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Abstract

The main purpose of solid or fluid lubricants in ball-bearings is to separate the balls and races from contacting each other in so-called asperity collisions. Steel to steel contacts lead to microwelds which roughen functional rolling-contacting surfaces and deteriorate the lubricant.
By using balls with a ceramic TiC coating, two goals are achieved. First, there are fewer asperity collisions because of the extreme smoothness of the high precision polished TiC coated balls. Second, if collisions do occur, there is practically no microwelding taking place, leaving the surfaces and the lubricant in good condition. Examples are given where the bearing lifetime is increased up to 10 times if the steel balls are replaced by TiC-coated balls.

Introduction

Ball bearings are complex systems where many mechanical components are in rolling and/or sliding contacts. The performance of the bearing itself is strongly dependent on the performance of each individual tribocontact. The friction and wear properties of a mechanical part are largely determined by the character of the surface, e.g. the nature of the material, the hardness and the roughness.

The use of suitable coatings is an ideal means to change the surface characteristics, without noteably changing the bulk mechanical properties of the bearing component[1].

Tribocontacts in steel bearings

The basic components encountered in a standard ball bearing are the inner and outer races, the balls, and the ball-retainer. During rotation, the following mechanical tribocontacts are operating:

- **ball to race:** This is a most important contact since it is the one that transmits the force/loads. This contact consists of a mixture of rolling and sliding. Since the specific loads can be quite high, and since the contacting partners are both of steel, this tribocontact can lead to adhesive wear situations.

- **ball to retainer:** The balls, rolling inside the pockets, are in sliding contact with the walls of the retainer. The specific loads encountered here are definitely lower than those seen between balls and races. Additionally, the balls and retainer are normally of different materials. Therefore these tribocontacts do not often cause problems.

- **retainer to races:** The retainer can be suspended on the balls themselves, or can be in sliding contact with the inner or outer race. This sliding contact is usually under low specific load, and in addition the materials are most often of different nature. Therefore these tribocontacts seldom cause problems.

Therefore only the ball to race contacts will be examined more in detail. Figure 1 is a schematic representation of an uncoated steel ball in rolling/sliding contact with an uncoated steel race surface, in the presence of a lubricant. The role of this lubricant is to physically separate the contacting components.

Besides this "mechanical" function, the lubricant is also called on to remove heat and to protect against corrosion. However, at this time the interest is mainly with the tribological aspects.

Although the contacting surfaces are smooth and although the lubricant may contain special additives to increase its load-bearing capacity, there will still be asperity collisions. When peaks of the ball and race surfaces contact each other, as seen in Figure 1, there is an significant possibility that micro- or cold welding will take place. Since the bearing is in continuous movement, the contact will rupture almost instantly. This microweld formation and its break-up has two important consequences for the bearing:

a) A weld does not fracture through the welded surface, but instead breaks through one of the components, at a certain distance from the weld itself. The direct consequence of this is that there will be material transport from ball to race, or from race to ball. The overall result will be a roughening of the surfaces which often shows up as easily visible bands on the balls and races after only a few hundred hours of use.

b) The bending and breaking up of the microweld causes an instantaneous and very localized temperature rise. This phenomenon and the reaction of the "fresh" iron-base surface contributes to a systematic breakdown of the fluid lubricant through either cracking or polymerizing of its internal chemical bonds[2],[3]. It has often been observed by bearing specialists that during the early stages of operation a bearing lubricant darkens, and that this is frequently accompanied by the formation of strongly adherent solid resins[4].

Normally, one or the other of these two trouble sources will eventually become the determining limitation for the bearing lifetime.

Tribocontacts in modified bearings

There are several ways one can think of for how to improve the asperity contact problem. The surface qualities could be dramatically improved, the contacting components could be made of materials that resist or only weakly cold weld, or materials of the same composition could be separated by a coating. These possibilities are shown schematically in Figure 2.

1. Improved surface qualities

One can imagine two ideally smooth surfaces, without defects or asperity peaks. With an optimized lubricant it would then be possible to maintain a separating film between the two components. In reality however, the surfaces have defects inherent in the material itself, or to the machining or assembling operations. The surface roughness encountered in very high precision ball bearings are as follows:

steel raceways	: $Ra < 0.03\ \mu m$
steel balls	: $Ra < 0.01\ \mu m$

It is practically impossible to economically produce steel surfaces smoother than this. In addition, the steels often used (SAE 52100 or AISI 440C) have a heterogeneous microstructure of martensite and carbide phases which cut, grind, polish, wear, etc. at different rates. It appears that the steel surface qualities presently achieved in the bearing industry are well optimized, and significant improvements are not considered likely with current technology.

2. Different materials

Lately there are an important series of applications where ceramic (Si_3N_4) is used instead of steel[5]. The main characteristics of this Si_3N_4 material are:

density	: 3.2 g/cm^3
modulus of elasticity	: 31'000 daN/mm^2
thermal conductivity	: .073 cal/s/cm/°C
thermal expansion coef.	: $3.5x10^{-6}$/°C
hardness (Vickers)	: 1500 - 2000

In most cases the steel balls are replaced with ceramic balls. This results in the tribocontact situation shown schematically in Figure 2(b), where the important advantages are:

a) Due to its increased hardness and its more homogeneous and finer microstructure compared to steel, the finished, polished surface is smoother. Thus there will be less possibilities for asperity collisions.

b) In the case of contact between steel and ceramic, the probability of microweld formation is much lower than for steel to steel contacts.

c) The low density of this material results in light-weight balls that are well suited to high speed applications.

In some cases, for example high temperature or corrosive environment applications, both races and balls can be of ceramic. This is, however, an expensive solution and is not as common as where only the balls are ceramic. The use of ceramic components is a means to increase the performance of ball bearings in certain operating conditions, and is presently extensively used, but the combination of steel and Si_3N_4 can encounter problems due to the differnence in the thermal expansion coefficients.

3. Coatings

By using a solid coating on one of the steel components, direct steel to steel contacts can be avoided. The question is which coating has the required characteristics concerning mechanical and chemical properties, compatibility with the substrates, etc.?

In the early seventies, the use of carbide, nitride or oxide coatings on cutting tool components became standard. It turned out that such coatings had favorable tribological properties and constituted good candidates for application to bearing components[6].

Figure 2(c) shows schematically the tribocontact between a steel bearing race and a TiC-coated steel ball. The coating is obtained by CVD (Chemical Vapor Deposition), which is a high temperature (800 - 1000° C) process. The coating has a good metallurgical bond with the substrate, due to the high temperature treatment. It is in a favorable compressive state, because of the thermal expansion mismatch with the steel substrate. After the deposition, the balls are heat treated to recover their core hardness, and then high-precision polished. The main characteristics of the coating are:

coating microstructure	: single phase
grain size	: submicron
hardness	: 35'000 MPa
thermal expansion coef.	: $8x10^{-6}/°C$
coating thickness	: 3 µm (typical)

The important advantages of this solution are as follows:

a) The extremely hard, fine grained, single phase TiC is well suited to produce a very smooth polished surface. This means that there should be fewer asperity collisions than with uncoated steel balls. Typical roughness data for steel and TiC-coated balls are:

uncoated steel	: Ra < 0.01 µm
TiC-coated steel	: Ra < 0.005 µm

b) When TiC comes in contact with steel, the tendency to cold weld will be negligible, as in the case of ceramics.

c) The coated ball still exhibits the bulk properties of the uncoated steel ball, such as elasticity, hardness, thermal expansion, thermal conductivity, etc. This is an important factor since it means that steel balls can be replaced with TiC-coated balls without the necessity of recalculating bearing characteristics such as stiffness, elasticity, preload, angle of contact, etc.

Applications

1. Spin axis gyroscope with oil lubrication

The oil used to lubricate ball bearing mounted gyroscopes normally is not replenished during the life of the unit. The bearing is also not being run under fully elastohydrodynamic conditions, so significant probabilities for ball to race contact exist. Degradation due to the mechanisms discussed above, namely transfer of material from the races to the balls, and deterioration and hardening of the oil, is observed.

Comparisons between steel balls and TiC-coated steel balls were made in hysteresis-type test motors, using the gyro spindles and bearings[7]. By monitoring the power variation required to drive the motors, the torque variation due to bearing friction was indirectly measured. The test conditions were:

bearing type	: R3, angular contact
outer diameter	: 25 mm
ball diameter	: 2.38 mm
rotation speed	: 22'500 rpm
bearing environment	: 100 Torr hydrogen, 82° C
measurement intervals	: 100 hr, 200 hr, weekly, monthly

Inspections were made during and after the tests, with no visible evidence of ball or race wear, nor any evidence of lubricant degradation. Also, the milliwatt variation in motors incorporating TiC-coated balls was consistently lower in comparison to motors using uncoated steel balls (Fig. 3), indicating lower friction. Finally, the milliwatt measurement traces were substantially smoother than their steel ball counterparts (Fig. 4), leading to the expectation for lower random drift and improved performance in actual gyroscopes. Another study using TiC-coated races rather than balls, showed similar results[8].

2. Space application with fluid lubricant

The effectiveness of TiC-coated AISI 440C stainless steel balls in preventing the in-vacuum degradation of Fomblin Z25 oil was investigated[9]. TiC-coated balls were incorporated in SAE 52100 steel angular contact bearings, and run in vacuum. The bearings had the following characteristics:

outside diameter	: 42mm
inside diameter	: 20 mm
ball diameter	: 7.14 mm
precision	: ABEC 7

One pair was run at 200 rpm for 1 x 10^8 revolutions, while another pair was run at 1400 rpm for 9 x 10^8 revolutions. In both cases the preload was 40 N. Figure 5 shows the results of the bearing lifetime tests, and compares bearings using uncoated steel balls with those using TiC-coated steel balls.

The use of TiC-balls delayed the onset of lubricant degradation in bearings operating in vacuum. At 1400 rpm, there was approximately a ten-fold increase in life expectancy when TiC-coated balls were used. At 200 rpm, there was also a significant increase (by at least a factor of 10) brought by the TiC-coating to the life expectancy of the lubricant, with no evidence of degradation after 1.4 x 10^8 revolutions. At the end of the tests, the TiC-coated balls had no evidence of surface damage.

3. Space application with solid lubricant

In some mechanisms designed for use in space, solid lubricants are preferred to liquids[10]. Molybdenum disulphide (MoS_2) is commonly used in such cases[10],[11]. The rather soft MoS_2 can be applied by burnishing or by sputtering techniques directly onto the functional surfaces of the tribomechanical contacts in bearings, gears, etc. The use of TiC layers in combination with this solid lubricant also appears to give an improvement in performance.

Laboratory tests have shown that the combination of MoS_2 and TiC films is beneficial to sliding and rolling contact performance. The lifetime of the MoS_2 in a ball bearing is extended if TiC-coated balls are used instead of conventional balls (Fig. 6). Adhesion characterization by the scratch test method indicates that the adhesion of MoS_2 may be better on TiC than on steel (Fig. 7).

The TiC-coated steel balls with uncoated or MoS_2-coated steel races will have the same influence in reducing the asperity contact → microwelding → fracture → surface roughening and particle generation degradation cycle already described. There may be additional improvements coming from the enhanced ability of the MoS_2 to transfer to, and stick on, the TiC surface of the balls, thereby being better able to fulfil its lubricating function.

Conclusions

The most critical tribocontact in ball bearings is between the ball and the race. The performance and lifetime of a lubricant may be improved by using different materials for these components, either replacement or by coating. With the proper choice of materials, the effects of cold welding can be dramatically reduced. The use of TiC as a coating on steel balls has demonstrated such improvements in both fluid and solid lubricated applications.

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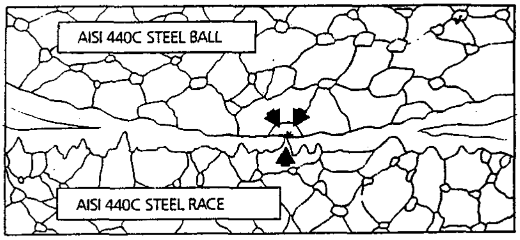
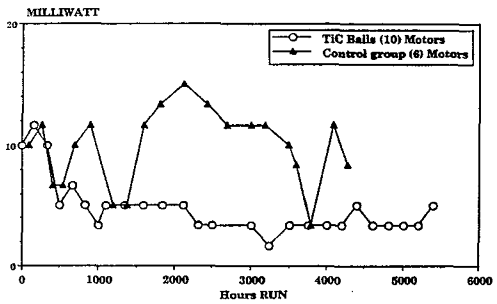


Figure 1: Steel ball in rolling/sliding contact with a steel race, showing asperity contact even in the presence of a lubricant film.



Comparing milliwatt values

Control Group..............10.9 mW, std dev = 7.83
TiC-ball Group.............. 6.2 mW, std dev = 4.58

Figure 3: Mean power variation vs. time measured for oil-lubricated motors containing TiC-coated balls and uncoated steel balls (control).

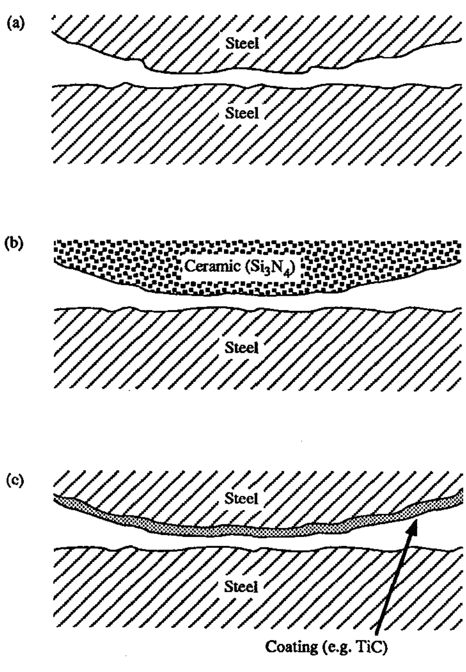


Figure 2: Representation of 3 methods of reducing asperity contacts and microwelds: (a) very smooth surfaces, (b) dissimilar material pair and (c) coating on one surface of a similar material pair.

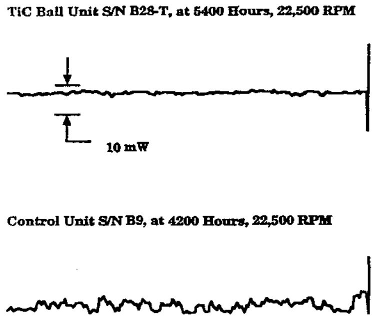


Figure 4: Comparative milliwat traces for oil-lubricated motors containing TiC-coated balls and uncoated steel balls (control).

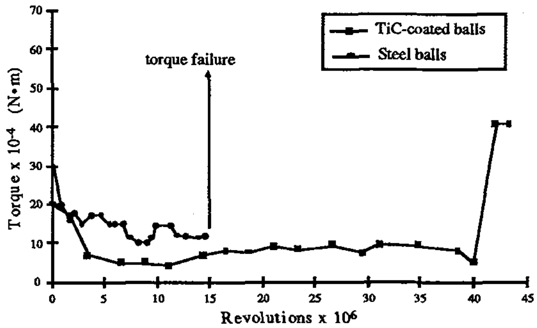


Figure 6: Lifetime of ball bearing pairs running in vacuum with MoS_2 lubrication, and with MoS_2 lubrication and TiC-coated balls.

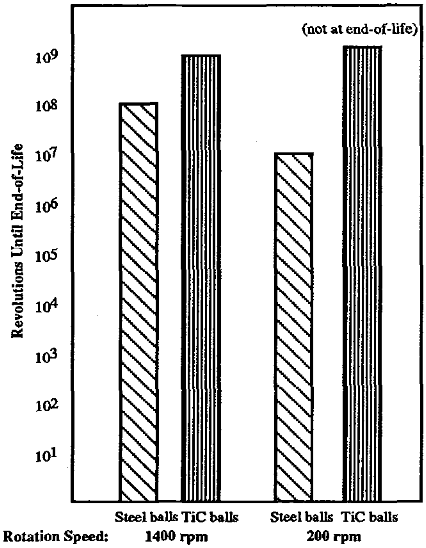


Figure 5: Number of revolutions until end of life for bearings running in vacuum with TiC-coated and steel balls, lubricated with Fomblin Z25 oil.

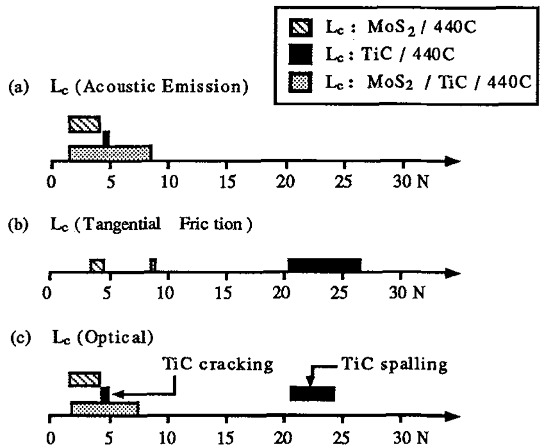


Figure 7: Scratch test adhesion characterization of MoS_2 steel and MoS_2 on TiC-coated steel (440C).