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Damage progression in silicon nitride undergoing non-conforming hybrid cyclic contact

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ABSTRACT

Bearings experience one of the most severe mechanical loading of all machine elements. The contact stresses engendered are highly localised and bound to a very small volume of the material. The aim of this study was to investigate how localised stresses influence the damage mechanism in hybrid contact. Cyclic contact loading of a gas pressure sintered silicon nitride (GPSN) was investigated. Silicon nitride disks and tungsten carbide (WC) indenters were tested under different media, initially at "application relevant" low contact pressures (4–6 GPa) and further on, to accelerate damage, at high contact pressures (10–15 GPa). The low load experiments showed various forms of surface damage with no significant difference between dry and lubricated contact. Whereas, the high load experiments showed different damage behaviour under unlubricated and lubricated conditions. Unlubricated contact resulted in the formation of transfer layers and Hertzian cracks on the silicon nitride surface whereas, damage under lubricated contact was mainly dominated by grain removal and delayed crack formation. Finite element simulations were carried out to study the stress state under different loading conditions. The FEM results indicated that the combination of surface tensile and shear stresses predominantly influence the fatigue damage observed in the experiments rather than fluctuating tensile stresses only.

1. Introduction

Hybrid bearings (i.e., bearings with steel rings and ceramic rolling elements) are nowadays being extensively used due to their many advantages over conventional bearings [1–4]. Out of numerous structural ceramics such as aluminium oxide, SiAlONs, silicon nitride, zirconium oxide and silicon carbide, silicon nitride ceramics are considered to be superior for the modern hybrid bearing applications due to their exceptional properties [5] and failure mechanisms under non-conforming contact [1,6]. The combination of properties such as, high strength, high hardness, thermal stability, moderate fracture toughness, good corrosion resistance makes silicon nitride prime contender for hybrid bearing applications [7]. In addition, hybrid bearings are relatively less susceptible to damage under marginal lubrication due to the low adhesion affinity between silicon nitride and steel, which results in extended service life [8–11]. Another significant reason for considering silicon nitride for hybrid bearings is the dominant non-catastrophic fatigue failure mode, i.e., spalling, similar to all-steel bearings [12–14].

Depending on the manufacturing technique and the sintering additives, silicon nitride can be produced with different microstructures (i.e., with various grain sizes). As a result, these microstructures govern the macroscopic damage behaviour of the material. In order to study damage is silicon nitride undergoing non-conforming contact various researcher have used different model experiments either by performing rolling contact experiments [15–20] or with cyclic contact experiments [21–26]. Rolling contact experiments are used to mimic the contact conditions appearing in hybrid bearings, whereas cyclic contact experiments are conducted to achieve quantitative and qualitative understanding of the ongoing damage mechanism under localised stresses. Chen et al. [21] were the earliest researchers to study the damage initiation and wear evolution in bearing grade silicon nitride under oil lubricated cyclic loading using a tungsten carbide indenter. They showed that wear evolves in three different stages, initially roughening of the contact area due to loading and unloading cycles, followed by cone crack initiation and finally, progressive damage in form of material removal. Eyzop and Karlsson performed a multitude of similar cyclic loading experiments to study the damage mechanisms in bearing grade silicon nitride under different environmental conditions [26] and with different microstructures [25]. In the former study, cyclic contact fatigue

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experiments were performed on two different materials both having fine grain microstructure in different media (air, water and ethylene glycol). The authors reported the formation of deep indentation cracks on the surface for the experiments run under water when compared to those run in air, in which no damage was observed up to certain threshold load. Furthermore, they argued that the damage under water is assisted by stress corrosion, which mainly causes micro-fracture and wear at the grain bridging location as described in [27]. In the latter study, the experiments were performed with different material microstructures under different media. It was reported that the material with the most uniform microstructure showed the best fatigue resistance whereas, the material with the highest content of glassy phase showed lowest surface damage. Nevertheless, under water lubrication, the material with higher content of glassy phase was the first to show damage, which as well indicates the importance of stress corrosion cracking. Lee et al. [28] showed the influence of different grain sizes on the damage behaviour of silicon nitride through static contact experiments. The fine microstructure underwent brittle fracture with formation of Hertzian cone cracks without indication of any quasi-plastic deformation. On the other hand, damage in the coarse and medium microstructures was mainly dominated by quasi-plastic deformation without any Hertzian cracking. Additionally, with FEM simulations the authors described the critical contact stresses influencing the damage behaviour in the materials.

In a recent study, Azeggagh et al. [29] performed similar indentation experiments with different diamond indenter sizes (indenter radius of 0.2 mm and 1.0 mm) on silicon nitride with increasing grain sizes (i.e., fine, medium and coarse microstructures) produced using spark plasma sintering techniques. The contact damage results echoed the results observed by Lee et al. [28] for the fine and medium microstructure; however, the damage of the coarse grain material showed a different mechanism altogether, in which quasi-plastic deformation was observed only when a small enough indenter was used. Xu et al. [22] reported no known differences to exist between static and cyclic damage mechanisms with respect to both quasi-plastic deformation and microcrack propagation. This was demonstrated as well in the extended work of Lee and Lawn [23] on cyclic contact damage of different grain size microstructures under different media (air, water and nitrogen). The results showed no difference in damage mechanisms (i.e., brittle fracture and quasi-static deformation) with respect to microstructure when compared to static contact damage [28]. They reported inert strength degradation with increasing number of loading cycles in the fine and medium microstructures due to chemically assisted slow crack growth under water. On the other hand, the coarse microstructure underwent accelerated strength loss within the quasi-plastic zone with increasing load cycles, especially under water. Consequently, there is general agreement that a fine grain microstructure ceramic with moderate fracture toughness is essential for the bearing applications [30,31].

The purpose of this study aims at understanding the damage mechanisms in gas pressure sintered silicon nitride (GPSN) undergoing non-conforming hybrid contact. Gas pressure sintered silicon nitride is gaining much importance in the bearing industry due to its cost effectiveness and reliable reproducibility. To gain qualitative understanding of damage initiation and evolution, cyclic contact experiments were conducted. A systematic study was performed by carrying out experiments at two load levels: (i) application relevant loads, i.e., relatively low loads, to investigate early stages of surface and subsurface damage, and (ii) high loads, aimed at accelerating the damage and observing its evolution within a reasonable experimental time frame. The tests were also carried out under different media to study the influence of environment. Additionally, finite element (FE) simulations were employed to extract contact stresses under various loading scenarios. Quantifying stresses made it possible to understand their influence on damage initiation and propagation in the material.

2. Experimental description

2.1. Experimental method

In order to study damage in silicon nitride under localised stresses, cyclic contact loading experiments were carried out on an electro-dynamic testing machine (Instron E10000) under different media. A tungsten carbide (WC) ball indenter was brought in cyclic contact with a silicon nitride (Si_3N_4) disk. The nature of cyclic contact loading experiments cannot be described based on a load ratio (R), due to the fact that contact stresses are not considered far field stresses and are highly influenced by the contact configuration. Fig. 1(a) depicts the experimental setup in detail. The silicon nitride disk was held in-place by a disk holder inside the lubricant container and the load was transmitted through a load cell unit. Fig. 1(b) illustrates the load application during the experiments. Initially, a preload is applied during which both samples stay in contact throughout the experiments and further a specific maximum load is applied. As a consequence the area formed in between the preload and maximum load experiences alternating stresses. Furthermore, the experiments performed under cyclic contact loading were classified into two groups, namely, low load cyclic contact (llcc) and high load cyclic contact (hlcc). In the former, the experiments were performed with a preload of 12 N and in the latter with a preload of 100 N. For both cases, the experiments were performed under unlubricated and lubricated conditions. A non-additivated mineral oil (SKF-TT9, Nieuwegein, The Netherlands) was used as lubricant. A constant frequency of 80 Hz was set for all the experiments.

Table 1 summaries the parameters considered for the experiments. Moreover, in order to show the influence of preload on the damage an additional experiment was performed with a preload of 63 N and a maximum load of 212 N. Finally, the load at which Hertzian cone cracks initiate was measured by running unlubricated static contact tests at high loads (1000 N, 1500 N and 2100 N).

The contact pressure and contact area for a ball-on-disk configuration can be analytically obtained by the Hertzian theory [32]. The Hertzian contact pressure (p_o) and semi-contact radius (a) can be calculated as follows

$$p_o = \left(\frac{3F_N}{2\pi a^2}\right) \tag{1}$$

$$a = \left(\frac{3F_N R}{4E^*}\right)^{1/3} \tag{2}$$

with $\frac{1}{E^*} = \frac{(1-\nu_1^2)}{E_1} + \frac{(1-\nu_2^2)}{E_2}$ and $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$ where ν is Poisson's ratio, E is the Young's modulus, $E^*$is the effective Young's modulus, F_N is the normal applied load and R is the relative radius of curvature. The peak value of maximum principal stress (tensile) can also be computed according to equation (3)

$$\sigma_a = \frac{(1-2\nu)p_o}{3} \tag{3}$$

where σ_a is the maximum tensile stress. Table 2 shows the analytical Hertzian values obtained for the different loads used in experiments.