



Effect of deposition method on the RCF performance of Cr_xN thin film ball coatings

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ABSTRACT

Cr_xN thin films are of interest due to their wear and corrosion-resistant attributes. However, the tribological and functional performance of these coatings greatly depends upon their material properties and deposition processes. In this study, the tribological and functional performance of Cr_xN coatings on AISI 52100 spherical rolling elements were evaluated. Two types of deposition processes were used to apply the coatings: a closed-field unbalanced magnetron sputtering system (CFUMS) and an ion beam assisted e-beam deposition (IBAD) system. Whereas the mechanical and compositional properties of the coatings obtained from the two deposition processes were found to be similar, the topographical and microstructural properties of the coatings differed. The tribological performance of the coated specimens was evaluated under boundary layer lubrication in a rolling (three ball-on-rod) contact tribometer, and the functional performance of these coatings on spherical rolling elements was examined in thrust ball bearings. The L_{50} fatigue life of M50 rods paired with IBAD-coated balls was four times greater than that obtained with the 52100 balls. Significantly, the L_{50} fatigue life of the M50 rods paired with the IBAD-coated balls was comparable to the fatigue life of M50 rods when paired with high-quality ceramic (Si_3N_4) balls. Finally, bearings with IBAD-coated balls were observed to operate with lower torque than those with CFUMS-coated balls.

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1. Introduction

Surface engineering is a method used to address the issues of friction, wear and corrosion [1]. Over time, many new and novel coatings have been developed to overcome the challenges faced in automotive, manufacturing and tribological applications involving components like engine parts, cutting tools, bearings and gears, to name a few [2]. Rolling element bearings are considered one of the most vital components in a mechanical system, and their durability can be enhanced by surface engineering methods [3]. Several types of coatings have been developed over time to address issues faced by rolling element bearings operating under boundary lubricated conditions [4,5].

Coatings created for rolling element bearing applications can be classified according to hardness (H) as soft, intermediate and hard, where $H < 10$, $10 < H < 15$ and $H > 15$ GPa, respectively. Soft coatings such as Ti containing MoS_2 have shown promise as candidates for rolling contact applications in dry, vacuum and boundary lubricated conditions [6–8]. Carbon- or hydrocarbon-based soft and intermediate coatings such as TiC/a-C , TiC/a-C:H and WC/a-C:H are used in bearings to mitigate severe wear modes under boundary lubrication conditions

[2,5,9,10]. Titanium-based hard nitride (TiN) and carbide (TiC) coatings have been developed for cutting tools and rolling contact applications, respectively [4,11–14]. However, all these coatings have been evaluated primarily through tribological testing procedures performed on flat and/or near-flat surfaces. Fewer studies have evaluated coatings on balls under rolling contact [3,15,16].

While hard coatings are being evaluated for rolling element bearing applications, ceramics are also under consideration as an alternative material for rolling elements [17]. Bearings employing ceramic balls and steel raceways are known as “hybrid” bearings. Hadfield et al. reported that low fracture toughness coupled with defects such as voids, inclusions, machining or polishing damages and cracks are detrimental to the performance of ceramic balls [18]. Nevertheless, through advanced ceramic processing techniques, hybrid bearings are now being employed in critical applications because of advantages over all-steel bearings such as higher stiffness and higher hot hardness [19]. In ultra-low speed applications such as in spacecraft instruments, it was reported that the energy required to reverse the velocity of a hybrid bearing is much higher than that for an all-steel bearing [20]. Recently, Mosleh et al. reported a reduction in fatigue life of 52100 and M50 steel raceways when mated with ceramic instead of steel balls, even though the torque of the hybrid bearings was lower than the all-steel bearings [21].

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It is envisioned that hard nitride and carbide coatings on steel balls can be potential alternatives to ceramics for precision ball bearing applications. Although hard coatings are being offered commercially for niche ball bearing applications (e.g., TiC), only a few papers have been published concerning the deposition of hard coatings on spherical rolling elements and characterization of the coatings for their tribological performance in rolling contact. For example, Hintermann [12,13] and others [11,14] coated precision balls for gyroscope applications with TiC using a CVD process, followed by a post-deposition heat treatment step and polishing. On the other hand, TiN coatings have not shown much promise for rolling contact fatigue applications [4,22]. However, the appreciable mechanical, tribological, thermal, chemical and corrosion resistance properties of chromium nitride (Cr_xN) may make it an attractive alternative to TiN coatings [23,24]. Therefore, Cr_xN coatings have been studied as a viable substitute to TiN coatings for automotive [25,26], manufacturing [27–31] and tribological [22, 32–41] applications.

Although Cr_xN coatings are being pursued for tribological applications, there are only a few reports available elucidating the performance of Cr_xN coated balls under rolling contact. For example, cathodic arc deposition and thermo-reactive diffusion methods were used by Fuentes et al. [42] and Sen [43], respectively, to deposit chromium-based carbonitride or carbide coatings onto balls that were evaluated in sliding contact. Cr_2N coatings were deposited onto spherical rolling elements and tested for performance under oil-starved conditions by Eichler et al. [40], who reported that the coating improved the L_{50} life of the bearings. However, due to the larger roughness of the coated balls relative to the uncoated balls, a polishing cycle was necessary to reduce the surface roughness. Drory and Evans [39] deposited a smoother Cr_xN coating onto precision balls using ion beam assisted e-beam deposition and evaluated the performance of thrust bearings in lubricated conditions, but observed no significant changes in torque and temperature trends when compared to the uncoated bearings.

The purpose of this study is to evaluate Cr_xN coatings as a viable alternative to titanium carbide (TiC) and/or ceramic (Si_3N_4) balls for rolling bearing applications. Coatings were deposited onto balls by two different PVD processes and their performance was evaluated under rolling contact. A three ball-on-rod RCF tribometer was used to evaluate the ability of the coatings to enhance the L_{50} life of the M50 rods. Furthermore, the effect of the coatings on the performance of the bearings under normal operation, debris-damaged and oil-starved conditions was evaluated in a thrust-bearing tester.

2. Experimental details

2.1. Deposition

Physical vapor deposition (PVD) methods are used extensively to synthesize coatings because of their overall advantages over other methods [5]. Sputtering and evaporation employ kinetic and thermal energies, respectively, to synthesize coatings [44]. Cr_xN coatings in this study were deposited on the balls using both a closed-field unbalanced magnetron sputtering (CFUMS) [45] and an ion-assisted e-beam evaporation deposition (IBAD) system [39,44]. The Cr_xN coating was deposited in the respective systems onto AISI 52100 steel balls of 12.7 mm (1/2 in.) and 11.125 mm (7/16 in.) diameter (ABMA Grade 25) with an average roughness (R_a) of $0.015 \pm 0.005 \mu\text{m}$. Prior to deposition, the specimens were degreased in a solvent followed by ultrasonic cleaning in hexane and isopropanol (IPA), and dried in compressed air. The specimens were further cleaned with IPA, placed in the CFUMS deposition chamber, and immediately mounted on small magnets on a substrate holder with three-axis rotation.

In the IBAD process, the balls were immediately placed on a proprietary substrate manipulation system in the deposition chamber. To ensure strong adhesion to the steel substrates, Cr interfacial bond layers (Layer 1) were used for both coatings. Chromium (99.95%) was

sputtered (4 targets – CFUMS) and evaporated (pellets – IBAD) in the presence of Ar and/or N_2 to synthesize the Cr_xN coatings onto the balls (Layer 2). In CFUMS, Ar was used in Layer 1, and Ar + N_2 in Layer 2, whereas in IBAD Ar was used in Layer 1 and N_2 in Layer 2. N_2 was supplied to the substrate in IBAD Layer 2 by means of an ion source (60 W @ 200 V). The deposition parameters used for the Cr_xN coatings are displayed in Table 1.

2.2. Characterization

Thickness measurements were made non-destructively on the balls using x-ray fluorescence (XRF – Fischerscope X-ray XDAL) [46]. Adhesion of the deposited coatings to the balls was determined qualitatively per VDI 3198 guidelines using a Rockwell C indenter [47]. 3D optical interferometry (Zygo New View 7300) was used to quantify the surface topography of the coated specimens prior and subsequent to testing. This instrument was also used to map the debris dents on the raceways of the bearings before and after testing. A JEOL JSM 5310 scanning electron microscope (SEM) equipped with energy dispersive x-ray spectroscopy (EDS) was used to determine the composition of the coatings. At least three measurements were made on the balls for all characterization methods, and average values are reported here.

2.3. Tribological tests

2.3.1. Rolling contact fatigue (RCF) tests

Rolling contact fatigue tests were conducted with uncoated M50 rods and uncoated/coated 12.7 mm diameter 52100 balls in a three ball-on-rod RCF tribometer at 5.0 GPa contact stress. The tribometer used three different test heads in parallel to quantify the L_{50} life of the M50 rods against the uncoated and coated balls. Experiments were randomized and distributed over the three heads and a minimum of five data points was obtained for each coating. The standard operating procedure of the tribometer, including load and fatigue cycles calculations, was described by Glover [48].

Balls in the RCF test do not precess, so the coated balls were placed in such a way that the uncoated spots on the balls (deposited in CFUMS) did not come into contact with the cups or rod. Baseline experiments (52100 steel balls vs. M50 rod in neat oil) were performed, followed by the testing of the coated balls. A minimum of five tests was conducted for each coating; for each test, a new spot on the M50 rod was used with the untested coated balls.

2.3.2. Thrust bearing tests

Thrust bearing tests were conducted to evaluate the influence of the coated balls on the performance of the bearing under normal, debris-damaged and oil-starved conditions at a contact stress of ≈ 1.0 GPa. Heavy-duty single-row thrust ball bearings (51306), with a dynamic load rating of 43 kN and made of AISI 52100 steel, were sourced commercially. A full complement of 12 balls was used in all the experiments to eliminate tribological contributions arising from the steel retainers [40]. Bearing raceways and balls were cleaned with IPA to remove any packaging oil. The lower and upper raceways were pressed into the stationary and rotating chucks, respectively. The coated or uncoated

Table 1
CFUMS and IBAD deposition parameters used in this study.

Parameters	CFUMS	IBAD
Base pressure (torr)	2×10^{-6}	3×10^{-6}
Working pressure (layers 1 and 2)	2×10^{-3}	5×10^{-4}
Cr power/deposition rate (layer 1/layer 2)	3 kW/3 kW	0.1 Å/s/0.3 Å/s
N_2 flow rate (sccm)	23 (layer 2)	20 (layer 2)
Ar flow rate (sccm)	50 (layers 1 and 2)	20 (layer 1)
Substrate bias voltage (V)	75 (layers 1 and 2)	600 (layers 1 and 2)
Layer 1 thickness (nm)	100	100
Layer 2 thickness (nm)	1400	300

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