ANL/ET/CP-99845

ROLLING-CONTACT FATIGUE RESISTANCE OF HARD COATINGS ON BEARING STEELS

Ali Erdemir
Tribology Section
Energy Technology Division
Argonne National Laboratory
Argonne, IL 60439

August 1999

Invited paper to be presented at the H. S. Cheng Tribology Symposium in conjunction with the 1999 Joint Tribology Conference of the ASME/STLE, Kissimmee, FL, Oct. 10-14, 1999

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ROLLING-CONTACT FATIGUE RESISTANCE OF HARD COATINGS ON BEARING STEELS

Ali Erdemir
Tribology Section
Energy Technology Division
Argonne National Laboratory
Argonne, IL 60439

ABSTRACT

Ball- and roller-bearings of the 21st Century are expected to perform better and last longer while operating under more stringent conditions than before. To meet these great expectations, researchers have been constantly exploring new bearing designs or refining existing ones, optimizing microstructure and chemistry of bearing materials, and alternatively, they have been considering the use of thin hard coatings for improved bearing performance and durability. Already, some laboratory tests have demonstrated that hard nitride, carbide (such as TiN, TiC, etc.) and diamondlike carbon (DLC) coatings can be very effective in prolonging the fatigue lives of bearing steels.

This paper provides an overview of the recent developments in hard coatings for bearing applications. Previous studies have demonstrated that thin, hard coatings can effectively prolong the fatigue lives of bearing steel substrates. In particular, thinner hard coatings (i.e., 0.2 - 1 μm thick) provide exceptional improvements in the fatigue lives of bearing steel substrates. In contrast, thicker hard coatings suffer microfracture and delamination when tested under high contact stresses, hence are ineffective and may even have a negative effect on bearing life. Overall, it was concluded that thin hard coatings may offer new possibilities for bearing industry in meeting the performance and durability needs of the 21st Century.

1. INTRODUCTION

During recent years, we have been witnessing the development of a new generation of mechanical systems that are highly miniaturized, very sophisticated, yet extremely robust. Smooth operation of these systems is critically dependent on the performance and durability of their sliding and or rolling bearings. Downsizing with no compromise in performance and efficiency is likely to continue at an accelerated pace during the next Century. It is possible that the increasingly demanding and more stringent operating conditions of the next-generation bearing systems may exceed the capabilities of current materials. Fortunately, the very strong and diverse technology base acquired over the years in bearing design, surface engineering, and tribology will be able to handle these new challenges.

In general, the performance and durability of ball and roller bearings are determined by a combination of several factors such as microstructure, chemistry, and mechnical properties of the bearing steels used, rolling contact geometry, and operating conditions [1,2]. Great strides have been made in the design and development of high performance bearings since 1950's. In fact, today's modern bearings hardly fail under normal operating conditions. However, the operating conditions of future bearings are anticipated to be much harsher and more demanding (i.e., higher temperatures and contact pressures, starved lubrication, severe environments that can cause corrosion, oxidation, and erosion) than before [2-4]. When used under such severe conditions, bearings may still fail by the formation of pits or spalls on their rolling contact surfaces [5,6], or by extensive surface/subsurface deformation [7,8] oxidation and/or corrosion [9-11]. Erosion and surface damage or dents caused by abrasive particles in dirty oils can also lead to bearing failure [12,13].

There exist several papers addressing the mechanism(s) of failures resulting from the materials and/or service related phenomena [14]. There are also several theoretical models that can predict the lifetime of a particular bearing system and explain the failure mechanisms under specific operating conditions [15-19]. These analytical and theoretical studies have greatly increased our knowledge base in bearing technology and led to the development of some very unique bearing designs affording very long lifetime. However, the model predictions may not always match with the experimental or field results and such disparities in predicted and experimental results are perhaps due to the very complex nature of the contact and fracture mechanics involved in each particular case and to the statistical nature of the bearing failures.

It is generally accepted that when two solid bodies of curved shape are brought into contact, the maximum orthogonal shear stresses are developed somewhere beneath the contact spots. The depth of these stresses is dictated by the magnitude of applied loads and the elastic properties of the contacting bodies. For example, for a peak Hertz pressure of 5.42 GPa the depth is estimated to be ≈150 μm for a hardened AISI M50 steel [20]. From this knowledge, it has been postulated that fatigue failures or pits should originate at depths where maximum shear stresses develop [21,22]. Figure 1 shows the shape and morphology of a typical fatigue failure. Dislocation entanglement around inclusions, second-phase precipitates, and other types of volume defects that are located at depths where maximum shear stress develop are thought to act as stress concentration points and hence initiate subsurface microcracks resulting in failure [23,24].

To eliminate the causes of material specific fatigue failures, a number of materials engineering approaches have been pursued in previous years. The general aim of these approaches has been to increase bearing performance by structural refinement, mechanical-property enhancement, and smart surface engineering. Early studies have clearly demonstrated that a bearing component is only as good as the material it is made from. Therefore, researchers have developed a variety of methods (i.e., vacuum induction melting (VIM), vacuum arc-remelting (VAR), and electroslag remelting (ESR)) to better control and refine the microstructure and chemistry of bearing steels [25,26]. These methods were extremely effective in reducing both the number and size of volume defects that acted as stress-concentration and hence crack initiation points during cyclic loading [27,28]. In particular, such volume defects as voids, entrapped gas bubbles, and sulfur/phosphourus-based inclusions were virtually eliminated. Oxygen content of bearing steels was also reduced to some very low levels, as a result, the size and population of oxide-based inclusions become much smaller than before. Bearings made out of such super-clean steels have enjoyed dramatic improvements in their fatigue lives [29].

For mechanical-property enhancement, a number of novel microalloying and heat treatment techniques were developed in recent years and used to prolong the fatigue life of bearings [30,31]. Alternatively, advanced powder metallurgical methods were employed to control the shape, size, and distribution of second-phase carbides within the structure [32]. Low-carbon bearing steels (e.g., M50 Nil and M50 Supernil) with improved toughness and case-hardening capability were also developed and used in bearing applications [33,34]. Retained austenite which occasionally caused fatigue failure was also eliminated by new heat-treatment and quenching techniques.

The recent progress in structural refinement and mechanical-property enhancement has led to marked improvements in rolling contact fatigue (RCF) lives of bearing steels. Moreover, smart bearing design and improved filtering of abrasive particles from the lubricating oils had a substantial positive impact on bearing life. In fact, the failure modes of today's bearings are seldom related to microstructure or mechanical property of the base material. However, failures due to near surface defects and/or deficiencies still occur and limit the useful lifetimes of bearing components under cyclic loading [35,36]. Surface defects, such as grinding furrows, nicks, seams, notches, and dents introduced during manufacturing and/or machining operations and deep scratches caused by abrasive particles in lubricants, as well as shallow pits due to progressive corrosion and wear damage, were found to cause fatigue failures in modern bearings [37-41]. In addition, very high normal and tangential pressures developing at asperity levels during rolling contact have given rise to severe deformation and surface distress that can lead to premature bearing failures [5,6,13].

From the foregoing, it is clear that bearing failures are increasingly initiated by near-surface irregularities or defects that result from machining and/or improper handling, and abrasive particles in lubricants. In order to improve the surface-specific properties of bearing steels, researchers have tried two general approaches. First, they developed new methods to better control surface irregularities and secondly they used a variety of surface engineering tools to achieve better protection against corrosion and abrasive wear particles or contaminants. Recent advances in surface metrology, polishing, and handling methods have significantly reduced the number of surface irregularities and thus reduced the causes of fatigue initiating from such irregularities. The use of advanced filtering techniques in bearing systems has eliminated most of the abrasive particles and thus reduced the surface damage caused by such particles [41].

In recent years, hard coatings or surface engineering methods have attracted a great deal of interest from researchers and bearing manufacturers for a variety of rolling/sliding bearing applications (i.e., ball and roller bearings, gears, cams, tappets, etc.). The idea of using hard coatings to achieve longer bearing life is not new, but it has taken very long time to scale up and exploit for commercial applications. This paper will provide an overview of the present state of the art in bearing-performance improvements achieved through the use of hard coatings. A brief description of the coatings used in bearing systems is given first and followed by a detailed discussion of the recent progress made in the development of new bearing components through the use of surface engineering approaches. Special emphasis is placed on hard coatings applied on these components by a variety of physical and chemical vapor deposition processes. In particular, the effects of coating adhesion and thickness on the fatigue life of hard coatings are discussed. Recent progress in understanding of the mechanisms of the fatigue failures of coated bearing materials is also covered.

2. SURFACE ENGINEERING APPROACHES TO IMPROVE BEARING DURABILITY AND PERFORMANCE

The major goal of the surface engineering approaches has been to further reinforce the surface metallurgical and tribological characteristics (i.e., wear, corrosion, oxidation, and fatigue) of the bearing steel substrates and hence to improve their lifetime. In the past, researchers have employed a variety of surface engineering techniques (i.e., ion implantation [42-46], case carburizing/nitriding, and physical and chemical vapor deposition techniques) to enhance the surface properties of bearing steels. The range and usefulness of these techniques were discussed in details in previous review articles [4,47].

Because of their excellent mechanical, chemical, and tribological properties, hard ceramic coatings (e.g., TiN, TiC, NbN, NbC, ZrN, HfN, and DLC) have enjoyed the greatest attention [47-49]. In particular, TiN, TiC, and DLC coatings were studied the most. In most cases, these coatings resulted in remarkable improvements in both the L_{10} and L_{50} fatigue lives of bearings. The general conclusion of previous studies was that the extent of fatigue life improvements in bearing steel substrates is very much dictated by the thickness and adhesion of the hard coatings. In general, thinner coatings (i.e., 0.2-1 μm thick) performed the best, while strong bonding between coating and substrate steel was extremely important for achieving any type of life improvements. In addition to hard ceramic coatings, a number of pure metallic coatings were produced on bearing steel substrates and tested for improved fatigue life [50-52]. These coatings are typically produced by ion plating, magnetron sputtering, cathodic-arc plating, ion-beam-assisted deposition, and chemical vapor deposition methods. Most of these methods are now commercially available and highly cost-effective.

Nitride and Carbide Coatings

Hard nitride and carbide coatings (i.e., TiN, TiC, CrC, etc.) are routinely used in tooling industry to achieve longer tool life and smoother surface finish on machined work pieces. Figure 2 shows the film morphology of a TiN film in cross-section. There exist several deposition methods by which these coatings can be produced on steel and other substrates with excellent bonding. In the past, these coatings were also applied on bearing steel substrates to achieve longer wear and fatigue life. Early studies by Dill et al. [53], Hochman et al. [51], Thom et al. [54], and Erdemir and Hochman [55-57] explored the effects of hard CrC, TiC, and TiN coatings on the RCF performance of a variety of bearing steels (i.e., 440C, M50, and BG-42, etc.). Coatings with a wide range of thicknesses (i.e., 0.24 to 2.4 μm) were produced on bearing steel substrates by CVD, ion-plating, and magnetron sputtering. Tests were conducted on a three-ball-on-rod fatigue tester at two stress levels; 4.04 and 5.42 GPa. Test results showed that the thickness of the TiN coatings had the most profound effect on RCF life. As summarized in Table 1, the thinner TiN coatings (less than 1 μm thick) resulted in substantial improvements in the L_{10} and L_{50} fatigue lives of the base steels. A few thick coatings also performed well when tested at 4.04 GPa. Microscopic examination of the rolling tracks indicated that thinner coatings remained intact on the surfaces whereas, the thicker TiN coatings (above 2 μm) suffered severe microfracture and delamination especially at 5.42 GPa as shown in Fig. 3. The L_{10} and L_{50} fatigue lives of thick TiN coated bearing steels were shortened due to abrasive third body wear caused by the delaminated and crushed TiN particles. Some of the thicker films behaved rather well when tested under lower contact stresses (i.e., 4.04 GPa). Microscopic examination revealed that these TiN coatings remained intact on the rolling tracks mainly due to minimal plastic deformation of the underlying substrates and film microfracture and detachment did not occur.

Cheng et al. [58] and Chang et al. [59,60] investigated the RCF behavior of TiN-coated rollers using a twin-disk rolling-contact machine at a peak Hertzian contact pressure of 2.3 GPa. Coatings were deposited by a high-rate reactive sputtering technique. The goal of this study was to ascertain the effect of TiN film thickness (i.e., from 0.25 to 5 μm) on RCF life of rollers. The experimental results revealed that 0.25 μm thick TiN coatings gave the best fatigue resistance. The thicker coatings suffered larger initial spalls. TiN coatings of 0.25 μm lasted more than 60 million cycles while thicker TiN coatings (2.5 to 5 μm) peeled off rather quickly and shortened the fatigue life of the steel substrates. For example, a roller coated with 2.5-μm-thick TiN developed a large spall after 4.2 million stress cycles. The RCF life of uncoated rollers was about 10 million cycles.

Electron microscopic examination of the rolling contact surfaces by Chang et al. [59,60] showed that thinner TiN coated surfaces underwent principally elastic deformation without coating debonding. However, uncoated surfaces were heavily deformed even after shorter rolling contact cycles. For the uncoated rollers, cross-sectional micrographs revealed the presence of many near-surface microcracks at an asperity scale nearly parallel to the surface. Metallographic examinations of the uncoated subsurface revealed a thin layer of dark etching region corresponding to the microcrack failure region. For the coated rollers, few cracks were found and the dark etching region was essentially absent. These researchers have concluded that TiN coatings minimized the surface distress and suppressed the initiation of microcracks [60].

In a comprehensive research program directed by Thom et al. [54], eight different nitride coatings (i.e., TiN, ZrN, HfN, CrN, Mo2N, Ti0.5Al0.5N, Ti0.5Zr0.5N and (Ti-Al-V)N) were deposited onto hardened 440C stainless steel for RCF improvements. They produced four different coating thicknesses (i.e., 0.25, 0.50, 0.75 and 1.0 μm) of each type of coating. The tests were carried out in a lubricated three-ball-on-rod test machine at two different stresses of 4.0 and 5.4 GPa. Their results indicated that six of the eight coatings gave significant improvements in RCF life. Only CrN and Ti0.5Al0.5N showed little or no improvement over that of an uncoated specimen. The best improvement (i.e, 12 times over that of an uncoated 440C) was provided by the HfN coating (0.5 μm thick) at both stress levels of 4.0 and 5.4 GPa. They concluded that the coating thickness was critical in improving the RCF life and, in general for these coatings, the optimum thickness was in the range of 0.5-0.75 μm.

More recent theoretical and experimental studies by Polansky et al. explored the effects of hard coatings and surface roughness on near-surface contact fatigue initiation in bearing steels [61,62]. They developed a set of approximate analytical formulae to estimate the optimum coating thickness required to protect the substrates effectively from the small-scale contact stress spikes caused by surface roughness. They proposed a model taking into account the multiscale nature of real surface roughness, as well as interaction between different roughness and coating thickness. Their model predicted that in order to be truly effective against RCF, a hard coating has to be relatively thick (say, >3μm), adherent, have fine microstructure and resistance to cohesive failure under cyclic contact loading.

Experimental studies by Polonski et al. [62] showed that the optimum TiN film thickness was about 0.75 μm, short of predicted film thickness of 3μm and over. TiN coatings thinner than 0.75 μm could not significantly affect the fatigue life, while much thicker ones had negative effects. The fatigue life reduction observed with thick coatings is explained by comparison of the coated surface roughness in the damaged and the intact portions of the rolling track. Their test results also indicated that the stress-affected material volume played an important role in near-surface initiated rolling-contact fatigue. The fatigue life enhancement observed is some instances was attributed to the polishing of the loading balls by hard TiN coating.

Carvalho et al. [63] investigated the interfacial fatigue stresses in TiN coated tool steels under RCF conditions. Specifically, they explored the effects of substrate hardness and surface roughness on RCF. From their results, it appeared that the fatigue life of bearing steels was significantly influenced by both the pre-treatment and the final surface finish of the material. The polished surfaces provided the best fatigue life. However, at a higher contact stress, there appeared to be very little influence of pre-treatment and surface roughness. Two mechanisms of crack propagation under pure rolling conditions were found, depending on the substrate hardness. For the softer substrates, the cracks propagated mainly perpendicular to the surface, whereas for the harder substrate, the cracks generally originated at the interface and progressed in the coating parallel to the rolling surface.

Miyoshi et al. [64] explored the RCF damage in TiC- and TiN-coated steels using a Scanning Acoustic Microscope (SAM). SAM was extremely useful in revealing delamination and crack propagation below the rolling surface. The results showed that in the case of TiC-coated steels, cracks initiated at micro pits generated during deposition in the CVD reactor and propagated in a parallel direction to the rolling direction of balls and at the interface between TiC film and the substrate. This resulted in the detachment and finally the peeling of the TiC film. In the case of TiN-coated steels, micro delamination appeared at spherical defects between the film and the substrate, and grew into macro delamination and finally TiN film peeled off the substrate. Both TiC and TiN films had an extremely large compressive residual stress and the film delamination may have been initiated by these additional compressive stresses.

In another study, Sawamoto et al. [65] explored the influence of TiN coating on the RCF resistance of mild steel. The TiN films were uniformly produced on the surface of steel specimens by an activated reactive evaporation method. The results indicated that the annealed mild steel specimens coated with TiN had superior RCF strength than the uncoated ones. The fatigue life of the specimen coated with TiN was about eighteen times as large as that of the uncoated specimen under the same contact stress. TiN film on the surface of specimen was effective in suppressing the generation of surface cracks on the specimens.

Liston [66] has explored the RCF properties of TiN/NbN superlattice coatings on M-50 steel. The superlattice coating consisted of alternating layers of TiN and NbN and was deposited using an unbalance magnetron sputtering system. Her RCF test results showed that the coating was successful in increasing the L_{10} life of the M-50 steel by as much as10 times. Lives of the coated M-50 specimens varied depending on the approximate thickness of the individual coating layers. Thinner coatings resulted in better RCF performance.

In another investigation, Middleton et al. [67] reported a nearly fourfold improvement in the L_{50} fatigue life of M50 bearing steel after coating with a 1- µm-thick TiN coating. This coating was produced by the IBAD process at room temperature and possessed excellent adhesion. Their tests with a 0.25-µm-thick TiN coating failed to improve RCF life of the substrate steel.

Overall, the recent studies by a number of researchers have confirmed the findings of Erdemir and Hochman [55-57], and Chang et al. [59,60] in that the coating thickness plays an important role in the RCF performance of bearing steel substrates. Thinner hard coatings (i.e., 0.2 to 1 µm-thick) provide the best fatigue life improvements. Thicker coatings most often delaminate and may shorten the life.

A few other studies [68,69] investigated the RCF performance of hybrid bearings consisting of CVD-TiC-coated REX20 steel balls and REX20 steel raceways and the effects of surface residual stresses on the RCF and wear performance of CVD-SiC coatings. These studies reported strong correlation between intrinsic properties of the coating materials and RCF performance. Wedeven and Miller [70] explored the effect of several bulk materials, surface treatments and coatings on the RCF, friction, and wear behavior of some bearing materials. Their studies showed that the RCF life was significantly improved with the use of silicon nitride and hard coatings of CrC, TiN, and thin dense chrome.

DLC Coatings

DLC coatings fall into the catagory of amorphous carbons that combine high chemical stability and mechanical hardness with attractive tribological properties. Unlike most other tribometerials, these coatings can afford both low friction and high wear resistance to sliding surfaces even without any additional lubrication. DLC films can be deposited at room temperature and at fairly high deposition rates by a variety of methods, including ion-beam deposition, plasma source ion implantation, DC and RF magnetron sputtering, arc-physical vapor deposition, plasma-enhanced chemical vapor deposition, and laser ablation [71-75]. DLC coatings can be made very hard (i.e., up to 9000 kg/mm^2) and highly hydrogenated (containing up to 50 at.% hydrogen) or essentially hydrogen free (i.e., less than 1% hydrogen) using appropriate deposition methods and/or carbon sources [76,77]. They can also be doped by a variety of elements (e.g., nitrogen, fluorine, oxygen, silicon, tungsten, titanium, and niobium) to achieve better mechanical, electrical or tribological properties [78-80].

Because of their excellent friction and wear performance, DLC films were tried on bearing steel substrates early on by Wei et al. [49,81]. Specifically, they explored the effect of DLC coating thickness (i.e., 0.5- to 1-μm-thick) on the RCF behavior of M50 steels at a stress level of 5.5 GPa. They observed that 1-μm-thick DLC coating delaminated, but that a 0.5 μm-thick DLC coating remained largely intact and in some instances improved the L_{50} RCF life of M50 steel by factors of up to 10. Further studies by Wei and his coworkers [82] explored the RCF performance of DLC coatings on AISI M-50, 52100, 4118 and 440C steels. Again, order-of-magnitude increases in the fatigue lives of all four rod materials were observed. Systematic RCF tests coupled with microscopic examination after various test intervals show that micro-polishing by hard DLC coating fragments may have played an important role in prolonging fatigue lives of bearing steel substrates. Raman spectroscopic measurements suggested that cyclic stressing of the DLC layer causes it to gradually transform from what was initially amorphous carbon to the more lubricous and stable graphite phase.

Rosado et al. [83] investigated the RCF and wear characteristics of uncoated and diamond-like carbon coated VIM-VAR M50 bearing steels at room temperature and 177 °C at a Hertzian stress level of 4.8 GPa. The coatings were deposited via ion beam enhanced deposition and were approximately 33 nm thick. Rolling fatigue and wear tests were conducted using a ball-on-rod type tester. Results did not indicate any significant difference in the fatigue life of coated and uncoated specimens at room temperature, at 90% confidence level. However, the coating significantly improved the fatigue life (90% confidence level) at 177 °C and wear resistance at both temperatures.

Other Hard Coatings and/or Treatments

Besides hard nitride, carbide, and DLC coatings, various thermal diffusion processes (such as nitriding and carburizing [84 85], plasma spray and high-velocity oxyfuel deposition methods [86-89] were also used to enhance the surface fatigue properties of bearing steel substrates. In general, under certain conditions, carbonitriding could result in improved fatigue life. The thickness of white layers in carbonitrided surfaces played the most critical roles in fatigue life [84]. Coatings produced by plasma spraying or other methods were too thick, highly stressed, and hence suffered from premature crack formation and delamination during RFC tests. Therefore, they were not very useful, especially under high contact stresses.

3. MECHANISTIC MODELS

From the RCF test data presented above, it is clear that thin coatings of TiN and DLC can substantially improve the fatigue life of bearing steel substrates. Thinner coatings were able to remain intact on the rolling-contact surfaces and thus extend the RCF life of bearing steel substrates. However, the thicker coatings tended to fracture and delaminate, reducing the RCF life of the substrate steels, especially under high pressures. Under lower contact pressures, some of the thicker TiN coatings were also able to remain intact and extend the fatigue lives of bearing steels. In short, strong adhesion between film and substrate was extremely important for achieving improvements in the fatigue lives of underlying substrates.

A mechanistic understanding of the beneficial effects of thin coatings and detrimental effects of thick coatings on RCF behavior of bearing steel substrates would be extremely valuable, though quite difficult. The difficulty is in making a reliable analysis of the state of extrinsic stresses due to external loading and that of intrinsic stresses resulting from thermal expansion and lattice mismatches between coatings and substrate materials. Using FEM, a few attempts were made to analyze the state of stress and strain on layered-half-spaces where the layers were much stiffer or harder than the underlying substrates.

Using the finite-element method (FEM), Ishikawa et al. [90] analyzed the deformation characteristics of two bearing materials coated with SiC under conditions of pure rolling and of rolling and some sliding. They concluded that both coating thickness and mechanical properties of substrate steels significantly affect deformation and the distribution of stress and strain within the contacting bodies. For thin SiC coatings (4.9 μm), their FEM analysis showed that substantial reductions in the magnitude of stress and strain in substrates are feasible when sliding is present. On the other hand, thick SiC coatings (28 μm) were shown to reduce the maximum stress and strain in substrates under pure rolling conditions.

Based on phenomenological observations, Erdemir and Hochman [55,57] proposed that thinner TiN coatings, i.e., less than 1 μm thick, can easily fit and follow the deformation contours of the relatively softer steel substrates that undergo repetitive loading/unloading. As evident from Fig. 3a, despite some detachment along the original surface scratches, the thinner TiN coatings indeed remain largely intact throughout the RCF tests that, in some instances, lasted more than 100 million stress cycles. The thicker coatings, however, were largely removed from the rolling tracks (see Fig. 3b). Because of their inherent brittleness and high internal stress levels, the thicker coatings were unable to sustain the same amount of elasto-plastic deformation that the softer substrates underwent during cyclic loading and unloading, thus, they suffered brittle fracture and delamination. In other words, the three-dimensional stress effects of RCF loading produce failures in the thicker coatings because these films behave more like a separate entity. It is now well established in the literature that many deposition processes for hard coatings may leave high compressive stresses on the coating side of the interface and high tensile stresses on the substrate side. The magnitude of these residual stresses is even more pronounced when dealing with thicker coatings deposited at elevated temperatures. Compression on the coating side and tension on the substrate side result in another tensile component that is normal to the coating-substrate interface. It is reasonable to believe that the tensile stresses acting in a direction normal to the coating/substrate interface can add to the stresses, causing delamination and/or adhesive failure of the thicker TiN coatings undergoing cyclic loading and unloading.

For the excellent RCF life and remarkable resistance of the thinner TiN coatings to fracture and delamination, Cheng et al. [58] and Chang et al. [59,60] oposed that these coatings can effectively minimize the extent of plastic deformation of asperity contacts by reducing simply the magnitude of the stress field. Using scanning and transmission electron microscopes, they clearly showed that the numbers of microcracks in underlying substrates were markedly reduced when thinner TiN coatings were used. However, uncoated test samples underwent severe plastic deformation and developed large colonies of near-surface cracks. As a result, these uncoated samples failed rather quickly. Based on these observations, the investigators argued that extensive microcracking in uncoated samples was mostly due to extensive interactions between opposing asperities during rolling contact occurring in an elasto-hydrodynamic lubrication regime. Apparently, such interactions can cause severe microstressing of the regions beneath the asperity contacts and this can eventually initiate microcracks and cause surface distress.

For interpretation of premature failure of thick coatings during rolling contacts, Chang et al. [59] used an analytical model proposed by Kim et al. [91]. This model evaluates the effect of concentrated contacts on thin layers having perfect bonding to an elastic half-space. This model demonstrates that the magnitudes of shear stresses and stress intensity factors at interfaces are increased with increasing coating thickness. Consequently, in a concentrated contact situation, e.g., RCF testing, the thicker coatings will be more susceptible to debonding than the thinner coatings. For this model to work properly, it is important that a region of debonding or a crack exist initially or develop eventually at the interface between the rigid coating and the substrate.

A few researchers observed that during rolling contact, the rolling surfaces of balls and rods undergo progressive polishing by hard coatings and eventually they achieve a mirrorlike finish on their surfaces. Obviously, highly polished surfaces will improve the elastohydrodynamic behavior of rolling bodies and hence the RCF.

4. SUMMARY AND FUTURE DIRECTIONS

The results of previous investigations suggest that, depending on the application conditions and environmental constraints, surface defects and/or irregularities (caused by wear, corrosion, and deformation) may in the future be the dominant modes of failure limiting the lifetime of bearing components. Studies also suggest that with proper surface engineering, bearing-steel substrates may live up to their expectations. In particular, hard coatings (such as TiN, TiC, and DLC) hold promise for high performance bearing applications. The thickness and adhesion of these coatings are critically important for improved fatigue life. The first and most important requirement is that the coating must remain intact on the rolling contact surfaces. Thinner hard coatings, 0.2 to 1 μm thick, seem to provide the best overall performance under high-stress RCF situations. Hard coatings thicker than 2 μm undergo severe delamination and/or fracture and, in most cases, reduce the RCF life of the base steels, especially under high contact stresses (5.42 GPa).

As for the future trends in surface technologies for bearing applications, lately we have been seeing new and exciting developments that can allow novel coating architectures capable of meeting the increasingly mulifunctional needs of highly miniaturized and sophisticated bearing systems. For example, new developments in hard nitride and carbide coatings by sophisticated magnetron sputtering and cathodic arc technologies increased the flexibility of a coating specialist in designing and developing a multifunctional coating. With these new capabilities, a new generation of hard and self-lubricating coatings with a multilayer architecture has recently been developed, optimized, and offered for commercial uses. These exotic architectures, based on layers of a self-lubricating dichalcogenides and a hard transition metal nitride or carbide, work extremely well under harsh tribological conditions. Multifunctional, nanocomposite films have also been produced by magnetron sputtering and are quite hard and self-lubricating, thus raising the prospect for dry or marginally lubricated bearing applications. Duplex/multiplex surface treatments and multilayer coatings have recently made their way into the commercial marketplace and have been meeting the ever-increasing performance needs of more severe tribological applications. A breed of superhard, nano-structured and superlattice films has also been developed for demanding applications and tried on bearing steel substrates [67]. These films are quite stiff and tough, hence hard to initiate or propagate cracks.

The usefulness of diamondlike carbon films for bearing applications has already been demonstrated by previous researchers [48, 81,82]. Recent advances in this field have led to the development of a class of nearfrictionless (i.e., 0.001 friction coefficient) and -wearless (i.e., 10^{-11} $mm^3/N.m$, under 2 GPa initial peak Hertz pressure) carbon films. It is anticipated that these new generation films with ultralow friction and wear should function extremely well under the increasingly stringent operating conditions of bearing systems.

In recent years, researchers have developed a few mechanistic models describing the failure modes of thin and thick hard coatings subjected to concentrated contacts. Although these models are effective in analyzing the failure modes of coated-substrates, more studies of this kind are needed to address the critical relationship(s) between fatigue life, film thickness, and adhesion. Specifically, new models and/or computer codes must be developed to increase our predictive capabilities in assessing the optimum coating thickness for a given bearing application. For greater commercial exploitation of hard coatings in the bearing industry, effective quality control tools and/or techniques must be developed to ensure the quality of coated-bearing components from one batch to another.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy, Office of Transportation Materials, under Contract W-31-109-Eng-38.

REFERENCES

1. P. J. L.Fernandes, Eng. Fail. Analysis, 4(1997)155.

2. E. V. Zaretsky, Isr. J. of Technol., 20(1982)3.

3. T. E. Tallian, ASME Preprint No. 86-Trib-13, 1986.

4. R. E. Maurer, J. Vac. Sci. Technol., A4(1986)3002.

5. T. E. Tallian, Proc. 5th Leeds/Lyon Symp. Tribol., pp. 253-281, 1978.

6. A. M. Kumar, S. M. Kulkarni, V. Bhargava, G. T. Hahn, and C. A. Rubin, "Rolling-Contact Spalling in Bearings," NASA Tech Briefs, MFS-27201, George C. Marshall Space Flight Center, AL, 1987.

7. Y. P. Chiu, T. E. Tallian, and J. I. McCool, Wear, 17(1971)447.

8. V. Bhargava, G. T. Hahn, C. A. Rubin, Wear, 133(1989)65.

9. J. E. Merwin, K. L. Johnson, Proc. Inst. Mech. Engrs. 177(1963)676.

10. P. Schatzberg, Corrosion Fatigue, Int. Corrosion Conf. Ser., National Association of Corrosion Engineers, Houston, TX 1972, p. 670.

11. J. L. Sullivan and M. R. Middleton, ASLE Preprint No. 84-LC-3C-4, 1984.

12. R. J. Parker, E. N. Bamberger, and A. H. Hahm, ASLE Trans., 40(1984)299.

13. K. L. Johnson, Proc. Instn. Mech. Engrs., 203(1989)151.

14. D. Nelias, M. L. Dumont, F. Champiot, A. Vincent, D. Girodin, R. Fougeres, L. Flamand, American Society of Mechanical Engineers, Paper No. 98-TRIB-1-61 (1998)

15. Y. P. Chiu, Tribol. Trans., 40 (1997)658.

16. E. Beghini, R. S. Dwyer-Joyce, E. Loannides, B. Jacobson, A. A. Lubrecht, J. H. Tripp, J. Phys. D: Appl. Phys., 25(1992)379.

17. M. Shibata, A. Yoshida, S. Ahara, A. Nitanai, and N. Tsushima, J. Japan. Soc. Tribol., 39 (1994)698.

18. K. Ichmarc, J. Japan. Soc. Tribol., 39(1994)660.

19. R.-H. Zhou, H. P. Nixon, SAE Technical Paper Series International Off-Highway and Powerplant Congress and Exposition Sep 14-17 1992 1992 Publ by SAE Warrendale PA USA p 1-8 Paper No. 921720

20. E. N. Bamberger, and J. C. Clark, Rolling Contact Fatigue Testing, Ed. by. J. J. C. Hoo, ASTM-STP No. 771, p. 85, 1982.

21. J. A. Martin and A. A. Eberhardt, J. Basic Eng., 89(1967)932.

22. A. P. Voskamp, J. Tribol., 107(1988)359.

23. T. L. Carter, R. H. Butler, H. R. Bear, and W. J. Anderson, ASLE Trans., 1(1958)23.

24. F. A. Butterfield and T. R. McNelley, ASME Preprint No. 85-Trib-39, 1985.

25. R. Schlatter, Industrial Heat., 41(1974)40.

26. R. Schlatter and J. P. Stroup, J. Vac. Sci. Tech., 9(1972)1326.

27. E. N. Bamberger, E. V. Zaretsky, and H. Singer, J. Lubr. Technol., 98(1976) 580.

28. E. V. Zaretsky, NASA TM-88881, 1986.

29. G. Auclair, F. Ruby-Meyer, R. Meilland, P. Rocabois, ASTM Special Technical Publication Proceedings of the 1996 Symposium on Bearing Steels: Into the 21st Century Nov 19-21 1996 v 1327 Apr 1998 New Orleans, LA, , USA, p 39-54.

30. R. J. Parker and E. N. Bamberger, NASA TP-2189, 1983.

31. R. J. Parker, NASA CP-2210, 1983, p. 40.

32. J. A. Whitehead, P. D. Nurthen, P. R. Brewin, Int. J. Powder Metall., 26(1990)345.

33. E. N. Bamberger, B. L. Averback, and P. K. Pearson, Interim Progress Report, AFWAL-TR-87-2059, Wright Patterson AFB, OH, October 1987.

34. B. L. Averbach, S. G. Van Pelt, and P. K. Pearson, and E. N. Bamberger, Lubr. Eng. 47(1991)837.

35. W. Cheng, H. S. Cheng, T. Mura, and L. M. Keer, J. Tribol., 116(1994) 2.

36. W. Cheng, H. S. Cheng, L. M. Keer, and X. Ai, J. Tribol., 115(1993)658.

37. H. K. Lorosch, "Influence of Load on the Magnitude of the Life Exponent for Roller Bearings," ASTM STP 771, 1982, pp. 275-292.

38. B. L. Averbach and E. N. Bamberger, Tribol. Trans., 34(1991)241.

39. M. Liu, and T. N. Farris, Journal of Tribology, 114(1994)841.

40. E. Ioannides, Proc. Australia Tenth International Wheelset Congress, Sep 27-Oct 1 1992
Published by IE Aust Barton, Aust p 65-70.

41. K. Chao, C. S. Saba, P. W. Centers, Tribology Transactions, 39(1996)13.

42. P. Sioshansi, Mat. Sci. Eng., 90(1987)373.

43. F. M. Kustas, M. S. Misra, and P. Sioshansi, Proc. MRS Symp. 27(1984)685.

44. F. M. Kustas, M. S. Misra, S. R. Smith, P. J. Wilbur, and R. L. Thom, Surf. Coat. Technol., 37(1989)1.

45. R. F. Hochman and A. Erdemir, "Ion Implantation and Plating to Improve Hardness, Wear and Rolling Contact Fatigue Resistance of Bearing Steels," Final Report, NASA-George C. Marshall Space Flight Center, Contract Number: NASA-35048, May 1987.

46. B. Torp, B. R. Nielsen, A. Dodd, J. Kinder, C. M. Rangel, M. F. DaSilva, B. Courage, Nuclear Instruments & Methods in Physics Research B: 80-81 (1993) 246.

47. A. Erdemir, Surf. Coat. Technol., 54/55(1992) 482.

48. R. Thom, L. Moore, W. D. Sproul, and T. P. Chang, Surf. Coat. Technol., 62(1993)423.

49. R. Wei, P. J. Wilbur, M.-J. Liston, G. Lux, Wear, 162-164(1993)558.

50. J. H. Davis, NASA/ASEE Summer Faculty Research Fellowship Program," Marshall Space Flight Center/The University of Alabama, 1982.

51. R. F. Hochman, A. Erdemir, F. J. Dolan, and R.L. Thom, J. Vac. Sci. Technol., A3(1985)2348.

52. W. P. Washiewicz, Proc. of SAE Int. Off-Highway and Powerplant Conf., SAE Preprint #841124, 1984.

53. J. F. Dill, M. N. Gardos, H. E. Hintermann, and H. J. Boving, ASLE Proc. on 3rd Int. Conf. on Solid Lubrication, ASLE-SP-14, p. 230, 1984.

54. R. Thom, A. Erdemir, and R. F. Hochman, Proc. Conf. on Ion Plating and Implantation; Applications to Materials, Ed. R. F. Hochman, ASM, Metals Park, OH, 1986, p. 183.

55. A. Erdemir and R. F. Hochman, Surf. Coat. Technol., 36(1988)755.

56. A. Erdemir and R. F. Hochman, Proc. Conf. Ion Implantation and Plasma Assisted Processes for Industrial Applications, Eds. R. F. Hochman, H. Legg, and K. O. Legg, ASM, Metals Park, OH, 1988, p.43.

57. A. Erdemir, "A Study of Surface Metallurgical Characteristics of TiN Coated Bearing Steels, Ph.D. Thesis, Georgia Institute of Technology, Atlanta, Ga, 1986.

58. H. S. Cheng, T. P. Chang, and W. D. Sproul, Proc. Conf. 16th Leeds/Lyon, 1989, Tribology Series 17, Elsevier, Amsterdam, 1990, p. 81.

59. T. P. Chang, H. S. Cheng, and W. D. Sproul, Surf. Coat. Technol., 43/44(1990)699.

60. T. P. Chang, H. S. Cheng, W. A. Chiou, W. D. Sproul, Tribol. Trans. 34(1991)408.

61. I. A. Polonsky, T, P. Chang, L. M. Keer, and W. D. Sproul, Wear, 208(1997)204.

62. I. A. Polonsky, T, P. Chang, L. M. Keer, and W. D. Sproul, Wear, 215(1998)91.

63. N. J. M. Carvalho, A. J. Huis, and J. Th. De Hosson, Surf. Coat. Technol., 105(1998)109.

64. Y. Miyoshi, K. Ogura, and K. Kida,, J. Soc. Mater. Sci.-Japan, 46(1997) 77-83.

65. A. Sawamoto, S. Nokubo, Y. Ide, T. Fujita, T. Fukui, and K. Yasuoka, J. Soc. Mater. Sci.-Japan, 45(1996)912.

66. M.-J. Liston, ASTM Special Technical Publication Proceedings of the 1996 Symposium on Bearing Steels: Into the 21st Century, STP: 1327 1998 New Orleans, LA, , USA, p 499-510.

67. R. M. Middleton, P. J. Huang, M. G. H. Wells, and R. A. Kant, Surf. Eng., 7(1991)319.

68. G. Radhakrishnan, J. C. Uht, W. Park, M. R. Hilton, P. M. Adams, P. C. Ward, E. G. Herbert, and B. N., Materials Research Society Symposium - Proc. Fundamentals of Nanoindentation and Nanotribology, Apr. 13-17, 1998 No. No. 522 1998 pp 445-450.

69. K.-D. Bouzakis, N. Vidakis, and S. Mitsi, J. Tribol., 120(1998)835.

70. L. D. Wedeven, N. C. Miller, Lubric. Eng., 47(1991)1009.

71. L.-Y. Chao, R. Lakshminarayanan, D. K. Shetty, and R. A. Cutler, J. Am.Cer. Soc., 78(1995)2307.

72. K. Miyoshi, J. J. Pouch, and S. A. Alterovitz, Mater. Sci. Forum, 52/53(1989)645.

73. A. Erdemir, M. Switala, R. Wei, and P. Wilbur, Surf. Coat. Technol., 50(1991)17.

74. S. Neuville and A. Matthews, MRS Bull., 22 (9)1(997) 22

75. J. J. Cuomo, J. P. Doyle, J. Bruley, and J. C. Liu, Appl. Phys. Lett., 58(1991)1.

76. A. A. Voevodin, M. S. Donley, and J. S. Zabinski, Surf. Coat. Technol., 92(1997)42.

77. H. Ronkainen, J. Koskinen, A. Anttila, K. Holmberg, and J.-P Hirvinen, Diamond and Rel. Mat., 1(1992)639

78. H. Dimgen and C. P. Klages, Surf. Coat. Technol., 49(1991)543.

79. S. J. Harris, A. M. Weiner, and W.-J. Meng, Wear, 211(1997)208.

80. A. K. Gangopadhyay, P. A. Wolermet, M. A. Tamor, and W. C. Wassell, Tribol. Int., 30(1997)9.

81. R. Wei, P. J. Wilbur, and F. M. Kustas, J. of Tribol., 114(1992)298.

82. R. Wei, P. J. Wilbur, and M.-J. Liston, Diamond and Rel. Mater., 2(1993)898.

83. L. Rosado, V. K. Jain, H. K. Trivedi, Wear, 212 (1997)1.

84. J. F. Braza, Tribol. Trans., 35(1992)89.

85. J. F. Braza, and P. K. Pearson, ASTM Special Technical Publication Symposium on Creative Use of Bearing Steels Nov 6-8 1991 No. 1195 1993 San Diego, CA, , USA, pp. 49-60.

86. M.Uma Devi, and O. N. Mohanty, Surf. Coat. Technol., 107 (1998) 55.

87. D. W. Hetzner, ASTM Special Technical Publication Proceedings of the 1996 Symposium on Bearing Steels: Into the 21st Century, STP: 1327 1998 New Orleans, LA, , USA, pp. 471-495.

88. R. Ahmed and M. Hadfield, Wear, 220(1998)80.

89. R. Nieminen, P. Vuoristo, K. Niemi, T. Mantyla, and G. Barbezat, Wear, 212 (1997) 66.

90. H. Ishikawa, H. Ishii, and T. Uchida, J. Tribol., 113(1991)349.

91. S. H. Kim, L. M. Keer, and H. S. Cheng, Tribol. Trans., 33(1990)53.

Table 1. Rolling contact fatigue performance of uncoated, thin, and thick TiN coated bearing steels during tests in a three-ball-on-rod test machine (lubricant:MIL-L-7808, loading balls: 9.5 mm diameter 52100 steel, rotational velocity: 3600 rpm).

Bearing Material	**TiN Coating Thickness (μm)**	**Contact Pressure (GPa)**	**L_{10} Life ($X10^6$)**	**L_{50} Life ($X10^6$)**
440C	Uncoated	4.04	8.3	18.5
440C	Uncoated	5.42	3.7	9.1
TiN -coated 440C	0.24	4.04	94	230
TiN-coated 440C	0.24	5.42	11.7	24.1
TiN-coated 440C	0.87	4.04	28.9	51.2
TiN-coated 440C	0.87	5.42	7	18.7
TiN-coated 440C	2.2	4.04	54	140
TiN-coated 440C	2.2	5.42	0.4	5.8
BG-42	Uncoated	4.04	17.4	49
BG-42	Uncoated	5.42	13.7	29.9
TiN-coated BG42	0.24	4.04	No failures	No failures
TiN-coated BG42	0.24	5.42	16	31.1
TiN-coated BG42	0.87	4.04	No failures	No failures
TiN-coated BG42	0.87	5.42	48	106
TiN-coated BG42	2.2	4.04	50	115
TiN-coated BG42	2.2	5.42	6.9	18.5
M50	Uncoated	5.42	5	11
TiN-coated M50	0.38	5.42	8.1	23.1
TiN-coated M50	2.2	5.42	3.6	8.1