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Damage initiation and evolution in silicon nitride under non-conforming lubricated hybrid rolling contact

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ABSTRACT

This study focuses on the damage mechanisms in silicon nitride rolling elements used in hybrid (ceramic–metal) bearings that operate under non-conformal contact. To get an insight into the prevailing damage modes compared to the real application, a rolling contact experiment was designed to mimic the contact conditions. Hertzian contact pressures ranged from 3.0 to 5.9 GPa (500–4150 N). In order to approach pure rolling, the experiments were run without inducing any gross slip. Extensive surface and subsurface damage analysis was performed using conventional ceramography as well as FIB cross-sectioning. Finite element simulations were carried out to illustrate the stress state prevailing under different loading conditions. Surface damage to rollers subjected to contact pressures up to 5.1 GPa (2500 N) was mainly dominated by micro-spalling, which was induced due to the presence of snowflake structures. At the highest applied loads, damage appeared as a combination of macro-cracking and micro-spalling. Crack propagation was attributed to different mechanisms: (a) fatigue-induced fracture and (b) lubricant-driven crack propagation in the subsurface.

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1. Introduction

Silicon nitride (Si_3N_4) is the first choice of ceramic materials for modern hybrid bearing applications where conventional bearings fail to meet the prerequisites [1–3]. The unique combination of properties such as, high strength, high hardness, adequate fracture toughness, thermal stability and good corrosion resistance makes silicon nitride attractive for hybrid bearing applications.

Despite being industrially deployed, the reliability of the rolling elements made from silicon nitride undergoing non-conforming contact is still a topic of research. It is evident from full-scale hybrid ball bearing endurance tests that silicon nitride fails due to non-catastrophic fatigue similar to that in conventional bearings [3]. Nonetheless, the damage mechanism of ceramics undergoing rolling contact is completely different [2,4,5]. Full-scale bearing endurance tests are expensive and time consuming, moreover component testing involves many other influencing factors, which complicate the interpretation of results. For this reason many researchers have relied on various rolling contact fatigue (RCF) model experiments either to study damage mechanisms [1,3,6–11], fatigue life predictions [1,3,12,13] or wear characteristics [14–23]. A general review on quality requirements of materials for bearing application can be found in [24] and a recent extensive literature review on various types of damage in silicon nitride is given in [25].

Even when materials are being used under ideal conditions, failure is certain due to deterioration of material by rolling fatigue [1,3,8,9,15]. Damage under rolling contact loading is a complex phenomenon and involves many aspects which affect the material behaviour. The damage mechanism is primarily governed by the tribological conditions as well as the material properties. From the tribological point of view, damage is influenced by the rolling and contact conditions (i.e., with and without slip), contact stress distribution due to the applied load, and lubrication regime. From the point of view of materials properties, the microstructure among other aspects determines the macroscopic mechanical behaviour [26,27]. Due to the fact that silicon nitride could be produced with various microstructures, depending on the sintering technique, sintering aids, and forming process employed, it is possible to obtain materials with different mechanical properties required for specific applications. However, there is a general consensus pertaining to Si_3N_4 based materials that natural flaws such as inclusions of foreign matter, pores and voids, and surface machining cracks are inevitable [24,28,29]. The aforementioned microscopic non-homogeneities play a decisive role in determining material fatigue life. Variations in tribological conditions or in

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material properties could cause considerable changes in the RCF behaviour of the material.

The fatigue life of silicon nitride becomes orders of magnitude shorter when rolling is accompanied by friction and sliding and as c-cracks appear on the surface under non-conforming contact (refer to [23,30] for lubricated cases and [20,22] for the less commonly unlubricated cases). However, damage could be affected substantially even in the absence of sliding, when the rolling elements experience lubricant starvation. Bunting [18] demonstrated how abrasive wear due to direct asperity contact in hybrid bearings changes the contact conformity in a full-bearing test rig.

O'Brein et al. [3] analysed failure mechanism under lubricated conditions in silicon nitride in a full-bearing test. The damage in the silicon nitride rolling elements was mainly dominated by spalling, which initiated from volume defects. They proposed the defect to be sintering voids (less than 2 μm in diameter) and argued that such small defects were inherent material properties rather than manufacturing defects. Burrier [15] studied 11 different grades of silicon nitride materials in RCF tests. The author demonstrated that the materials exhibited fatigue life difference of several orders of magnitude under same working conditions. However, the material with fine grain and uniform minimum distribution of secondary phase showed better fatigue life performance.

In order to understand the crack propagation mechanisms under rolling contact, numerous researchers have performed rolling contact fatigue experiments with artificial ring cracks on the surface [31–46]. Crack propagation in the subsurface is mainly caused by alternating cyclic stresses and in some cases due lubricant entering the crack gap. In the latter case, crack propagation is mainly driven by hydrostatic pressure buildup in the crack gap [42]. Analytical models describing lubricant driven crack propagation can be found in [43–45], however there are only handful of experiments demonstrating the lubricant driven crack mechanism in ceramics [37]. Furthermore, Wang [32] showed the influence of ring crack locations in the contact path on rolling contact fatigue life. He found cracks at certain locations in the contact path to be critical and to contribute to the determination of rolling contact fatigue life based on their stress intensity factor values.

When pre-existing cracks/natural flaws in silicon nitride are negligible, then the failure mode is governed by the porosity of the material [36,46]. In a study [11] performed on fully densified, micro-porous, and porous silicon nitride grades under identical working conditions, the results showed the influence of porosity in the material on the damage mechanism. In case of the fully densified silicon nitride no damage was observed, however the comparison between micro-porous and porous silicon nitride resulted in an order of magnitude difference in the fatigue life failure. In both cases, micro-porous and porous, the damage was dominated by spalling.

For hybrid bearing applications, mostly hot isostatically-pressed silicon nitride (HIPSN) balls are used due to their optimum combination of material properties, nonetheless, high manufacturing cost is still a concern [24]. Nowadays, gas pressure sintered silicon nitrides (GPSN) are gaining importance due to their cost effectiveness and reliable reproducibility in comparison to other manufacturing process. Lengauer [47], Lengauer et al. [48], and Harrer et al. [49] have demonstrated the damage mechanism in GPSN silicon nitride rolling tools applied in wire rolling. However, in GPSN there exists large scale of micro-structural inhomogeneities called "snowflake" structures. A snowflake is a designation for a local region of incomplete densification (i.e., microporosity) in a homogeneous material were intergranular glassy phase is missing and only the grain skeleton is present. Herrmann et al. [50] studied silicon nitride produced with various compositions from different manufacturing techniques. They concluded that snowflakes structures are mostly caused due to thermal mismatch between the grain boundary phase and the Si_3N_4 skeleton. Out of four different sintering techniques (HIPSN, hot pressed sintering, GPSN and spark plasma sintering) these regions were only formed in GPSN and hot pressed sintered materials. There are no studies relating how these snowflakes regions affect damage mechanisms under rolling contact.

The uniqueness of this study emerges from addressing the damage mechanisms involved in non-conforming lubricated hybrid rolling contact of a GPSN silicon nitride, which is considered a more feasible and easier to manufacture alternative to HIPSN. Accordingly, the most crucial parameters influencing damage initiation and evolution in this grade of silicon nitride were analysed by performing model experiments on a twin-disk tribometer. Moreover, the behaviour of snowflake structures (volume defects intrinsic to GPSN) in contact was taken into consideration. This has been achieved by observing crack formation and propagation as function of increased load and number of stress cycles and through extensive post-experimental analysis with focused ion beam (FIB) and conventional cross-sectioning. Additionally, finite element (FE) simulations were employed to study the effect of plastic deformation on contact stresses and their influence on damage and crack formation in the ceramic material.

2. Experimental description

2.1. Experimental method

In order to study damage in silicon nitride undergoing lubricated hybrid rolling contact, twin-disk experiments were carried out using ceramic rolls and crowned 100Cr6 steel discs. A non-additivated mineral oil (SKF TT9, Kroon Oil BV, The Netherlands) was used as lubricant. During the experiments, the tribometer records the normal force in addition to the rotational velocity, test time, torque and the coefficient of friction generated in contact. The samples in contact are rotated at the same velocity, thus, eliminating any gross slip.

Fig. 1(a) depicts the experimental setup. The geometry of the samples results in an elliptical contact as shown in Fig. 1(b). The major contact width ($2a$) lies in the circumferential direction and the minor contact width ($2b$) lies in the axial direction which also represents the contact track width.

Initially, experiments with different loads for a minimum of 10 million revolutions (Mrev) were performed. In order to understand damage initiation and progress of micro-spalling, evolution test were carried out for 850 N from 10 Mrev to 50 Mrev, for 2500 N from 10 Mrev to 30 Mrev and for 4150 N with revolutions ranging from 7500 rev (short test) to 10 Mrev. Table 1 summaries the experimental parameters.

The Hertzian equations [51] for solid bodies undergoing non-conforming contact can be used to calculate the contact pressure p_o and the corresponding major (a) and minor (b) contact ellipse radii.

$$a = c(1-e^2)^{-1/4} \tag{1}$$

$$b = c(1-e^2)^{1/4} \tag{2}$$

$$c = \sqrt{ab} = \left(\frac{3F_N R}{4E^*}\right)^{1/3} \tag{3}$$

$$e = \left[1-\left(\frac{b}{a}\right)^2\right]^{1/2}, \quad b < a \tag{4}$$

$$p_o = \left(\frac{3F_N}{2\pi ab}\right) = \left(\frac{3F_N}{2\pi c^2}\right) \tag{5}$$

where F_N is the normal applied load, E^* is the effective Young's

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