The Effect of Superfinishing and PVD/CVD Coatings on Torque and Temperature of SAE 52100 Rolling Element Ball Bearings Under Starved Lubrication Conditions

John W. Eichler and Allan Matthews, The University of Sheffield, Sheffield, United Kingdom; Gary L. Doll, Timken Research, Canton, OH; and Adrian Leyland, The University of Sheffield, Sheffield, United Kingdom

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Abstract
This paper reports on tests carried out using a bespoke high-cycle rolling contact test facility based on a thrust ball bearing configuration. The test machine is instrumented for temperature, torque, vibration and speed measurement. Following our recent publications, this paper concentrates on the rolling contact behaviour of coated and uncoated counterfaces under starved lubrication conditions. Cr$_2$N and WC/a-C:H coatings deposited by PVD and hybrid PVD-CVD processes, respectively were tested. In addition, the effect of vibratory superfinishing on rolling contact, both in isolation and as a surface pre-treatment prior to PVD coating, is investigated. Data are presented illustrating the benefits provided by surface modifications under these extreme operating conditions and their ability to delay the onset of catastrophic bearing failure in the event of lubricant starvation.

Introduction
Rolling element bearings are considered to be one of the most common machine elements. Modern steel processing methods have all but eliminated material defects and inclusions from high quality bearing steels. This has shifted the rolling contact fatigue failure mode to surface initiated failure [1]. In this mode, dents from debris or other damage mechanisms initiate microcracks which then propagate to damage the bearing surfaces. A modern bearing under light, constant load and running in the full film thickness lubrication regime would be expected to last almost indefinitely [2]; however, most bearings operate in more extreme conditions. The drive to increase power density means that components are running faster, at increased loads and at higher temperatures. One way to extend the life of bearings running under severe conditions is to use a tribological coating. Several bearing manufacturers offer commercially available bearings which employ various coatings. Previous work carried out by many authors concentrates on depositing coatings on the bearing races or rings to improve performance [3-5]. This work examines the effect on temperature and torque of vibratory superfinishing and two coatings applied to the raceways of a heavy duty thrust ball bearing under oil starvation conditions, continuing from previous research into coated rolling elements [6].

A bearing running under a well-lubricated condition benefits from a lubricant film which completely separates the two counterfaces. There is no contact between the asperities and the bearing operates under elasto-hydrodynamic lubrication. However, if there is, or is likely to be, contact between asperities then the bearing is said to be running in the boundary lubrication regime. The dimensionless parameter $\lambda$ is often called the lambda ratio and it describes the lubrication regime. This parameter is expressed below [7]:

$$\lambda = \frac{d}{\sigma}$$

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$$

The composite roughness of the two surfaces in the contact and the lubricant film thickness are denoted by $\sigma$ and $d$, respectively. The RMS roughness values for the contacting surfaces are $\sigma_1$ and $\sigma_2$. A lambda value of less than 1.5 indicates boundary lubrication and a value of more than 3 indicates elasto-hydrodynamic lubrication [7] where asperity interactions are rare. By allowing the bearing to run under boundary lubrication conditions, increased friction and low cycle fatigue wear will result [8].

Experimental
The test specimens were type 51306 metric heavy duty thrust ball bearings. These bearings consist of two circular grooved races which are manufactured from AISI SAE 52100 steel. The races are separated by twelve spherical rolling elements and a pressed steel cage. The bearing steel has been through hardened to a nominal HRC 60. This bearing is designed for purely axial loading and has an outer diameter of 60 mm. Its limiting speed under oil lubrication is 4300 RPM and the dynamic load rating is 43 kN.

The performance of the test specimens was examined using a bespoke high-cycle bearing test rig. This facility is instrumented to measure the bearing torque, temperature, vibration and rotational speed. The fully computer-controlled system is capable of monitoring the levels of all sensors signals and stopping the bearing test once a pre-determined threshold has been exceeded. A schematic of the equipment used is shown in Figure 1.

Figure 1. A schematic diagram of the bearing test equipment.

Some of the test specimen raceways were modified by vibratory superfinishing using high density ceramic pellets in an aqueous, alkaline solution [9]. The thrust ball bearing raceway geometry is formed by a precision grinding process and, as such, has grinding marks in the rolling direction. The ceramic media remove these grinding marks producing an isotropic finish (i.e., the surface finish has no directionality). This surface modification was tested in isolation and also used as a surface pre-treatment for PVD coating (as shown in Figure 2). This combination of superfinishing and PVD coating is described as a ‘duplex’ treatment. Unfortunately, no Cr$_2$N coated standard bearing races were available for testing and so the effect of superfinishing on the performance of the Cr$_2$N coating could not be determined.
Additional test specimens were modified with chromium nitride (Cr$_2$N) and tungsten-carbide / amorphous hydrogenated carbon (WC/a-C:H) coatings. Both coatings were deposited at a nominal thickness of 2 microns by the Timken Company using closed-field magnetron sputtering. The hardness of the WC/a-C:H coating was 13 GPa with a very dense morphology. Its composition was 10-15% nanocrystalline (<5 nm) WC and the remainder is amorphous hydrocarbon. The hardness of the Cr$_2$N coating was 26 GPa with a zone 2 to 3 morphology, as described by the Thornton diagram [10,11].

![Figure 2. Photographs of (a) WC/a-C:H coated raceway and (b), superfinished and WC/a-C:H coated raceway.](image)

It was found during the initial stages of testing that bearing damage was cage related. These relatively inexpensive test bearings use stamped metal cages which can fail catastrophically in a very short time under accelerated testing. This indicates that the cages are the weakest element of this bearing under lubricant starvation conditions. When the bearing damage is caused by the cage, the effectiveness of the coatings cannot be evaluated after testing. The function of the cage is to separate the rolling elements and to prevent friction between them. However, with little or no lubricant film between the rolling element and the cage, high temperatures and severe wear resulted, regardless of the bearing surface treatment condition. For these reasons, all subsequent tests were carried out with a full complement bearing configuration, i.e., no cage. The aim of the experiments was to examine the general behaviour of the coatings on rolling element bearings under interrupted lubricant flow and not to improve the performance of this bearing in particular. These coatings are intended for use in critical applications (such as aerospace) and on high quality bearings where cage related failures of this type are not an issue.

**Results**

The torque behaviour for all of the bearings in this experiment is as follows. At the start of the experiment, the frictional torque rapidly increases with both speed and load. After approximately 1 minute, the torque decreases to a stable "plateau" region. The torque then stays at this level until failure commences. At this point the torque curve displays several sharp upward, excursions before complete failure occurs. All the bearings tested in this experiment showed a similar temperature response. The gradient of the temperature curve decreases after the start of the experiment which is probably due to reduced friction as the bearing “runs in”, resulting in less heat generation. The temperature of the bearing continues to increase but the gradient steadily decreases.

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This continues until a sharp increase in torque is exhibited. The system responds with a delayed sharp increase in temperature. The two events do not coincide because of the lag in response of the bearing material to the increased heat flow input. Figure 3 below shows sample torque and temperature curves for two test specimens.

![Figure 3. Temperature and torque curves for (a) a WC/a-C:H coated bearing, (b) a superfinished and WC/a-C:H coated bearing.](image)

Two interesting observations can be made from the torque and temperature data in Figure 3. Firstly, spikes in the torque data appear to occur in groupings. This effect may be caused by one ball skidding on a raceway which then impacts the dynamics of the rest of the ball complement. Eventually, the magnitude of the instability decreases and the dynamics of the bearing return to a more normal state. Secondly, the torque spikes appear to cause a stepwise increase in the bearing temperature, the magnitude of which scales with the density and magnitude of the spikes. Further study of the relationship between the temperature and torque data in these types of experiments in particular may result in better understanding of the thermodynamics of rolling contact bearings in general.

Weibull analysis was used to calculate the $L_{50}$ life (the time at which 50% of the population will fail) for each group of specimens. Figure 4 a shows that of the five surface modifications tested in this experiment, the WC/a-C:H coating was the highest performer with an 84% increase in bearing life over the uncoated specimen. It is also important to note that both the ‘duplex’ treatments of a superfinished substrate coated with either Cr$_2$N or WC/a-C:H performed well with approximately 43% and 36% increases in life, respectively, over the uncoated specimens. Superfinishing alone is shown to offer almost negligible improvements in performance under these test conditions. Figure 4 b shows that the WC/a-C:H coated raceways also ran at the lowest torque (measured in the ‘plateau’ region of each test). The figure shows that pre-treating the substrate with superfinishing before coating causes an increase in bearing torque.

![Figure 4. Graphs showing (a) the effect of surface modification on $L_{50}$ life and (b), the effect of surface modification on bearing torque in the plateau region under test conditions.](image)

**Discussion**

**Failure Modes**

It is interesting to note that the failure of the bearings with non-carbon-based surface modifications was dominated by excessive frictional torque. However, the carbon-based coatings changed the failure mode from ‘high torque’ to ‘high temperature’, where the temperature of the raceway reached the prescribed upper limit before the torque limit was reached. This result is likely to be due to the carbon-based coatings’ ability to reduce adhesive interactions between the counterfaces, thereby enabling the test to continue until an excessive temperature is reached.

**Unmodified Bearings**

Before testing, the standard bearing displayed a morphology dominated by residual grinding lines from the manufacturing process. Analysis of the failed surfaces of the standard bearing showed a severely spalled surface characterised by high surface roughness and delaminated surface material which is likely to be the result of a combination of adhesive wear and rolling contact fatigue.

**Superfinished Bearings**

The micrographs of the unused, superfinished raceways showed a
surface with few asperity peaks. There are flat regions which are separated by shallow areas of pitting caused by the superfinishing process as shown in Figure 5. After testing, the superfinished raceways show a similar appearance to the unmodified raceways. The original surface morphology is not exhibited, indicating that significant wear has occurred. The high surface roughness observed is likely to be as a consequence of abrasive and adhesive wear in the boundary lubricated contact. However, the severity of the damage appears to be less than that of the uncoated specimen, which can be correlated to the slight increase in $L_{50}$ life for this surface treatment. The increase in performance created by reducing the height of the asperities may have been offset by undesirable pitting.

Figure 5. An electron micrograph of the surface of an unused superfinished bearing raceway.

**Duplex Cr$_2$N Coated Bearing**

In both of the duplex treatments, the as-deposited coating appears to have a surface characterised by droplets and nodular regions, as shown in Figure 6 a. The coating replicates the surface roughness in areas without pitting.

After testing, the superfinished and Cr$_2$N coated raceways showed droplets and some nodular regions outside the wear track. In the centre of the wear track, the coating was severely damaged, showing cracks and material removal. However, X-ray energy dispersive spectography (EDS) analysis indicated that the coating had not been completely removed. The chromium nitride ceramic film has a much higher modulus of elasticity than the steel substrate and also a higher hardness which could explain the fracture failure mode observed.

**Duplex WC/a-C:H Coated Bearings**

The superfinished and WC/a-C:H coated raceways showed a banded wear track after testing. The unworn area outside the wear track showed a coating with some porosity and regions with a 'nodular' morphology. At the outer edges of the wear track very little wear had occurred as the isotropic finish resulting from the superfinishing treatment could still be seen, along with some porosity. In the centre of the wear track (where the contact stress is highest) the replicated surface finish from the superfinishing had been removed and cracking perpendicular to the rolling direction was present. EDS analysis indicated that the chromium adhesion interlayer and/or the substrate had been exposed, as high intensity peaks from chromium and iron were present. The severity of the wear may have been limited by a lubricious transfer layer formed on the rolling elements.

Figure 6. Electron micrographs of (a) The as-deposited surface finish of a superfinished and WC/a-C:H coated raceway, and (b), as-deposited surface of a WC/a-C:H coated raceway showing replicated roughness.

The Influence of Superfinishing

Superfinishing (in this case) appears to produce a surface profile that is devoid of asperity peaks which is desirable. Figure 6 a shows smooth regions with few grinding marks. However, it also appears to produce pits which were not present in the original surface profile. The origin of the pits is probably associated with the interactions of the steel microstructure with the acids used in the superfinishing process to accelerate stock removal.

The unexpectedly poor performance of the duplex treated raceways could be due to the modified contact conditions. Removal of the grinding lines will increase the contact area between the raceway and rolling element which could also increase friction and torque. The increased contact area will also modify the kinematics of the bearing. In a thrust ball bearing, pure rolling is only present in the centre of the contact patch and elsewhere, relative sliding between the counterfaces occurs [12]. The moment from the sliding friction causes the rolling elements to spin on their own axes as they orbit the axis of the raceways. In this case, increasing the contact area will result in a greater moment and an increase in the spin velocity of the rolling elements, thereby increasing the bearing frictional torque and the shear stress in the contacting surfaces. The increase in shear stress caused by superfinishing the races could be enough to cause the cohesive failure of the coatings observed in this investigation. The influence of superfinishing on the interface between coating and substrate has also been considered. However, given that both coatings employ chromium

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adhesion layers (rather than relying on mechanical interlocking), any detrimental effects on coating adhesion were discounted. In support of this conclusion, all EDS analyses of worn areas of each coating showed conclusively that Cr was still present on the steel surfaces, indicating that the adhesion layers remained and the coatings did not delaminate from the substrate.

A secondary but nonetheless extremely important consequence of superfinishing a component is the effect on the dimensional tolerances. The chuck on the test machine was accurately machined to create a medium interference fit with the test specimens. In this investigation it was found that the superfinishing process removed enough material from the precision ground bore and outer diameter of the bearing races to change this from interference to a sliding fit. This effect has been reported previously by Krantz et al. [13], who employed superfinishing to improve the RCF resistance of case-carburized gears. They found that, in total, approximately 2 to 3 μm had been removed from the surface of their samples by the superfinishing process. Although they concluded that this modification would not affect the operation of the gears, a removal of 2 or 3 μm of material from the raceways of these bearings could greatly alter the kinematics of the bearings.

Superfinishing is a surface treatment with process parameters which must to be carefully tuned to the application and component. The rate of material removal by the vibratory finishing procedure employed in this work depends on the size and type of the abrasive media, as well as the composition of the aqueous solution. In this work, the material removal from the outer and inner diameters caused problems with mounting. In hindsight, these surfaces do not experience RCF and could possibly have been masked to avoid compromising the tolerances of the component. To superfinish a precision component which experiences RCF (such as a high speed bearing in a gas turbine) this removal of material must be anticipated. For example, the component could be manufactured slightly oversized and then superfinished to within the final tolerances. Such a manufacturing process requires knowledge of material removal rates, which could only be gained by extensive testing, and fine control over the process parameters.

**WC/a-C:H Coated Bearings**

The WC/a-C:H coating which was deposited on an unmodified substrate shows none of the undesirable features present in the duplex treatments. It appears to simply replicate the surface roughness of the substrate, as shown below in Figure 6 b. The WC/a-C:H coating also showed a banded wear track after testing. The surface roughness replicated by the coating was smoothed in the outer areas of the wear track and, in the central region of the wear track, the coating is severely crazed. EDS analysis of the coating shows responses from tungsten and chromium, indicating that the coating is slightly worn but still largely intact. Since EDS cannot easily detect light elements such as carbon, the heavy element tungsten (known to be present in the WC/a-C:H coating) is used as an indication of coating presence.

**Rolling Elements**

Electron microscopy of the rolling elements which were run against coated bearing races showed little damage. EDS analysis of rolling elements from a WC/a-C:H coated bearing confirmed that carbonaceous material had been transferred from the raceway. The beneficial effects of graphitic tribolayers have been reported previously by many authors [14-23]. Traces produced by EDS analysis of rolling elements from
Cr2N-modified bearings showed a more intense chromium peak than the response from bearing steel, indicating that chromium material had been transferred from the coated raceway to the rolling element. The mechanism by which chromium is transferred between the contacts is unknown. However, the frictional forces betweenasperities on a micro- (or nano-) scale could be expected to generate large temperatures and several authors have estimated these local “flash” temperatures to be up to approximately 1000°C in unlubricated sliding [24,25]. These local temperature excursions, coupled with the high pressure within the contact region, could be part of the mechanism by which the chromium is transferred. It is also possible of course that the transferred material is simply part of the film that has been removed from the coated component by a combination of fatigue and the extreme conditions imposed by the unlubricated rolling contacts. Any removed material that became entrained in the contact patch could be pressed into and/or adhered onto the counterface.

Conclusions
In this investigation, the WC/a-C:H coating offered the best performance under lubrication starvation conditions. This coating is likely to function as a barrier to adhesive interactions between the raceway and rolling element, thereby increasing bearing life. Evidence of carbonaceous material on the rolling elements was found. This transferred material is likely to act as a solid lubricant, delaying bearing failure under boundary lubricated conditions. The performance of the superfinished specimens was unexpectedly low. Superfinishing alone did not provide an appreciable improvement in performance and it also reduced the performance of the WC/a-C:H coating when used as a surface pre-treatment. The superfinished substrate topography is unlikely to have caused poor coating adhesion. However, the modified raceway surface will result in a larger contact area which could increase the spin of the rolling elements, increasing frictional torque and shear stress in the coating. Experimentation with the ceramic media size, type and process duration is likely to yield better results and will be the subject of future investigations.

References
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