Surface & Coatings Technology 284 (2015) 302–309

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Deposition, characterization, and performance of tribological coatings on spherical rolling elements

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ARTICLE INFO

Article history:
Received 22 April 2015
Revised 1 June 2015
Accepted in revised form 1 June 2015
Available online 21 July 2015

Keywords:
PVD
Ball coatings
Cr_xN
Ti–MoS_2
DLC
Rolling contact fatigue

ABSTRACT

Increasing demands on the performance of intricate parts like bearings in biomedical and aerospace systems have created the necessity for tribological coatings that can enable systems to achieve enhanced performance in challenging environments. In this work, we have developed a process to deposit wear-resistant (Cr_xN, WC/a-C:H, TiC/a-C) and solid lubricant (Ti–MoS_2) coatings onto spherical rolling elements. The tribological performance of coated specimens has been evaluated under boundary layer lubrication in rolling and sliding contact tribometers. Although all of the coatings are wear-resistant under sliding contact, only Ti–MoS_2 coated balls provide a significant improvement over uncoated balls in rolling contact fatigue experiments. Specifically, in rolling contact fatigue experiments performed using M50 steel rods, Ti–MoS_2 coated balls improved L_{50} life by more than two times over uncoated balls. Ti–MoS_2 appears to be a promising candidate for rolling bearing applications in both lubricated and unlubricated conditions.

1. Introduction

Costs due to friction and wear losses in mechanical systems are cited to represent a significant percentage of the global economy [1,2]. Liquid lubrication, the well-established method of reducing friction and wear, involves interposing a fluid film between the contacting surfaces of a component [3]. Lubricated contacts are classified as boundary ($\lambda < 1$), mixed ($1 < \lambda < 3$) or hydrodynamic ($\lambda > 3$) regimes depending upon the lambda (λ) value, which is the ratio of the minimum film thickness to the composite roughness value of the surfaces in contact [4]. For mechanical systems, boundary lubrication is the most typical regime, where significant asperity contact takes place that can be detrimental to the surfaces in contact [5,6]. Demands to improve the performance of mechanical components operating under boundary lubrication have necessitated the development of highly engineered coatings and surface treatments because conventional lubrication practices cannot address many of the damage modes [7,8].

Rolling element bearings are vital and widely used components in mechanical systems ranging from small microelectromechanical systems (MEMS) to gigantic wind turbines. Material fatigue damage attributable to subsurface stress concentrations arising from nonmetallic impurities, and surface stress concentrations due to rough and poorly profiled raceways, is of lesser concern today due to advanced steel making and bearing manufacturing practices. According to Tallian [9] and others [10,11], wear mechanisms – not fatigue – are the leading causes of premature failures of rolling element bearings.

In an attempt to address the most significant wear issues faced by rolling element bearings operating in boundary layer lubrication, hybrid bearings, which employ ceramic balls and steel raceways, are sometimes used. However, hybrid bearings are employed mostly in critical applications because of their high cost [5]. In order to improve the performance of rolling element bearings, several types of coatings have been developed but few, if any, have been implemented to improve the tribological performance of ball bearings. The most widely studied tribological coatings for steel ball bearing applications are metal doped diamond-like carbons (DLC), metal nitrides and dichalcogenides [8,12–16] due to their mechanical and tribological properties — high hardness, wear and corrosion resistance, and lubricity. Nevertheless, these coatings have been evaluated primarily through tribological testing procedures performed on flat and/or near-flat surfaces.

Despite the fact that they are being used in several niche ball bearing applications, only a few papers have been published concerning the deposition of coatings on spherical rolling elements and characterization of the coatings for their tribological performance in rolling contact. However, there are several noteworthy publications discussing the tribological performance of coatings on balls. For example, Savan et al. [5] and Hintermann [17,18] coated precision balls for gyroscope applications with TiC using a CVD process, followed by a post-deposition heat treatment step and polishing. Danyluk and Dhingra [19] deposited

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http://dx.doi.org/10.1016/j.surfcoat.2015.06.075

silver coatings using a UHV evaporation technique and observed that the depletion and delamination of the silver coating from the balls caused early failures when tested for rolling contact fatigue (RCF) performance in vacuum. Wear-resistant WC/a-C:H and Cr_2N coatings were deposited onto spherical rolling elements and tested for performance under oil starvation conditions by Eichler et al. [20], who reported that the coatings improved the L_{50} life of the bearings. Drory and Evans [21] deposited a Cr_xN coating onto precision balls with ion-assisted e-beam deposition and evaluated the performance of a thrust bearing in lubricated conditions, but observed no significant changes in the torque and temperature trends when compared to the uncoated bearings.

In this work, coatings were deposited onto spherical rolling elements in a closed-field unbalanced magnetron sputtering system (CFUMS) and their mechanical, compositional and microstructural properties were examined. The tribological performance of the deposited coatings under boundary lubrication in rolling and sliding contact tribometers was also evaluated.

2. Experimental details

2.1. Selection of coatings

A wide range of coatings has been developed over the last 50 years to address issues of friction and wear in mechanical systems [14]. Among these, nanocomposite metal carbide-reinforced amorphous carbon (MC/a-C) or hydrocarbon (MC/a-C:H) coatings have been very successful at mitigating several wear modes encountered by roller bearings [7]. Although different versions of these coatings are currently being used in applications, tungsten carbide-reinforced amorphous hydrocarbon (WC/a-C:H) and titanium carbide amorphous carbon (TiC/a-C) are successfully being employed to address the various wear issues of roller bearings [7,20,22–26]. Since these two coatings are known to enhance the performance of roller bearings in boundary lubrication, they are both included in this study. Another well-explored family of coatings in this study is metal nitrides; e.g., TiN and Cr_xN. These coatings are primarily used for cutting tool applications due to their appreciable mechanical properties [27]. However, since its wear properties and corrosion resistance lead Cr_xN to show promise for tribological applications as well [16,20,21,25,28–30], a Cr_xN coating is also included for evaluation in this work.

Additionally, since the selected metal doped carbides and nitride coatings are hard coatings, a soft coating has been included for study. It is evident from the literature that MoS_2-based coatings are tribologically attractive due to their lubrication properties under dry and vacuum conditions [31,32]. The properties of MoS_2 are further improved by doping the coatings with different metals and/or oxides [33–35]. Singh et al. [36,37] reported that titanium-doped, sputter-deposited MoS_2 (Ti–MoS_2) has friction and wear mitigating abilities under both humid and vacuum environments. Although the performance of metal-doped MoS_2 coatings under lubricated conditions has not previously been reported, a Ti–MoS_2 coating is also included in this study. The mechanical, compositional and microstructural properties of the selected coatings reported in the literature are summarized in Table 1.

2.2. Deposition of coatings

Thin film coatings were deposited onto AISI 52100 steel substrates in a closed-field unbalanced magnetron sputtering system (CFUMS), a description of which can be found elsewhere [42,43]. Substrates included 12.7 mm diameter balls (ABMA Grade 25), 50 mm diameter discs and 10 mm diameter discs with an average roughness (R_a) of 0.01–0.02 μm, 0.2 μm and 0.01 μm, respectively. Although the CFUMS system is capable of accommodating several hundred balls in each batch, coatings were deposited onto the substrates in batches of fewer than 100 (12.7 mm diameter balls) for testing on a laboratory scale.

Prior to deposition the substrates were degreased in a solvent, followed by ultrasonic cleaning in hexane and isopropanol (IPA) and then dried in compressed air. The specimens were further cleaned with IPA and immediately mounted on a substrate holder with three-axis rotation in the CFUMS deposition chamber. Balls and discs were mounted on small magnets except the 50 mm diameter discs, which were mounted via screws to a plate fixture.

Once the samples were loaded into the deposition system, the chamber was pumped to a base pressure of 1.33×10^{-4} Pa (1×10^{-6} Torr) followed by sputter etching to remove residual contaminants and oxides from the substrate surfaces. Sputter etching was achieved by using DC power with a pulse width and frequency between 1000 and 1600 ns and 200–250 kHz, respectively. During sputter etching, the substrates were negatively biased with 500 V and bombarded with argon ions at a partial pressure of ~213×10^{-3} Pa (1.6×10^{-3} Torr).

Argon (99.99%) gas flow was maintained at 8.33×10^{-7} m^3/s (50 sccm) during the deposition of the coatings. While this procedure was followed irrespective of the coating being deposited, later steps in the deposition procedure were highly coating-specific. A surface dial thermometer was used to measure the deposition temperature and was observed always to be well below 120 °C for all the coatings.

The target materials ($5 \times 15 \times 0.375$ in^3) used for the sputter deposition of each film have standard high purity levels (99.6+%). To ensure strong adhesion to the steel substrates, Cr interfacial bond layers were used for the WC/a-C:H and Cr_xN films, while Ti interfacial bond layers were used for the TiC/a-C and Ti–MoS_2 films. Acetylene and nitrogen reactive process gases were used in combination with the argon to deposit the WC/a-C:H and Cr_xN films, respectively. The Ti–MoS_2 and TiC/a-C films were deposited by a non-reactive co-sputtering of separate MoS_2 and C targets in combination with Ti targets, respectively.

2.3. Characterization

The coatings were characterized for their thickness, adhesion to the substrate, surface topography and composition prior to tribological testing. At least three measurements were made on the balls for all characterization methods, and average values are reported. Thickness measurements were made non-destructively on the balls using x-ray

Table 1
Mechanical, compositional and microstructural properties of the selected coatings from literature.

Coating	Mechanical properties	Composition (at%)	Microstructure	Reference(s)
Cr_xN	H − 20 GPa E_{ind} − 280 GPa	Cr − 69; N − 31	Nodular dense crystalline microstructure	[25,38,39]
Ti–MoS_2	H − 7.9 GPa E_{ind} − 172 GPa	Ti − 16 S/Mo: 1.8	Dense, nonporous and featureless morphology with dispersed nm sized Ti particles in amorphous MoS_2 matrix	[36,37]
WC/a-C:H	H − 14 GPa E_{ind} − 130 GPa	W − 11; C − 89	Alternating W and C rich layers; nanoparticles of tungsten carbide dispersed in an amorphous hydrocarbon matrix	[24,25,40]
TiC/a-C	H − 10 GPa E_{ind} − 110 GPa	Ti − 8 to 14	Nanoparticles of titanium carbide dispersed in an amorphous carbon matrix	[24,41]