Wear 392–393 (2017) 29–38

Contents lists available at ScienceDirect

Wear

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

Effects of ultrasonic nanocrystal surface modification on the wear and micropitting behavior of bearing steel in boundary lubricated steel-steel contacts

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ARTICLE INFO

Keywords:
UNSM
Rolling-sliding
Wear
Micropitting

ABSTRACT

An ultrasonic nanocrystal surface modification (UNSM) technique has been used to treat AISI 52100 steel specimens and thrust ball bearing raceways. Tribological performances of untreated specimens were compared to UNSM-treated specimens in reciprocating sliding and rolling/sliding contact under boundary lubricated conditions. Friction and wear coefficients, micropitting, and changes in surface profiles and surface roughness of the specimens were studied. Results showed that UNSM treated specimens had higher wear and micropitting resistance than the untreated specimens. The improvements in wear and micropitting resistance may be attributed to increased surface hardness, refined grain sizes and compressive residual stress near surface region as a result of UNSM treatment. The UNSM technique has been proven to be a powerful tool to improve the durability and tribological performance of contacting surfaces of mechanical components such as bearings, gears, and seals.

1. Introduction

Micropitting is a surface initiated failure mode in bearings and gears that can occur under poor lubrication conditions, which can lead to macropitting, surface spalling and debris generation. Micropitting appears as a series of dull, etched, or stained regions on the surface [1]. The formation of a micropit is related to the lubrication regime, which is typically characterized by the λ parameter, i.e., the ratio of the lubricant film thickness (h) to the composite surface roughness of the mating surfaces. The λ parameter is used to characterize the lubrication regime: boundary, mixed, elastohydrodynamic, and hydrodynamic [2]. In many industrial applications with lubricated rolling and sliding contacts, the lubricant film may not be sufficiently thick to separate the contacts under severe working conditions (e.g. highly loaded with sliding and/or low speed). At low λ values, the basic elements of surface roughness, micro-size asperities, intimately interact with each other and generate localized stress enhancements [3–5]. Repetitive localized stresses can cause surface micro crack initiation, and propagation of micro-cracks can lead to the removal of discrete pieces of material (appeared as micropits). The typical size of a micropit has a characteristic depth of 5–10 m and diameter of 10–30 m, at a shallow angle to the surface [1,6]. Once incubated, micropits can enlarge and coalesce in the form of crack branching. The micro-level fatigue soon evolves to a much larger area, leading to the formation of macro-level pits, surface spalling and debris generation, significantly reducing the functional life of mechanical components such as rolling element bearings and gears. This is exemplified by gearbox design in wind turbines [7]. The design life of a wind turbine is 20 years, which is already a reduction from a 30-year design goal [8]. Many wind turbine gearboxes can only sustain an average of 5 years before a replacement. The cost incurred by excess maintenance and replacement can account for 10–15% of the total income for a wind farm [9]. To meet the challenge, the National Renewable Energy Laboratory (NREL) has initiated a gearbox reliability project dedicated to identify and solve the underlying issues behind the gearbox failure. It has been recognized that micropitting was one vital failure mode for gearbox bearings [10]. The general strategy to mitigate micropitting is to improve lubrication conditions and/or surface finish, which reduces asperity/asperity interactions [11–14]. Under boundary lubricated conditions ($\lambda \le 1$), wear competes with micropitting. Mild wear can reduce the roughness of the surface and remove the layer where micro-cracks initiated, which suppresses micropitting [15]. Morales-Espejel and Brizmer [14] developed a model to predict wear and micropitting damage in rolling/sliding contacts. Their results showed the micropitting risk was reduced

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http://dx.doi.org/10.1016/j.wear.2017.09.012
Received 30 May 2017; Received in revised form 21 August 2017; Accepted 16 September 2017
Available online 20 September 2017
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as the wear rate increased. Lubricant additives are also used to form additive-derived films that can reduce wear in boundary lubricated conditions. However, some studies have shown that ZDDP and some other anti-wear additives can promote micropitting by reducing beneficial wear of the surfaces undergoing micro-cracking [16–18].

Surface engineering techniques (such as coatings [19], carburizing, nitriding [20], shot peening [21,22], laser shock peening [23] and laser glazing [24]) can be used to impart favorable surfaces or subsurface that can improve mechanical properties and tribological performance. During rolling or mixed mode contact, microstructural changes can occur in the near-surface areas. Oila and Bull [25] showed that micropitting is related to the generation of plastic deformation regions (PDR) and dark etching regions (DER) that are formed from the decay of martensite under high stress cycle contact. Micro-cracks were observed to initiate along PDR boundaries as a result of dislocation pileups, and propagation of the cracks along the PDR boundaries eventually liberate the PDR regions from the surface forming micropits.

The hypothesis tested in this research is to determine if plastic deformation, compressive residual stress, improved hardness, strength and crack resistance imparted by surface treatments can mitigate or delay the occurrence of micropitting. With conventional surface treatment techniques, it is challenging to generate uniform plastic deformation without deteriorating surface finishes. A recently developed surface modification technique called ultrasonic nanocrystal surface modification (UNSM) can overcome the disadvantage of surface deterioration [26–30]. Due to its controllability, UNSM can control the surface roughness from 0.04 to 0.5 μm, and create homogeneous plastic deformation and compressive residual stress in the near surface region to prevent the wear and propagation of micro-cracks. With the unique combination of superior surface finishing and microstructural modification, it is of interest to study the tribological performance of UNSM-treatment bearing steel. To the best of our knowledge, no investigation about the effect of UNSM on the development of micropitting has been reported.

In this work, the effects of UNSM treatment on the wear and micropitting behaviors on bearing steel in boundary lubricated conditions was systemically studied. Wear behavior of through-hardened AISI 52100 steel disks with and without UNSM treated were examined in both dry and boundary-lubricated conditions by high frequency reciprocating sliding contact. AISI 52100 steel rollers with and without UNSM treatment were tested in rolling/sliding contact under two different λ values (λ ~ 0.7, micropitting is the dominated failure mode; λ ~ 0.2, wear is the dominated failure mode). Additionally, thrust ball bearings were tested to evaluate and compare the tribological performance of UNSM treated bearing raceways with untreated bearings. A technological goal of this study was to develop a low-cost, easy-to-operate surface modification technique that could be used to improve the durability and tribological properties of rolling elements under severe working conditions.

2. Experimental procedure

2.1. UNSM processing

The UNSM process is schematically shown in Fig. 1. Compared with conventional severe surface plastic deformation techniques, the advantage of UNSM is its controllability in reducing surface roughness while producing various surface structures on complex geometries. In a UNSM process, a tungsten carbide indenter attached to an ultrasonic device scans over the surface while striking it at high frequency (20 kHz). At the same time, a static load is applied to the indenter against the material surface. High frequency strikes cause severe surface plastic deformation on metallic surfaces. In this study, the following UNSM parameters were used: tungsten carbide indenter diameter 2.4 mm, static load 10–30 N, vibration amplitude 8–24 μm, frequency 20 kHz, scanning speed (V_1) 500–1000 mm/min, interval (distance between neighboring scans) 10–70 μm.

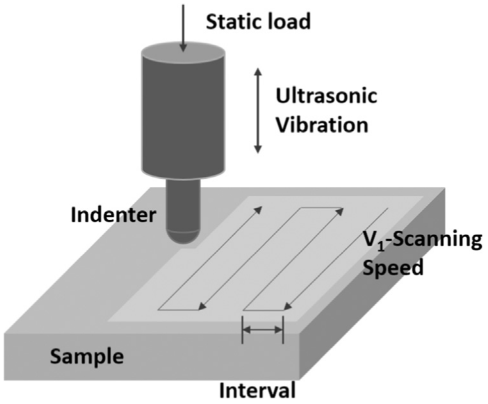

Fig. 1. Schematic of the UNSM process.

2.2. Tribological tests

2.2.1. High-frequency reciprocating sliding tests

Friction and wear performance were studied in reciprocating sliding contact under both dry and boundary lubricated conditions. A PCS high frequency reciprocating rig (HFRR), a convenient tool for tribological studies [31], was used in this study. UNSM treated and untreated AISI 52100 disks were used as the test specimens. AISI 52100 steel balls (6 mm diameter, Ra = 0.02 μm) were used as the counter faces. The test conditions are listed in Table 1. In this work, we focused on friction and sliding wear performance of the samples, other failures (such as scuffing, welding) were avoided. Thus, in dry conditions, lower loads and sliding speeds were selected to avoid scuffing and welding. In lubricated conditions, higher loads with higher temperatures were deliberately applied to reduce λ (boundary lubricated conditions) so that wear could be observed. By measuring the wear scar volume of the disks, the wear resistance of specimens can be determined. Each test was carried out three times to provide mean values of wear scar volumes.

2.2.2. Micropitting tests

Micropitting tests were performed in a PCS micropitting rig (MPR). Three equal diameter rings were placed in contact with a roller with smaller diameter (Fig. 2) [19,32]. Both rings and roller are cylindrical (R_{ring} = 27 mm, R_{roller} = 6 mm), which generates a line contact area with a 1.0 mm contact width. The rings and rollers used in these experiments were made of AISI 52100 steel and hardened to values of 62 HRC and 55 HRC, respectively. The surface roughness was Ra ~ 0.4 μm for the rings and Ra ~ 0.2 μm for the rollers. Rings with higher hardness and rougher surfaces than the rollers were selected to accelerate micropitting and wear on the roller surface [1]. Rings and rollers were circumferentially ground with residual grind lines running parallel to the rolling/sliding direction. The surface skewness of the rings was ~ 0.3. Roller surfaces were treated by UNSM, and both treated and

Table 1
High frequency reciprocating rig (HFRR) test conditions.

	Dry condition	Lubricant: PAO ISO 10 base oil
Temperatures	25 °C	90 °C
Humidity	40–45%RH	40–45%RH
Load/Maximum contact pressure	1 N / 0.6 GPa	10 N / 1.4 GPa
Frequency	20 Hz	20 Hz
Stroke amplitude	500 μm	1000 μm
Run time	1, 2, 5, 10, 20 min	15, 30, 60, 90, 120 min

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