HYBRID CERAMIC AND ALL CERAMIC ANTI FRICTION BEARINGS

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ABSTRACT

New bearing materials, coatings and particular designs have innovated bearing solutions in the recent past. The introduction of silicon nitride (Si3N4) as bulk material for bearing components allowed to use this new type of anti friction bearings even under very demanding conditions. The low tendency of adhesion between steel and silicon nitride and even more between silicon nitride parts among themselves provide significant advantages in dry run and under-lubricated run. In several steps a production technology has been established for a quality safe manufacture not only of the balls, but also of cylindrical rollers and complete bearing rings from the very hard to machine silicon nitride. The technology of hybrid ceramic and ceramic bearings will be discussed in this paper, presenting recent results of the development of dry running and under-lubricated ceramic bearings with high stiffness and low friction. Examples for ground and space applications will be given.

1. CERAMIC IN ROLLING BEARINGS

CEROBEAR is the worldwide leading manufacturer of ceramic rolling bearings. Founded in 1989 CEROBEAR is presently the only company which serially produces ceramic rolling bearings in all common designs starting from ball bearings via rolling bearings up to needle bearings. CEROBEAR's success rests upon its fundamental knowledge of machining high performance ceramics and other special materials. And like no other material ceramic demands totally new methods in production technology. The final machining of ceramic, for example, is possible only by grinding and polishing. Because of its extreme hardness high performance ceramics can only be machined by diamond tools. But thorough know-how of machining technology isn't the only key to a successful product. The employment of this group of material in machine elements in severe ambient conditions, i.e. vacuo, high/low temperature, corrosive agents also demands far-reaching experience in material science. The combination of both - knowledge of machining technology in addition to experience in material science - is necessary to create a successful product. CEROBEAR today produces:

- Ceramic Rolling Bearings
- Hybrid Bearings
- Ceramic Rolling Elements
- System Components

Advanced ceramic materials have a high resistance against wear and corrosion, combined with lower mass compared to steel. General properties of advanced ceramics are given in fig. 1, showing the high potential of these materials for bearing applications. The use of ceramic materials in rolling bearing applications has already been considered for two or three decades [1,2]. Initially the intention was to benefit from the high hardness and the tribological advantages of new developed structure ceramics in turbine bearings for aeroengines.

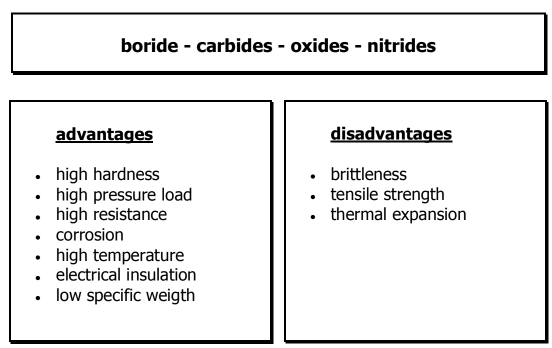

fig 1: General Properties of different groups of Ceramics.

When regarding different ceramic materials like oxide ceramics Al2O3 or ZrO2, SiAlONes, Silicon Nitride (Si3N4) and Silicon Carbide (SiC) it gradually turned out that only dense sintered Silicon Nitride meets the specific requirements for use in rolling bearings. The characteristic parameter is the overrolling strength of a bearing material under cyclic compressive stress. From all ceramic materials Silicon Nitride as Hot isostatic (HiP-) pressed or Gas Pressure Sintered (GPS-) grade has the best overrolling strength for long term application under the cyclic load of the rolling contact.

2. ADVANCED HYBRID BEARINGS

With existing hybrid bearings the speed limits of conventional bearings can be extended to about 20-30% and the service life is prolonged to 2..4 times in grease lubricated systems. The reasons are the low ball mass and the good tribology of the rolling contact between steel (races) and Si3N4 (ball). Today Hybrid Ceramic Bearings with Si3N4-rolling elements therefore are more or less standard for high speed bearings in machine tools or in textile spindles.

Comprehensive investigations of Silicon Nitride ceramic for balls in high speed spindle bearings showed that dense and homogenous grades have a long lifetime in lubricated operation. Rolling elements made of homogenous Si3N4 achieve fatigue life comparable or even better as common bearing steels like SAE 52100. Especially when maximum Hertzian contact stress stays below 2.000 MPa lifetime becomes very high, so that calculation after ISO 281 method gives rather pessimistic figures. Another advantage is, that ceramic bearing components have an uncritical failure behaviour. This was the result of experiments conducted with hybrid and full ceramic bearings and can be observed in various applications. Fatigue in the lubricated rolling contact leads to inititation of grain pull out and non catastrophic spalling [3,4].

But also besides pure high speed bearings the hybrid ceramic technology based on new materials, coatings and material mixes has gained other very demanding fields. Due to the outstanding tribological behaviour (almost no adhesive wear/fretting, less friction, less sensitivity against abrasives in rolling contact, increased lifetime of lubricants) hybrid ceramic bearings open up also solutions for the field of cryogenic and high temperature conditions, as well as in vacuo or within aggressive ambient. Especially under conditions of poor lubrication like boundary friction, media lubrication or dry run hybrid bearings have already been successfully employed. A key for this is the combination of corrosion resistant steels with Si3N4, table 1.

table 1: Material of bearing Ccomponents in advanced hybrid ceramic bearings.

Component	Material
Ball/Roller	Slicion Nitride (HiPSN)
Rings	X102 CrMo 17, X30 CrMo V 15 2, X40 CrMoVN 16.2, HSS 6-5-2, Alloy 718
Cage	PEEK, PTFE, PI, CrNi Steel, Monel

For particular high requirements in respect of corrosion and temperature range, hybrid bearings are available with rings made of corrosion resiostant bearing steels X102CrMo17 and X30 CrMoN 15 1. Bearings from these materials can sustain cryogenic, but also elevated temperatures of up to 250°C. Even further increased heat resistance achieve hybrid bearings with rings made of high speed steel HSS 6-5-2 or Ni-base alloys, extending the field of rolling bearing applications up to 500..750°C. These advanced hybrid bearings are successfully operating i.e. in

- coating lines of glass manufacturers (vacuum)
- coating plants for turbine blades at temperatures of 800°C
- Sterile bottle cleaning and packing machinery
- corrosion resistant bearings for vacuum pumps

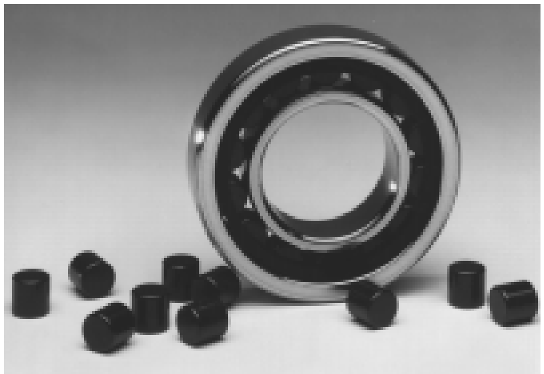

fig. 2: Hybrid ceramic roller bearing.

3. CERAMIC BEARINGS – A NEW DIMENSION IN BEARING TECHNOLOGY

Far more increased wear resistance in dry run have the all ceramic bearings, which are manufactured completely from ceramic. For a long time it was extremely difficult to produce these bearings as the techniques for machining of the ceramics were not available. The high hardness allows only grinding with diamond tools. Initially ceramic bearings were manufactured as ball bearings, angular contact and deep groove type, with balls made from ceramic. The manufacturing process of silicon nitride balls is easier to conduct as that of rollers or rings and thus the hybrid bearing was the first step. Additionally, the fact that the ball production is characterised by a mass production technology encouraged the earlier introduction of hybrid bearings. Things became completely different with cylindrical rollers and complete bearing rings, which pose particular requirements:

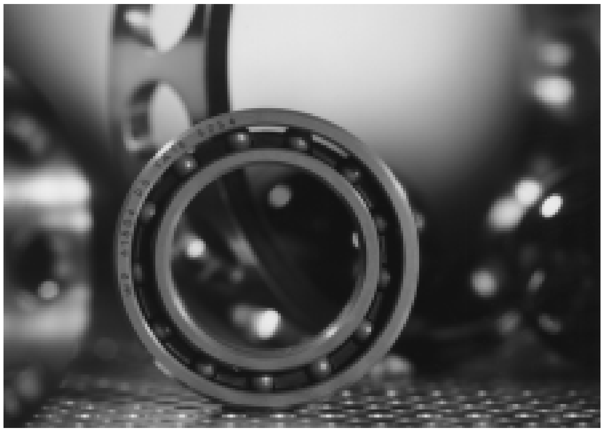

fig. 3: *Silicon Nitride all Ceramic Ball Bearing.*

- Only grinding with diamond tools is applicable for machining of Silicon Nitride ceramic.
- Bearing components have to be manufactured with advanced quality requirements (dimensional and form) as a consequence to the high Youngs modulus of Silicon Nitride.
- 100% quality assurance from powder to the ready made component because of costly blank material and procuction process.
- New clamping and grinding tools
- High flexibility of production lines because of small lot sizes.
- High reproducibility because of limited opportunities for dimensional sorting.

Besides the material processing, another problem has to be solved. Every sintered silicon nitride bearing blank has to be hard machined by a grinding process to a superior quality compared to conventional steel bearings. This is due to the higher rigidity of the material and its higher sensitiveness against surface defects. Consequently, the inhomogenous sintering skin has to be removed and a high surface finish of the high loaded raceway surfaces of the bearings has to be achieved in the manufacturing process. Because of the different and more complicated manufacturing it took much longer to establish a reproducible, quality safe serial production at reasonable costs for the whole ceramic bearing. CEROBEAR developed appropriate methods in the recent years and is now producing all ceramic bearings today in dimensional range of bore 8 mm to external diameter of 200mm and in qualities similar to ABEC 5 to ABEC 7. CEROBEAR ceramic rolling bearings, fig. 5, are available as:

- Angular contact ball bearing,
- Radial ball bearing,
- Roller bearing,
- Spherical roller bearing and as
- Tapered roller bearing.

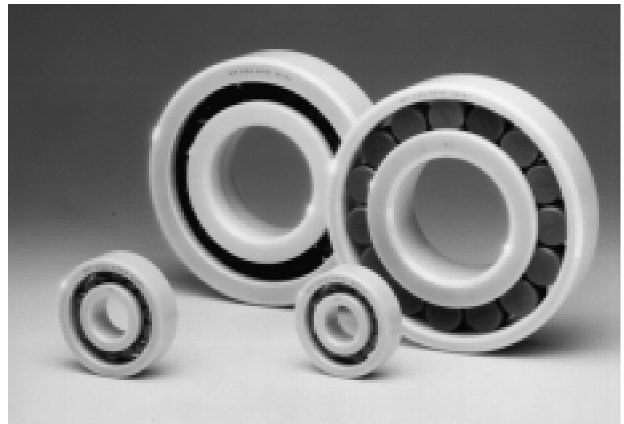

fig 4: *ZrO2/Si3N4 bearings.*

One of the major advantages of the all ceramic bearings is the capability of dry run in the rolling contact. But furthermore, these bearings are extremely resistant against temperature (<800°C) and corrosion, have reduced weight of about 58% and are completely nonmagnetic. This opens up entirely new application scopes by ceramic bearings in applications that were not accessible by rolling bearing technology before. Terrestrial applications of the all ceramic bearings are:

- Coating facilities for semiconductor industry
- Hot dip galvanising lines for sheet metal
- In-process measurement in food packing machinery
- Steam fans for pharmaceutical production
- Furnaces for plastic foil treatment
- Motor engines running under-lubricated
- Vacuum pumps and turbo fans running dry
- Compressors running with water injection
- Fans for process gas in Laser plants

While the majority of ceramic bearings are based on silicon nitride components, at present also bearings are made of fine grain Zirconia (ZrO2), fig. 4. This ceramic has a thermal expansion coefficient which is similar to steel or Ti-alloys. Integration into ambient parts is much easier when high temperature ranges or gradients occur.

4. NEW DEVELOPMENTS FOR DRY RUN AND UNDER-LUBRICATION

In the past various ceramic materials have been developed that are suitable for rolling bearings. HIPed and gas pressure sintered Silicon Nitride with Al2O3, Y2O3 and MgO additions today are standard materials available with high mechanical strength and good corrosion behaviour. With increased understanding of wear and fatigue behaviour of ceramic rolling bearings there is growing demand for improved materials for specific tribological strains.

New ceramic materials for use in bearing components, particularly enforced for conditions of poor lubrication, are currently in development in research activities between CEROBEAR, the German Fraunhofer Gesellschaft and a material producer. One of the main intentions is to enhance the dry run capability of ceramic bearings by means of special silicon nitride composites and surface modifications.

Dry run in applications like fans, agitators and pumps with gas containing fluids are performed successful already. But load capacity for a long time operation is quite limited. For a better understanding, it is necessary to have a look on the dry rolling contact and the wear mechanisms that are observed within ceramic bearings. Silicon Nitride ceramic does not tend to critical adhesive wear, thus providing the capability of lubricant free operation with hybrid and all ceramic bearings. Typical wear mechanism of a dry running ceramic bearing accordingly is not fretting, but propagating abrasion, provided that the load stays undercritical. When regarding the dry running or under-lubricated rolling contact with strong boundary friction it turns out that load capacity of ceramic bearings in this conditions is limited by critical tension loads near to the raceway surface that may cause traction cracks. The critical stress has been identified for dry run (atmosphere) at max. Hertz´ contact pressure p_0 = 1.000 MPa and for poor lubricants like H20 at p_0 = 1.500 MPa. All ceramic bearings are capable of running 10^7-10^9 revolutions depending on acceptable wear-out of the bearing races. Even above the critical load level, ceramic bearings are operating. In this case lifetime is reduced by the initiation of cracks, but is still in the range of $2x10^7$-10^8 revolutions at p_0 = 1.500 MPa.
The most important parameter, influencing the failure of the bearing components, is the friction coefficient in the rolling contact. Even in rolling contact, there are slip zones between the roll bodies and the raceways when the bearing is revolving. In these areas high tangential stresses are generated due to the friction coefficient. In fact the friction coefficient of dry Si3N4/Si3N4 and Steel/Si3N4 contact is quite high reaching values of around 0.4..0.8, depending on ambient atmosphere and surface topography. This causes an intensified stress field containing increased tension stresses at the boundaries of the contact area. The objective of current material development is therefore to reduce the friction in the unlubricated rolling contact. Several strategies have been identified:

- Soft Coatings (AG, MoS2)
- Hard coatings DLC, CrN
- Ion Implantation of raceway surface
- Silicon Nitride composites with solid additions for reduced friction coefficient
- Transfer lubrication from cages with dry lubricant additions (PEEK+MoS2, PI+ MoS2 and others)

As a result of above mentioned research activities, several new silicon nitride composites with additions of friction reducing TiN and BN phases were developed. A difficulty was, that hardness, strength and toughness tend to decline with increasing content of the TiN and BN additions. In overrolling tests [5] and in field tests it was shown, that these new materials have kept their mechanical and fatigue strength while contact friction could be reduced. The work is still in progress, but there have been very promising results in friction measurements with pairs of spring-preloaded all ceramic angular contact bearings of 7006 E type in test rig, fig. 5. Friction tests so far have been performed only in atmosphere. But good wear resistance and lifetime with silicon nitride bearings were observed in bearings for vacuum pumps. In combination with coatings very good friction and performance is expected also for hybrid bearings in dry conditions or under-lubrication.

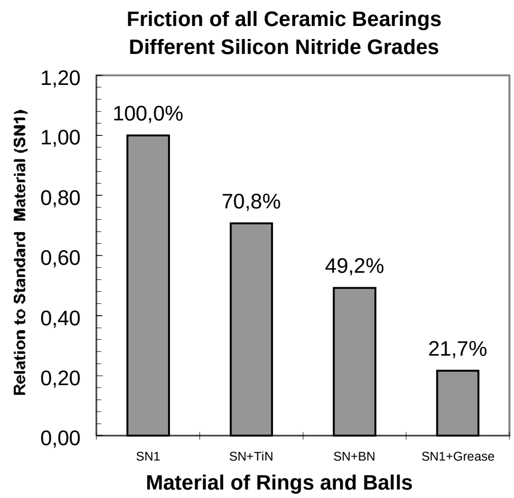

fig 5: *Bearing friction of different materials in angular contact bearing 7006 E related to a standard Silicon Nitride ("SN1"). Dry run, p_0 = 1.500 MPa*

5. CERAMIC BEARINGS IN SPACE APPLICATIONS

Ceramic bearings have also a high potential for the solution of bearing problems in space. Lubrication, thermal and vacuum conditions, accuracy and mass reduction here put strong tribologic requirements. Two general fields for ceramic bearings in space applications can be identified: high accurate bearings, for mechanisms and high speed bearings like already approved for fuel turbopumps of spacecraft engines. Problems or limitation of today's conventional bearing technology are:

- **Vacuum conditions:** Problems with the steel to steel contact between rolling elements and the raceways of the bearing rings. Especially for bearings that perform oscillations and/or stand still for certain times this encourages effects like adhesion between the contact surfaces of the rolling components.

- **Low friction momentum:** Important feature of bearings for positioning mechanisms is a minimised and preferably constant friction momentum. This requires low and constant friction coefficients of the dry running rolling contact. Stick slip effects and high initial friction have to be limited.
- **Dry run or under lubrication:** A typical strain for bearings in space applications is that proper lubrication is not possible due to vacuum conditions, high/low temperatures and that long time service often exceeds the service time of the lubricant.
- **Accuracy and stiffness:** Bearings for mechanisms have to be highly accurate. Radial and axial run out, as well as the bearing clearance have to be reduced down to a minimum, whereas the bearing stiffness should preferably be very high. This requires special bearing design (higher contact angle, osculation)
- **Variation of load situations:** Take off loads can differ up to the factor 30 from that of the long term loads in orbit. It is a well known phenomenon, that a low preload which is beneficial for minimised bearing friction in the most cases is not sufficient for the load situation in the take off phase. In general the not properly preloaded bearing can suffer damage by the vibration and micro sliding of unloaded balls during launch.

In an actual research project [6] a new hybrid ceramic bearing pair is developed for the investigations of hybrid ceramic angular contact bearings with improved tribology for mechanisms. The objective is to develop a bearing design for high accurate and low friction motions in mechanisms. The design is characterised as follows:

- Material of Rings: X30 CrMo N15 1
- Material of Balls: ZrO2 (for thermal expansion reasons), alternatively Si3N4
- Lubricant: Ag-coated rings (0,5-1,5 micron layer) with and without additional lubricant (PFPE)
- Cage: PEEK (-65 .. 240°C), one part
- Assembly: O-Arrangement
- Preload: hard mounted

The silver coated hybrid bearing pair has P5/ABEC 5 class accuracy and light preload. Fig. 6 shows a similar bearing design already realised. This 2-row precision hybrid angular contact bearing is designed for extreme acceleration as dry running emergency bearing for turbo machinery with magnetic bearing system. Field experience showed a lifetime extension against steel bearings of up to 10 times.

fig 6: Two row hybrid angular contact bearing with thin silver coating for improved dry run capability.

In order to investigate the performance of the new bearing concept three test modes were chosen: Vibration test, vacuum test and thermal vacuum test. The work in this project has recently started, and experimental the following improvements of the bearing concept are expected:

- Improved tribology by the combination between steel and silicon nitride rolling elements.
- Reduced degradation of lubricant like PFPE in the coated steel to silicon nitride rolling contact.
- light weight silicon nitride balls (app. 58% less weight than steel balls) reduces the total weight of the system.
- Higher Youngs modulus of silicon nitride reduces friction and increases stiffness.
- Vibrations during launch will be less violent, because of the reduced inertia of the balls and high pre-load necessary for the launch phase can be reduced.

Outstanding results on the other hand were already achieved by hybrid high speed bearings based on innovative ceramic technology. Hybrid ceramic ball bearings are already used in the space shuttle main engine turbo fuel pumps [7]. These bearings operated at extraordinary speeds in liquid Oxygen undergo extreme tribologic strains. In the meantime also the cylindrical roller bearing can be substituted with an innovative ceramic hybrid bearing after qualification for the space application. The hybrid bearings replace high developed steel bearings which had reliable lifetime of no longer than one flight. Intensive qualification of material, production process and bearing performance on ground proved that the new bearing concept now allows 16 missions. This impressively underlines not only the cost and advantages in application but also the high reliability of bearing components made of advanced ceramics, s. fig 7 and 8.

6. SUMMARY

Hybrid ceramic bearings with precise ceramic balls and rollers have a significantly improved tribocontact behaviour compared to conventional bearings. Equipped with rings made of corrosion resistant bearing steels and coated raceways, these bearings can be employed at extended speed limits, under conditions of media lubrication and even in dry run in vacuum. Today already in serial production manufactured all silicon nitride ceramic bearings have even further increased wear and temperature resistance and protrude into applications prior not accessible for rolling bearing technology. New ceramic materials showed in tests the potential to further minimise the friction in non lubricated rolling contacts allowing to improve load capacity and lifetime of the bearings. As a consequence of the outstanding properties of silicon nitride as bearing material, hybrid and all ceramic bearings can be found already in various terrestrial applications. Particularly because of the light weight and the outstanding tribocontact ceramic bearings possess great potential for space applications. In fuel pumps media lubricated hybrid bearings already are used, while developments and evaluation of advanced hybrid ceramic bearings for mechanisms are in progress.

fig. 7 : CEROBEAR Ceramic balls and cylindrical rollers.

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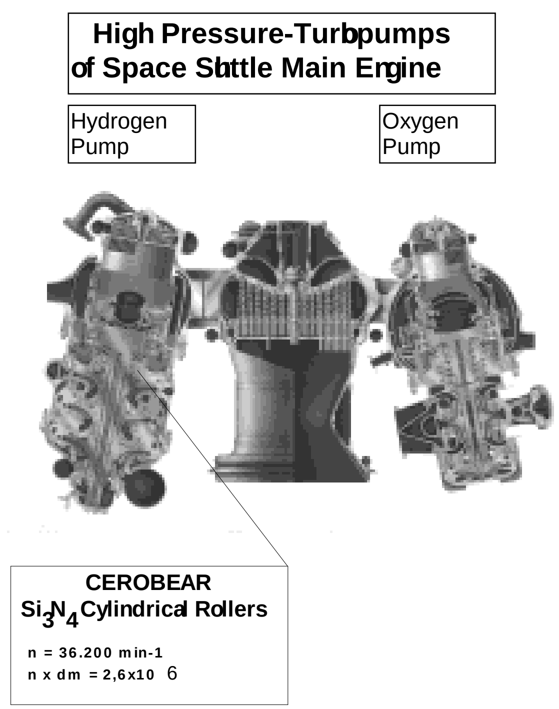

fig. 8: CEROBEAR Cylindrical rollers in turbo pump of space shuttle main engine. (United Technologies Pratt & Whitney, West Palm Beach, FL, U.S.A.