Conf-920439--6

ROLLING-CONTACT FATIGUE AND WEAR RESISTANCE OF HARD COATINGS ON BEARING-STEEL SUBSTRATES*

ANL/CP--74638

DE92 011834

Ali Erdemir
Tribology Section
Materials and Components Technology Division
Argonne National Laboratory
Argonne, IL 60439

Phone : (708) 252-6571
Fax : (708) 252-4798

February 1992

Invited paper for presentation at the 19th International Conference on Metallurgical Coatings and Thin Films, April 6-10, 1992, San Diego, CA

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

ROLLING-CONTACT AND WEAR RESISTANCE OF HARD COATINGS ON BEARING-STEEL SUBSTRATES

Ali Erdemir
Tribology Section
Materials and Components Technology Division
Argonne National Laboratory
Argonne, IL 60439

ABSTRACT

Ever-increasing needs for high-performance ball- and roller-bearing components that can endure extreme applications have led to a growing interest in hard coatings for improved fatigue life and wear resistance. In particular, hard TiN and TiC coatings and, quite recently, diamondlike carbon films have attracted much attention from manufacturers that produce bearing systems for both rolling- and sliding-contact applications. This paper presents an overview that highlights recent incremental progress in achieving improved fatigue and wear resistance in bearing steels through the use of hard coatings. Effects of coating adhesion, thickness, and morphology on fatigue and wear resistance of hard coatings are discussed in detail. Specific references are made to a few mechanistic models that correlate coating thickness and adhesion to improved fatigue life and wear resistance.

1. INTRODUCTION

Advanced bearing components (e.g., ball- and roller bearings, gears, traction drives, cams and tappets) contemplated for future transportation systems and advanced aircraft engines are required to operate under severe tribological and environmental constraints. High service temperatures, extreme contact pressures, and severe lubrication and harsh environmental conditions are some of the concerns that require better tribological designs, high-performance bearing materials, and effective lubrication methods [1-3]. One of the most common failure modes observed in current bearing components is the rolling-contact fatigue (RCF) often manifested by a spall or pit that forms on rolling surfaces after several million cycles of loading and unloading [4,5]. Recent studies suggest that spalling failures usually initiate from defects on or beneath the stressed surfaces [4,6]. Also possible is bearing degradation due to severe deformation [7], corrosion [8-10], and wear and scuffing [11,12].

Despite a large volume of research reported in the previous literature, the specific mechanism(s) of RCF and reliable life prediction models are lacking. This is thought to be due mainly to the complexity of the contact mechanics involved and the statistical nature of the eventual failures. However, it is generally accepted that when two solid bodies of curved shape are brought into contact, the maximum orthogonal shear stress is developed somewhere beneath the contact spots as illustrated in Fig.1. The depth of these stresses is dictated by the applied load and the elastic properties of the contacting bodies. Bamberger and Clark [13] reported a depth of 150 μm for AISI M50 steel when peak Hertz pressure is at 5.42 GPa. From this knowledge, it has been postulated that fatigue failures under cyclic loading should originate at depths where maximum shear stresses develop [14,15]. Dislocation entanglement around inclusions, second-phase precipitates, and other types of volume defects can cause microcrack initiation under repetitive loading [16,17]. Fig. 2 shows the shape and morphology of a typical fatigue spall.

The primary purpose of this paper is to provide an overview of the present state of the art in bearing-performance improvement achieved through the application of hard coatings. A brief description of the recent materials engineering methods used in structure and property improvements in bearing steels will be given first. This is followed by a detailed discussion of the recent progress made in the development of high-performance bearing components through the use of surface engineering approaches. Special emphasis is placed on hard TiN, TiC, and diamondlike carbon coatings applied on bearing-steel substrates by a variety of advanced deposition processes. In particular, the effects of coating adhesion and thickness on the fatigue life and wear resistance of hard coatings is discussed. A few references are made to those mechanistic models that correlate coating thickness and adhesion to improved fatigue life and wear resistance.

2. REVIEW OF MATERIALS ENGINEERING APPROACHES

To meet the high-performance bearing needs of advanced transportation systems, a number of materials engineering approaches have been proposed in previous years and pursued rather vigorously. The overall goal of these approaches has been to increase bearing performance by structural refinement and property enhancement.

For the structural refinement approach, a number of advanced melting practices (e.g., vacuum induction melting (VIM), vacuum arc-remelting (VAR), and electroslag remelting (ESR)) were developed and used extensively in past years [18,19]. As a result, both the number and size of volume defects (i.e., voids, inclusions, entrapped gas bubbles, and pinholes), that cause premature fatigue failures were reduced and significant improvements in bearing lifetime were obtained [20,21].

For mechanical-property enhancement, novel microalloying and heat treatment techniques were mostly used [22,23]. Alternatively, advanced powder metallurgical methods were employed to control the shape, size, and distribution of second-phase carbide particles within the structure. 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 [24,25].

Quite recently, efforts have focused on development of a new class of ultrahigh-strength steels for bearings and other engineering applications. Advanced computer models and theoretical approaches have been employed at atomic levels, and has been demonstrated that when the structure and chemistry of steels are controlled at such fine scales, one can achieve greatly improved mechanical strength and fracture toughness and hence better performance [26].

Incremental advances made through these materials engineering approaches have greatly improved both structure and propertyies, and thus the performance, of bearing steels in use today. In particular, those volume defects (i.e., voids, entrapped gas bubbles, and inclusions) responsible for premature fatigue failures were virtually eliminated. However, failures due to surface defects and/or deficiencies have continued to limit the useful lifetimes of bearing components. Surface defects, such as grinding furrows, nicks, seams, notches, and dents introduced during manufacturing and/or machining operations, as well as shallow pits due to progressive corrosion and wear damage, were found to promote fatigue failures [27]. 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 cause premature bearing failures [4,5,11].

3. REVIEW OF SURFACE ENGINEERING APPROACHES

From the foregoing, it is clear that higher-performance bearing components with prolonged lifetimes are quite feasible and can be achieved through reinforcement of such surface metallurgical characteristics as wear, corrosion, and friction. Accordingly, a variety of surface engineering approaches - including ion implantation, case carburizing/nitriding, and vapor-phase deposition techniques - were recently tried on bearing steel substrates. In a recent review article, Maurer has summarized the results of recent experimental work focused on RCF behavior of surface engineered bearing steels [3].

Mainly because of their excellent mechanical, chemical, and thermal properties, hard coatings (e.g., TiN, TiC, NbN, NbC, ZrN, HfN) have enjoyed much attention in recent years. Among others, TiN and TiC coatings have drawn the greatest industrial interest and have long been available for a variety of commercial applications. Currently, metal-forming and -cutting tools are routinely coated with one of these materials to enhance their service lives. Deposition methods used for hard coatings include ion plating, magnetron sputtering, cathodic-arc plating, ion-beam-assisted deposition (IBAD), and chemical vapor deposition (CVD). As is discussed in detail in the following sections, all of these deposition processes have been used on bearing-steel substrates.

3.1. Ion Implantation

Ion implantation has been used widely to improve the wear and corrosion resistance of a variety of bearing-steel substrates (e.g., M50, 440C, and 52100) [28,29]. Through implantation of certain active elements (B, C, N, P, Cr, Ti) [30-33], both the corrosion- and wear-resistance of these steels were markedly improved. Aerospace bearing components used in aircraft turbine engines and NASA-Space Shuttle applications are surface treated by ion implantation [34].

Over the last decade, attempts were also made to improve the fatigue lives of bearing steels by ion implantation [35,36]. However, in most cases, fatigue-life data were inconsistent and/or the extent of improvement was rather insignificant, especially under high rolling contact stresses. In a few instances, even a decrease was observed in the fatigue lives of some bearing steels (i.e., 440C and

AMS 5749) subjected to ion implantation [37].

3.2. Soft Surface Coatings

To achieve improved fatigue lives in bearing steels, a number of soft metallic coatings were applied to bearing-steel substrates and subjected to RCF tests. For example, Davis produced ion-plated Cr coatings of 440C bearing steels and specifically investigated the effect of coating thickness on RCF life [38]. He reported significant improvements in the fatigue life of 440C steel with film thicknesses of <0.3 µm. In another study, Averbach et al. [25] applied thin dense Cr coatings on M50-Nil bearing steel components and subjected them to RCF testing. The results showed that these coatings can afford significant improvements to the fatigue lives of bearing-steel components. Hochman et al. [39] evaluated the RCF behavior of 440C and AMS 5749 steel substrates with and without a 0.5 µm-thick Cu film. The fatigue life data from Cu plated AMS 5749 bearing steels were rather inconsistent; however, the data from Cu-plated 440C samples showed that an order-of-magnitude improvement in both the B10 and B50 lives is feasible. Note that the B10 and B50 are statistical values used in RCF studies to indicate the number of stress cycles below which 10% and 50%, respectively, of the test specimens will fail.

In the past, the potential usefulness of Ni and hard-Cr coatings was also evaluated on bearing-steel surfaces and discussed in a recent review paper by Maurer [3]. Ni coatings on M50 steel suffered from poor adhesion, and no improvement in fatigue life was observed. However, hard-Cr coatings increased the fatigue life of 52100 bearing-steel components by a factor of 2. Hard-Cr coatings are now applied to a variety of bearing-steel components and are available for commercial applications.

The beneficial effects of soft metallic coatings on the RCF life of bearing steel substrates is not well-understood. Especially, mechanistic modeling of the phenomenon is missing. For the excellent life-improving capability of Cu films on 440C steels, Hochman et al. speculated that because of its low shear strength, the Cu coating deforms easily to fill in the valleys between surface asperities. As a result, the load-bearing capacity of the contact surface is increased and the magnitude of microcontact stresses on asperities is decreased. A theoretical analysis of the effect of soft coatings on contact stress distribution over surface asperities by Merriman and Kannel has shown that the magnitude of stress concentrations at asperity levels is indeed substantially lowered when a soft coating is present on the rolling-contact surfaces [40].

After further examining the failure modes of uncoated and Cu-coated 440C steel samples used by Hochman et al [39], Kumar et al. [5] concluded that the life-extending capability of the Cu coating may have been due to its abilities to render surface defects less harmful and to dislocate crack-initiation sites from surface to subsurface. Failure analysis of fatigue spalls suggested that uncoated 440C bearing steels failed mostly through cracks emanating from surface defects, whereas the Cu-coated 440C samples appeared to fail through subsurface-initiated fatigue cracks.

3.3. Hard Surface Coatings

During the last decade, a number of studies have reported on the RCF behavior of hard coatings on bearing steel substrates. Especially, TiN, TiC, and, quite recently diamondlike carbon coatings have attracted increasing attention from manufacturers and end-users. As will be deduced from the following, the extent of fatigue life improvements was primarily dictated by the thickness and adherence of hard coatings. It was also found that the mechanical and structural characteristics of the base steels supporting these coatings are critical.

In an investigation reported in 1984, Dill et al. [41] evaluated the RCF behavior of double-layer coatings of TiC and CrC prepared by CVD as well as TiN coatings produced by sputter deposition on a number of bearing steel substrates. Samples with CVD coatings suffered chemical, structural, and mechanical degradation mainly because of the tempering of the substrates at the high deposition temperatures (e.g., 900 to 1000°C) of CVD process. Post heat-treatment and machining for structural and dimensional corrections were needed in most cases. Nevertheless, most of the refinished samples displayed wide variations in fatigue lives. Only the TiC-CrC double-layer-coated AISI M50 sample endured the high stress levels and exhibited some improvement in fatigue life. Rolling contact fatigue tests with a 1-μm-thick-TiN coating on AISI M50 produced by sputtering showed a significant improvement over the baseline.

In a series of papers published between 1985 and 1988, Hochman et al. [39], Thom et al. [42], and Erdemir and Hochman [43,44], as well as the Ph.D. thesis of Erdemir [45], presented the results of a systematic study focused on the RCF behavior of TiN-coated bearing steel substrates. The principal aim of these studies was to improve the RCF performance of 440C bearing steel components for use in the cryogenic turbopump bearing applications of the NASA-Space Shuttle main engines. Because under the harsh application conditions of the Shuttle engines, bearing degradation had occured at or near the operating surfaces under the concurrent actions of wear, corrosion, and fatigue. It was proposed that TiN coatings with controlled structure and adequate bonding should impart improved wear and corrosion resistance and RCF life to 440C bearing steel. Later, the research was expanded to include AISI M50 and AMS 5749 bearing steels to determine their potentials as alternative substrates for TiN coatings. These steels also provided a basis for comparison of the 440C test results.

Coatings with a wide range of thicknesses (i.e., 0.24 to 2.4 μm) were produced on bearing steel substrates by ion-plating and magnetron sputtering. Tests were conducted on a three-ball-on-rod fatigue tester at 4.04 and 5.42 GPa maximum-Hertz stresses. Test results showed that the thickness of the TiN coatings has a profound effect on RCF life. As illustrated in Figs. 3 and 4, thinner TiN coatings (less than 1 μm thick) were generally able to improve B10 and B50 RCF lives of base steels substantially at the both 4.04 and 5.42 GPa stress levels. As evident from a scanning electron micrograph in Fig. 5, these coatings remained intact on the rolling-contact surfaces. However, the thicker TiN coatings (above 2 μm) were effective only at 4.04 GPa as shown in Fig. 3. When tested at 5.42 GPa, they suffered severe fracture and delamination (see Fig. 6). As a result, B10 and B50 fatigue lives of substrate steels were significantly shortened. Through microscopic examination, it was found that thicker coatings remained intact on the rolling tracks when tested at 4.04 GPa. This was mainly due to minimal plastic deformation of the film/substrate system at this stress; thus film fracture and detachment did not readily occur.

Recently, Cheng et al. [46] and Chang et al. [47,48] at Northwestern University 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 high-rate reactive sputtering at temperatures below 200°C. In these studies, particular emphasis was placed on ascertaining the effect of TiN film thickness on RCF life of rollers. Fatigue test results were combined with electron microscopy observations to reveal the fundamental mechanism of fatigue failure initiation in the TiN-coated bearing steels. It was anticipated that by understanding the failure mechanism of coated bearings, analytical models enabling RCF life predictions can eventually be developed.

In general, their test results were consistent with the earlier findings of Erdemir and Hochman [43,44]. TiN coatings of 0.25 to 1 μm have substantially improved the RCF life of bearing steel substrates and remained largely intact. TiN coatings of 0.25 μm lasted more than 60 million cycles and gave the best fatigue life improvement. Thicker coatings (2.5 to 5 μm), however, peeled off rather quickly and shortened of 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 specimens was about 10 million cycles.

In a recent investigation, Middleton et al. [49] reported a nearly fourfold improvement in the B50 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. This contradicts the findings of Erdemir and Hochman [43,44], and Chang et al. [47,48]. However, it is important to realize that in each of the studies, the coating processes and coated substrates were different. Disparity in RCF test results could have been due to the differences in substrate materials and/or deposition processes.

Diamondlike carbon (DLC) coatings have lately attracted increasing attention for a variety of tribological applications. Tribological tests by several investigators confirm that these films are extremely wear-resistant and provide very low friction coefficients, especially in dry and inert environments [50,51]. Because of such excellent prospects for bearing applications, Wei et al. [52] recently investigated the effect of 0.5- to 1-μm-thick-DLC coatings on the RCF behavior of M50 bearing steels at the very high Hertzian stress level of 5.5 GPa. They observed that 1-μm-thick DLC coatings delaminated, but that a 0.5 μm-thick DLC coating remained largely intact and in some instances improved the B50 fatigue life of M50 substrate by factors of up to 10.

Recently, Braza [53] investigated the RCF performance of nitrocarburized AISI M50 steels. In all cases, a compound layer and a diffusion layer formed on the outer surfaces. He found that for compound-layer thicknesses of <1 μm, both the B10 and B50 lives were improved, in some cases by factors of up to 6 over the untreated

M50 steel. Thicker compound layers (e.g., ≥ 2 µm) tended to spall off and shorten the RCF life. It is interesting to note that these findings are consistent with those of the previous investigators, despite the use of different surface treatment methods and/or coatings in each study.

In a study by Katsov et al. [54], it was shown that 5- to 7-µm-thick TiN coatings can significantly improve the RCF life (2 to 4 time over baseline) of bearing steel substrates. This contradicts the RCF test results presented above. It is possible that their test conditions were not as severe as those of the previous investigators. As demonstrated by Erdemir and Hochman [43,44], under milder contact stresses where plastic deformation of underlying substrate is minimal, insignificant, thicker coatings can also provide improved fatigue life to the substrates.

Using the finite-element method (FEM), Ishikawa et al. [55] 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.

4. MECHANISTIC MODELS AND INTERPRETATIONS

From the RCF test data presented above, it is clear that hard coatings have the potential to substantially improve the fatigue life of bearing steel substrates. RCF test results from several research laboratories have independently confirmed that thinner hard coatings remain largely intact on rolling-contact surfaces and usually extend the RCF life of bearing steel substrates. However, the thicker coatings tended to fracture and delaminate, reducing the RCF life of substrate steels, especially when contact pressures are high. Under lower contact pressures, some of the thicker hard coatings were able to remain intact and extend the fatigue lives of bearing steels. In short, for these coatings to have any beneficial effect on the RCF life of a bearing steel, it is important that they remain intact on the rolling contact surfaces.

A mechanistic understanding of the beneficial effects of thin coatings and detrimental effect of thick coatings on RCF behavior of bearing steel substrates is thought to 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 and harder than the underlying substrates.

Based on phenomenological observations, Erdemir and Hochman [43,44] proposed that thinner TiN coatings, i.e., 0.24 and 0.87 µm thick, can easily fit and follow the deformation contours of the softer substrates that undergo repetitive loading/unloading. As evident from Fig. 5, despite some detachment along the original surface scratches, the thinner TiN coatings remain largely intact throughout the 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. 6). 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 stress 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. [46] and Chang et al. [47,48] proposed that these coatings can effectively minimize the extent of plastic deformation of asperity contacts by reducing simply the size of the stress field. Using scanning and transmission electron microscopies, 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 argue that extensive microcracking in uncoated samples was mostly due to extensive interactions between opposing asperities during rolling contact occuring in an elasto-hydrodynamic lubrication regime. Apperently, such interactions can cause severe microstressing of the regions beneath the asperity contacts and this can eventually initiate microcracks and cause surface distress.

The mechanistic explanation above was consistent with the FEM analyses of Ishikawa et al. [55], Komvopoulos et al. [56] and Komvopoulos [57], who evaluated the state of von Mises stresses across the hard coatings and coating-substrate interfaces. In their analysis, Komvopoulos et al. demonstrated that an 0.8-μm- thick TiN coating could eliminate yielding at and below the coating/substrate interface for the conditions they evaluated.

For interpretation of premature failure of thick coatings during rolling contacts, Chang et al. [48] used an analytical model proposed by Kim et al. [58]. This model evaluates the effect of concentrated contacts on thin layers having perfect bonding to an elastic half-space. 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.

SUMMARY AND FUTURE DIRECTIONS

This overview demonstrates that hard coatings have much to offer for future bearing applications. The results of previous investigations suggest that depending on application conditions and environmental constraints, wear, corrosion, and micropitting may in the future be the dominant modes of failure that limit the lifetime of bearing-steel substrates. Existing data suggest that with proper surface engineering, bearing-steel substrates may live up to their expectations. Hard coatings and other forms of surface engineering practices (i.e., ion implantation, case carburizing, and/or nitriding) can effectively prolong the fatigue lives of bearing steel substrates. Strong adhesion is essential for achieving long endurance life in hard coatings subject to rolling-contact fatigue (RCF). Advanced surface engineering processes such as magnetron sputtering, ion plating, and ion-beam-assisted deposition can impart adequate adhesion between hard coatings and bearing steel substrates. Nitrocarburizing is also feasible and appears promising for large-scale bearing applications. Initial test results from diamondlike-carbon-coated bearing steels are encouraging.

The thickness and adhesion of hard coatings play the most important roles in RCF life. To achieve improved lifetimes, coatings must remain intact on the rolling contact surfaces. Thinner hard coatings, 0.2 to 1 µm thick, 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).

In recent years, a few mechanistic models have been developed to interpret 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 are urgently needed to address the critical relationship(s) between fatigue life and thickness of hard coatings. 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-steel industry, new coating systems with increased overall capacity and quick turnaround time must be developed. Effective quality control tools and/or techniques must be placed in the production line 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. The author wishes to thank Mr. R. Thom of the NASA Marshall Space Flight Center for financial support during the author's Ph.D. studies at the Georgia Institute of Technology.

REFERENCES

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

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

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

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

5. 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.

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

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

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

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

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

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

12. T. E. Tallian, J. Trib., 104(1982)336.

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

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

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

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

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

18. R. Schlatter, Industrial Heating, 41(1974)40.

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

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

21. E. V. Zaretsky, NASA TM-88881, NASA Lewis Research Center, Cleveland, OH, 1986.

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

23. R. J. Parker, NASA Conference Publication 2210, 1983, p. 40.

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

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

26. G. B. Olson, Innovations in Ultrahigh-Strength Steel Technology, Eds. G. B. Olson, M Azrin, and E. s. Wright, 34th Sagamore Army Materials Research Conf. Proc. 1990, pp 3-66.

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

28. D. M. Follstaedt, J. A. Knapp, and L. E. Pope, Proc. MRS Symp., 140 (1989) 133.

29. Y. F. Wang, C. R. Clayton, G. K. Hubler, W. H. Lucke, and J. K. Hirvonen, Thin Solid Films, 63(1979)11.

30. M. Hirano, and S. Miyake, J. Tribol. 107(1985) 467.

31. J. Sasaki, M. Iwaki, Proc. MRS Symp., 104 (1989) 159.

32. I. L. Singer, C. A. Carosella, and. J. R. Reed Nucl. Inst. Meth, 182/183(1981)920.

33. F. A. Smidt, Nucl. Inst. Meth. B10/11(1985) 532.

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

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

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

37. 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.

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

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

40. T. Merriman and J. Kannel, J. Tribol., 11(1989)87.

41. 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.

42. 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.

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

44. 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.

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

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

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

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

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

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

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

52. R. Wei, P. J. Wilbur, and F. M. Kustas, ASME Preprint No. 91-Trib-63, 1991.

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

54. K. B. Katsov, V. N. Zhitomirskii, and R. A. Khrunik, Soviet Materials Science (Fiziko-Khimicheskaya Mekhanika Materialov) 22(1986)534.

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

56. K. Komvopoulos, N. Saka, and N. P. Suh, J. Tribol. 109(1987)223.

57. K. Komvopoulos, J. Tribol., 110(1988)477.

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

FIGURE CAPTIONS

Fig. 1. Schematic illustration of stress distribution at a typical point contact.

Fig. 2. Shape and crack morphology of a typical fatigue spall.

Fig. 3. Effect of TiN film thickness on (a) B10 and (b) B50 life of 440C test samples. (Test Conditions: Hertzian stress, 4.04 and 5.42 GPa; rotational speed, 3600 r/min; lubricant, MIL-L-7808; test balls, AFBMA grade 10 52100 steel).

Fig. 4. Rolling contact fatigue performance of TiN-coated and uncoated M50 at 5.42 GPa Hertzian stress.

Fig. 5. (a) Secondary and (b) back-scattered electron images of rolling track formed on 440C test sample coated with 0.87-μm-thick TiN coating.

Fig.6. (a) Secondary and (b) back-scattered electron images of rolling track and fatigue spall formed on AMS 5749 sample coated with 2.2-μm-thick TiN coating.

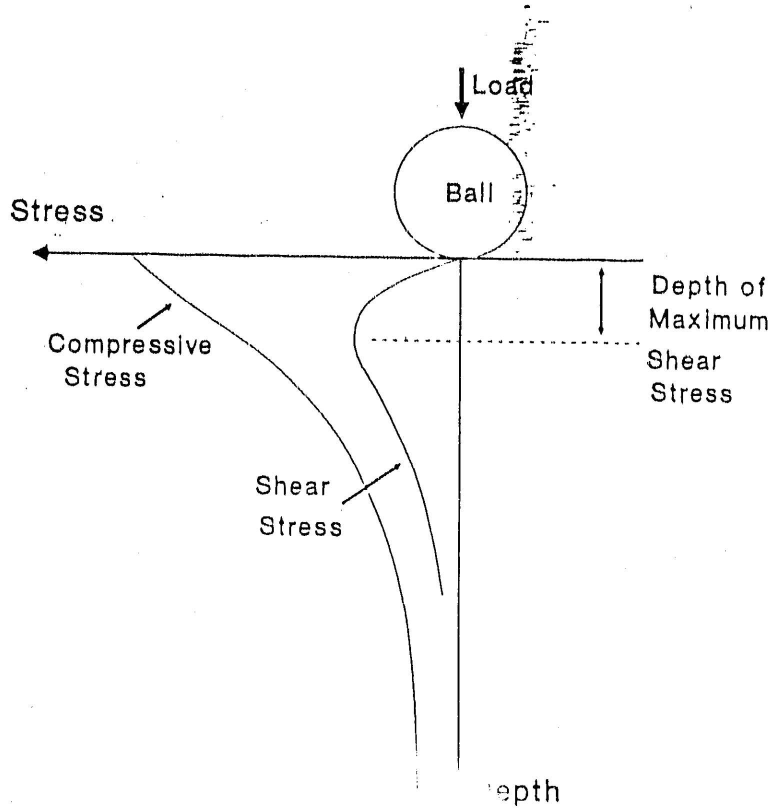


Fig. 1. Schematic illustration of stress distribution at a typical point contact.

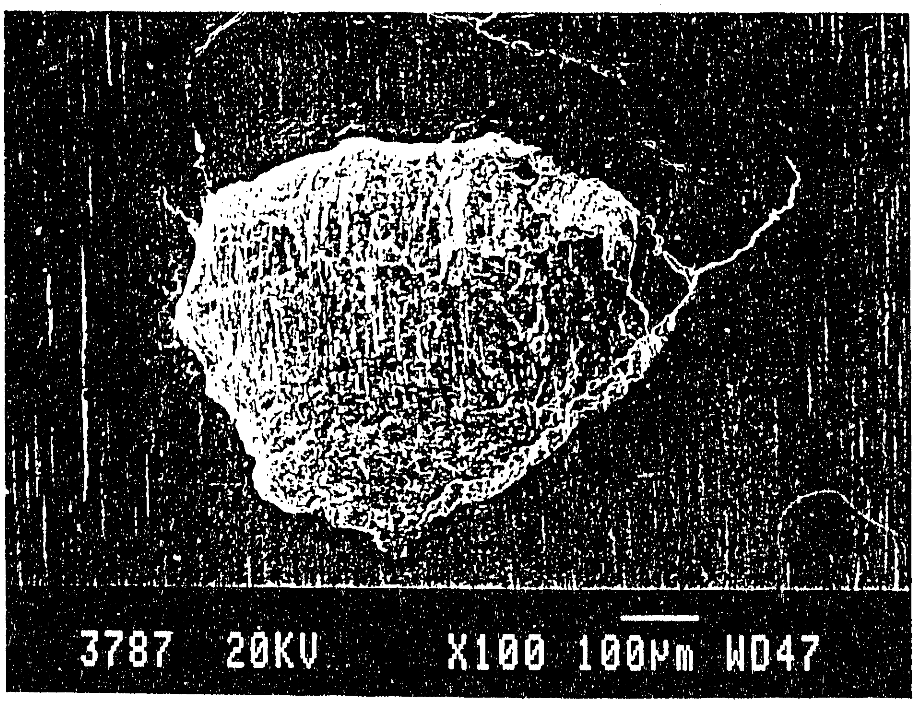
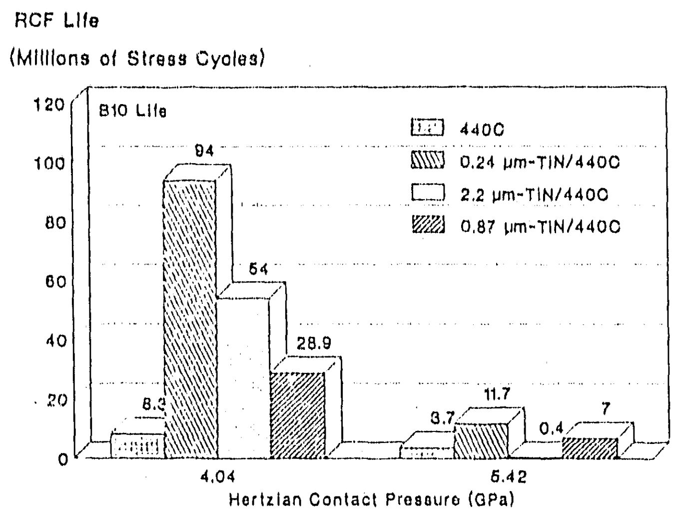
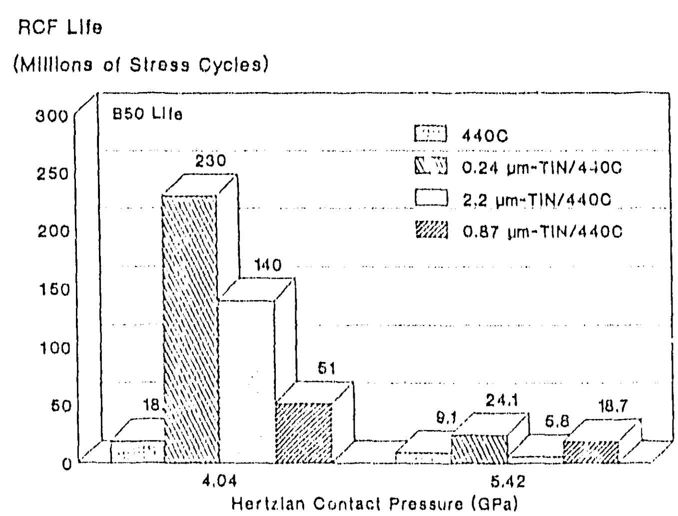


Fig. 2. Shape and crack morphology of a typical fatigue spall.



a



b

Fig. 3. Effect of TiN film thickness on (a) B10 and (b) B50 life of 440C test samples. (Test Conditions: Hertzian stress, 4.04 and 5.42 GPa; rotational speed, 3600 r/min; lubricant, MIL-L-7808; test balls, AFBMA grade 10 52100 steel).

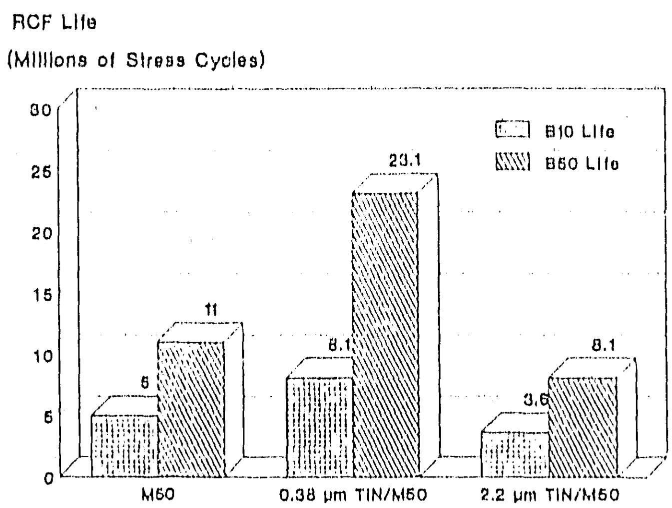
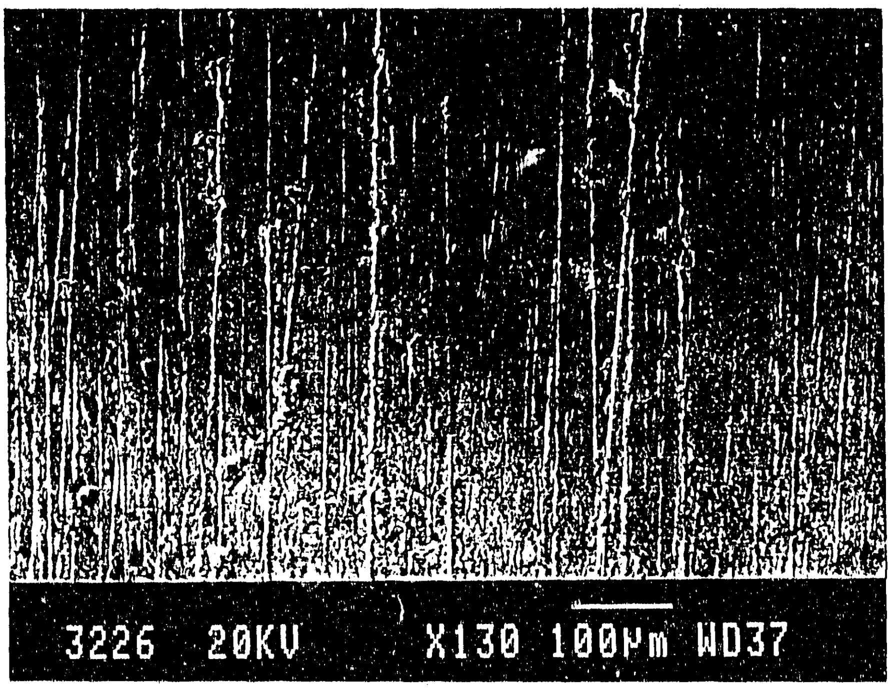
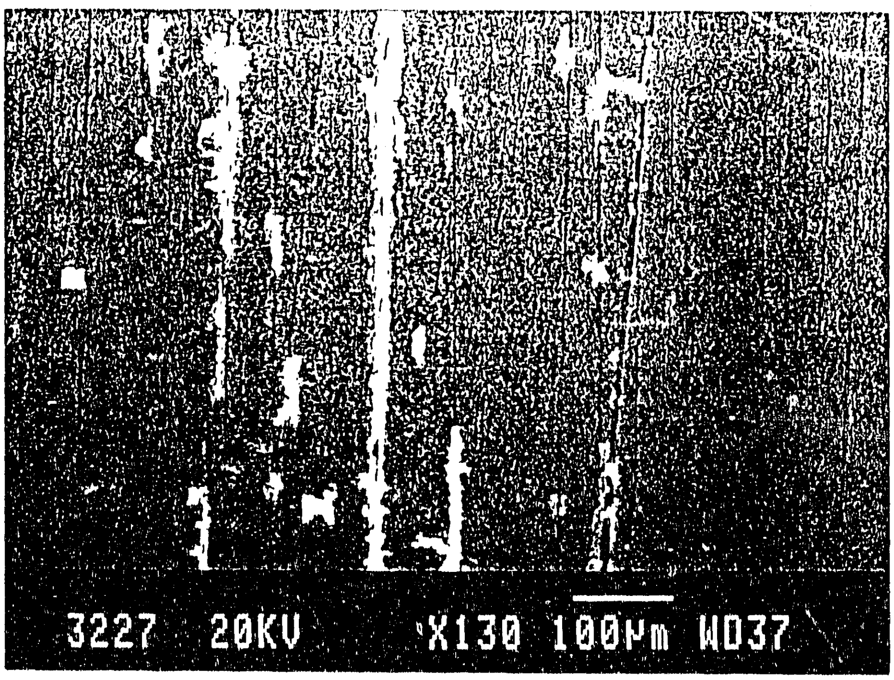


Fig. 4. Rolling contact fatigue performance of TiN-coated and uncoated M50 at 5.42 GPa Hertzian stress.



a



b

Fig. 5. (a) Secondary and (b) back-scattered electron images of rolling track formed on 440C test sample coated with 0.87-μm-thick TiN coating.

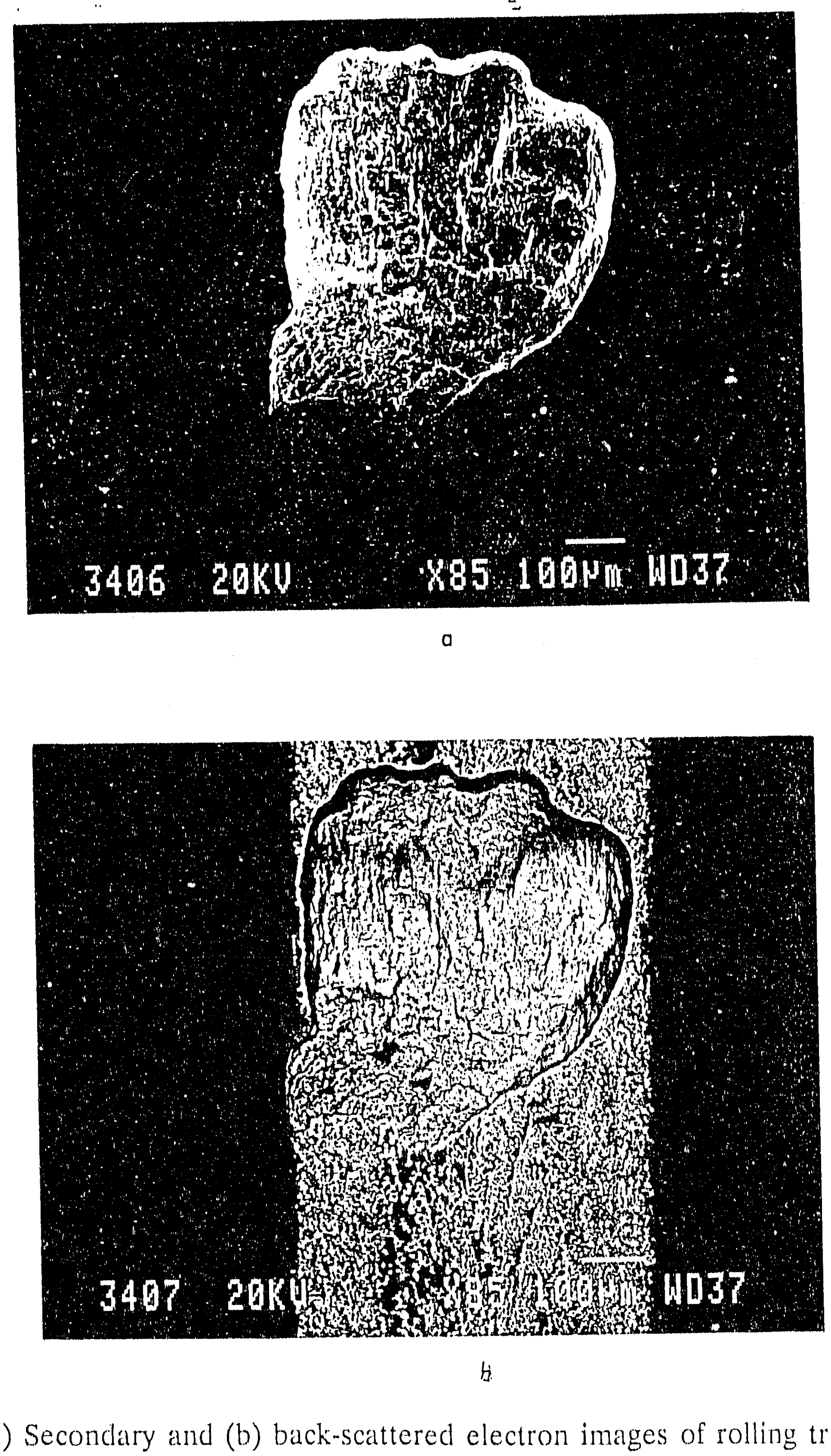


Fig.6. (a) Secondary and (b) back-scattered electron images of rolling track and fatigue spall formed on M50 sample coated with 2.2-μm-thick TiN coating.

END

DATE
FILMED
6/11/92