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"Hybrid- and Ceramic Rolling Bearings with modified Surface and low Friction Rolling Contact"

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1. Abstract

Conventional steel bearings often fail under extreme strains. All ceramic bearings and bearings with ceramic rolling bodies, the so called hybrid ceramic bearings, provide a good alternative for such applications. However, important fields of application of the hybrid- and all ceramic bearings can be accessed only, if long lasting load capacity and easy motion of dry running bearings can be ensured even under increased loads. A main objective is to reduce friction within the rolling contact and to significantly enhance the rolling strength particularly in unlubricated contact through modification of the working surfaces of the bearing rings and roll bodies. The approaches are: optimised DLC coatings on steel for hybrid bearings and the incorporating of friction minimising additions of BN and TiN into the Silicon Nitride bulk material for hybrid and ceramic bearings. Coatings yielded good results in lab scale while the friction reducing Si3N4-composites already showed their potential to significantly reduce the rolling friction in underlubricated bearings. A new method of surface treatment of Si3N4 was developed based on a shot peening process. Under optimized conditions load capacity of a ball on plate contact can be increased remarkable. Additionally, in an innovative approach the project focuses on intelligent adaptation of the rolling contact macrogeometry of ball bearings. This development, intended to allow a load related control of the bearing characteristics, now is in the status of numeric and practical evaluation. The work described is funded by BMBF within the MaTech programme (Projects 03N2002 and 03N2018).

2. Reduction of Friction

The reduction of friction is one of the keys for a successful application of hybrid or full ceramic roller bearings under dry or nearly dry environmental conditions [1]. In case of hybrid bearings diamond-like thin film coatings deposited on the raceway seem to be an appropriate method for improvement of the performance. For full ceramics roller bearings, newly developed silicon nitride materials with self-lubricating phases promise to be the successful way. The main goals have been defined to be: a significant reduction of the friction coefficient (<< 0.6) and a load capacity of more than 1 GPa, both under dry conditions.

<u>Coatings</u>

The optimization of diamond-like coatings (doped a-C:H) deposited by a PA-CVD-process to steel raceways needs three steps: (a) optimization of the coating-substrate interface, (b) reduction of the friction coefficient, (c) improvement of life time.

The results of scratch tests (figure 1) show that an improved control of the residual stress state of the coating results in a significant gain of adhesion. Once the adhesion between substrate and coating is optimized, the friction coefficient and the thickness of the coating are the most relevant characteristics determining the performance of the hybrid bearing. An important detail in the subsequent optimization of the coating techniques is the configuration of the standard pin-on plate-test with the relevant pin material. Although for different ceramic materials the friction between ball and coated substrate could be dropped well below a factor of 0.25, it turnes out, that silicion nitride reveals a slightly higher friction and shorter lifetime.

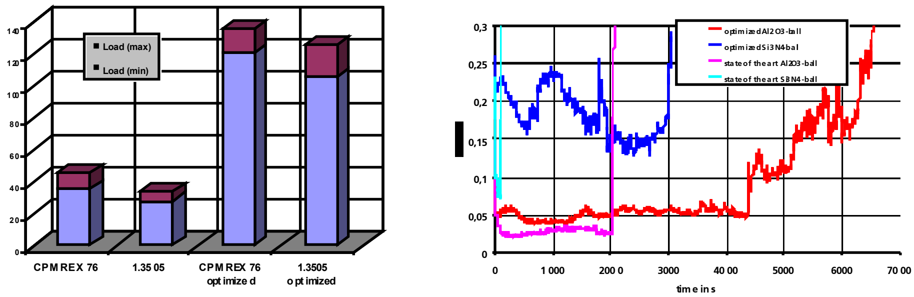


Figure 1: *Left: Optimization of the adhesion of diamond-like coatings on different steel substrates by control of the residual stress states (micro-indenter scratch tests, 10 µm indenter tip radius)*

Right: The optimization of the coefficient of friction and the life time of coatings have to be related to the ball material (oscillating pin-on-disk sliding wear test, ball diameter = 10 mm, initial normal pressure = 1.4 GPa, frequency = 20Hz, amplitude = 1mm, dry)

Self-Lubricating SN-Based Composites

Besides the coating concept, the introduction of self-lubricating phases into the basic silicon nitride material is a second approach to reduce friction under dry-running conditions. According to literature, primarily BN and TiN are recommended for this aim. Bearing applications, however, require a certain level of load capacity of the bearing components. Thus, the introduction of these phases may not weaken the basic material markedly. As it is well-known that the introduction of crystalline BN-powder into silicon nitride is associated with processing problems and loss of strength and hardness, within this project the synthesis of BN during processing was developed using a SiBN-precursor as BN-source. This precursor can be distributed very homogeneously within the basic composition during its preparation and decomposes to BN and Si_3N_4 during thermal consolidation. Varying the concentration of the added precursor resulted in an essential reduction of mechanical properties with about 5 vol% BN and more in comparison with the BN-free reference material. With half of this concentration, bending strength and hardness are only reduced by about 10 – 15 % with respect to the reference material, qualifying such a composition for bearing applications. The microstructure is characterized by finely and homogenously distributed BN-plates between the silicon nitride grains.

There resulted problems to machine this material to bearing balls with a quality grade G10. With these balls as well as bearing races out of this material, friction tests were performed under dry-running conditions. Results demonstrate that this material has a significantly reduced the rolling friction coefficient compared to the reference SN under these conditions. As the load-carrying capacity of bearings is exponentially influenced by the fiction coefficient, its reduction allows an increase of load of about 60 % in comparison with the reference. This demonstrates that also this development is successful to reduce friction under dry-running conditions, opening up a variety of new applications and designs.

2.1 Bearing Performance with new Silicon Nitride Materials

Test bearings have been manufactured from four different materials as given in table 1. The main interest focussed on the performance in dry run and the reduction of the bearing friction torque at dry run.

Table 1: New ceramic bearing materials tested in all ceramic bearings.

Material	Si3N4-MgO	α' / β' SiAlON	Si3N4-TiN (0,95%) composite	Si3N4-BN (2%) composite
Development Objective	advanced corrosion resistance in acid liquids	very high level of hardness	reduced friction in rolling contact	reduced friction in rolling contact

The experimental approach for the investigation of bearing friction was a test set-up in which an axial spring loaded angular contact bearing couple of 7006 E Type (30x55x13mm, 25° contact angle) is mounted. Tests were performed at ambient temperature with minimal grease lubrication, with water and in dry run, respectively. Tests performed with reference bearings made of a modified standard Silicon Nitride (Si3N4-MgO, CFI No. N3209) showed the completely different bearing friction at various lubrication levels. Obviously the bearing fiction of the tested angular contact bearings is closely associated with the fiction coefficient between balls and rings in the rolling contact as figure 2 demonstrates.

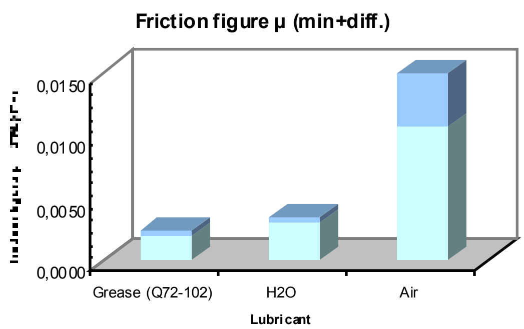
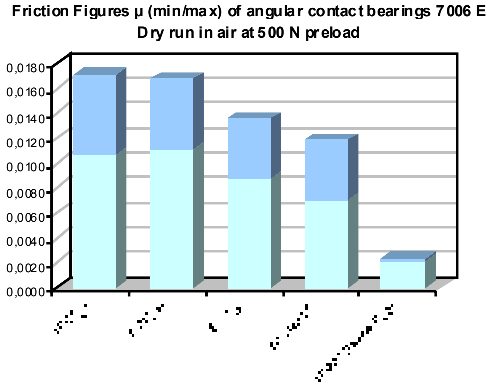


Figure 2: Normalized friction figures of an angular contact bearing 7006 E at operation with varied lubrication condition. Load 500 N axial, p_0 = 1.500 MPa.



<u>Figure 3:</u> *Normalized friction figures of angular contact bearings 7006 E. Material: new developed Si3N4-basesd composites with improved friction behaviour. Dry run, 500 N axial load, contact pressure p_0 = 1500 MPa.*

Dry run in air even with ceramic bearings result in a 5-8 times higher bearing friction as measured for proper lubrication. When operated in water, the friction torque is a function of bearing speed and load. At low speeds almost dry-run friction can be observed whereas with increasing speed a lubricant film is established and friction drops down to values similar to a full lubricated operation. In a test series carried out with all ceramic angular contact bearings the performance of the four developmental ceramics from table 1 was assessed. Bearing friction figures for dry-run in air and in water at room temperature are given in <u>figure 3</u>. Both friction reduced Si3N4-base composites exhibit a reduction of the overall friction around 20% (Si3N4-BN) and 35%(Si3N4-TiN) compared to the reference. Although these values do not reach that of lubricated service, this is already a remarkable improvement. Tests in water again demonstrated the improved rolling contact friction of both materials, that had a friction behaviour (level and ripple) like grease lubricated reference bearings. Here the improvement was around 35% against the reference. Thus, the approach of minimising the contact friction by way of self lubricating phases in a Si3N4 material provides a good potential for ceramic bearing applications in dry running or underlubricated hybrid bearings.

2.2 Improvement of surface integrity

Residual stresses due to mechanical loading have been thought to be no significant effect in brittle materials like ceramics. Recent contact loading tests (ball-on plate tests) show that it is possible to introduce macroscopic plastic deformation without creating damage, if the diameter of the indenter sphere is below a certain critical value [2]. The aim of the investigations was therefore to develop a method for the improvement of the near-surface load capacity of ceramics based on a shot peening process [3]. In <u>figure 4</u> the load capacities determined in the ball-on-plate test point out that a significant gain of strength (up to 50 %) with respect to the polished reference samples can be established by the developed shot peening process.

The increase of the load capacity depends mainly on the peening time for a treatment with fine (75 µm - 125 µm) ZrO_2-beads and on the peening pressure for the coarse (250 µm - 425 µm) beads. The highest load capacity is found for the long time shot peening at high pressure using coarse grained beads.

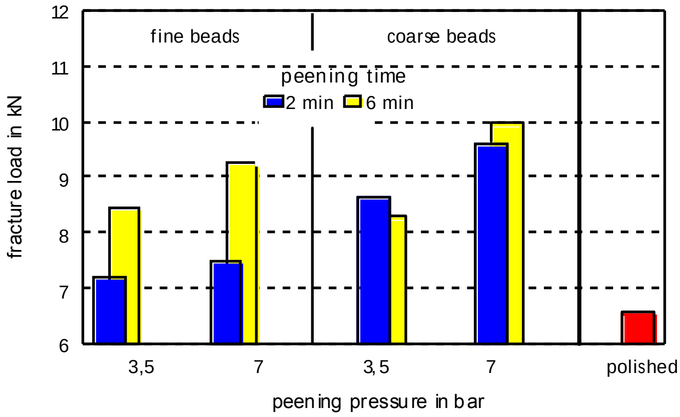


Figure 4: *Gain of load capacity of silicon nitride due to the developed shot peening process (determined in the ball on plate test with a 11.11 mm silicon nitride ball).*

2.3 Optimization of contact geometry

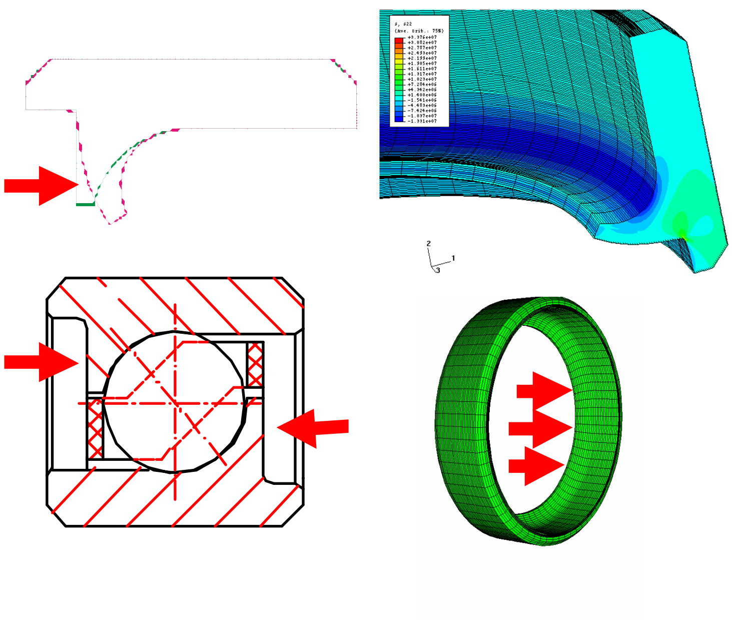


Figure 5: *General principle and FEM-based design study of a roller bearing with piezo-actor controlled raceway geometry.*

A quite novel strategy to optimize the performance of hybrid roller bearings is the on-line control of raceway geometry by piezo actor and sensor elements integrated into the bearing. The aim of this challenging project is to enable a bearing to a) run with a loose Osculation in case of a moderate loading conditions resulting in less friction, or b) to increase load capacity by a close Osculation in case of high loading. The results of a first FEM-based design-study on the principal possibilities of a geometry-controlled angular contact ball bearing (Figure 5) show the change in raceway geometry due to a force applied by an piezo-ceramic actor element.

3. Summary and Examples of application

One target application of the above mentioned developments are lubricant free screw and turbo compressors for energy supply, for clean semiconductor production processes and in food industry. Reduced rolling contact friction is a key for realizing lubricant free operation. Another essential fact is that only ceramic or corrosion resistant bearing steels can be utilized in unlubricated bearings. The developments for optimised rolling contact, DLC coating and friction reduced Si3N4-components, both showed a good potential for applications with poor lubrication conditions like hermetic sealed chemical pumps, agitators, compressors, vacuum pumps and fans for process gases. The improvement of surface strength and surface integrity through shot peening can be considered for Si3N4 bearing components with strong requirements of reliability. The shot peening treatment is expected to reduce sensitiveness of surface defects due to the induced compressive stresses near surface and the macroscopic plastic deformation. This opens up new opportunities i.e. for bearing components with a high stress on reliability i.e. for aircraft engines or space applications. Examples for the potential of an intelligent bearing with load adapted friction and stiffness are HSC-spindles. Large cutting tools with moderate shaft speed require in first place high stiffness and load capacity while small tools typically need bearings that are capable for running at high speeds and moderate loads. The variation of contact geometry here can provide a very smart solution.

4. References

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