Wear 364-365 (2016) 211–223

Contents lists available at ScienceDirect

Wear

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

An experimental and theoretical study of surface rolling contact fatigue damage progression in hybrid bearings with artificial dents

C. Vieillard [a,*], Y. Kadin [a], G.E. Morales-Espejel [a,b], A. Gabelli [a]

[a] SKF Engineering & Research Centre, Nieuwegein, The Netherlands
[b] Université de Lyon, CNRS LaMCoS UMR 5259, F69621 Lyon, France

ARTICLE INFO

Article history:
Received 3 March 2016
Received in revised form
22 July 2016
Accepted 24 July 2016
Available online 29 July 2016

Keywords:
Rolling sliding
Indentation
Steel-ceramic contact
Cyclic micro-plasticity
Finite element modeling
Micro-elastohydrodynamic lubrication

ABSTRACT

An experimental study followed by modeling is carried out for pre-dented hybrid rolling bearings to observe the raceway surface damage evolution and to try to understand its behavior. The experiments and modeling are repeated in similar all-steel bearings and conditions for comparison purposes. The results show that hybrid bearings tend to re-accommodate the dent raised edges on the steel surface by mild wear and plastic deformation and this stabilizes the local pressures much faster than all-steel bearings. Followed by a lower boundary friction coefficient, when the lubricated oil is broken by the surface features, hybrid bearings give still longer dent lives than the all-steel bearings, even though the conditions are at equal bearing load (which means higher stresses in the hybrid bearings).

1. Introduction

In the last twenty years, hybrid rolling bearings, i.e. bearings with silicon nitride rolling elements and steel rings, have become a common product readily available in many types and sizes by several bearing manufacturers. The use of ceramics as a bearing material was proposed in the early sixties by the need of extreme temperature bearings for aero and space applications. Ceramic material purity, sintering technology and the process for surface super-finishing of silicon nitride balls were developed in the 80s and early 90s to levels required for bearing applications offering performing Si3N4 based products. In the last few years hybrid bearings have been increasingly used in many other applications with challenging environment [1–4]. Lubrication contaminated with solid particles is a challenging environment, such as in gearboxes and cutting fluid pumps. Although much work has been performed in this area for all-steel bearings, a major complication in studying mechanisms of damage progress and surface fatigue related to dents is the random nature of denting. The particle distribution is mixed with a lubricant quantity and made in suspension to flow through the running bearings. Some particles will get entrapped in the loaded contacts. Controlling the number, the geometry and the location of the dents is challenging, this is why many studies have introduced artificial dents.

1.1. All-steel bearing studies

Artificial dents, produced by means of a Rockwell penetrator, were used by Coulon et al. [5] to study fatigue life reduction and damage process under rolling and rolling/sliding conditions on a 2-disc machine. There, under nominally pure rolling conditions, plastic deformation in the first cycles occurs and quickly reaches a stabilized geometry, for a steel–steel contact. Micro-cracks were found to propagate below the surface at a slow pace, to coalesce and lead to microspalls. A direct relation to stressed volume was developed with the use of a 2-D dry point contact model. Under rolling/sliding condition, the fatigue life was considerably reduced. Udea and Mitamura [6] experimentally observed the spall initiation at the trailing edges of an artificial dent relative to the rolling direction. Large tensile stresses due to tangential forces were generated at the trailing edge, which leads to crack initiation. The location of the crack initiation was therefore influenced by the direction of the tangential force. High traction coefficient oils would further reduce the dent life with earlier spall formation. In a different work the same authors [7] addressed the influence of the rolling element roughness on the life of a dent on a bearing raceway life. In [8] some of the current authors carried out semi-analytical simulations of an artificial dent into an EHL lubricated contact to detail the stress concentration and high tangential force acting on the surfaces and highlighted additional mechanisms depending on the rolling/sliding magnitude and the lubrication conditions. Lubricating film collapse (including mild-wear and fatigue) was modeled at the leading edge of the dent. Further modeling by the

* Corresponding author.
E-mail address: charlotte.vieillard@skf.com (C. Vieillard).

http://dx.doi.org/10.1016/j.wear.2016.07.016
0043-1648/

same authors [9] confirmed the typical V-shaped crack and initial propagation behavior from the trailing edges of an artificial dent in a standard steel deep groove ball bearing as experimentally observed. The V-shape crack system was found to be driven by the maximum orthogonal shear stress distribution.

1.2. Hybrid bearing studies

Regarding performance and mechanisms for hybrid bearings in contaminated environment, pioneer work by Wan et al. [10] has shown excellent wear resistance performance of Hybrid bearings under heavily contaminated oil lubrication conditions. From 6305 all-steel and hybrid bearings tested in oil with SiC, cast iron and M50 particles for a fixed time, the wear rate of the Hybrid bearings was found much lower than the all-steel bearings. Weight loss measurements at the end of the test also showed almost no wear from the Si3N4 balls, while the steel balls showed the highest relative wear, and slightly reduced steel ring wear for the hybrid bearings. It was proposed that a so-called “self-healing” mechanism from the hybrid contact related to the higher Young modulus and hardness of the Si3N4 is responsible for the better performance. The ceramic balls plastically deform any raised edges from dents on the steel counterpart, thus inhibiting surface distress, spalling and destructive wear. Additionally, it was also hinted that hybrid bearings under the same load could be less sensitive to entrapment of particle for denting damage due to smaller contact and lower surface friction, a later study by Strubel et al. seems to point towards the same direction [11]. In [12] Wang et al. measured lower wear by axial displacement for bearings with only two Si3N4 balls in the steel ball set (so called partial hybrid bearing) in similar tests on 6206 deep groove ball bearing with SiC particles and hydraulic oils using a contact pressure of about 3.8 GPa. Lower wear damage was significant for the partial hybrid bearing outer raceway. A smoothening effect from the Si3N4 balls was observed as mechanisms in a similar fashion as [10].

Oil lubricated ball-on-rod tests comparing M50-M50 and M50 – Si3N4 contacts under equal load (giving contact pressure in the range of 5.14 GPa in the all-steel contact and around 6–6.5 GPa in the hybrid contact) were performed by Mitchell et al. [13] using Arizona dust (mostly silica) or pure Al2O3 particles. Ball wear and damage was stated as lower on the Si3N4 balls than on the M50 balls, however at these contact pressures and contamination levels, the wear on the M50 rod was found larger for the hybrid contact than for the steel contact. The higher contact pressures and the higher number of denting and deeper dent depth created on the steel rod surface in the hybrid contacts were proposed as explanation.

Other denting experiments carried out by Tonicello et al. [14] using M50 and WC particles for a high speed twin disks contact configuration showed that the created dents can be up to 3 times deeper on the steel counter-parts for the hybrid contact (Si3N4 disc on 32CrMoV13 disc) than in the all-steel contact. This was explained by the high yield stress and Young's modulus of the Si3N4. However no details on test conditions were given for contact pressure, film thickness or slip to roll ratio. The later work from Strubel et al. [11] points in the same direction.

Artificially created dent overrolling experiments for all-steel and hybrid contacts using a roller–ring contact configuration [12] showed a higher raised edge height reduction for the hybrid contact than for the all-steel contact. This plastic deformation and reshaping of the dent edge was shown to reduce the maximum shear stress experienced at the dent edge for the hybrid contact, hence showing life improvement potential. However, the dent morphology used had a raised edge of more than 10 μm and a depth of more than 80 μm, which is far beyond the range of common bearing dent practice. The hybrid contact showed a 5% higher reduction of the raised edge compared to the steel contact.

Published results on hybrid contact in complex contaminated environment still do not offer a clear view of its potential advantages in contaminated environments. By reviewing the literature one finds somehow contradictory results on the performance of hybrid contacts/bearings. In some cases wear is higher than all-steel contact in others is lower. When it comes to indentations, hybrid bearings seem to produce deeper indents when overrolling particles than the all-steel counterparts. However, they also seem to be more forgiven when it comes to the surface fatigue damaged produced by those indentations.

1.3. Objective of the present paper

Given the diversity of opinions and results in the published literature about the performance of hybrid contacts/bearings under contaminated conditions or indented raceways, this paper with the use of experiments and modeling tries to shed some light into the tribological mechanisms to clarify on how this type of contact really operates and what is its performance and the mechanisms responsible.

2. Results

2.1. Experimental work

The study focuses on the use of artificial dents of controlled geometry and locations on a bearing steel inner ring, in order to observe and characterize the tribological mechanisms under bearing operation and to produce dent life data to quantify potential performance difference between an all-steel and a hybrid bearing contact. Artificial-dent overrolling tests were performed using standard 6205 hybrid and all-steel deep groove ball bearings under radial load according to the test conditions given by Table 1.The bearings were tested in SKF type 2 rig, as shown in Fig. 1(c) and similar than in [8]. The steel rings of both bearing variants were made of standard AISI 52,100 hardened bearing steel. Four artificial dents in the middle of the deep groove of the steel inner ring spread evenly over the ring circumference were created by means of a 1 mm diameter WC ball

Table 1
Summary of test conditions for overrolling of indentations for all-steel and hybrid bearing.

Parameters	Test condition 1	Test condition 2	Dent life
Bearing	6205	6205	6204
Speed rpm	6000	6000	6000
Oil viscosity, cSt[a]	68	9	68 for steel – 9 for hybrid
OR temperature °C	47	43	53 for steel – 43 for hybrid
κ	6	1	4.1 for steel – 1 for hybrid
Maximum contact pressure GPa IR	2.12 for steel – 2.38 for hybrid	2.78 for steel – 3.12 for hybrid	2.78 for steel – 3.12 for hybrid
Test interruption for dent investigation	60, 120, 180, 240, 360,480 and 650 Mrevs	1, 3, 6, 12, 25, 75, 120, 250 Mrevs	No interruption – running till failure or suspension time

[a] at 40 °C.