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

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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

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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 overolling 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.

indentation Rockwell hardness device with 31.25 kg load, Fig. 1(a). Typical dent geometry was about 200–220 μm diameter, 5–6 μm deep with a raised edges of about 0.2–0.3 μm, see Fig. 1(b).

A first test condition was applied with medium contact pressure and full-film condition, see Table 1. A second test condition involved lower κ conditions (κ, kappa, is the viscosity ratio representing the lubrication quality of the bearing according to ISO 281, as in [8–10]) and under higher contact pressure. To study the dent evolution with respect to the running time, regular interruptions were scheduled in order to dismount the all-steel and hybrid bearing and to inspect the

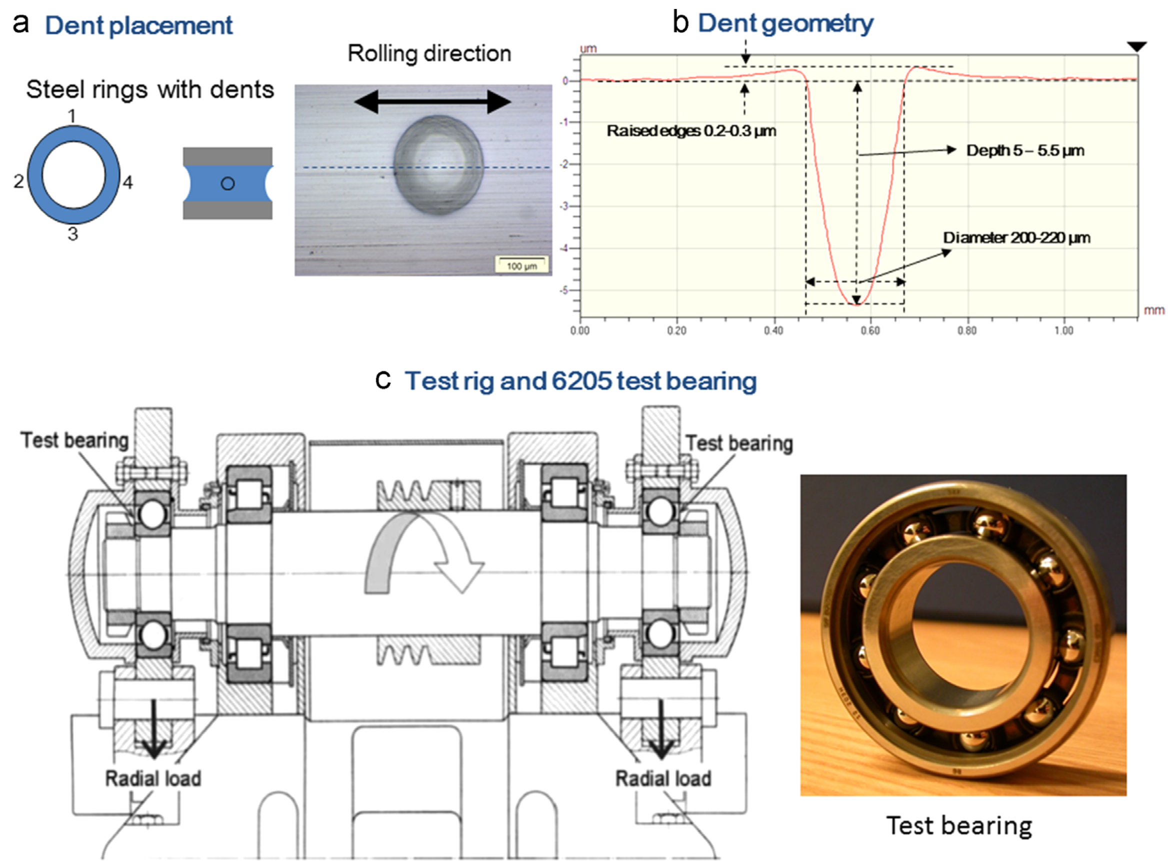

Fig. 1. (a) Artificial dent placement on steel rings by indentation and top view topography for the dent aspect, (b) detailed typical dent geometry in cross-section, (c) test rig and test bearing configuration, the steel 6205 variant is shown, for the hybrid variant the balls were made of silicon nitride.

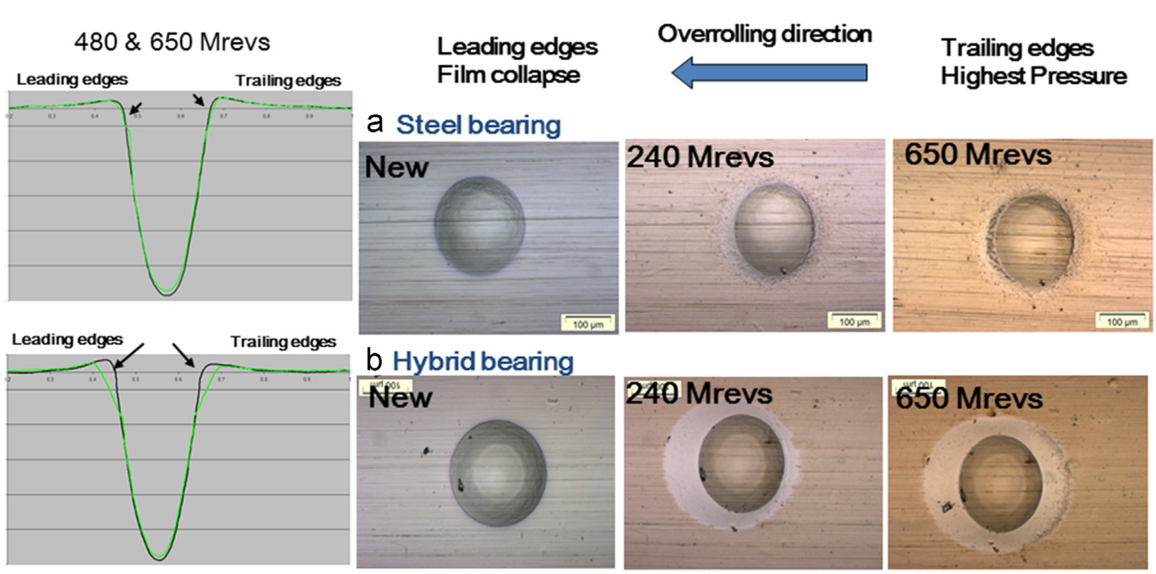

Fig. 2. Optical observation of the dent with running time under test condition 1 for the all-steel bearing a) and for the hybrid bearing b) an illustration of the center profile measurements of the dent at end of test is also shown. The black line is the dent profile as new; the green line is the tested dent shape. The overrolling direction is defined as the direction of movement of the ball; the contact inlet is on the left of each picture. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dents and the rolling elements. During these interruptions, optical microscopy, scanning electron microscopy and surface mapping by light interferometry were used for observation and measurements of the dents. The topography measurements of the dents as new and along the tests are used as input to the models, as will be shown below.

2.2. Results

Results showed over running time a noticeable difference between the all-steel and hybrid contact in the surface aspect and changes of the dent raised edges. All 4 dents of the rings for every bearing showed similar aspects during overrolling in each test condition.

2.2.1. Test condition 1: medium contact pressure and full-film conditions

Fig. 2 shows the optical observations over running time and dent profile measurements towards the end of the test.

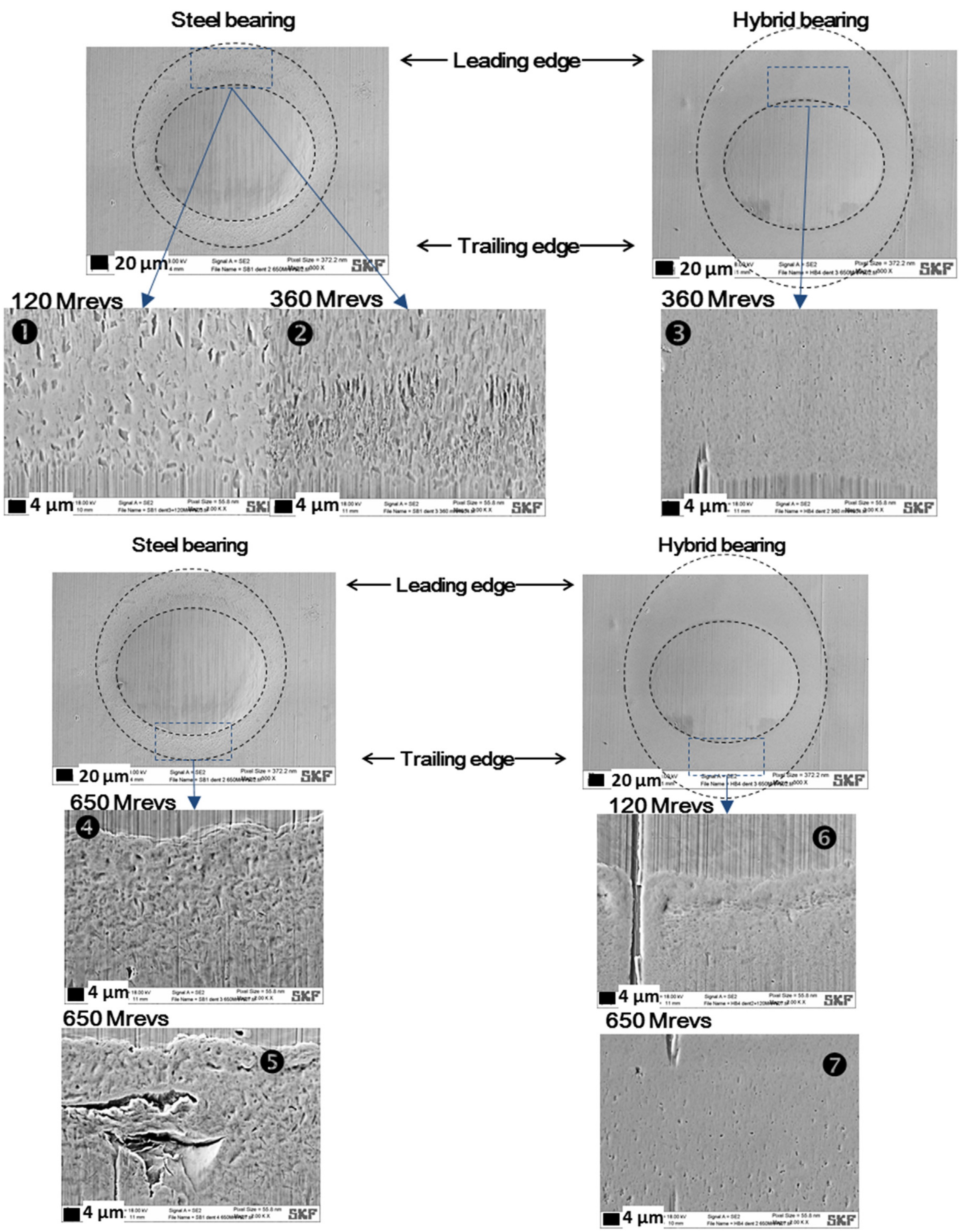

Fig. 3. SEM observation of dent for leading and trailing edges and the 2 different bearing variants. Steel bearing is shown on the left side, hybrid bearing is shown on the right side. Surface aspect for both leading edge (upper panel) and trailing edges (lower panel) are detailed for different Mrevs of operation as indicated.

2.2.1.1. All-steel bearing. Only minute shape change of the dents raised edges over the test time was observed for the all-steel bearings, see Fig. 2. However, clear surface damage was observed in the form of superficial surface marking on the raised edges of the dents erasing the initial inner ring finishing marks, over the first 240 Mrevs on the leading edges, see Fig. 3, mark ❶. These markings consist of asperities micro-denting in the halo area of the dent, creating micro-plastic work of the surface, without major change in the macro shape of the dent raised edges. Directional kinematic shape of these asperity dents suggests tangential forces (friction). For 240 Mrevs, some adhesive wear damage appears on the leading edges of the dent but is still superficial, Fig. 3 mark ❷. On the trailing edges, superficial plastic work by asperities micro-denting the raised dent edges, but without major change in the overall shape is observed in Fig. 2. With running time there is more deformation showing material pushed into the dent as observed, Fig. 3 mark ❹. For one dent, the trailing edge showed a small surface crack initiation from 240 Mrevs due to another additional smaller hard brittle particle denting that area, see Fig. 3, mark ❺. The crack is slowly propagating upon further operation.

2.2.1.2. Hybrid bearings. Clear changes in surface aspect and shape were observed for the hybrid bearing. Mild wear is found to create a smooth surface early in the test for the leading edges of the dents which further extend with running time, Figs. 2 and 3, mark ❸. This mild wear occurs over the first 240–360 Mrevs. With further running, tiny surface details are maintained, and the shape is no longer changed, indicating that pressures have been reduced to a level where mild wear is no longer acting, shown in Fig. 2, where the dent observation and dent profile at both 480 and 650 Mrevs are the same.

Some shape changes take place at the trailing edges of the dents at a slower rate by plastic work and the raised edge pushed down by the Si3N4 ball over the first 240 Mrevs, shown in Figs. 2 and 3 mark ❻. From 240–360 Mrevs, mild-wear seems to contribute and accelerate the changes of the trailing edges shape and the slope change to a symmetric shape between the leading and trailing edges of the dents which no longer change with further running, Fig. 3 mark ❼.

The overrolled halo of the dents in the Hybrid contact developed faster to wider dimensions than in the steel bearings and they also gained symmetry over time in the alteration of raised edges and the surface slopes. This is probably due to a “higher” mild-wear rate (under higher local pressures) which stops after sufficient slope re-conforming lowering the local pressures or changing the film behavior.

The steel balls suffered from surface damage and some roughening as well as surface oxidation, while the Si3N4 balls remained in good original condition.

Test condition 1 provided a very good film thickness and medium contact pressures.

- Excessive adhesive wear was prevented in the all-steel bearing. However, surface plastic work at the trailing edges did show the possibility to initiate a crack for one of the dents. Material pushed back into the dent was visible.
- The hybrid bearing provided mostly mild wear process at the leading edges and a combination of plastic deformation and mild wear at the trailing edge that modified the dent shape to a stable shape after a certain running time. The noticeable slope changes influence the stresses level and the stresses gradient. The mild-wear may have contributed to the prevention of crack initiation contrary to the all-steel bearing.

Mild wear appears at the trailing edge of the dent in the hybrid bearing. It could be due to the a-symmetry created in the dent shape as the leading edge has already changed substantially, changing also the stresses, slip and lubrication conditions.

2.2.2. Test condition 2: high contact pressure and thin film conditions

The test condition 2 (Table 1) showed similar results as before see Figs. 4 and 5, with some more specifics:

- For the all-steel bearing, more pronounced but still superficial adhesive wear can be seen after one Mrevs. Early in the test steps, the steel balls show roughening by asperity contacts and adhesive wear damage, more general surface marking was seen in the rest of the rolling track under the thin film condition of the test for the inner ring. Possible crack initiation can again be observed for the trailing edge, Fig. 5. These damages only produced minor changes in the shape of the dent, shown in Fig. 4.

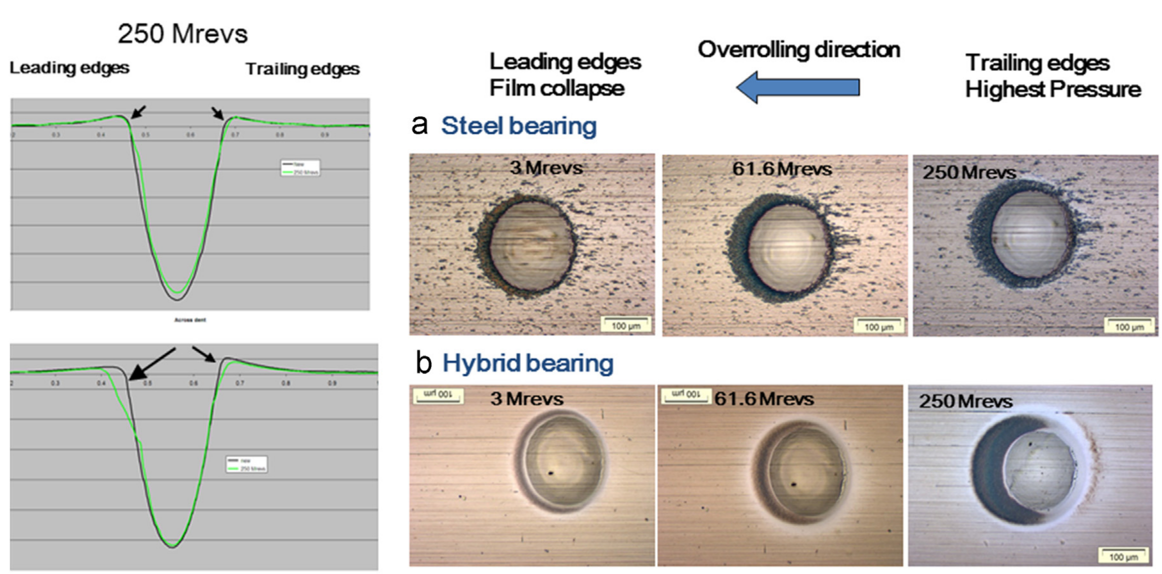

Fig. 4. Optical observation of the dent with running time under test condition 2 for the steel bearing a) and for the hybrid bearing b) an illustration of the center profile measurements of the dent at end of test (i.e. 250 Mrevs) is also shown. The black line is the dent profile as new; the green line is the tested dent shape. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

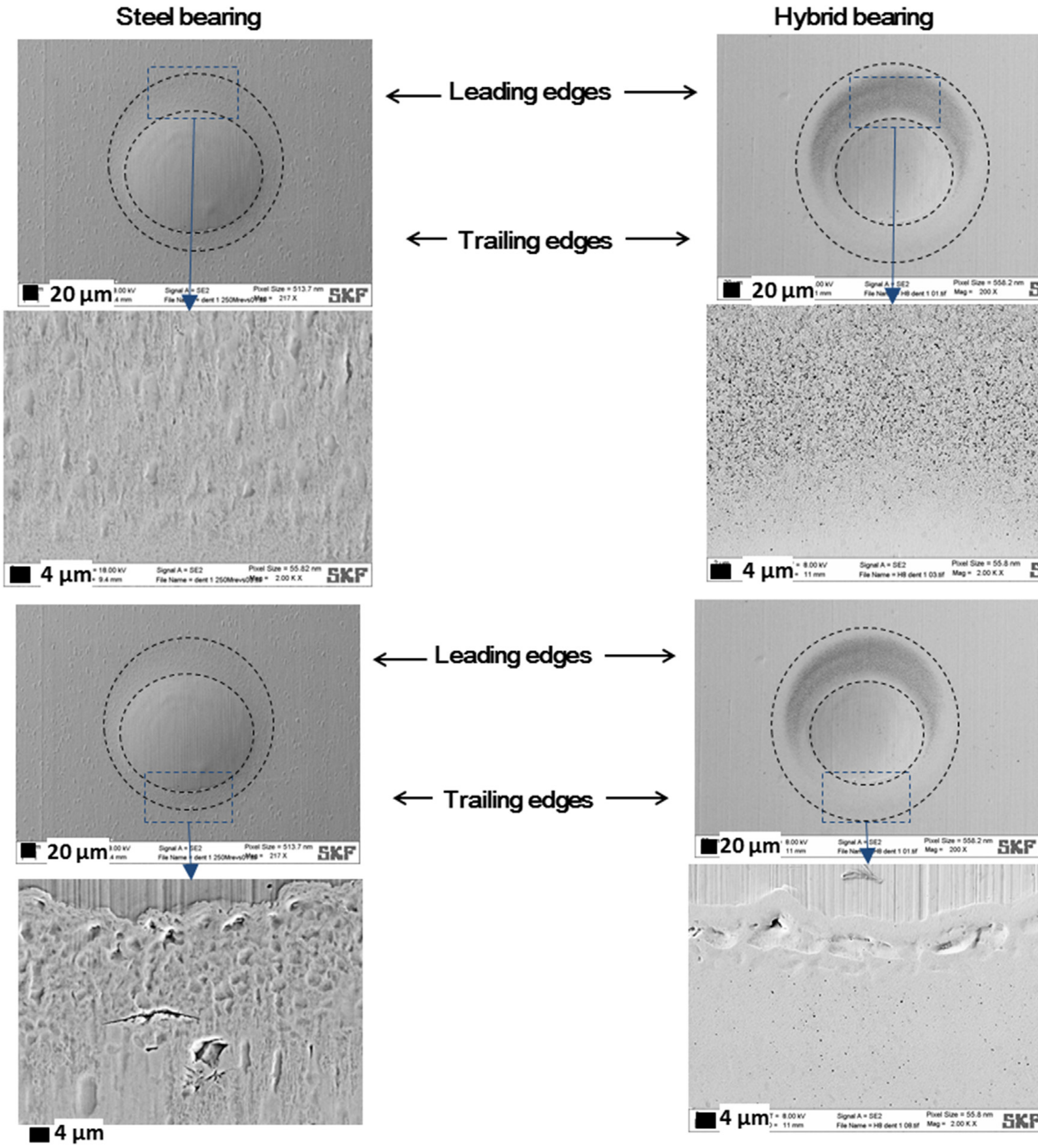

Fig. 5. SEM observation of dent for leading and trailing edges and the 2 different bearing variants at 250 Mrevs (end of test).

For the hybrid bearing, a faster mild-wear process at the leading edges can be observed. The coloration seen in Fig. 4 is from lubricant depositions. A more dominant plastic deformation process at the trailing edge modifies the dent shape. Material can be seen as pushed back into the dent area, see Fig. 5. As the Si3N4 ball surface stays in good condition, the rest of steel raceway does not show any surface damage.

These differences in raised edges shape and slope changes in the hybrid bearing will influence the stress level and stress gradient. Mild-wear at the leading edge in the hybrid and mild-wear to adhesive wear at the leading edge in the steel bearing is in good agreement with possible lubricant film collapse as mentioned in [8], perhaps here aggravated by the fact that the Hertzian width along the rolling direction is around 140 µm, which is smaller than the dent diameter (~200 µm), promoting some oil escape from the dent. For the all-steel bearing the situation was similar, since the Hertzian width is 150 µm.

At the leading edges, mild wear in the hybrid bearing provides an early and pronounced dent edge re-conforming, stabilizing over time which can be 3–4 times more at medium contact pressure and 10 times more at higher contact pressure and equal running time than the change occurring in the all-steel dent shape. Once the mild wear has re-conformed the dent shape and the pressure are sufficiently reduced, the mild wear mechanism stops.

Although the low load tests did show over time (650 Mrevs) a pronounced difference of trailing edge reshaping between the bearing variants (thanks to a contribution of mild wear beyond 250–300 Mrevs in the hybrid bearing), the high load tests did not show such pronounced increased difference between the bearing variants. The plastic deformation, although strongly visible at the surface, did not push the raised edge down so much as in the lower load tests over similar running time (240–250 Mrevs). This could be linked to similar strain hardening effect achieved at this higher load condition for both bearings.

2.3. Modeling

2.3.1. Dry contact finite element analysis

The contact between a rolling element and a bearing ring is frequently assumed as Hertzian which is not a case in dented

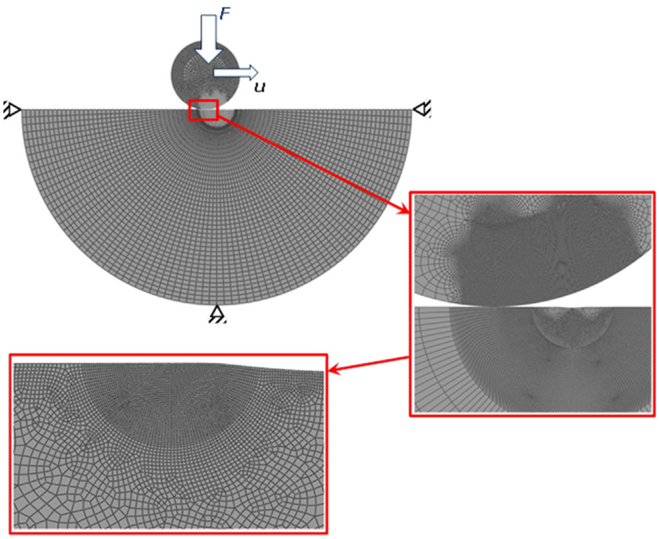

Fig. 6. Schematic of the FE model.

surfaces where the effect of surface dents on the contact pressure needs to be considered. In the current work, the Finite Elements (FE) method is used to simulate the pressure distribution at the damaged zone of the ring. The current FE model considers dry contact conditions, or in the other words, the effect of lubrication on the contact interaction between the rolling element and the ring, is omitted. The problem is simplified to the 2D contact and is modeled by the commercial FE package ABAQUS, based on the plane-strain conditions.

As shown in Fig. 6, the model consists of the following bodies: the lower body – substrate, simulating the bearing ring, and the upper body – the rolling element, ball. The bottom of the substrate is constrained and the ball is free to roll along the substrate [15]. For this, initially the contact force, *F*, is applied (shown in Fig. 6), and as the contact between the two bodies is established, the displacement *u* is applied at the center of the rolling element, which causes the ball propagation in the horizontal direction. The force *F* is kept constant and since the friction between the two bodies is present, the ball starts to roll along the ring, which simulates the rolling contact in a ball bearing.

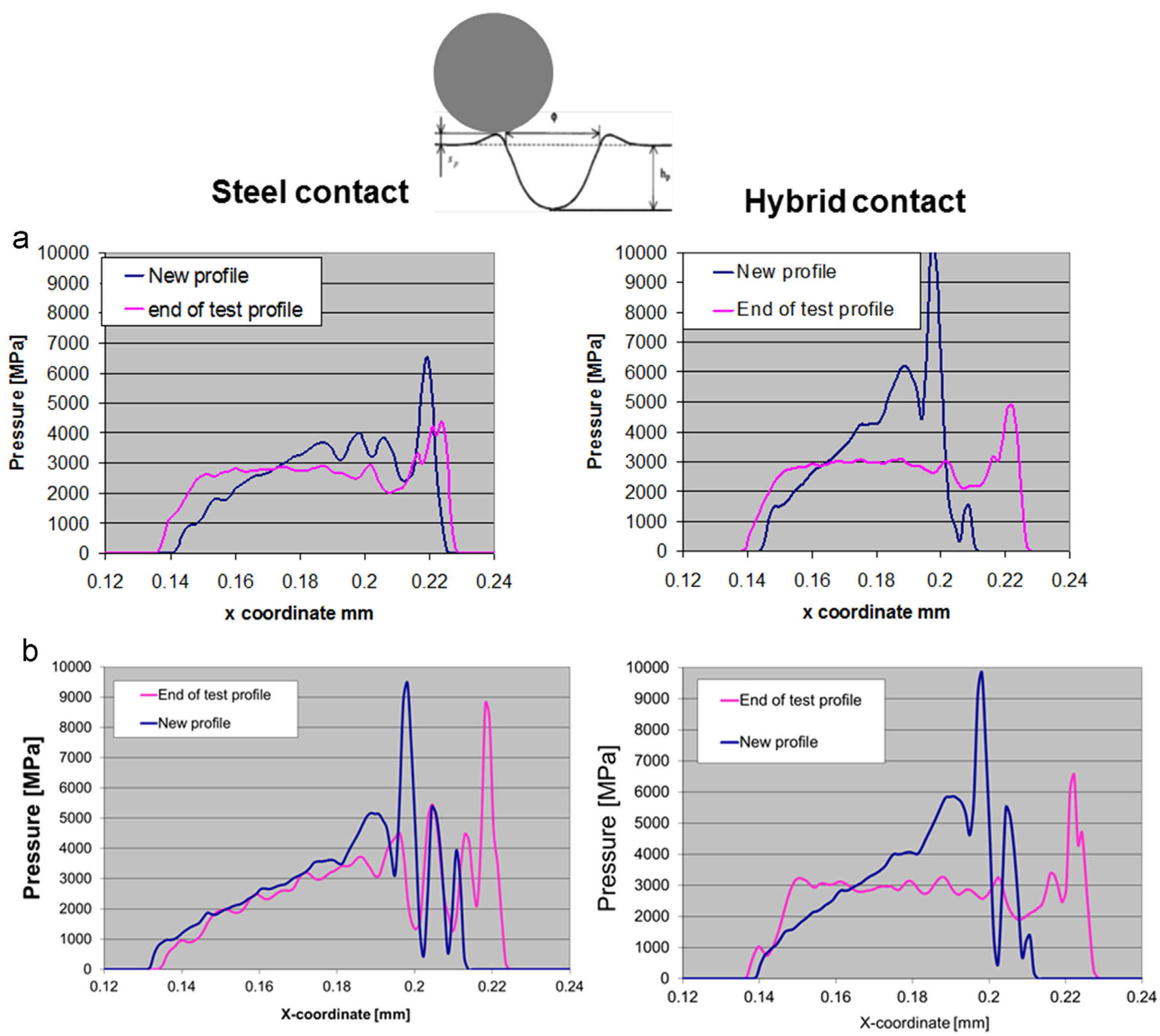

Fig. 7. Pressure distribution at raised edge overrolling by Dry Elastic 2D FE model. For the new dent shape and the end of test dent shape from test condition 1 ending at 650 Mrevs in a) and of test condition 2 ending at 250 Mrevs in b). Steel bearing results are on the left, hybrid bearing results are on the right.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The distance which the ball rolls along the substrate is rather short: it has to be sufficient to cover the over-rolling of the dent in order to investigate contact pressure and local material behavior in the damaged zone.

Using a special script developed in Python (the language of the ABAQUS programming environment) the interferometry measured dent profile is imported into the ABAQUS preprocessor, where the points defining the profile are connected by spline lines. As it is shown in Fig. 6, the mesh density is not uniform: it is very fine at the vicinity of the dent, where the contact is considered, and coarsens as the distance from the zone of interest increases. In total, the rolling element comprises around 60,000 and the substrate around 35,000 linear elements. The contact interaction between the two bodies is modeled by the standard surface-to-surface contact, defining the harder and smooth ceramic ball as the "master" and the softer steel substrate containing the dent as the "slave" surface.

Two FE models were developed in the current work: an elastic model and an elastic–plastic one. The elastic model is developed to study the redistribution of contact pressure due to the presence of a dent in order to be able to compare the newly dented surface with the surface at the end of test in terms of contact pressure distribution at the dented zone. The plastic behavior of material at the edge of the dent is out of the scope of the elastic model. According to this model the material shakes-down to purely elastic state and the contact pressure redistribution is caused solely by the surface imperfection (dent) and not by plasticity. Finally, the distribution of the contact pressure at the dented zone is post-processed by the ABAQUS function "path", and using this distribution the average contact pressure is evaluated.

Now, the elastic–plastic model is focused on the study of the material behavior at the dent edges, where the stress can be rather high and can lead to plasticity. This model assumes more realistic elastic–plastic behavior of the substrate material. To simulate cyclic plasticity due to repeated dent over-rolling, the non-linear kinematic hardening plasticity behavior was used [16,17]. The stress–strain curve defining the elastic–plastic material response was measured in a compression test, which is relevant for the contact analysis in bearing. Under contact load, the stresses are predominantly compressive and the behavior of hardened bearing steels under compression and tension can be rather different [18]. By using the current plasticity model, the shake-down material behavior under cyclic contact loading can be studied, which is not in the scope of the simple isotropic hardening plasticity.

Elastic model results, the pressure distributions were computed for both test conditions 1 and 2 for the all steel and Si3N4 ball overrolling the dent edge. As mentioned before, the new and end-of- test dent profiles were imported in the FE model.

Considering the leading edge, Fig. 7 shows that the changes in the raised edges of the dent in the all-steel bearing only reduces the initial average pressure by 7.7% and 8.9%, respectively for test condition 1 and 2, while the more effective re-conforming of the raised edges of the dent in the hybrid bearing mostly by mild wear reduces the initial pressure by 25.7% and 21.5%, respectively for test condition 1 and 2.

Considering the trailing edges, As the leading and trailing edges ended up with very similar shape for test condition 1 at the end of the tests, corresponding average pressure reduction of 25.7% is also valid for the trailing edge in the hybrid bearing.

However, since the raised edge deformations were not so different between all-steel and hybrid bearing at the trailing edge under test condition 2, the average pressure reduction is no longer significant for the trailing edge on the hybrid bearing and would become close to the all-steel bearing.

2.3.1.2. Elastic–plastic model results. Three overrollings of the rolling element on the new dent were cumulated and the results showed:

-A Si3N4 rolling element would generate more plastic deformation pushing the raised edges downward and modifying the local edges slopes as observed in the tests, see Fig. 8(b).

-A small plastic zone just below the raised edges suffers from higher Von Mises stresses, plastic strain and shakedown hysteresis for the hybrid contact as illustrated in Fig. 8(a).

For the test condition 1 and the hybrid contact, the steel raceway raised dent edge undergoes further straining and work hardening but without straining beyond the plasticity plateau (blue dotted line for steel bearing and red dotted lines for the hybrid bearing in Fig. 8(c).

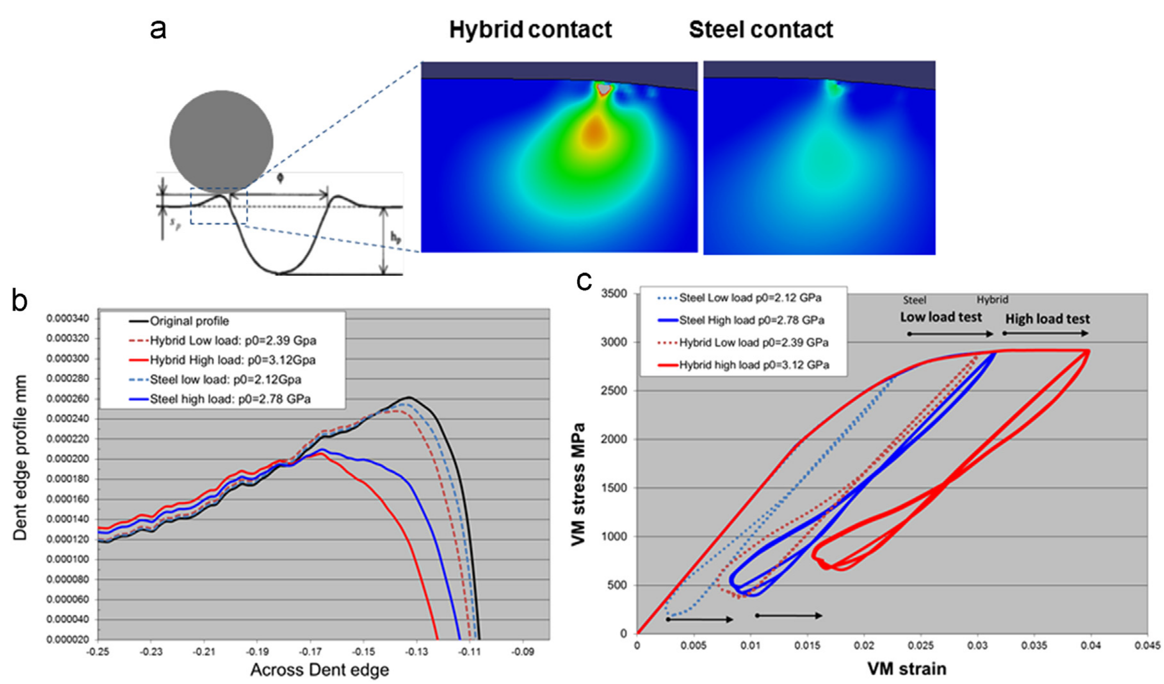

Fig. 8. Results from the dry 2D plain strain elastic–plastic model with zone of high von Misses stressed below raised edges in a), raised edge deformation after 3 overrolling in b) and shale down hysteresis analysis based on von Misses stresses in c). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Comparatively, in the all-steel contact, very limited strain hardening is produced. The hysteresis loop and integral of the loop for dissipated energy for the steel contact is very small indicating possible elastic shakedown stage (or borderline into plastic shakedown).

After the initial plastic deformation the steel contact does not sustain much plastic strain anymore. Experimentally, very small edge changes and pushing down over running time of 650 Mrevs were observed. The hysteresis loop is slightly bigger for the hybrid (clearer transition over into plastic shakedown – red dotted line in Fig. 8(c) where slightly more plastic strain would be accumulated but for a material volume that benefits from maximum strain hardening and higher residual stresses build up in the hybrid contact than in the steel contact. These considerations are possibly contributing to the good response of the dents in the hybrid bearings, where none of the dent indicated crack initiation risk under test condition 1, although higher nominal and local contact pressure are experienced.

However, for test condition 2, the all-steel and hybrid contacts show fairly similar plastic shakedown, hysteresis loop see Fig. 8(c). The experimentally observed difference of trailing edge reduction is less than 20% between the hybrid and all-steel contact. While the higher load condition enables the all-steel contact to benefit from the strain hardening effect, this effect is exhausted for the hybrid one. Due to this dominant plastic shakedown behavior, both all-steel and hybrid contact behave more in a similar way from a cumulated plastic strain response point of view on the steel raceway. Experimentally, the differences of edge deformation on the trailing edges were indeed very small between the 2 bearings compared with the lower load tests.

2.3.2. EHL and surface distress modeling

Micro-elastohydrodynamic lubrication (micro-EHL) modeling considering mixed-lubrication is attempted here, more than to give quantitative results is to give information on trends and behavior. Since in the experiments the dent diameters slightly exceeded the Hertzian contact width, thus some lubricant is expected to leak out from the dent, aggravating the lubrication conditions locally, more than the model can predict.

The surface distress (micropitting) model developed by one of the authors and described in [19] as applied in [8] and [20] is also used here to study the effects on hydrodynamic pressures, stresses and eventually surface distress of the artificial indentations for

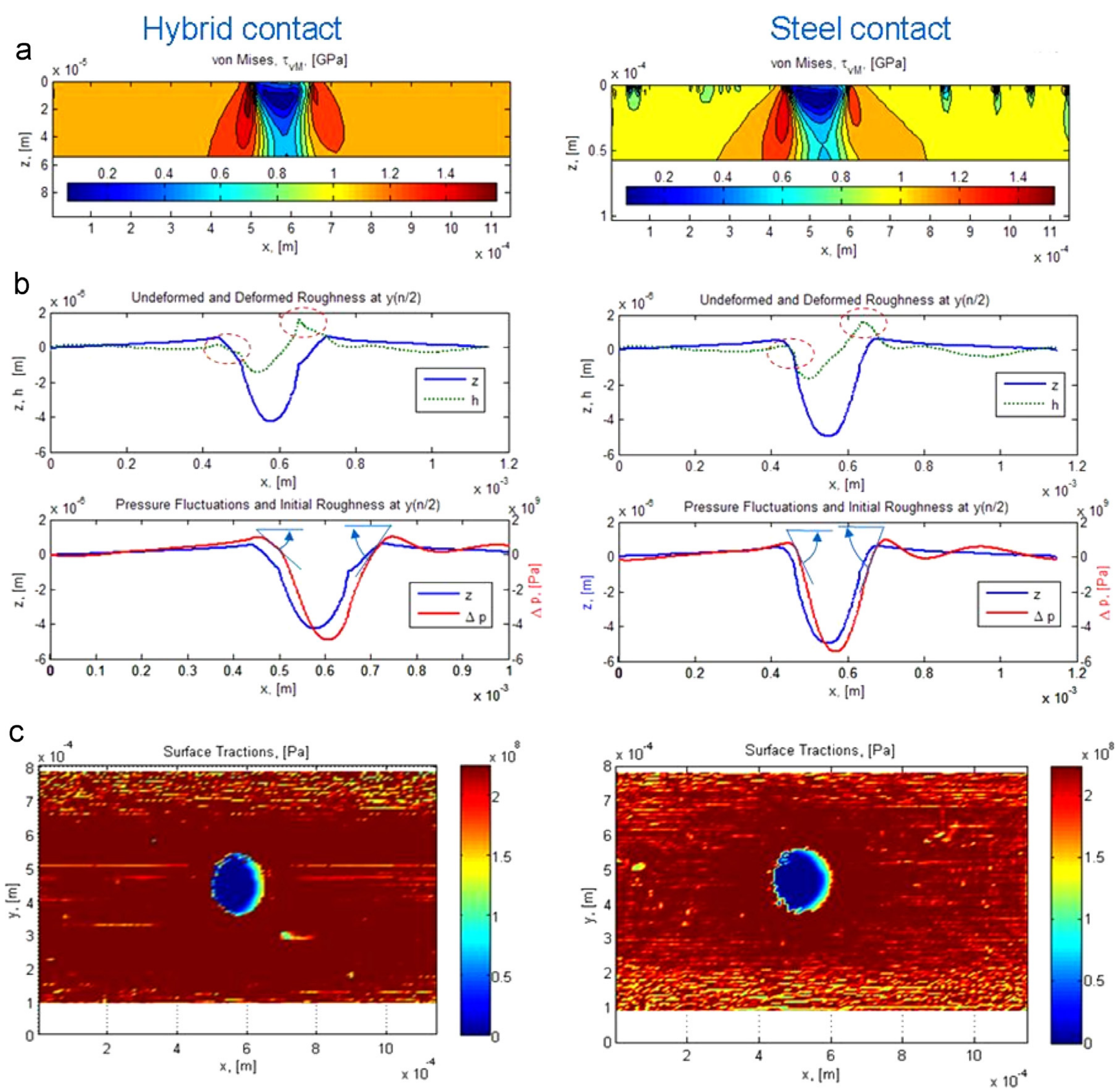

Fig. 9. EHL contact calculation based on interferometry measurement of the overolled dent at 360 Mrevs for test condition 1. The contact inlet or leading side is on the right of each picture, the trailing side on the left.

hybrid and all-steel bearings and their interaction with the lubrication conditions. Since the model has been described elsewhere it will not be repeated here. Just a brief explanation is added next.

The surface distress model [19] needs a micro-geometry measurement file of the two contacting surfaces in a matrix form, where the rows and columns represent axis directions and the matrix number represent the surface heights. This measurement is carried out with an optical microscope. The model then considers two moving (nominally flat) surfaces where the micro-geometry is contained, having a mean central clearance and pressure corresponding to the EHL conditions, these roughness samples are followed in time as they cross the EHL contact. Pressures and deformed clearances are calculated at each time step (according to the rapid methodology described in [21]) including mixed-lubrication effects. With the pressures, subsurface stresses are calculated and the stress history at every overrolling can be stored. After this, a fatigue criterion is applied (here Dang Van is used with the same material properties as described in [19]). Finally, a damage accumulation criterion is used (here the Miner-Palmgren rule is applied). After the specified number of overrollings in the simulation, the process is stopped and the areas in the surface or below that have exceeded the fatigue criterion are accounted as damaged areas and the total percentage of damaged surfaces is measured. This is the final result of the model.

For the cases considered here, the topography of the indents were measured as new and during the over-rolling times and were used in EHL contact simulations. A typical ball bearing sliding/rolling ratio value of 2% was selected. The test and simulations were performed using the same bearing load and therefore generating higher contact pressure in the hybrid contact. The surface distress model with given friction coefficients from the oil rheology and the boundary ("dry") contact can calculate the distribution of tractions on the surface by using a mixed-lubrication model, the generated stresses, thus include normal and tangential directions. Here for the boundary lubrication conditions, the parameters for hybrid and all-steel bearings given in [20] were used, allocating a boundary friction coefficient to the hybrid contact substantially lower than that of the all-steel contact.

Test condition 1 offered very good lubricating film (bearing lubrication quality, kappa > 4). Still, the subsurface von Mises stress maps for the all-steel bearing showed general surface damage with stress concentration points elsewhere (outside the dents) shown in Fig. 9(a), contrary to the hybrid bearing.

Neither a large difference in surface traction nor in the surface Palmgren-Miner crack accumulated risk were observed between the

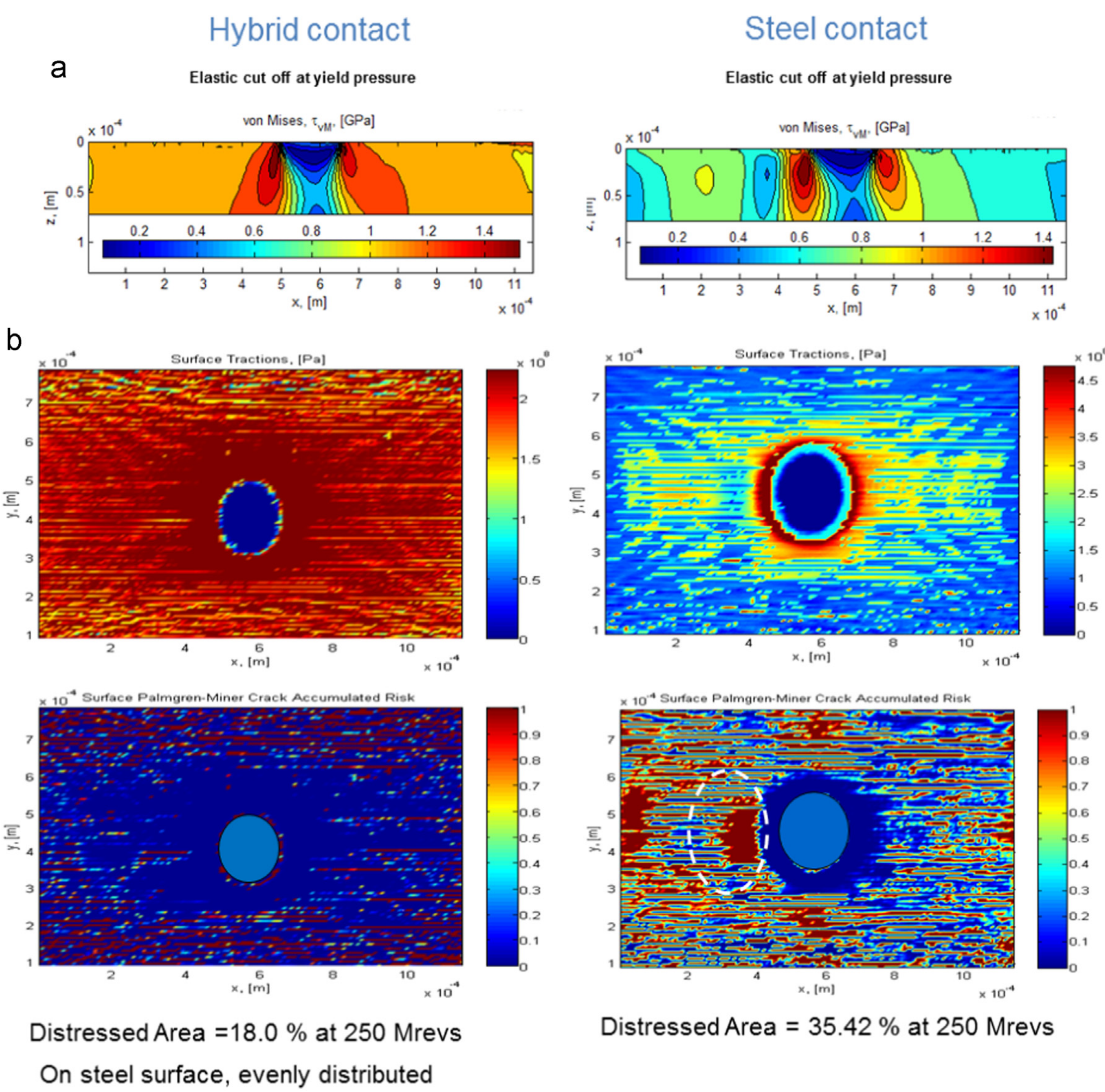

Fig. 10. EHL contact calculation based on interferometry measurement of the new dent for test condition 2 and simulated to 250 Mrevs for accumulated fatigue (≥ 1). The contact inlet or leading side is on the right of each picture, the trailing side on the left.

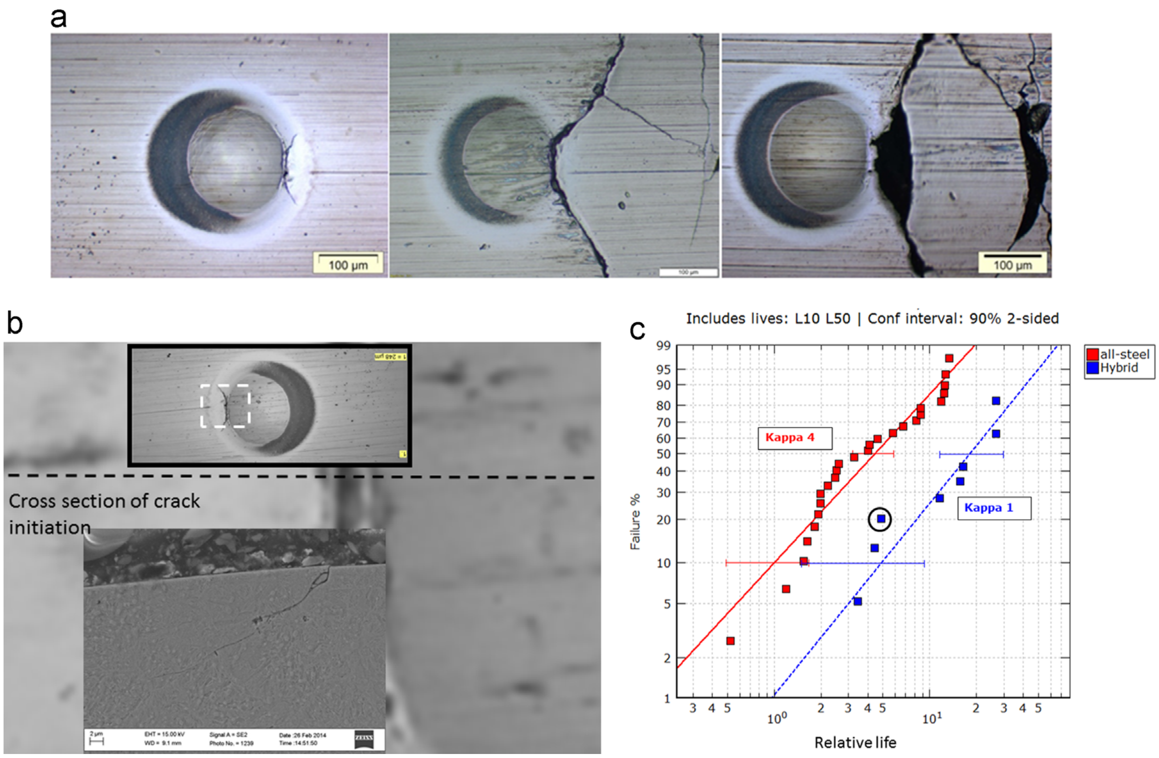

Fig. 11. Illustration of trailing edge damage progression to spalling for a hybrid bearing in a) and cross-section of early crack initiation in b) for the hybrid bearing with artificial dents on the inner ring and tested as indicated in Table 1. Relative dent life plot results in c) lives are calculated relative to the experimental L10 all-steel dent life Lref. All all-steel and hybrid dent lives results are divided by this Lref for the plot. The Beta for the all-steel life was 1.27, the Beta for the hybrid life was 1.44. The black circle highlights one of the experimental results for which modeling had predicted a high risk of crack initiation at this running time.

two contact configurations, Fig. 9(c). However, importing the measured dent shape after tests, showed that the re-conforming of the raised edges and change of surface slope for the hybrid contact reduces the pressure gradient experienced at the surface and in the thin layer below , Fig. 9(a) and (b). These dent shape changes were not found to affect much the film thickness only small reductions on the film thickness fluctuations are predicted, Fig. 9(b).

For test condition 2, the EHL simulations were performed on new dents and a different boundary lubrication condition coefficient for the all-steel and hybrid contact was considered as recommended in [13,20]. In this case the dent dimensions for the all-steel bearing and hybrid bearings were chosen as similar as possible.

Simulations to 250 Mrevs indicated a higher surface fatigue for the steel bearings. This can be seen in Fig. 10(b), where a map for the accumulated fatigue risk is shown for the analyzed indented surface.

The map shows the covered area with a cumulated Palmgren-Miner fatigue initiation risk equal or higher than the fatigue criterion. Based on this, the risk area is of the order of 35% mainly concentrated in the trailing edge of the dent for the all-steel contact, while the Hybrid contact would produce a lower distressed area more evenly distributed, see Fig. 10(b). These results are from a dent in the hybrid bearing test that was suspended at 250 Mrevs with no indication of upcoming failure by crack initiation. The dent in the all-steel bearing although suspended at 250 Mrevs had shown a very small crack initiated at the trailing edge.

However, as dent geometry can slightly vary, additional EHL simulations applied to other hybrid dent topographies showed that to a certain amount of Mrevs simulation range, risk of spalling by localized distressed area as high as 50% could be generated at the trailing edge of the dent. This is thus in line with the fact that such a dent L10 and L50 life was experimentally obtained in a corresponding operation time range, see following section.

Surface distress simulations applied on a new dent, which was suspended in the test, indicated low or no risk of crack initiation when simulated to experimental test time, other simulations on slightly different dent geometry indicated risk of failure to test time, of around 50% distressed area based on the simulations that experimentally gave a spall at this running time as illustrated in Fig. 11(c) by a black circle.

Based on tested surfaces, in addition to the reduction of local pressure indicated by dry FE analysis, EHL contact simulations indicated a reduction of pressure gradient at the dent raised edges in the hybrid thanks to the dent shape change.

Based on new surface and EHL simulation for fatigue damage, the trend and behavior predictions were in good agreement with the experimental results. The local area of high surface distress and crack initiation risk corresponds to the experimental results and give the same distinction between the steel and the hybrid contact than the observed in the tests.

2.4. Dent life

Dent life was determined by testing several bearings each one with 4 dents equally distributed on the inner ring raceway as described in Fig. 1 under the test conditions as indicated in Table 1. The all-steel bearings were tested in full-film conditions, while the hybrid bearings were tested with a poorer lubrication quality.

Spalling at the trailing edges of the dents was systematically observed with typical V-shaped surface initiated cracks; see Fig. 11 (a) and as discussed in [9]. Spalling characteristics by cross-section indicated a typical crack propagation angle of about 38° to the race surface as illustrated in Fig. 11(b) for a cross-section performed on one of the crack initiation stage.

Experimental dent life results show a longer L10 dent life for the hybrid bearing than for the steel bearing. With a 90% confidence:

- L10 dent hybrid $> 1.8 \times$ L10 dent steel
- L50 dent hybrid $> 1.12 \times$ L10 dent steel

The Weibull curve representative of this test is shown in Fig. 11 (c) given as relative life to the all-steel bearing life results.

3. Discussion

Mild wear was shown to play an important role in hybrid rolling contacts, particularly at the leading edges of indentations. While superficial plastic work and texturing by asperities contact roughening up to superficial adhesive wear or micro-smearing damage depending on the lubrication condition is found in the all-steel contact, the mild wear in the hybrid contact effectively re-conforms the leading raised edges of the dent thus reducing local pressures, pressure gradients while maintaining a very smooth surface on the steel surface and for the Si3N4 rolling element.

In the tests, the loading conditions were the same, thus higher nominal maximum contact pressures were acting in the hybrid contact (by 12%). From the FE analysis, a larger local plastic work for the hybrid contact upon the steel raceway raised dent edges can be beneficial at the trailing side, within a certain range of pressures (below $\sim$2.5 GPa). While the all-steel contact stays close to the elastic limit or has limited plastic hysteresis, the hybrid contact can take full advantage of the strain hardening material behavior and compressive residual stress build up from a more pronounced hysteresis strain–stress loop and plastic shakedown.

However, beyond a certain contact pressure the local plastic hysteresis will extend into the stress plateau area of the strain–stress loop for both contacts variants. For even larger strains in the hybrid contact no longer brings additional beneficial steel material response. Quite clear plastic work of the trailing edges was observed in the SEM for the hybrid contact for the higher contact pressure tests. The reduction of the raised edge height or re-conforming by plastic work was still slightly more pronounced (19%) than in the steel contact and still contributed to a better relative reduction of local stress concentration.

The hybrid bearing operating at higher maximum contact pressure and thinner film condition still gave a better dent life than the all-steel bearing operating at lower maximum contact pressure in full film. These findings can be seen as counter-intuitive given the higher contact pressure and poorer lubrication quality used for the hybrid bearing. From a film thickness point of view, the raised edge of the dent is possibly for both test conditions pronounced enough to break through the lubrication film.

Failure by V-shapes crack initiation at the trailing edge of the dents was observed for all-steel and hybrid bearings and as explained by modeling [9]. Initial pressures and stresses generated at the dent are, however, more changed and reduced relatively to the initial pressures, by mild wear and higher plastic deformations for the hybrid bearing. Surface distress simulations did support the trailing edge failure location (as they did for the all-steel bearing). The simulations also confirmed a noticeable change in the pressure concentration gradient at dent edges thanks to the re-conforming behavior in the hybrid contact when using the tested surface as input. It also showed a slight improvement in the film thickness fluctuations. The simulations also confirmed the trend observed in the experimental tests when applied to new dent geometry. High traction forces were seen in the all-steel contact around the dent, but not observed for the hybrid contact due to lower boundary friction. The higher traction forces contribute to near-surface stress concentration and faster fatigue accumulation in the all-steel bearing. The experimental spalling results were associated to a high risk of surface crack formation when that specific dent as new was processed through the model to similar running time. Suspended dents after long running times were associated to low risk of surface crack formation by the model when that specific dent geometry as new was processed through the model.

The mechanism described above may have beneficial effects for the performance of hybrid bearings in contaminated environment that may compensate to some extent the nominal or initial higher pressure and stresses in the hybrid bearing compared to the all-steel bearing under same loading condition.

4. Conclusions

Considering a similar artificial dent on a steel raceway of a rolling bearing, the current work shows:

1. The rolling contact life of hybrid bearings with indented steel rings raceways is superior to an indented all steel bearing when testing at the same load. This is in spite of the resulting contact pressure being slightly higher and the lubrication condition being worse for the hybrid bearing.
2. Several mechanisms observed in the hybrid bearings contributed to the improved dent response in rolling contact. Mild wear, higher plastic deformation and lower boundary friction contribute to a re-conforming of the raised edges of the dents, maintaining smooth surface and low surface traction on the steel surface and with accumulating overrolling cycles lowering local pressure concentration and their gradient.

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References

[1] G.E. Morales-Espejel, A. Gabelli, C. Vieillard, Hybrid bearings lubricated with pure refrigerant liquid, Turbomachinery 32 (7) (2004) 387–394.
[2] H.H. Wallin, G.E. Morales-Espejel, Hybrid bearings in oil-free air conditioning and refrigeration compressors, Evolution Online, 2011. ⟨http://evolution.skf.com⟩.
[3] B.O. Jacobson, G.E. Morales-Espejel, High pressure investigation of refrigerants HFC245fa, R134a and R123, in: Proceedings of the International Compressor Engineering Conference. Paper, 1789, 2006. ⟨http://docs.lib.purdue.edu/icec/1789⟩.
[4] L. Kahlman, Oil-flooded screw compressors: predicting MTBF under various H2S, CO2 and H2-rich conditions for rolling bearings designed for process gas use, in: Proceedings of the 2013 Gas Machinery Conference, Albuquerque, 2013.
[5] S. Coulon F. Ville A.A. Lubrecht, Experimental investigations of rolling contact fatigue of dented surfaces using artificial defects, Life Cycle Tribology, Elsevier, 2005, pp. 691–702.
[6] T. Udea, N. Mitamura, Mechanism of dent initiated flaking and bearing life enhancement technology under contaminated lubrication condition part I: effect of tangential force on dent initiated flaking, Tribol. Int. 41 (2008) 965–974.
[7] T. Udea, N. Mitamura, Mechanism of dent initiated flaking and bearing life enhancement technology under contaminated lubrication condition part II: effect of rolling element surface roughness on flaking resulting from dents, Tribol. Int. 42 (2009) 1832–1837.
[8] G.E. Morales-Espejel, A. Gabelli, The behaviour of indentation marks in rolling-sliding elasto hydrodynamically lubricated contacts, Tribol. Trans. 54 (2011) 589–606.

[9] G.E. Morales-Espejel, A. Gabelli, The progression of surface rolling contact fatigue damage of rolling bearing with artificial dents, Tribol. Trans. 58 (2015) 418–431.

[10] G.T.Y. Wan, A. Gabelli, E. Ioannides, Increased performance of hybrid bearing with silicon nitride balls, Tribol. Trans. 40 (4) (1997) 701–707.

[11] V. Strubel, N. Fillot, F. Ville, J. Cavoret, P. Vergne, A. Mondelin, Y. Maheo, Particle entrapment in hybrid lubricated point contacts, Tribol. Trans. (2015), http://dx.doi.org/10.1080/10402004.2015.1106631, accepted manuscript.

[12] W. Wang, P.L. Wong, F. He, G.T.Y. Wan, Experimental study of the smoothing effect of a ceramic rolling element on a bearing raceway in contaminated lubrication, Tribol. Lett. 28 (2007) 89–97.

[13] D.J. Mitchell, J.J. Mecholsky, J.H. Adair, All-steel and Si3N4 –steel hybrid rolling contact fatigue under contaminated conditions, Wear 239 (2000) 176–188.

[14] E. Tonicello, D. Girodin, C. Sidoroff, A. Fazekas, M. Perez, Rolling bearing applications: some trends in materials and heat treatments, Mater. Sci. Technol. 28 (1) (2011) 23–26.

[15] Y. Kadin, A.V. Rychahivskyy, Modeling of surface cracks in rolling contact, Mater. Sc. Eng. A 541 (2012) 143–151.

[16] A.F. Bower, K.L. Johnson, The influence of strain hardening on cumulative plastic deformation in rolling and sliding line contact, J. Mech. Phys. Solids 37 (1989) 471–493.

[17] M. Abdel-Karim, Shakedown of complex structures according to various hardening rules, Int. J. Pressure Vessels Pip. 82 (2005) 427–458.

[18] I.L. Arregui, B. Alfredson, Elastic–plastic characterization of a high strength bainitic roller bearing steel – experiments and modelling, Int. J. Mech. Sci. 52 (10) (2010) 1254–1268.

[19] G.E. Morales-Espejel, V. Brizmer, Micropitting modelling in rolling-sliding contacts: application to rolling bearings, Tribol. Trans. 54 (2011) 625–643.

[20] V. Brizmer, A. Gabelli, C. Vieillard, G.E. Morales-Espejel, An experimental and theoretical study of hybrid bearing micropitting performance under reduced lubrication, Tribol. Trans. 58 (2015) 829–835.

[21] G.E. Morales-Espejel, A.W. Wemekamp, A. Félix-Quiñonex, Micro-geometry effects on the sliding friction transition in elastohydrodynamic lubrication, Proc. IMechE, Part J: J. Eng. Tribol. 224 (2010) 621–637.