Surface Roughness Measurements as a Method for Tribological Characterisation of Ball Bearings

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Abstract

A series of experiments using steel or hybrid balls in an SNFA VEX25 type bearing was conducted, at a rotational speed of 50,000 rpm. The race material was 100Cr6 steel, whereas for the balls various steels, coatings, and ceramics were used. The different materials used for the balls as well as the method of lubrication (air/oil or grease) strongly influenced the surface degradation of the ball bearings. Hybrid bearings with ceramic balls showed very little wear of either the balls or the steel races, and so offer potential for high-speed applications. The degradation of the bearings was examined using scanning electron microscopy, atomic force microscopy, and laser scanning profilometry. The disadvantages and advantages of these methods are given, along with the results of surface roughness measurements.

Keywords

surface roughness, characterisation, ball bearings, steel, coatings, ceramics, scanning electron microscopy, atomic force microscopy, laser scanning profilometry

INTRODUCTION

In high-speed applications, the life of ball bearings is still the limiting factor. Therefore, much effort is put into research concerning bearings, e.g., geometry, materials, surface treatments, and type and application of lubricants.[1] The goal of the present research project is to design spindles that are capable of turning at frequencies exceeding 100,000 rpm. These frequencies translate into rolling contact velocities of up to 180 m/s and to dissipated powers approaching 1 kW. Bearings with steel races and steel balls reach their limitations in this regime, which makes hybrid bearings, consisting of a steel race and ceramic balls, particularly attractive for high-frequency spindle systems. The balls can be made entirely of a ceramic material, such as Si_3N_4 or ZrO_2, or ceramic coatings may

Table 1 Parameters for high-speed spindle testing

Run-in procedure	Stepwise 10,000 to 50,000 rpm
Rotation speed	50,000 rpm
Test duration	50 h
Axial preload	240 N
Type of bearing	SNFA VEX25 (47 mm external diameter and 25 mm internal diameter, 13 balls)
Ball materials	100Cr6, steel/MoS_2, steel/TiC, sintered ZrO_2, HIP ZrO_2, Si_3N_4
Lubricant	air/oil (ISO VG 32 filtered) or grease (Lubcon L 182)

offer a less expensive alternative. TiC-coated steel balls have been used for many years in ball bearings used in high-frequency aerospace applications, such as gyroscopes.

When ball bearings that are properly lubricated and free of dirt fail in service, it is usually due to surface degradation of the balls or the races. Therefore, one should be able to predict the service life of a ball bearing by closely monitoring the surface state of its components.[2,3]

TESTING OF BALL BEARINGS

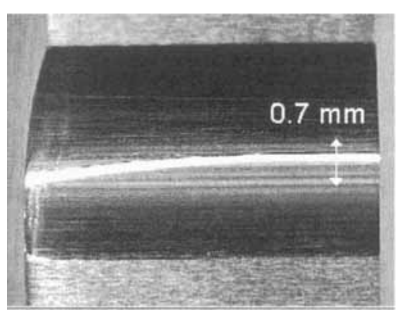
The test stand in the present research consists essentially of a high-speed spindle coupled with a data logger. In each run, two identical bearings (front and back) were tested in an 'X' configuration. The rotation speed and bearing temperatures were recorded on-line. The dissipated power was determined in a flywheel deceleration test. Ideally, the bearing tests should be interrupted regularly to allow microscopic observation of the components. In reality however, it is impossible to stop the test, disassemble, analyse, and reassemble the bearing without changing its configuration. Consequently, the tests were run for a fixed period of time, stopped well before bearing failure, and not continued after analysis (**Table 1**).

SURFACE ROUGHNESS MEASUREMENTS

The deterioration of the ball and race surfaces can be observed using optical and electron microscope imaging. Scanning electron microscopy (SEM) is very useful for visualising the state of the surface, but it is difficult to attach a quantitative value to an SEM observation. Quantification, however, is the main

Figure 1 Wear tracks on a steel ball (7.14 mm diameter) after run-in procedure and 50 h testing at 50,000 rpm

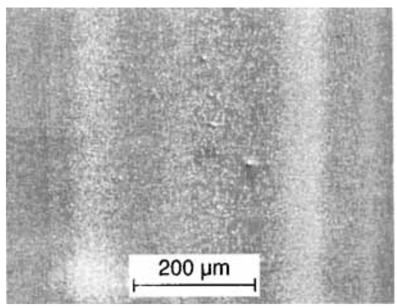
Figure 2 Optical image of wear track (grey) of a steel race after 50 h testing using steel balls and air/oil lubrication (the curved white line is a reflection)



advantage of atomic force microscopy (AFM) or laser scanning profilometry (LSP) where surface roughness values can be obtained by 2D or 3D profiling. The determination of a 'real' surface roughness value for a worn bearing is not a trivial matter. Critical issues are the locations where the measurements are taken, the surface area covered, and the measurement method itself. It is important to realise that, depending on the method, the resulting roughness values may be vastly different for exactly the same surface.

The balls can be easily placed in an atomic force microscope or laser scanning profilometer for roughness measurements once the bearing is disassembled. However, the inhomogeneous distribution of wear over the total ball surface presents a major drawback. **Figure 1**, taken in an optical microscope, shows several wear tracks on a steel ball that was run at five different velocities,

Figure 3 SEM image of wear track of steel race after run-in procedure and 50 h testing at 50,000 rpm using steel balls and grease lubrication

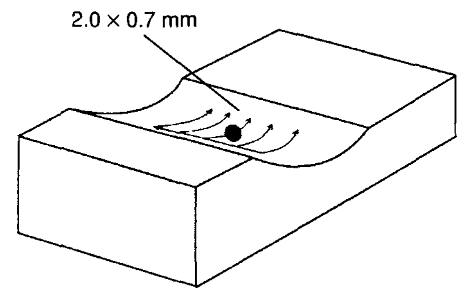


from 10,000 to 50,000 rpm, and tested for 50 h. The balls are not, because of this inhomogeneity, ideal objects for the determination of representative roughness values.

An examination of the steel races shows that the wear track is well defined, as seen in **Figure 2**, taken by optical microscopy after 50 h testing using steel balls. The width of the wear tracks is from 0.7 mm to a maximum of 1.0 mm for all configurations tested. While the wear track was quite homogeneous along the circumference of the race, it was not so over its width, as the SEM image in **Figure 3** shows. For the determination of a mean roughness value, the measurement distance has to be long enough to cover the width of the wear track in the steel race; to rule out statistical errors due to single measurements, the measurement should be repeated at different locations along the perimeter of the bearing. Measurements of the steel races present one disadvantage: the races have to be cut and (if AFM measurements are performed) sectioned very precisely.

Once the ideal location for the roughness measurements has been established, a suitable method has to be selected. AFM profiling would be the method of choice for the surfaces considered here, with roughness values, R_a, as low as 10 nm.[4] The AFM method is, however, limited to small surface areas, generally not exceeding 100 × 100 µm, so that only part of the wear track can be observed in one measurement. Moreover, it is well known that the measured roughness values R_a, R_z, or R_t increase with increasing track length up to a point where all important features are included within the surface covered. AFM measurements on the balls have shown that the measured S_a values (S_a for surface roughness as opposed to R_a for line roughness) may or may not approach the [illegible] the maximum surface area of 100 × 100 µm.[3] In the present investiga[illegible]M was used as much for imaging of wear features as for roughness determination.

Figure 4 Set-up for the laser scanning profilometry surface roughness measurements of the steel races (0.7 mm; 1000 P/mm)



The LSP method allows complete coverage of the wear track. This method employs an optical sensor (type 'UBM Telefocus') to focus light from a laser diode on the sample surface. A feedback loop uses the light reflected back from the sample surface to maintain a constant lens–surface separation. The movements of the lens thus correspond almost exactly (to within some 30 nm owing to the vertical resolution of 10 nm and the mechanical stability of the sensor) to the surface profile of the scanned sample. The laser spot has a diameter of 1 μm, that defines the horizontal resolution in this method. The LSP is a non-contact alternative to the more widely used standard stylus profilometer where the surface profile is scanned with a diamond tip. It is generally employed for surfaces where R_a exceeds 30 nm, and typical surface areas range from 50 × 50 μm to several square millimetres.

The LSP measurements were made using five line scans of 0.7 mm length across the wear track (**Figure 4**). The individual lines were 0.5 mm apart, so the measurement covered an area of 2.0 × 0.7 mm. Unfortunately, despite the ideal measurement location, the LSP is not able to give the true roughness value of the surfaces under consideration because of its limited vertical and horizontal resolution. Nevertheless, it was selected as the method of choice for comparing the surface roughness of all new and worn steel races with each other in the present work.

RESULTS: Surface roughness of worn races and balls

The results of LSP measurements on the steel races after 50 h testing in air/oil show very clearly that the ceramic balls and the TiC-coated steel balls did not give an increase in surface roughness (**Figure 5**, overleaf). In contrast, when uncoated steel balls or an MoS_2 coating were used, the surface of the steel races experienced rapid degradation, which was measured as a large increase in surface roughness.

Figure 5 Surface roughness of steel races, new and after 50 h testing in different configurations (measured by laser scanning profilometry according to Figure 4)

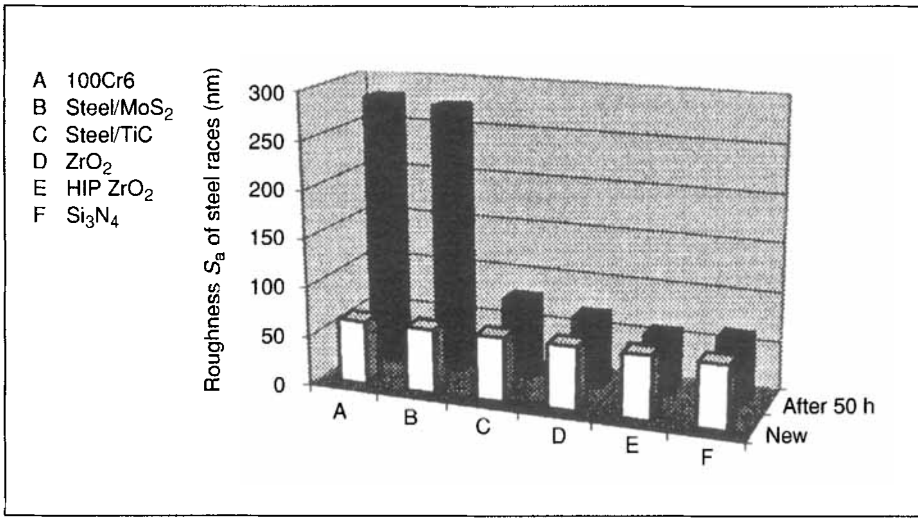


Figure 6 Surface roughness of balls, new and after 50 h testing in different configurations (measured by atomic force microscopy, area of 100 × 100 μm, 512 × 512 points)

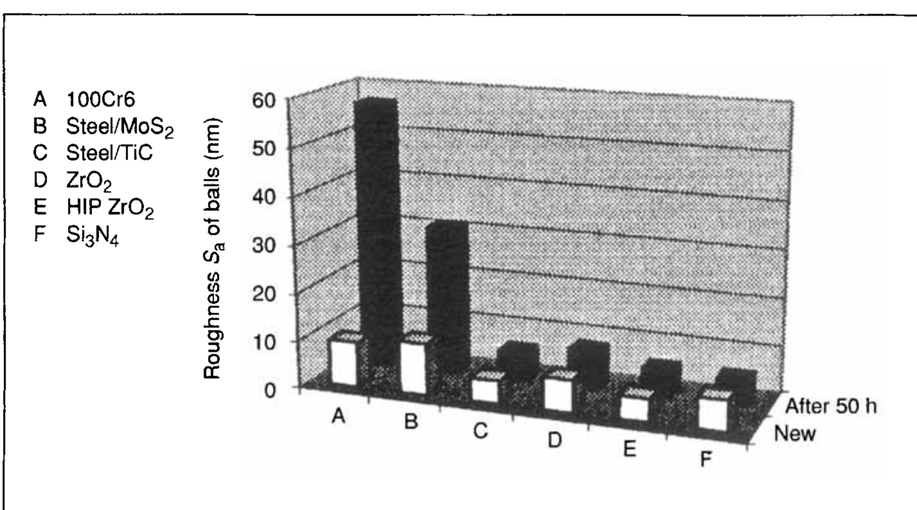
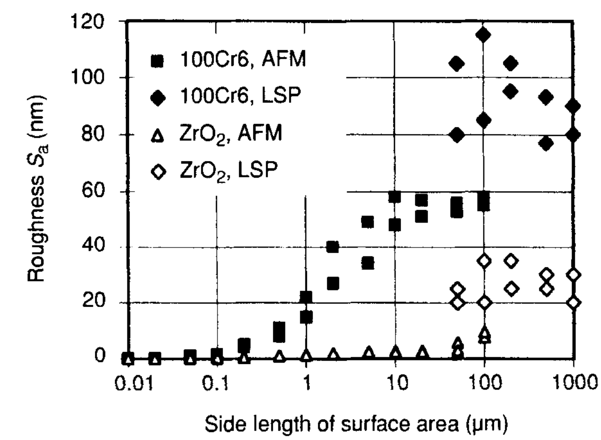


Figure 7 Surface roughness S_a of a steel ball and a ZrO_2 ball after 50 h testing in air/oil (measured by atomic force microscopy and laser scanning profilometry, 256 x 256 points)



The same results were also obtained with AFM measurements directly on the used balls (**Figure 6**). The surface state of the balls is obviously closely related to the nature of the steel race and *vice versa.*

If the roughness values S_a in **Figures 5** and **6** are compared, it can be seen that the balls have significantly lower roughness than the races. This might not be completely so in absolute terms because the measurement methods were not the same. **Figure 7** gives some insight into the difficulty of such a direct comparison. The S_a values, measured by AFM and LSP, are plotted as a function of the observed (square) surface area for a used steel ball and a used ceramic ball.

A number of important conclusions can be drawn from **Figure 7**. First, the large difference in surface roughness between used steel and ceramic balls is again evident. Secondly, an increase in roughness with measurement size is evident. The S_a value is a strong function of the surface area covered by the measurement. For the steel balls, the AFM measurements seem to stabilise around a 10 μm side length of the measurement area, whereas for the ceramic ball, at least 100 μm side length or even more is necessary to reach the plateau. Thirdly, the two measurement methods, ASM and LSP, do not produce the same values, even with a common measurement area of 50 x 50 μm or 100 x 100 μm. This is due partly to the fact that the optical sensor tends to exaggerate certain features that differ in reflectivity, and partly to the limited vertical resolution of the LSP.[5] However, the horizontal resolution also affects measurement – especially when

Figure 8 SEM of unworn steel race

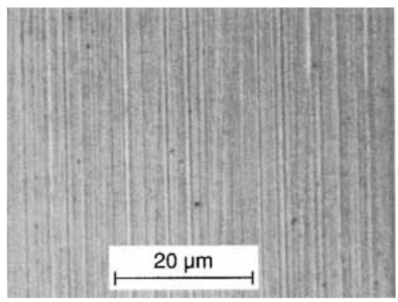
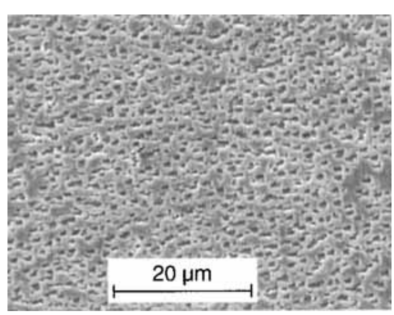


Figure 9 SEM of worn race after 50 h testing with steel balls and air/oil lubrication



the surface is covered in submicrometre features, such as are shown in **Figures 3** and **9**.

SEM and AFM observation of worn steel races

The SEM is the instrument of choice for imaging worn surfaces. In **Figure 8**, the unworn race track of the SNFA VEX25 bearing is shown. **Figures 9** to **12** are images of the worn race track after 50 h testing at 50,000 rpm using steel balls (**Figure 9**), TiC-coated (**Figure 10**), and MoS_2-coated (**Figures 11** and **12**) steel balls.

Figure 10 SEM of worn race after 50 h testing with TiC-coated balls and grease lubrication

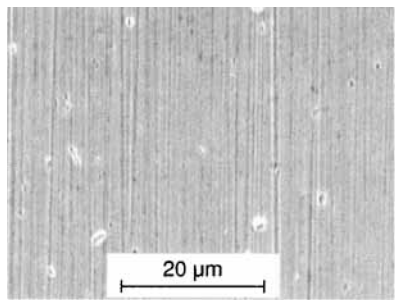


Figure 11 SEM of outer steel race after 50 h testing with MoS_2-coated steel balls with air/oil lubrication

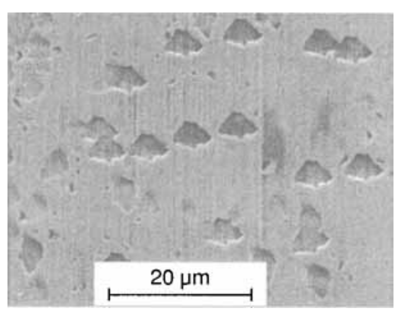


Figure 12 SEM of outer steel race after 50 h testing with MoS_2-coated steel balls with grease lubrication

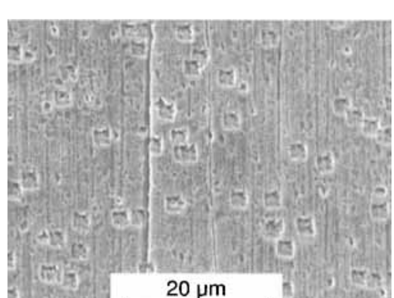


Figure 13 AFM image of inner steel race corresponding to Figure 11 after 50 h testing with MoS_2-coated steel balls and air/oil lubrication

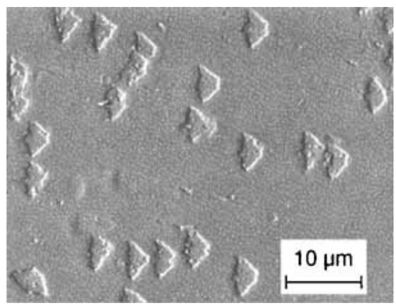
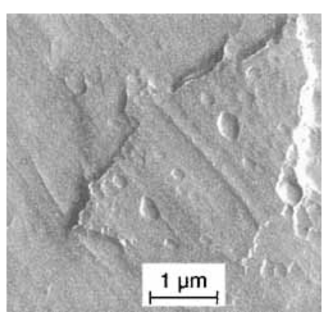


Figure 14 AFM image of one of the wear marks from Figure 13

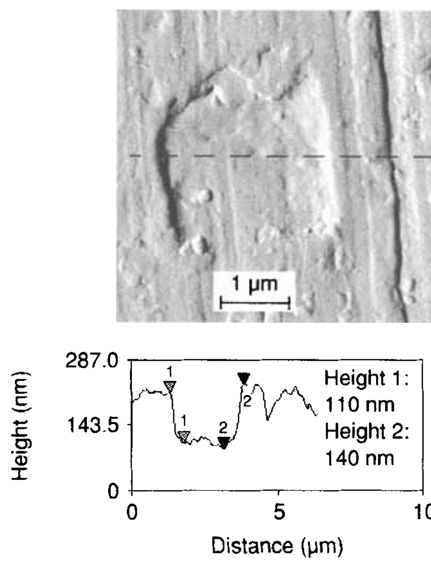


For steel balls in contact with the steel race, the 50 h of high-speed testing resulted in a heavily worn race (**Figure 9**) with both types of lubrication. The surface degradation was due to direct metal–metal contact that cannot be avoided at the high contact pressures in high-speed testing.

When ceramic balls are used in hybrid ball bearings, the wear track is almost invisible. The best results were obtained with HIP ZrO_2 and Si_3N_4 ceramic balls. Some indentation marks, presumably due to over-rolling of debris particles,[6] can be found on the track. They are most pronounced after testing in the configuration of TiC-coated balls and grease lubrication (**Figure 10**).

For all configurations using either steel balls or ceramic balls, both bearings (front and back) tested simultaneously showed very similar wear tracks and only small differences in the measured surface roughness values. For the

Figure 15 AFM image of one of the wear marks found on the inner steel race (MoS_2-coated steel balls, with grease lubrication, corresponding to Figure 12) and its height profile taken along the dotted line



two configurations using MoS_2-coated steel balls, this was not the case. With both types of lubrication, the testing led to a wider wear track in the front bearing and a corresponding surface roughness S_a of nearly twice the value of the back bearing. SEM observation of the front bearing revealed a pattern of surprisingly similar wear marks at both the inner and the outer race. With air/oil lubrication, 'butterfly' shapes appeared (**Figure 11**). Interestingly, the wear marks are lined up in two different directions, nearly perpendicular to each other. When grease was used for lubrication of the bearings, wear marks of a more rectangular shape appeared (**Figure 12**).

These wear marks were investigated by AFM because of their unusual and very regular shapes. **Figure 13** shows an 'overview' of the inner race corresponding to the outer race shown in **Figure 11**. Again, the similarity of the wear marks is striking. A closer view with the AFM reveals the fine structure of one of these marks in **Figure 14**.

The wear marks were observed only on the steel races, and not on the MoS_2-coated balls. The origin and mechanism of the observed wear marks is unclear. One possible explanation might be that the marks shown in **Figures 11** to **15** were 'stamped' into the races by a hard particle or a protruding feature at one location on one ball. This feature would be very hard to find, as it could be anywhere on any of the 11 balls of the bearing.

The size and depth of the marks were measured using AFM. The wear marks in **Figure 14** (after testing in air/oil lubrication) are several micrometres wide and 200–300 nm deep; the marks that appeared after testing with grease lubrication are all some 2.5 μm wide and have an average depth of 100–150 nm (**Figure 15**).

While the AFM investigation reveals the exact shape of the wear marks, this information is not sufficient to explain the mechanism that leads to the observed wear pattern. More insight may be gained by chemical surface analysis, which will be the next step in this investigation.

If it is assumed that the mechanism of 'stamping' is correct, then the total number of marks in one race can be calculated from the average density of the marks and the area covered with it. For the inner race tested with air/oil lubrication, the average number of wear marks in a 100 μm strip across the wear track was around 70. Multiplied by the perimeter of the inner race, this leads to a total of 65,000 wear marks of the butterfly shape on the inner race. A corresponding calculation for both races after testing with grease yields a total of some 160,000 rectangular wear marks. Compared to the total number of revolutions during testing, which was 150 million, these numbers are very small. The presence of the particle/protruding feature would have been only temporary. Assuming that one revolution led to one wear mark, this process would only have lasted for 1–3 min of testing, but its effect would certainly have been quite devastating for the integrity of the bearing.

CONCLUSIONS

1. The deterioration of ball bearings can be followed quantitatively by surface roughness measurement using atomic force microscopy and laser scanning profilometry. The shape and dimensions of the wear marks can only be characterised by AFM.
2. Since surface roughness values depend strongly on the measurement area and method, special care has to be taken when roughness values are compared.
3. Hybrid bearings consisting of steel races and ceramic balls (HIP ZrO_2 or Si_3N_4) showed the most promising results in terms of low surface degradation.

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