Improving the Performance of Rolling Element Bearings with Nanocomposite Tribological Coatings

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ABSTRACT:

This study summarizes the development, characterization, and application of nanocomposite tribological coatings on rolling element bearings. Nanocomposite coatings consisting of nanocrystalline metal carbides embedded in amorphous hydrocarbon or carbon matrices (MC/aC:H or MC/aC) have been used to increase the fatigue life under boundary layer lubrication, provide debris tolerance, eliminate false brinelling, increase the operational speed, decrease the friction, and provide oil-out protection to rolling element bearings. MC/aC:H coatings are applied by magnetron sputtering at substrate temperature less than 180 °C, have small friction coefficients, high fracture strength, and can have hardness and modulus values twice and half that of carburized steel, respectively.

INTRODUCTION:

Rolling contact bearings are comprised of inner rings, outer rings, cages (usually), and rolling elements. The basic types of rolling contact bearings are ball bearings, cylindrical roller bearings, spherical roller bearings, tapered roller bearings, needle thrust bearings, and needle bearings. These bearings types are shown schematically in Figure 1. As application requirements dictate the type of bearing required, so do they dictate the type of tribological coating.

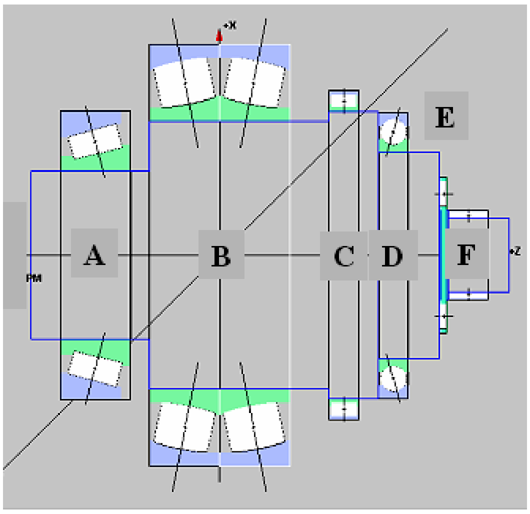

Figure 1: The basic types of rolling contact bearings are A – tapered roller, B – spherical, C – cylindrical, D – ball, E – needle thrust, and F – needle.

In a tapered roller bearing, the rollers are truncated cones that ride between an inner ring (cone) that has two retaining lips (ribs) and a lipless outer ring (cup). A cage separates the rollers and holds them in position against the cone. A schematic of a tapered roller bearing is shown in Figure 2. Tapered roller bearings typically can accommodate both radial and thrust loads. As a result, both rolling and sliding tribological contact motions are present during operation [1]. Sliding occurs between the large ends of the rollers and the cone rib with elliptical contact geometry. Rolling line contact is experienced between the roller bodies and the cup/cone raceways. There is also sliding contact between the rollers and the cages.

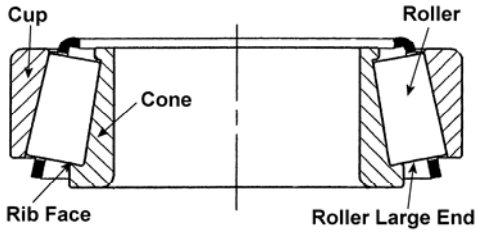

Figure 2: Cross sectional schematic showing the elements of a tapered roller bearing. Whereas rolling contact exists at the roller/cup and cone races, mostly sliding exists at the roller large end/rib face contact.

When a rolling contact bearing operates in ideal conditions, lubricant films form between contacting surfaces which are sufficiently thick to completely separate the contacting surfaces. If this is the case, then the bearing is operating in an elastohydrodymanic lubrication regime. If the lubricant film is thin enough that there is the potential for significant asperity interactions, then the bearing is operating in a boundary layer lubrication regime. The lubrication regime is usually identified by evaluation of the dimensionless parameter λ, defined as

$$\lambda = \frac{h}{\sqrt{\sigma_1^2 + \sigma_2^2}}, \tag{1}$$

where h is the lubricant film thickness and the radical expresses the composite *rms* roughness of the mating surfaces [2].

Situations commonly occur in applications where bearings become starved of lubrication. In these instances, the bearing surfaces come into contact and can experience adhesive wear that can promote or result in a reduction in the fatigue life, scoring or galling, and fretting or false brinelling. Coatings such as the MC/aC:H system make excellent barriers to adhesive interactions between contacting surfaces and are therefore well suited to defeating the adhesive wear mechanism. Another common situation that many roller bearing applications experience is a decreased operational lifetime due to damage associated with debris or foreign matter. It is demonstrated in a subsequent section that MC/aC:H coatings work well in repairing raceway damage from debris. A final motivation for using coatings on roller bearings is that torque losses associated with rolling on the raceways can be reduced by coatings such as MC/aC:H on the rolling elements.

In the late 1990's, the Timken Company began offering tapered rolling bearings with metal carbide reinforced amorphous hydrocarbon (MC/aC:H) and metal carbide reinforced amorphous carbon (MC/aC) coatings applied to roller ends to improve bearing performance under these conditions [3]. Also called metal-containing diamond-like carbon (Me-DLC), these coatings were first reported by Dimigen and Hubsch [4] in 1985. MC/aC:H typically contains ~2-10 nm metal carbide crystals dispersed in an amorphous hydrocarbon (aC:H) matrix. Meng et al. observed this for Timken's WC/aC:H [5], TiC/aC:H [6], and TiC/aC [7] coatings using NEXAFS and high-resolution transmission electron microscopy. MC/aC:H coatings are applied by reactive magnetron sputtering, a gaseous state process, whereby metal or metal carbide targets are sputtered in an argon/hydrocarbon gas mixture [8]. Some of the first reports of the use of MC/aC:H coatings on bearing rollers was made by Lunow *et al.* [9] and the Balzers Company [10]. TiC/aC coatings are deposited by non-reactive magnetron sputtering utilizing Ti and C targets.

EXPERIMENTAL DETAILS

The coatings that were employed in these studies were all developed and applied in a closed field, magnetron sputtering tool [11] following the methodology outlined by Bewilogua *et al.* [8]. For the TiC/aC and TiC/aC:H coatings, Ti targets are first sputtered in Ar gas to form a ~0.1 μm thick adhesion layer on the rollers. Whereas Ti and C targets are simultaneously sputtered with Ar to produce the ~1 μm thick TiC/aC coating, Ti or TiC targets are reactively sputtered in an Ar/C_2H_2 environment to form the ~2.5 μm thick TiC/aC:H coating. The WC/aC:H coating utilizes a ~ 0.1 μm thick Cr adhesion layer formed by sputtering Cr targets in Ar gas. Then W or WC targets are reactively sputtered in an Ar/ C_2H_2 environment to form the ~3 μm thick WC/aC:H coatings. The maximum temperature that the rollers obtain during deposition is always less than 180 °C, and usually less than 150 °C. The ratio of the metal carbide to the aC:H or aC phases of the coatings is kept less than about 20% because at greater concentrations, the metal carbide crystallites become large and the coatings, while harder, become more brittle [7]. That is, their fracture strength decreases. Nanoindentation measurements indicate that the hardness and modulus values of the TiC/aC, TiC/aC:H, and WC/aC:H materials prepared using our process conditions are about 10, 12, and 14 GPa, and 100, 125, and 130 GPa, respectively [3]. Friction coefficients for the TiC/aC, TiC/aC:H, and WC/aC:H coatings are typically measured to be about 0.08, 0.12, and 0.16, respectively [3].

RESULTS

Poor Lubrication Conditions

Mechanical engineers design roller bearings to meet statistical targets such as L_{10} (or L_{16}), the number of cycles that 90% (or 84%) of those roller bearings will complete before the first sign of failure. If roller bearings are expected to operate in a boundary layer lubrication environment ($\lambda < 1$), then the reduced lives of those bearings can be expressed as

$$L^*_n = a_\lambda L_n \, , \qquad (2)$$

where L^*_n is the reduced life of the bearing, and a_λ is an experimentally determined lubricant life adjustment factor that is related to the lambda value (Eq. 1). Specifically, a_λ approaches 0 as λ gets small, and approaches 1 as λ gets large.

An investigation was designed to determine the effectiveness of MC/aC:H coatings to enhance the fatigue life of poorly lubricated bearings. Bearings with uncoated rollers, and bearings with rollers coated with TiC/aC:H were tested until failure in SAE 10 oil at $\lambda \sim 0.6$. Figure 3 displays the results in terms of L_{16} life with 65% confidence bands of laboratory scale life testing for a typical tapered roller bearing operating under boundary layer lubrication. At a λ value of 0.6, the life adjustment factor a_λ is about 0.7. The L_{16} life of the bearings with TiC/aC:H coatings on the rollers is about double the life of the uncoated bearings ($a_\lambda \sim 1.4$), and greater than the predicted life of well-lubricated bearings from Eq. 2 with $a_\lambda = 1$.

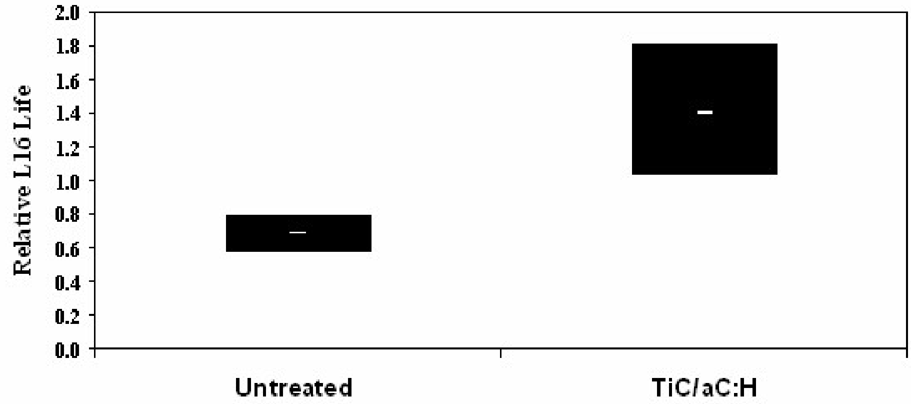

Figure 3: The L_{16} fatigue lives (normalized to the $a_\lambda = 1$ calculated bearing life) of tapered roller bearings operating in $\lambda \sim 0.6$ boundary layer lubrication with and without TiC/aC:H coatings on the rollers.

Because of large entrainment velocities, thick lubricant films usually exist at the rib-roller end sliding contact of a tapered roller bearing (See Fig. 2). Situations occasionally occur where the lubricant film at this interface is insufficient to separate the asperities of the roller end and rib face. In these situations, adhesive wear between the asperities can lead to scuffing, scoring, and eventually galling. Examples of situations where this adhesive wear can occur include the use of ultra-low viscosity lubricants, large axial loads, highly loaded-high speed operation, and lubricant interruption or loss.

A laboratory test was devised to measure the resistance to rib-roller end failure of tapered roller bearings with uncoated and both TiC/aC and TiC/aC:H coated large roller ends. The test was designed to mimic a field condition where bearings in gearboxes experienced an extended lubrication loss condition. Coatings were applied to the large roller ends only (i.e., the roller bodies were not coated). Nominal dimensions for the test bearings were: 64.3 mm outer diameter, 30.2 mm bore, and 21.4 mm overall bearing width. Test bearings were immersed in a solution containing 80% hexane and 20% GL-5 gear oil. Upon removal from the solution, the hexane was allowed to evaporate leaving behind a thin oil film on the bearing surfaces. Bearings were then tested one at a time in a vertical thrust test rig with an axial load of 4448 N (157 MPa contact stress) and 2700 rpm speed (1.2 m/s sliding speed between large roller end and rib face). The onset of rib-roller end failure was determined by a torque reading > 3 N-m or a cup temperature > 177 °C. Figure 4 displays the time to rib-roller end failure for bearings with and without coated roller ends. At least twenty-five bearings were tested for each condition. Results were analyzed using Weibull statistics (first in one) and 90% confidence bands were calculated around L_{50} lives. Whereas uncoated baseline bearings had an L_{50} value of about 6 minutes, bearings with TiC/aC and TiC/aC:H coated roller ends had L_{50} values of about 18 and 42 minutes, respectively. Bearings with TiC/aC and TiC/aC:H are currently being used in the metal forming and agricultural industries as well as in flight critical aerospace systems.

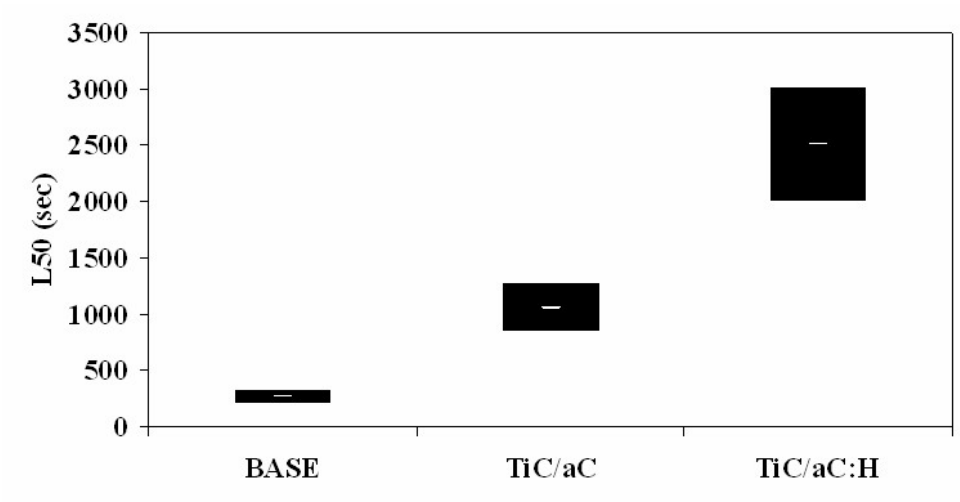

Figure 4: L_{50} time to rib-roller end failure of tapered roller bearings with and without coated roller ends. Tests were performed with an applied thrust load of 4448 N at a speed of 2700 rpm in a condition that mimics a loss of lubrication.

Debris Resistance

Bearings operating in pumps, gearboxes, or drilling heads are often exposed to debris that are either generated by other components (gears for example) or enter the system through worn or failing seals. Depending on the size, type, and density of the debris particles, bearing life can be severely compromised [12,13]. If debris is present in the mechanical system, a debris life factor adjustment factor, a_d, is added to Eq. 2 such that the adjusted life becomes,

$$L_n^* = a_\lambda a_d L_n \,. \qquad (3)$$

It was anticipated that MC/aC:H coatings applied to roller bodies could help offset the damage caused by debris to bearings. WC/aC:H was chosen based upon its abrasive wear resistance and ability to micro-polish counter-face surfaces. Specifically, it was believed that the abrasive wear resistance of WC/aC:H would enable the coating to remain on the roller while it repaired damage to the races caused by debris.

A laboratory-scale test was constructed to quantify a bearing's resistance to debris. Nominal dimensions for the test bearings were: 247.7 mm outer diameter, 177.8 mm bore, and 47.6 mm overall bearing width. The cups, cones, and rollers were made from case carburized alloy steel hardened to 58 to 64 HRC. In this test, bearings were rotated under load for a specific duration in an AISI/SAE type 52100 steel debris-laden oil. The debris particle sizes were 25-53 μm with a 0.5 mg/ml concentration in the SAE 10 weight lubricant. Next, the bearings were solvent cleaned to remove the debris. Finally, the bearings were life-tested using a first-in-four failure criterion in clean SAE 10 oil. The test radial load was 173 kN and shaft speed was 900 rpm. The lubrication conditions of the test correspond to an a_λ value of ~ 0.8. Statistically significant populations of baseline bearings with untreated rollers and bearings with WC/aC:H-coated rollers were tested. Results of those tests are shown in Figure

5, with the L_{16}^{*} values and upper and lower 65% confidence bands normalized to the predicted L_{16} bearing life (i.e., the predicted life of the bearing operating without debris in a well-lubricated environment). The damage to the raceways caused by the debris reduces the operating life of the untreated bearing by ~60%. In other words, the product of the life adjustment factors (a_{λ} and a_d from Eq. 3) is about 0.4, which implies that $a_d \sim 0.5$. Bearings tested for debris resistance with WC/aC:H-coated rollers have L_{16}^{*} lives about 80% greater than that of the predicted L_{16} life of the bearing operating in a clean (without debris) well-lubricated environment. That is, the product of the life adjustment factors is about 1.8. For this type of debris, a_d cannot be greater than 1, which implies that the WC/aC:H coatings on the rollers provide the bearings with at least an a_{λ} value of 1.8 for these test conditions. Bearings with WC/aC:H-coated rollers are currently being used in gearboxes for off-highway vehicles, in down-hole drilling heads, and in industrial manufacturing systems for example.

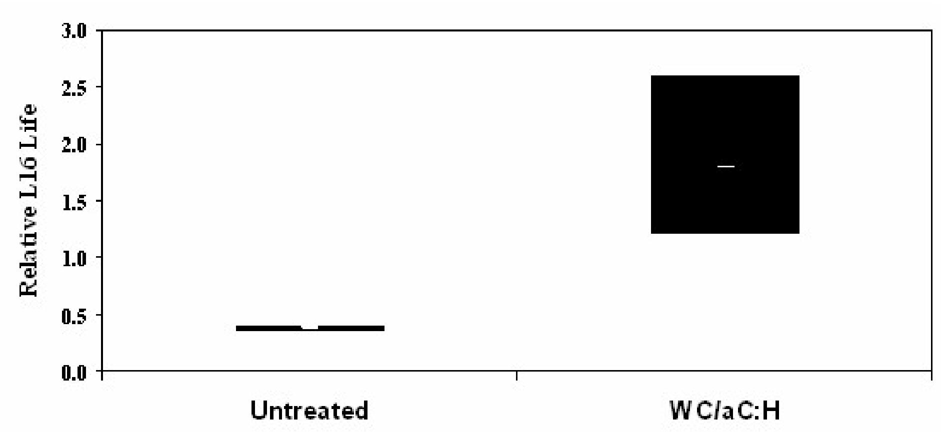

Figure 5: Results of laboratory testing showing the resistance to bearing life reduction caused by metallic debris provided by WC/aC:H coatings on rollers of tapered roller bearings.

False Brinelling and Fretting Wear

False brinelling is an adhesive wear mechanism that occurs between rolling elements and races. This condition can occur whenever a non-rotating bearing is subjected to external vibration. When the bearing is not rotating, a protective oil film cannot form between the races and the rolling elements. Thus, there can be metal-to-metal contact between the races and rotating elements, and the small, relative motion between these parts causes wear marks on both races at the location of each rotating element. Micro-welding of asperities leads to the formation of grooves on the races that appear similar to signs of brinelling, which is plastic deformation of the raceways due to excessive loading. False brinelling can occur during transportation (typically truck or rail), during storage if the storage area is subject to vibration, or can be a consequence of the machine design.

A laboratory-scale testing apparatus was designed to evaluate the ability of different surface treatments to inhibit false brinelling in roller bearings. Bearings without coatings, and bearings with WC/aC:H-coated rollers were tested. Nominal dimensions for the test bearings were: 117.5 mm outer diameter, 57.2 mm bore, and 33.3 mm overall bearing width. Test bearings were lubricated with GL-4 transmission gear oil before testing. The test apparatus applied an oscillating 18.7 kN axial load to bearing test articles for 500,000 oscillations that corresponded to an actual application experiencing false brinelling. Subsequent to testing, depths of the grooves produced on the outer race were measured. Figure 6 displays the average wear depths and standard deviations for the two test articles. After testing, the uncoated bearing exhibited grooves on the cup and cone raceways with an average depth of 1.85 μm. On the other hand, the bearing with the WC/aC:H-coated rollers had an average groove depth of only 0.68 μm. The wear of the race oscillating against the WC/aC:H coating was very slight, and appeared to be caused by abrasive micro-polishing rather than adhesive wear. Examples of applications that use WC/aC:H-coated roller bearings include off-road truck transmissions, rolling mills, tractors, and windmills.

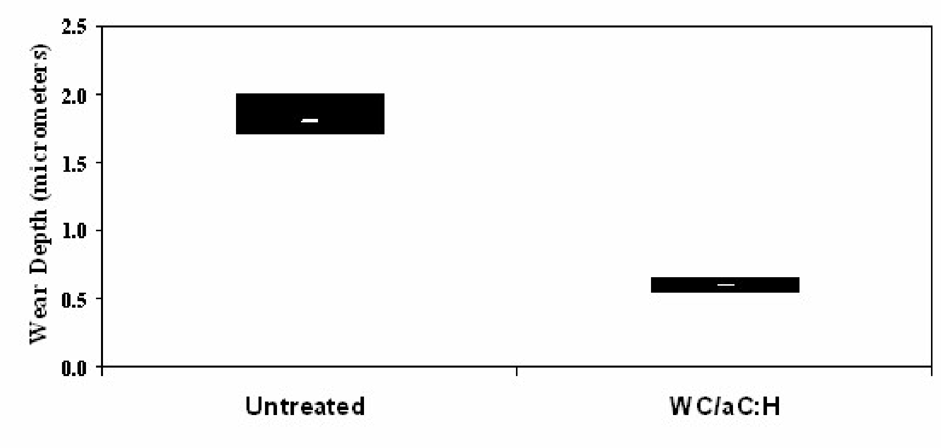

Figure 6: Results of laboratory testing for false brinelling in tapered roller bearings with untreated and WC/aC:H coated rollers. The data are expressed in terms of average wear depth with standard deviation. WC/aC:H coatings on the rollers changed the wear mode of the cup race from adhesive to mildly abrasive through the micro-polishing effect.

Torque Reduction

In most mechanical systems, it is desirable to operate as efficiently as possible while still being able to meet load, speed, and other requirements. One example of such an application is the gearbox of a passenger car. Tapered roller bearings are typically necessary to meet the design requirements to support pinion gears. In an actual automotive gearbox application, it has been observed that pinion bearings with WC/aC:H coatings on the roller bodies and large ends consumed about 1490 W less power than the same bearings without coated rollers. For the test conditions employed, this equates to about a 1.53 N-m torque savings for the gearbox, or about 0.75 N-m per bearing. To put this in perspective, for a mid-sized car traveling at about 150 km/hr, the torque savings provided by the WC/aC:H coatings on the rollers of the two pinion bearings would increase the fuel economy of the vehicle between 1 and 2 percent.

ANALYSIS OF RESULTS

In the previous section, the experimental results show performance enhancements accorded tapered roller bearings by MC/aC:H coatings applied to the bearing rollers. In this section, the results are analyzed with the goal of understanding why the MC/aC:H coatings provide these performance enhancements.

Poor Lubrication

Figure 3 illustrates that the fatigue life of a roller bearing operating in poor lubrication (λ ~ 0.6) can be increased beyond its calculated L_{16} life when operated in a well-lubricated environment (a_{λ} ~ 1). Investigation of the tested bearings reveals the mechanism by which the TiC/aC:H coating increases fatigue life. Optical images (100 x magnifications) of an outer ring raceway taken prior and subsequent to testing are shown in Figure 7. Whereas features associated with grinding of the raceway are evident in the before image, most of those features are absent in the after image. It is reasonable to conclude that TiC/aC:H coatings on the roller bodies polished the contacting raceways of the cup and cone. The polishing effect of cup raceway by the coated rollers can be evaluated quantitatively by an examination of the average roughness (R_a) and plasticity index values. The Greenwood Williamson expression of the plasticity index is

$$\Psi_{GW} = \left(\frac{E}{H}\right)\left(\frac{\sigma}{\beta}\right)^{1/2}, \qquad (4)$$

where E and H are the elastic modulus and hardness of the steel, σ is the standard deviation of the asperity height, and β is the asperity radius of curvature [14]. Ψ_{GW} is a dimensionless figure of merit that can predict the dominant mode of asperity deformation. If Ψ_{GW} is less than 0.6, asperities deform elastically and a surface is less likely to suffer from wear or similar problems. During the fatigue life testing, the coated rollers decreased the R_a values from 0.09 ± 0.01 μm to 0.05 ± 0.01 μm, dynamically increasing the λ value which in turn increases the fatigue life. At the same time, Ψ_{GW} was reduced from 0.52 ± 0.08 to 0.15 ± .02 leaving the cup and cone races in an improved state of wear resistance. The surface finish of the coated rollers was relatively unchanged as a result of the bearing testing. Counter-face micro-polishing by MC/aC:H coated gears has also been reported by Doll [15] and Anderson and Lev [16].

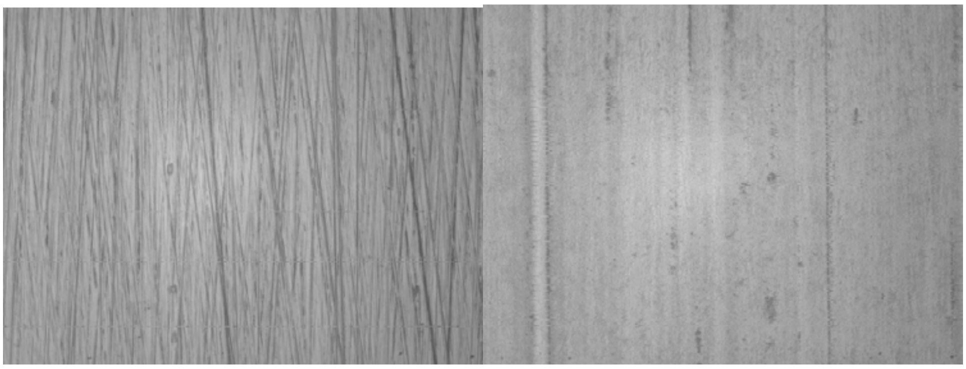

Figure 7: Optical images of cup raceways before (left) and after (right) being run against TiC/aC:H coated rollers in the fatigue life testing shown in Figure 3.

Figure 4 illustrates that TiC/aC and TiC/aC:H coatings applied to the large ends of rollers can postpone the rib-roller end failure of a tapered roller bearing that accompanies a loss of lubrication. Suppose that following a loss of lubrication, the time to failure of a given bearing without coatings is defined as t_0. The wear coefficient of a tribological coating can be expressed in terms of the Archard equation as $K = V / Fs$, where F is the applied load (in N), s is the sliding distance (in m), and V is the volume of material worn away (in m^3). If the sliding distance *s* can be equated to the product of the sliding speed (*v*) and the time (*t'*), and if *V* can be expressed in terms of the contact area (*A*) and the worn depth of the coating (*d'*), then the Archard equation can be solved in terms of *t'* as

$$t' = \frac{a\,d'}{FvK}\,. \qquad (5)$$

If a coating is applied to the critical elements of a bearing, which are otherwise responsible for bearing failure during a loss of lubrication, the life of that bearing will be extended while the coating is wearing away. Once the coating is worn away, the bearing will fail. If *d* is the total thickness of the coating, then *t'* describes the additional life provided by a tribological coating to a bearing subsequent to the loss of lubrication. Hence, the time to failure caused by a loss of lubrication of a tapered roller bearing with coated roller ends will be equal to

$$t = t_0 + t' = t_0 + \frac{Ad}{FvK}\,. \qquad (6)$$

K is a value that can be determined experimentally with laboratory tribometers. Since MC/aC:H coatings graphitize at temperatures around 300 °C, it is important to determine *K* for these types of coatings at contact stresses and sliding speeds near those of the actual application to account for elevated asperity temperatures. *F*, *A*, and *v* are values determined by the application and/or component design. For the bearings tested under the load and speed conditions used to generate Figure 4, *A/Fv* is calculated to be about $2.6\text{x}10^{-8}$ m-s/N. The family of metal carbide reinforced amorphous carbon and hydrocarbon coatings can be synthesized to have high values of *d* (~5 μm), low values of *K* (~10^{-17} m^3/Nm), and exhibit molecular or atomic wear without fracture and delamination. Additionally, the wear byproduct of these types of coatings is graphite, a very good solid lubricant.

L_{50} data of Figure 4 are plotted versus the ratio of *d/K* in Figure 8 and Table 1 lists the friction coefficients (μ), nominal thicknesses (*d*), and *d/K* values of the TiC/aC and TiC/aC:H coatings that were utilized in this study. The solid line in Figure 8 is not a fit, but a calculation from Eq. 6 using the *d/K* values for the coatings in Table 1. Evidently, the model of Eq. 6 appears to be very effective in terms of calculating the additional life that a coating on a roller end provides to a tapered roller bearing subsequent to a loss of lubrication. Furthermore, under the test conditions used in this study, there appears to be no clear relationship between the L_{50} values and the friction coefficients. However, the frictional heat generated at the rib-roller end contact during a lubrication loss event will scale directly with friction coefficient, so a coating with a low friction coefficient is desirable for this application.

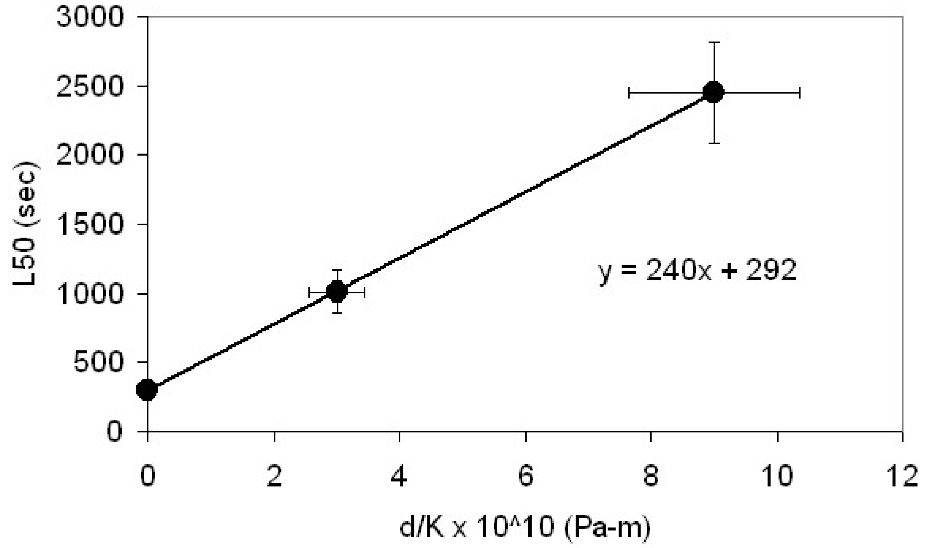

Figure 8: Data from Figure 4 plotted versus *d/K* for the bearings with uncoated roller ends (*d/K* = 0), TiC/aC coated roller ends (*d/K* = $3x10^{10}$ Pa-m), and TiC/aC:H coated roller ends (*d/K* =$9x10^{10}$ Pa-m). The line is not a fit, but a calculation from Eq. 6.

Coating	μ	*d* (μm)	*K* (Pa^{-1})
Uncoated	0.42	0	
TiC/aC	0.07	0.9	3 x 10^{-17}
TiC/aC:H	0.15	1.8	2 x 10^{-17}

Table 1: Values for the friction coefficient (μ), coating thickness (*d*), and wear coefficient (*K*) for the coatings evaluated in Figure 8.

Debris Resistance

It is believed that the polishing of the races by the coated rollers is also responsible for the debris-resistance shown in Figure 5. Figure 9 shows a magnified image of a dent (crater) in a bearing raceway caused by the impact of a debris particle, and a digitized image of that dent. Of particular significance is the raised edge or shoulder around the crater. If the lubricant film thickness (*h*) is sufficiently thin, as it would be in cases of boundary layer lubrication, then the shoulders of the debris craters would come into contact with opposing surfaces, in this case the rollers. Without a coating on the roller, this type of contact should result in adhesive wear between the contacting steel surfaces. Additionally, large contact stresses will exist on the shoulders, which will significantly enhance the opportunity for these sites to initiate fatigue cracks. Coated rollers coming into contact with these shoulders will not form adhesive junctions. Additionally, the polishing mechanism exhibited by coated rollers should function to remove the shoulders.

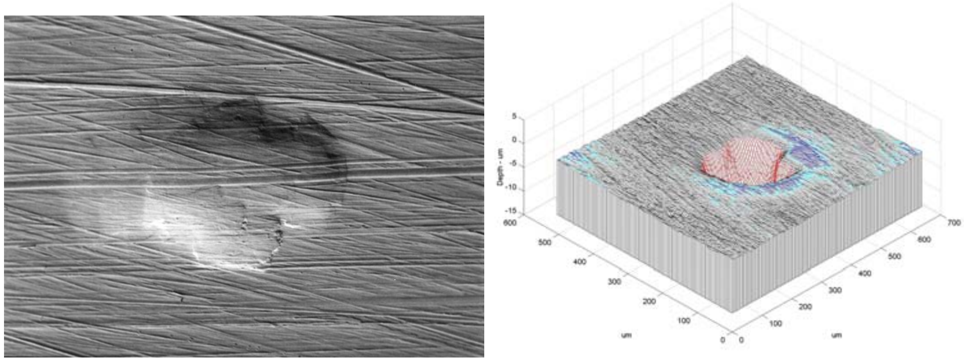

Figure 9: Magnified image of dent caused by metallic debris particle on raceway (left), and digitized image showing raised shoulders surrounding the dent (right).

False Brinelling and Fretting Protection

In the early 1980's, Boving et al. [17] developed a procedure for applying TiC coatings by CVD to 440C steel balls for gyroscope bearings that would exhibit false brinelling of the rings due to the oscillatory motion of the gyroscope. The function of the TiC coating was to defeat the adhesive wear mechanism that was responsible for the false brinelling. It is reasonable to assume that the MC/aC:H coatings function in a similar fashion as the data indicate in Figure 6. That is, MC/aC:H coatings on bearing rollers eliminate the adhesive wear mechanism (as long as they are present) that can occur between uncoated steel surfaces.

Torque Reduction

Zhou and Hashimoto examined the effects of raceway surface finish on the measured torque of tapered roller bearings [18]. Figure 10 shows their torque measurements after converting their surface roughness (R_a) data into λ. The relationship between the measured torque for this bearing and the λ value can be described by the function

$$M = M_0 + \delta e^{-\lambda/\alpha}, \qquad (7)$$

where α equals 0.055, and M_0 and δ equal 0.68 and 3.68×10^6 N-m, respectively, are determined by a least squares fit to the data. Although the $M(\lambda)$ relationship derived from the Zhou and Hashimoto results are for a different bearing than the pinion bearings tested in the automotive gearbox, the bearings are nearly the same size. Applying the values of δ and α derived from the fit to the data in Figure 10, it can be shown that a 7% increase in the λ value could account for a 0.75 N-m reduction in the torque losses per bearing. As it has been discussed several times previously in this article, improvements in the lambda value are easily accomplished through the micro-polishing action of MC/aC:H coatings on roller bodies.

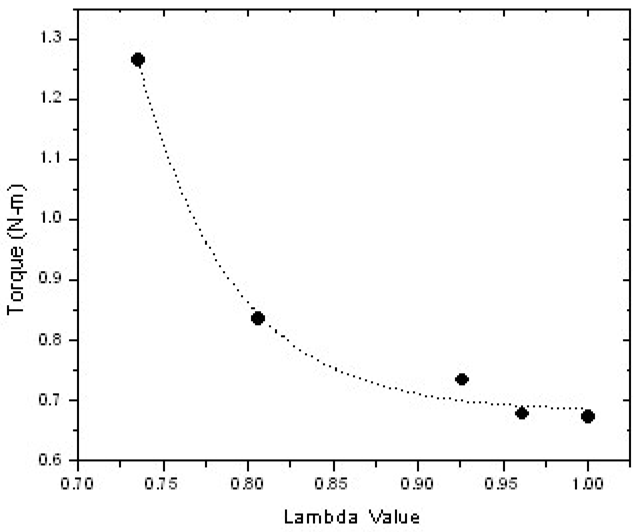

Figure 10: Measured torque of a tapered roller bearing as a function of λ (circles), and a fit to the data from Eq. 7.

CONCLUSIONS

This article has attempted to illustrate that MC/aC:H coatings applied to critical surfaces of the rollers of bearings can increase the fatigue life under poor lubrication conditions, can provide a temporary degree of protection against a loss of lubrication, can provide debris resistance under certain situations, can provide resistance to the adhesive wear responsible for false brinelling and fretting, and can reduce torque losses. Benefits provided to bearings by coated rollers such as those shown in this article are probably application specific and not universal. That is, one does not expect identical performance improvements across multiple product lines and application conditions.

Table 2 attempts to summarize the tribological concerns addressed in this article, along with the coating solutions that have been realized, and hypotheses about the mechanisms by which the coated rollers achieve the solutions. There are probably other hypothetical mechanisms that could be included in the Table; however, we have limited ourselves to including only those that have been supported by data and/or observations.

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Tribological Concern	Solution to Concern	Mechanism
Low λ Reduced Fatigue Life	TiC/aC:H or WC/aC:H coatings on roller bodies	Polishing of cup and cone races reduces surface roughness and increases λ.
Scoring from Loss of Lubrication	TiC/aC, TiC/aC:H, or WC/aC:H coatings on roller ends (sliding surfaces)	Barrier to adhesive wear, coating is sacrificial.
Reduced Fatigue Life due to Debris	WC/aC:H coatings on roller bodies and ends	Polishing action of coated rollers removes shoulders caused by debris craters and reduces overall surface roughness of the cup and cone races
False Brinelling and Fretting	WC/aC:H coatings on roller bodies and ends.	Coating forms a barrier to the adhesive wear mechanism.
Torque Reduction	WC/aC:H coatings on roller bodies and ends.	Coated rollers polish cup and cone races, reducing surface roughness, increasing λ, and thereby reduces torque.

Table 2: Tribological conditions, coating solutions tried, and the primary mechanisms by which the coated rollers provided benefit are displayed.

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