Experimental and numerical investigation of crack initiation and propagation in silicon nitride ceramic under rolling and cyclic contact

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Abstract. The focus of the work was to investigate crack initiation and propagation mechanisms in silicon nitride undergoing non-conforming hybrid contact under various tribological conditions. In order to understand the prevailing modes of damage in silicon nitride, two distinct model experiments were proposed, namely, rolling contact and cyclic contact experiments. The rolling contact experiment was designed in order to mimic the contact conditions appearing in hybrid bearings at contact pressures ranging from 3 to 6 GPa. On the other hand, cyclic contact experiments with stresses ranging from 4 to 15 GPa under different media were carried out to study damage under localised stresses. In addition, the experimentally observed cracks were implemented in a finite element model to study the stress redistribution and correlate the generated stresses with the corresponding mechanisms. Crack propagation under rolling contact was attributed to two different mechanisms, namely, fatigue induced fracture and lubricant driven crack propagation. The numerical simulations shed light on the tensile stress driven surface and subsurface crack propagation mechanisms. On the other hand, the cyclic contact experiments showed delayed crack formation for lubricated cyclic contact. Ceramographic cross-sectional analysis showed crack patterns similar to Hertzian crack propagation under cyclic contact load.

1. Introduction
Out of various structural ceramics such as zirconium oxide, aluminium oxide, SiAlONs, silicon nitride and silicon carbide; silicon nitride ceramics are considered to be the optimal choice of material for modern bearing applications due to their excellent properties [1]. The combination of properties such as, high hardness, adequate fracture toughness, high strength, superior corrosion resistance, thermal stability at elevated temperatures and longer service life makes silicon nitride attractive for hybrid bearing applications [2,3]. In addition, low adhesion affinity between steel and silicon nitride results in low friction and low heat generation, thus, extends the range of potential loading conditions even under marginal lubrication [4,5]. The emerging applications of hybrid bearings are seen in wind turbine generators where silicon nitride bearing balls of diameters reaching nearly 48 mm are used and in traction motors in the railway industry [6]. In spite of industrial deployment, the reliability of the rolling elements made from silicon nitride undergoing non-conforming contact is still a topic of
research due to their brittle nature and scatter in strength. The most widely used grades for hybrid bearing application are hot isostatically-pressed silicon nitride (HIPSN) ceramics. This is mainly due to ability of achieving flaw-free dense material with superior mechanical properties. However, high manufacturing cost is still a concern in applying HIPSN [7]. Alternatively, silicon nitride balls produced from gas-pressure sintered techniques (GPSN) are slowly gaining importance in the bearing industry due to their cost effectiveness and reliable reproducibility in comparison to other manufacturing processes. Nonetheless, GPSN grades may suffer from intrinsic inhomogeneities known as snowflakes [8]. Snowflakes are undensified regions, in which only the grain skeleton is present and the surrounding glassy phase is missing, which may attribute to premature material failure under service. Therefore, understanding damage mechanisms under various tribological loading becomes inevitable[9–15].

The distinctiveness in this work arises from the combination of experimental (rolling and cyclic) work and numerical simulations, which enabled studying crack initiation and propagation in GPSN. The rolling contact experimental results have been extensively described in [16] and cyclic contact results have been addressed for the first time. For both cases most crucial parameters influencing crack initiation and evolution are described by a systematic study with different loads. Minute details in terms of crack initiation and propagation are illustrated by performing extensive post-experimental analysis with focused ion beam (FIB) as well as conventional cross-sectioning. Additionally, finite element (FE) simulations were employed to explain the prevailing complex stress state in both cases.

2. Experimental

2.1. Experimental procedures

The rolling contact experiments were carried out on a twin-disk tribometer as shown in the figure 1. The roll was made of silicon nitride and the disk was made up of hardened 100Cr6 steel. The samples were designed in such a way that when they come in contact they make an elliptical contact. Furthermore, various normal loads from 500 – 4150 N were applied to induced contact pressure ranging from 3 – 6 GPa, respectively. Once in contact, both samples were rotated at same speed making the system run under pure rolling (i.e., without induced slip). Experiments were performed ranging from 7500 revolutions to 50 million revolutions (Mrev) under continues lubrication. A non-additivated mineral oil (SKF-TT9) was used.

![Figure 1. Rolling contact experimental set-up.](image1)

![Figure 2. Cyclic contact experimental set-up.](image2)

The cyclic contact experiments were carried out on an electro-dynamic testing machine (ET10000). A silicon nitride disk was loaded in cyclic contact with a tungsten carbide indenter. Figure 2 shows the experimental setup and the circular contact area arising during loading. In these experiments, an initial preload was applied to hold the samples in contact, after which the load is ramped up until reaching its maximum designated value; the contact area increases accordingly as shown in figure 2. Initially, the experiments were carried out within application relevant contact pressure range (i.e., 4 – 6 GPa with a preload of 2.5 GPa). Subsequently, and in order to accelerate damage, high load experiment with contact pressure ranging from 10 – 15 GPa with a preload of 4.3 GPa were carried out. The tests were
run for 1 to 40 million cycles (Mcycles) at a constant frequency of 80 Hz under dry and lubricated (SKF-TT9) conditions.

2.2. Material specifications
The ceramic rolls and disks were provided by FCT Ingenieurkeramik GmbH, Germany, the commercial designation for this silicon nitride is SN-GP black. The microstructure consists of β-Si₃N₄ grains with an aspect ratio of 7.4 and ca. 10 wt% glassy phase. The sintering additives consist of aluminium oxide (Al₂O₃) and yttrium oxide (Y₂O₃). The counter partners were hardened 100Cr6 steel (HV10>800) and tungsten carbide (WC) indenter for rolling and cyclic contact experiments respectively. The physical properties of the both materials are listed in table 1.

| Physical property        | Silicon nitride (Si₃N₄) | Steel (100Cr6) | Tungsten carbide (WC) |
|--------------------------|-------------------------|----------------|-----------------------|
| Density (g/cm³)          | 3.24                    | 7.28           | 15.63                 |
| Elastic modulus (GPa)    | 300                     | 212            | 640                   |
| Poisson’s ratio          | 0.26                    | 0.3            | 0.24                  |

3. Numerical simulations
The purpose of these simulations was to illustrate the tribological scenarios prevailing under rolling and cyclic contact loading. The physical geometry was discretised using a three-dimensional mesh for rolling contact as shown in figure 3a. A two-dimensional axisymmetric model was used for cyclic contact as shown in figure 3b.

![Figure 3(a)](image1)

![Figure 3(b)](image2)

**Figure 3.** Finite element model to mimic the contact conditions as in (a) rolling contact, (b) cyclic contact experiments.

For rolling contact, the initial sets of simulations were performed considering both materials to be isotropic linear elastic. In order to study the influence of plastic deformation on the contact stresses, a second set of simulations was performed taking the plastic behaviour of steel into consideration. A uniaxial yield strength value of 1100 MPa was assigned to 100Cr6 steel. A quasi-static analysis procedure was employed to initiate contact and to obtain a steady-state contact stress distribution using Abaqus/Standard. For cyclic contact, the simulations were performed without cyclic behaviour. A
single loading cycles was sufficient to capture the entire stress regime prevailing under cyclic loading due to the absence of accumulative plastic strain in both materials. A quasi-static analysis procedure in Abaqus/Standard was employed to run the simulations. Initially, frictionless simulations were performed in order to validate the model as well as to illustrate the stress state for lubricated contact condition with various loads. Additional simulations were performed with the Coulomb friction model used to introduce friction for unlubricated contact.

For both loading cases, additional simulations were performed with cracks of different lengths implemented in silicon nitride. Cracks were created using the partition function in Abaqus/CAE; the partitioned section was treated as a seam [17], so that during mesh regeneration it places overlapping nodes throughout the partitioned face, which act as crack during the analysis.

4. Results and Discussion

4.1. Rolling contact
Surface profilometry across the wear tracks resulted for all loads in barely quantifiable wear volumes and change in surface roughness in comparison to the virgin surface. Up to 2500 N and 50 Mrev, the damage was mainly in form of minute grain break-down from the edges of the machining striation and formation of micro-spalls as shown in figure 4a. These micro-spalls occurred only where snowflake were present. In other words, grain pulled out regions from snowflakes appeared as micro-spalls on the surface. Under certain condition (i.e., with excessive grain pull-out), the micro-spall formed craters as shown in figure 4b, which in turn trapped wear debris and lubricant, thus, allowing the lubricant to build up hydrostatic pressure within the crater during rollover. As a consequence, when sufficient hydrostatic pressure was reached within the crater, cracks would initiate and propagate in the depth as shown in the figure 4c.

![Figure 4](image-url)  
**Figure 4.** Optical image shows the wear track and surface damage (i.e., micro-spall) as observed for all loads and SEM micrographs shows the lubricant driven crack underneath a micro-spall.

For the highest applied load (4150 N), the damage appeared in form of macro-cracks and increased number of micro-spall regions on the surface. Figure 5a shows the top view of the wear track for 4150 N after 10 Mrev with the locations of cross-sections performed for subsurface analysis. The cross-sectional analysis performed at the crack free zones showed no signs of subsurface damage. However, the cross-sectional analyses performed on the surface crack showed that these cracks propagated in radial direction in the subsurface as shown in figure 5b.

The maximum crack length in the depth was measured and found to be 120±30 μm after 10 Mrev. Short experiments with a lower number of load cycles (7500 rev) suggested that crack formation was not spontaneous (i.e., not just after the initial contact or initial few rolling cycles) but rather due to fatigue [16,18]. No micro-spalls were observed for the short experiments and initial cracks on the surface were observed after 2 Mrev.

The FE simulations of pristine (uncracked) and cracked surfaces explained the fatigue crack propagation behaviour under rolling contact, as shown in figure 6. Figure 6a depicts the tensile stress ($S_{\text{max}}$) contours and the corresponding trajectories in the silicon nitride roll in a pristine surface. When
the contact ellipse approaches a crack (figure 6b), the tensile stress on leading edge drives the crack in the rolling direction; during rollover when the crack is engulfed by the contact ellipse (figure 6c) no tensile stress will be acting on it and compressive stresses retard crack propagation. However, when the crack is about to exit the compression dominated region, the trailing edge tensile stresses begin to dominate (figure 6d), thus, propagating the crack in the direction opposite to rolling. This continuous shifting of $S_{\text{max}}$ trajectories at crack tip during rolling contact results in crack propagation in the radial direction (mode I propagation).

**Tensile stress ($S_{\text{max}}$) contours**

![Tensile stress ($S_{\text{max}}$) contours](image)

**Figure 6.** FEM-generated contours of $S_{\text{max}}$ and the $S_{\text{max}}$ trajectories (a) without crack, (b) with crack at leading edge $S_{\text{max}}$, (c) crack in compressive region and (d) crack at trailing edge $S_{\text{max}}$.

### 4.2. Cyclic contact

Table 2 shows an overview of the damage as observed with low load experiments under lubricated and unlubricated conditions.

**Table 2.** Experimental sample material properties.

| Cycles (Millions) | Contact pressure (GPa) | Medium       | Remarks                        |
|-------------------|------------------------|--------------|--------------------------------|
| 20 (2)* and 40 (1)| 4.0                    | Lubricated   | No damage                      |
| 40 (2)            | 4.0                    | Unlubricated | No damage                      |
| 20 (3)* and 40 (1)| 5.0                    | Lubricated   | Damage in form of surface staining |
| 40 (2)            | 5.0                    | Unlubricated | Damage in form of surface fretting |
| 20 (1)* and 40 (2)| 6.0                    | Lubricated   | Damage in form of surface fretting |
| 20 (1)* and 40 (2)| 6.0                    | Unlubricated | Damage in form of surface striations |

* The number in brackets shows the number of tests

Initially, a set of experiments was carried out at 4 GPa and a number of load cycles ranging from 20 – 40 Mcycles. The surface analysis indicated no signs of damage on silicon nitride for both
unlubricated (dry) and lubricated tests. Starting from 5 GPa, three different patterns of damage were observed, namely, surface staining (figure 7a), surface fretting (figure 7b), and surface striation (figure 7c). The in-and-out squeezing of lubricant within the micro-slip zone triggered chemomechanical interactions between silicon nitride and the lubricant under the influence of alternating stresses which led to surface staining. Furthermore, the frictional stresses arising between the contact partners due to difference in elastic constants induced the surface fretting and striations in the microslip zone. Focused ion beam (FIB) cross-sections in the fretted zone suggest that damage is confined to a superficial layer.

Figure 7. Different type of damage patterns noticed for low loads (a) surface staining, (b) surface fretting and (c) surface striations.

The tests with high loads (10 – 15 GPa) showed different behaviour under dry and lubricated conditions. Firstly, upon reaching a threshold number of cycles of 30 Mcycles, similar damage patterns were observed in lubricated tests up to 13 GPa. The damage was mainly in form of grain pull-out from the surface of both materials with an extended fatigue zone, figure 8. Secondly, delayed crack formation without any transfer layer was observed in lubricated tests in comparison to dry tests. In dry tests, Hertzian ring cracks were initially observed from 11.5 GPa, whereas crack formation was observed only at 15 GPa in the lubricated tests.

Figure 8. Optical image showing damage under lubricated condition for 13 GPa after 40 Mcycles (a) on indenter, (b) on silicon nitride surface. (c) SEM micrographs show the damage in form of excessive grain pull-out.

Figure 9a and b show a Hertzian ring crack and transfer layer on the surface of the ceramic and figure 9c shows the subsurface crack propagation in a dry test after 10 Mcycles at 13 GPa. The surface analysis (SEM and EDX) suggested that the transfer layer consisted of W, Co and O. Thus, suggests formation of tungsten trioxide (WO$_3$) and cobalt oxide (Co$_2$O$_3$) on the surface of silicon nitride due to initiation of damage in the WC indenter. A comparison between crack initiation under static and cyclic lubricated contact at 11.5 GPa showed no particular difference. The crack initiation was nearly at the same location. Thus, indicating that the experimentally observed crack under cyclic loading spontaneously forms upon initial contact and propagates with repeated loading on the surface and in the depth with severe sliding between crack faces.
Figure 9. Damage under unlubricated condition. (a) Optical image shows the surface ring cracks with transfer layer. SEM micrographs (b) transfer layer formation and location of FIB cut and (c) Subsurface crack propagation.

Figure 10 and figure 11 show distribution of contact pressure, tensile stresses and the location of crack initiation measured from the lubricated and dry test. Under lubricated condition the experimentally observed initial crack appears exactly at the peak tensile stress; however the experimental crack for dry case is shifted. This behaviour was explained by considering the influence of friction in numerical simulations. The simulations with friction showed that the peak tensile stress increases in the indenter and decreases with a shift in position in the silicon nitride disk, hence, explains the shifted crack initiation in dry contact.

In addition, the crack initiation location on the surface as well plays a decisive role in its propagation. Figure 12 shows the stress intensity factor (K_I and K_II) with loading time for 10 µm crack length with different initiation locations outside the contact zone. The dashed line in the graph represents the fracture toughness of this particular material. It can be clearly seen from the results that when crack initiates just outside the contact zone (i.e., at 290 µm for this case) both K_I and K_II dominates nonetheless, K_II stress intensity tends to diminish as the crack initiates away from the contact zone. Thus, pure mode I crack propagation dominates when the crack initiates at certain distance outside the contact zone.

Figure 10. FEM generated contact pressure and tensile stresses for 2100 N. Figure 11. FEM generated contact pressure and tensile stresses for 3300 N.

Figure 12. Stress intensity values (K_I and K_II) with loading time for 10 µm crack with different initiation locations (13 GPa).
5. Concluding remarks

5.1. Rolling contact
- Surface damage was dominated by the formation of micro-spalls up to a certain load (i.e., 2500 N), above which it appeared in form of macrocracks and micro-spalls
- Micro-spalls formed due to grain pull-outs from the snowflake structure undergoing rolling contact (i.e., alternating cyclic tension-compression fields).
- The crack initiation and propagation were attributed to two different mechanisms: (i) Fatigue induced crack propagation and (ii) lubricant driven crack propagation

5.2. Cyclic contact
- Different types of damage behaviour depending on loading (low and high) and lubrication conditions.
- No peculiar difference was noticed for the surface and the subsurface crack propagation mechanism under cyclic and static contact loading (Hertzian crack). However, excessive sliding occurs at crack face under cyclic loading conditions.
- Frictional forces play a vital role in crack initiation location under cyclic contact configuration.

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