deformation of the steel around the hole, whereas the mechanism for the initiation of the horizontal cracks was not clear. The effects of the surface MM defects in ceramic balls, however, are hitherto not well-understood and remain to be explored.

This paper presents a study of the degradation of silicon nitride balls containing surface MM defects under lubricated rolling contact conditions by means of experimental characterization and numerical simulation. Based on the understanding of the damage mechanism, a theoretical model is developed to describe the damage tolerance of silicon nitride balls containing surface MM defects.

2. Experimental study

2.1. Material and specimens

The material used in the present study is the silicon nitride (Si_3N_4) grade (according to ASTM F2094) commercially available for rolling elements in rolling bearings. Ceramic balls with a diameter of 12.7 mm were produced by sintering and hot-isostatic pressing (HIP). Fig. 2a shows the microstructure that consists of interlocking needle-shaped grains surrounded by an intergranular phase resulting from the liquid phase sintering process and sintering additives. Here below are the properties of the hot pressed silicon nitride:

- Density: 3240 kg/m^3
- Young's modulus: 310 GPa
- Poisson's ratio: 0.26
- Vickers's hardness HV10: 1560 kg/mm^2
- Bending strength: 1030 MPa
- Indentation fracture resistance / toughness: 6.6 MPa √m
- Bending Strength (4 point bending): 1030 MPa

In order to study the effects of different size surface MM defects, artificial MM were produced on the surfaces of silicon nitride ceramic balls by means of the laser machining. Details about laser machining and production of the MM voids can be found in [26]. Each ball contains one artificial MM defect. Fig. 2b shows a cylindrical MM feature that is characterized by the two geometrical parameters: diameter, *D*, and depth, *d*. Table 1 shows the nine different configurations (labelled as “A” through “I”) of the cylindrical artificial defects produced on the surfaces of the silicon nitride balls for the rolling contact fatigue tests. Some balls with artificial defects of conical shape were also tested and compared with those containing cylindrical MM defects.

2.2. Testing set-up, conditions and procedure

The silicon nitride balls with the artificial MM defects were tested

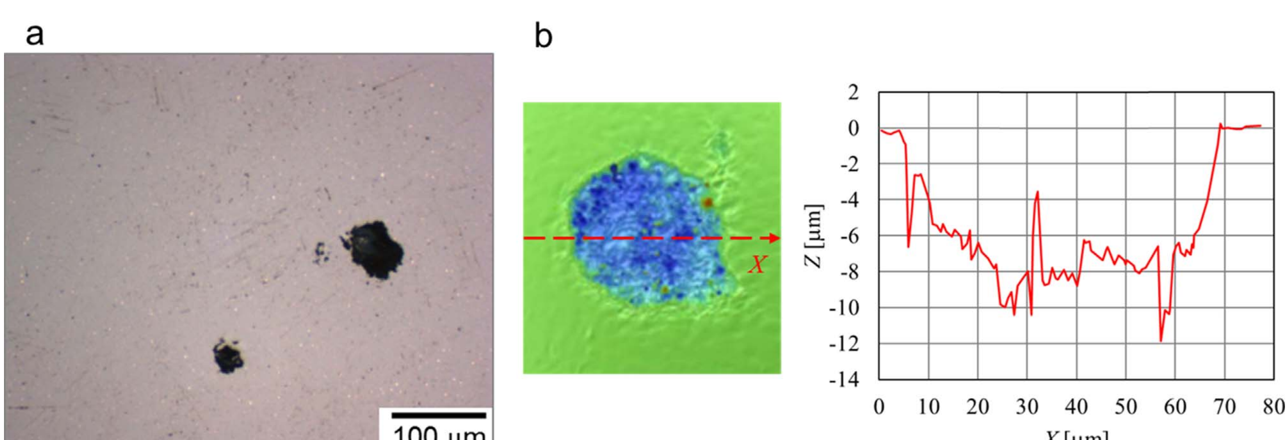

Fig. 1. Surface missing-material defects in a silicon nitride ball: (a) Appearance on the surface; (b) Depth profile measured by means of the Wyko Interferometer.