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Fatigue resistant carbon coatings for rolling/sliding contacts

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ABSTRACT

The growing demands for renewable energy production have recently resulted in a significant increase in wind plant installation. Field data from these plants show that wind turbines suffer from costly repair, maintenance and high failure rates. Often times the reliability issues are linked with tribological components used in wind turbine drivetrains. The primary failure modes in bearings and gears are associated with micropitting, wear, brinelling, scuffing, smearing and macropitting all of which occur at or near the surface. Accordingly, a variety of surface engineering approaches are currently being considered to alter the near surface properties of such bearings and gears to prevent these tribological failures. In the present work, we have evaluated the tribological performance of compliant highly hydrogenated diamond like carbon coating developed at Argonne National Laboratory, under mixed rolling/sliding contact conditions for wind turbine drivetrain components. The coating was deposited on AISI 52100 steel specimens using a magnetron sputter deposition system. The experiments were performed on a PCS Micro-Pitting-Rig (MPR) with four material pairs at 1.79 GPa contact stress, 40% slide to roll ratio and in polyalphaolefin (PAO4) basestock oil (to ensure extreme boundary conditions). The post-test analysis was performed using optical microscopy, surface profilometry, and Raman spectroscopy. The results obtained show a potential for these coatings in sliding/rolling contact applications as no failures were observed with coated specimens even after 100 million cycles compared to uncoated pair in which they failed after 32 million cycles, under the given test conditions.

1. Introduction

Wind energy is a promising and fastest growing power generation source [1]. An increase in the number of utility scale wind plants have increased the focus on the high operation and maintenance costs of wind turbines as these ultimately impact the cost of wind energy [2,3]. The drive train and actuators of wind turbines are major sources of failures arising from the variability of wind, torque reversals, fluctuation in energy demands, misalignment, and harsh environment conditions [4]. Bearings and gears in wind turbine drive trains suffer from failure modes like micropitting, scuffing, spalling, and smearing [5,6], although these elements were designed to meet 20 year service lives assuming that proper lubrication and maintenance practices, and especially no unusual loads were encountered. If a bearing has a low concentration of non-metallic inclusions in the steel, operates at the designed contact stress, and maintains an adequate lubricant film thickness in the contact, then end of service life will be due to subsurface originated spalling [7].

Another fatigue phenomenon known as surface originated fatigue, which is caused by surface or near surface stress risers such as non-metallic inclusions, plastically deformed material, martensite transformation products, or several other factors. A particular type of surface initiated fatigue is known as micropitting which is a common failure mode encountered by gears and bearings [8]. Specifically, many main shaft spherical roller bearings in wind turbines are life limited due to spalls arising from micropitting wear [9]. Micropitting is associated with the initiation and propagation of micro-cracks in the direction of traction forces. The progression of micro-pits alters the surface profile of a bearing raceway or gear tooth which generates regions of large stress concentrations. The increase in localized stresses leads to fatigue failure through the formation of macro-pits or spalls. Micropitting is affected by several factors such as lubricant type, contaminants, temperature, contact stresses, hardness, sliding speed, and surface roughness [10].

Studies were carried out over the last few decades to understand the mechanism of micropitting. According to Morales-Espejel and

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Brizmer, micropitting depends on the lubrication conditions and roughness of the contacting surfaces, the presence of slip (between 0.5% and 2%), and the associated boundary friction shear stress are required for the generation of micropitting [11]. Oila and Bull suggested that contact stress has the greatest impact on micropitting initiation, while the progression of micropitting is affected mostly by speed and slide to roll ratio [10].

Lubrication conditions are best quantified by the parameter lambda (λ), which is the ratio of the lubricant film thickness to the composite surface roughness. Operating temperature, viscosity, and operating speed all affect the lubricant film thickness and hence λ. Brechot et al. reported that oils with antiwear and extreme pressure additives that are used to prevent scuffing and wear can promote micropitting [12]. Micropitting has proven to be difficult to eliminate through lubricant chemistry alone.

A number of solutions have been suggested to mitigate micropitting. Super-finishing is a process used on gear teeth to increase load bearing area and reduce the severity of asperity interactions in boundary lubrication (i.e., $\lambda < 1$) [13]. Apart from super-finishing, other surface engineering techniques are also employed to reduce asperity contact and provide barriers to wear [14]. Physical vapor deposition (PVD) coatings composed of nitrides, sulfides and carbides were examined for their ability to prevent micropitting [15,16]. PVD coatings can be very effective at reducing or eliminating many wear modes [17]. Among these coatings, diamond like carbon (DLC) coatings are now being used in numerous applications for wear resistant purposes due to their desirable tribological performance [18]. DLC has been modified over the years to possess ultra-low friction and high wear resistance. DLC coatings can be doped or alloyed to increase their functionality. The properties (hardness, toughness, and thermal stability) of DLC coatings are further increased by using novel coating architectures that consist of nanocrystalline precipitates and nanosized multilayers [19]. Hydrogen-free DLC coatings deposited from solid carbon targets can be extremely hard, while hydrogenated DLCs are usually much softer.

In this research, coatings having indentation hardness values greater than 10 GPa are referred to as hard coatings, while coatings with indentation hardness values less than 10 GPa are referred to as soft coatings. Precursor hydrocarbon gases such as methane and acetylene are typically used in the deposition of DLC that contain large amounts of hydrogen. Hard DLC have been shown to be very successful at mitigating many wear issues encountered by bearings and gears operation in boundary lubrication, including micropitting [20,21]. Surface treatments such as black oxide and phosphate conversions are also applied to bearings and gears to address micropitting [20,22,23]. These conversions are thick, sacrificial layers that work to rapidly break-in the surfaces of the components, reducing asperity contact, and delaying the onset of micropitting. Most of the studies reported on exploring the use of DLC to mitigate micropitting prevention were carried out with hard DLC coatings. Few if any studies were performed using soft DLC coatings.

In this research, a soft highly hydrogenated DLC coating was sputter-deposited on rings and roller specimens, and the tribological performance of the coated specimens was evaluated in a micropitting rig. Four different material pairs were tested in a polyalphaolefin (PAO) base stock oil. The as-deposited and tested specimens were then examined using optical microscopy and Raman spectroscopy in an attempt to understand underlying mechanisms.

2. Materials and methods

2.1. Test apparatus

A PCS Instruments Micropitting Rig (MPR) was used for testing. The MPR is a computer controlled three rings on roller tribometer. A 12 mm diameter roller is mounted in the center and in contact with three rings of 54 mm diameter at an angle of 120°. Fig. 1a shows the MPR test chamber and the arrangement of rings and roller inside the test chamber is shown in Fig. 1b. A thermocouple was installed to measure the contact temperature and an external cooler was connected to control the temperature of the oil inside the test chamber. A load was applied to the top ring (0° position) by means of motorized ball screw, and vibration was measured with a piezoelectric accelerometer. The rig has a capability to control entrainment speed (0–4 m/s), slide to roll ratio (0–200%), temperature (25–135 °C), and load (0–1250 N).

2.2. Test material

The test material used in this study and their properties are given in Table 1. The roller had a 10° chamfer on each side of a 1 mm track width as shown in Fig. 2a. Rollers and rings were made of AISI 52100 steel and heat-treated to hardness values of 57–60 HRC and 62–65 HRC, respectively. The average surface roughness measured on the ring was about $R_a = 0.3$ μm and roughness of the rollers was about $R_a = 0.2$ μm. No change in the surface roughness was observed after coating deposition. Fig. 2b shows an optical image of the cylindrical roller and the track width prior to testing.

Table 2 presents the test parameters used for evaluating the tribological performance of different material combinations. An

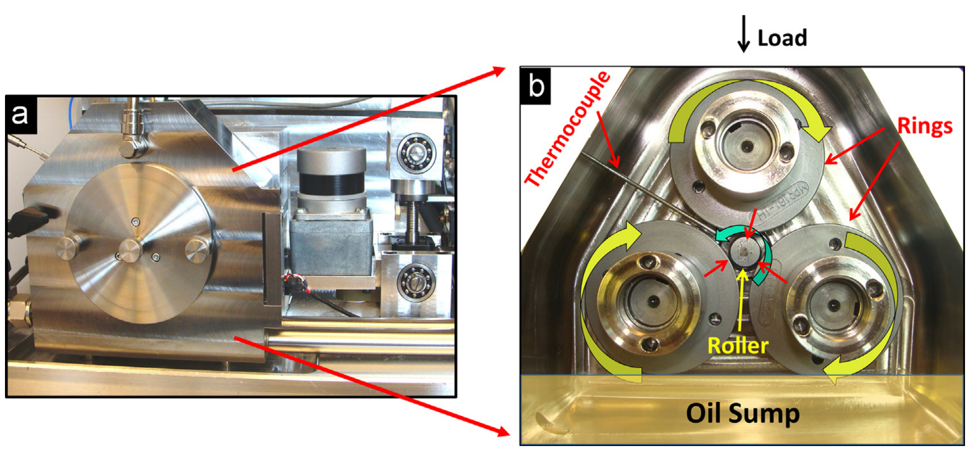

Fig. 1. (a) Micropitting rig test chamber and (b) arrangement of roller and discs inside the test chamber.