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STUDY OF THE INFLUENCE OF ABRASIVE PARTICLES ON A JOURNAL BEARING WITH A SOFT COATING (PB-CU-AL) UNDER BOUNDARY LUBRICATION CONDITIONS

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Abstract: *Some times operating conditions, namely, misalignment, overheating and the start/stop of engine generate boundary lubrication conditions increasing wear of journal bearings (JBs). Thus, debris are a consequence of wear and fatigue either from JBs or other lubricated mechanical components. Debris are commonly immersed in the oil and recirculated through the entire lubrication system interacting with all the lubricated mechanical elements and accelerating wear rate due to three-body abrasion. The aim of this work is to evaluate the effects of abrasive particles on the wear behaviour of sections of an actual JB coated with a soft alloy (Pb-Cu-Al) by replicating boundary lubrication in JBs using a micro-scale abrasion test set-up. Steel balls were used to replicate the shaft counter face for the tests. Initially, the tests were carried out with a slurry prepared with distilled water and SiC micro-particles at a concentration of 20% vol. On the other hand, a SAE 10W-30 engine oil was blended with SiC micro-particles at different concentrations to replicate an engine oil contaminated with abrasive particles. The slurry was tested at 26°C while the contaminated oil was tried at two different oil temperatures (26 and 100°C). The wear scars produced were measured and analysed by optical microscopy, SEM and contact profilometry. It was found that clean oil generated higher wear than oil contaminated with SiC particles at different concentrations since a layer of SiC particles was generated on the scars by embedment of many particles in the soft coating. It acted as protective layer for the JB's coating reducing wear. However, it generated significant wear in the ball surface.*

Keywords: *Journal bearings, oil contaminated abrasion, pure oily sliding wear, wear rate and abrasive particles.*

1. INTRODUCTION

Journal bearings (JBs) are components used to support a rotary shaft with a load applied, allowing relative motion between both elements (bearing and shaft) with relative low friction [1]. The motion is facilitated by a thin film of lubricant generating low friction by means of hydrodynamic lubrication conditions. The lubricant characteristics, conditions, texture, and coatings are the main parameters for consideration in the design and performance of these components. The operation of JBs is preferably expected to be under hydrodynamic lubrication regime (HL). However, operating situations, such as overheating, misalignment, oil ageing and debris generate premature damage due to wear caused by the transition from hydrodynamic to mixed, or even, boundary lubrication situations. Wear of JBs can be a consequence of corrosion, abrasion, adhesion, fatigue, cavitation, fretting and erosion [2, 3]. Nonetheless, the most common wear types in JBs are adhesive and abrasive wear produced by rupture of hydrodynamic film achieving the boundary lubrication regime. Also, the interaction with free abrasive particles (debris) in the oil causes damage in both the JB and the shaft. Severe damage of JBs and shafts results in machine shutdown and accidents, producing undesired high costs of maintenance and production stops [4].

There are two types of abrasion occurring in JBs: two-body abrasion and three-body abrasion. In two-body abrasion, the material is removed from the JB´s surface by hard protuberances on the shaft´s surface meanwhile three-body abrasion is generated by free hard particles (debris) that can roll and abrade both surfaces [5]. It happens commonly since much debris are immersed in the oil as a product from wear of other components, including those from JBs and shaft. To have a considerable effect of debris on wear of JBs, those particles should be larger than the minimum lubricant film thickness expected between the JB and the shaft [6].

In some research works [7-9], debris made of Fe, Al, Sn, Cu, Ag, SiC, SiN, silicates, and sand micro-particles have been found immersed at different concentrations in used engine oils. The hardness of such particles is in the range from 40 to 1300 HV depending of each material. As a reference, about 85 mg/kg of debris concentration was reported for an oil used in a four-cylinder engine during 100 hours in a bench test at a controlled temperature in the range of 88 and 110°C. [10].

The performance of JBs is mainly related to the material´s properties, namely, thermal conductivity, flexible conformability and debris embeddability [11-14]. Thermal conductivity refers to the intrinsic ability of a material to transfer or conduct heat. Flexible conformability is the ability to be deformed according to the shaft surface topographical characteristics meanwhile embeddability is referred to the capability of the material for trapping hard particles in the bearing surface to avoid damage caused by three-body abrasion for both the JB and the crankshaft. Embeddability is usually achieved in JBs by using soft coatings at the surface. However, soft coatings are highly susceptible to be damaged by two-body abrasion under boundary lubrication conditions [15, 16]. It usually produces abrasive and adhesive wear patterns. Adhesive wear is mainly ascribed to the chemical compatibility of the metallic surfaces in sliding contact producing high adhesion forces and seizure of JB material [15, 16]. Incompatibility between the steel shaft and the JB surface may be expected under boundary lubrication conditions (high loads, low speed, low viscosity of oil, etc.) producing increased wear and high friction coefficients.

Nowadays, most of commercial JBs are made of steel backs coated with an alloy made of Sb, Sn and Pb, which is named as “babbitt” alloy. There are two types of babbitt alloys, Sn-based and Pb-based alloys. The benefits of these coatings are related to properties, such as good chemical compatibility with steel shafts, good embeddability, low friction coefficient, ability to accommodate with small shaft misalignment and being a protective and/or sacrificial layer for scuffing (severe abrasion). Scuffing is expected to be produced in the running-in period and lubricant starvation [17-21].

In several studies, the tribological performance of JBs has been investigated by using different methodologies and testers, the most common being the pin-on-disk tester, full-scale test rigs and the block-on-ring tester [3, 22-25]. Also, experimental tests combined with simulation works have been used to investigate wear caused by metal-to-metal sliding contact in the start-stop process in JBs [6, 26-28].

According to the literature reported about wear of JBs, the effects of hard particles acting as contaminant in engine oil on the wear behaviour of JBs with soft coatings has been scarcely studied. Sep et al. [6] carried out tests of JBs in a test rig (ZAN research rig) using an oil (SAE 40) clean and contaminated with hard aluminium oxide powder (spherical micro-particles with a diameter of 21µm). The test bench allowed trying complete conventional JBs under lubricated conditions including contaminant particles. Overall, they found that wear of JBs is increased when the oil is contaminated with hard particles in comparison with clean oil [6]. In other research work, Gebretsadik et al. [29] studied the embeddability of JBs with a soft overlaying made of Pb-Free by full-scale tests using an engine oil (SAE 10W 30) contaminated with SiC particles at 95°C. The results suggested that three-body abrasion is mainly influenced by the variation of the lubricant film thickness at the different operating conditions (rotational speed of the shaft, dynamic loads and misalignment) [29].

This paper aims to contribute within a study of the effects of micro-abrasive particles on the wear behaviour of a commercial JB with a soft coating (Pb-based lining alloy (Babbitt)) under boundary lubrication conditions. To restrict effects of variations in parameters, such as sliding speed and distance, shaft misalignments, vibrations, oil temperature, as well as to accelerate the wear test and have an accurate control of the boundary lubrication regime conditions, an approaching test using a micro-abrasion tester was developed and used. The method has been demonstrated to be effective to reproduce wear features occurred in actual JBs in lubricated condition, generating small wear scars with defined geometry by saving time, lowering testing cost and allowing accurate wear scar measurements in comparison with other wear test techniques for JBs [30]. Steel balls were conditioned and used to reproduce the characteristics of typical shafts. Initially, as a reference to evaluate the pure effect of the abrasive particles on wear of the JBs and steel shaft material, conventional micro-abrasion tests [30-33] were carried out for JB samples using a slurry made of SiC micro-particles suspended in distilled water. Finally, tests were conducted under boundary lubrication regime using different concentrations of abrasive particles (SiC micro-particles) suspended in an engine oil (EO) at 26 and 100°C, respectively.

2. TESTS CHARACTERISTICS

2.1 Test set-up

Figure 1 shows a schematic view of the test set-up used. A micro-scale abrasion tester (TE-66) was adapted to perform the abrasive wear tests. The tribometer is equipped with a pivoted L-Shaped arm. Together the arm and the counterbalance allow the application of a predefined normal load between the steel ball and the JB by using dead weights.

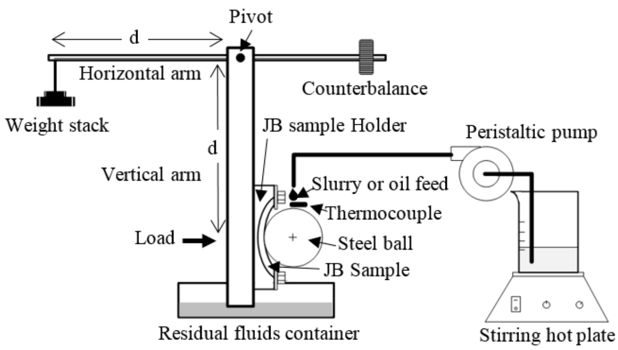

Figure 1. Schematic view of the tester arrangement.

A specimen cut from the JB is mounted in the arm by using a special holder while a steel ball sample is fixed between two coaxial shafts with auto-alignment, enabling the tangential contact of the ball and sample. The steel ball is rotated at constant speed and specified cycles by an electric motor. A stirring hot plate with a magnetic agitator was incorporated in the test arrangement to keep suspended the abrasive particles either in oil (contaminated oil) or distilled water (slurry) in a beaker and to heat up the temperature of the oil simultaneously.

A peristaltic pump is used to move the fluids from the beaker to the sliding contact region. The oil temperature is monitored in the dripping region exactly located upper the ball through a thermocouple.

2.2 Test samples

An actual automotive JB was sectioned to obtain samples with adequate geometry for the tests. The JB tested was made by two different coatings (a lining and an overlaying) on the steel substrate. The chemical composition of each coating was estimated through EDS analysis, see Table 1. Also, the thickness and elastic modulus were measured by Scanning Electron Microscopy (SEM) and instrumented nanoindentation tests, respectively. The results from the characterizations can be seen in Fig. 2a and Table 2.

Table 1. Chemical composition of the coating of JB

JB sample	Chemical composition (wt%)					
	C	O	Al	Fe	Cu	Pb
Overlaying	-	13.2	0.6	-	3.8	82.4
Lining	-	-	1.1	-	98.9	-
Substrate	4.7	-	0.5	94.8	-	-

Table 2. Mechanical properties of the specimens.

Sample	Steel ball	JB	
		Overlaying	Lining
Hardness (HV)	848 ± 17	10.7 ± 3.8	92.1 ± 6.4
E (GPa)	200 ± 10	7.85 ± 2.8	61.9 ±2.5
Poisson´s ratio	0.27	0.44	0.34
Roughness (µm)	0.22 ± 0.02 Ra 0.35 ± 0.03 Ra	0.87 ± 0.1 Sa	-

The ball specimens tested were made of steel (AISI 52100) with 25.4 mm in diameter. The steel ball´s mechanical properties are also given in Table 2. In order to achieve two different ball roughness, one required for conventional micro-abrasion tests using slurry (about 0.3 µm) while the other required to replicate the roughness of actual shafts (around 0.2 µm) using oil for the tests, the balls were etched into 20% nital solution during 30 and 8 s, respectively. The highest roughness is required in conventional micro-abrasion tests to allow abrasive particles being dragged along the contact interface [31-33]. Meanwhile, the lowest roughness is only to achieve an approached surface finishing suggested for actual crankshafts (0.20 – 0.25 µm Ra) through controlled pitting.

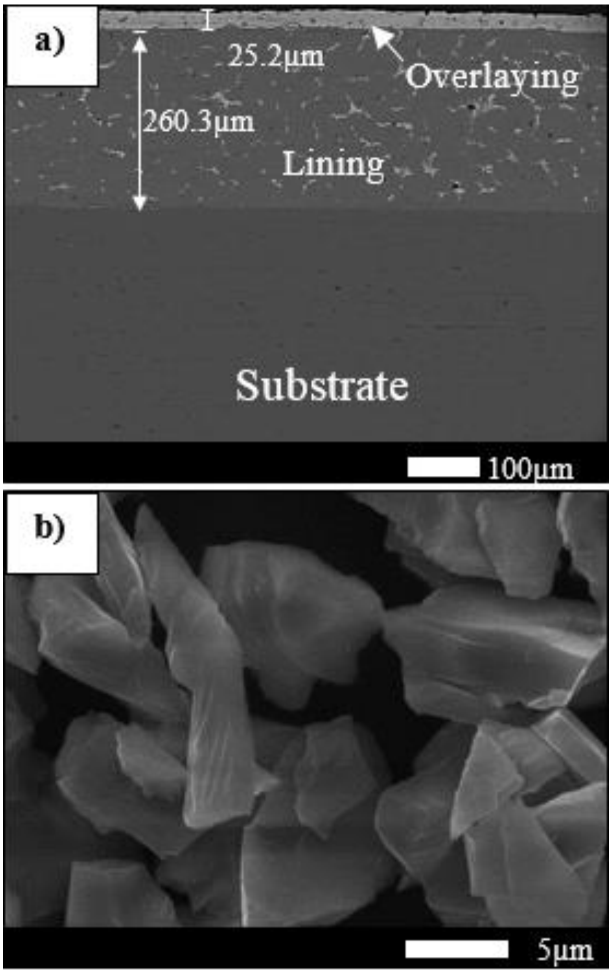

Figure 2. Electronic microscopy; a) SEM image from the cross-section of the sample; b) SEM image from the SiC particles tested.

The SiC particles were used to act as debris in the tests, with a mean particle size of 8 µm with angular shapes, as illustrated in Figure 2b. On the other hand, distilled water and a commercial engine oil (EO) with 10W-30 API SN/GF-5 specification were used to prepare the slurry and the contaminated oil samples, respectively. The EO viscosities were 112 and 12.4 cSt at 25 and 100°C, respectively.

2.3 Test procedure

The set of tests was established and carried out to examine the wear patterns and behaviour of the JB samples at different SiC micro-particles concentrations and temperatures. The tests conditions selected for the experiments are shown in Table 3.

Table 3. Test parameters.

Parameters	Micro-abrasive method	Micro-abrasive oily wear
Lubricant	Distilled water	EO
Normal force [N]	1	1
SiC particles concentration	20% [vol.]	0, 40, 80, 120, 160 [mg/kg]
Ball cycles	50, 100, 150 and 200	10 000
Sliding distance [m]	4, 8, 12, 16	798
Tangential sliding velocity [m/s]	0.11	0.22
Number of repetitions	3	3
Contact pressure [MPa]	110	110
Temperature [°C]	25	25, 100

Firstly, the micro-abrasive wear tests were carried out under parameters, namely, load, sliding velocity and abrasive slurry concentration specified in the classic micro-abrasion test reported for different materials in [3, 33]. The sliding distance was varied from 4 to 16 m (50, 100, 150 and 200 cycles) to evaluate the wear progression. For these tests, the steel ball sample was rotated every 50 cycles since it exhibited significant visual damage in the wear track in previous trials run after 50 cycles, which may influence the wear progression. Afterwards, wear tests were carried out using the clean EO and EO contaminated with SiC micro-particles at different concentrations (40, 80, 120, 160 mg/kg). These tests will be named as micro-abrasive oily wear tests in the following. The concentrations used were selected to approach the typical quantity of wear debris concentration found in used engine oils [10]. The oil samples were tested at 25 and 100 °C at the same load than that used for the micro-abrasive wear tests approaching the boundary lubrication regime. The regime was determined through the theory developed by Hamrock for elasto-hydrodynamic lubrication in elliptical conjunctions [34] and lambda ratio equations [35, 36]. These set of tests were carried out at a sliding speed of 0.22 m/s during 10,000 ball cycles to produce measurable and consistent wear scars.

3. RESULTS AND DISCUSSION

3.1. Damages on the journal surface

Micro-abrasive wear

The wear volume of scar was considered to have the shape illustrated in Figure 3a. Where a and b dimensions were measured by using optical microscopy while h was measured by using a contact profilometer obtaining the wear scar profile, as seen in Figure 3b.

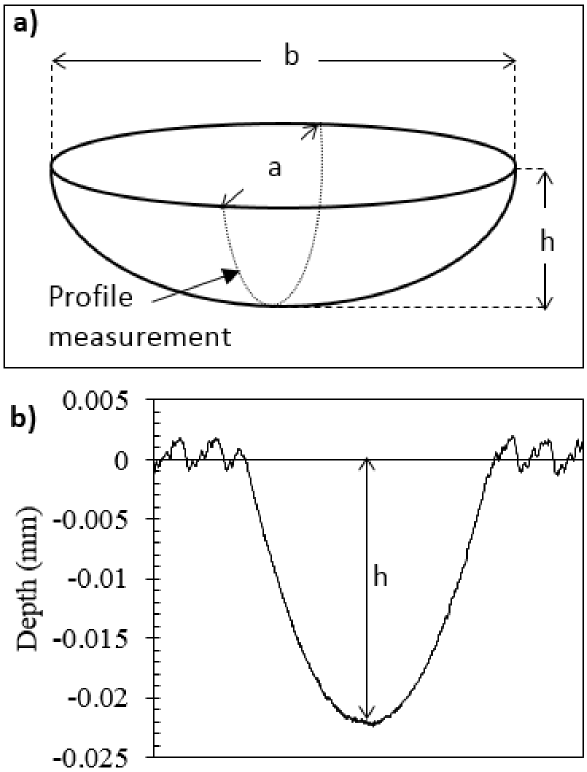

Figure 3. Measurement of wear scar; a) axes measurement, b) scar profile measurement

The wear scars had an elliptical shape due to the ball-on-concave flat sliding contact produced in these tests. Therefore, the Vwear and wear coefficient k were calculated by using Equations 1 and 2, respectively.

$$V_{Wear} = \frac{1}{6}(\pi * a * b * h) \quad (1)$$

$$k = \frac{V_{wear}}{S*P} \tag{2}$$

Where:
a = minor axis
b = mayor axis
h = wear scar depth
S = sliding distance
P = load

The micro-abrasion wear volumes obtained at for the sliding distances are showed in Figure 4. Wear volumes presented a proportional increase with sliding distance. Figure 5 shows a SEM image from a representative wear scar produced for a sliding distance of 16 m (200 cycles).

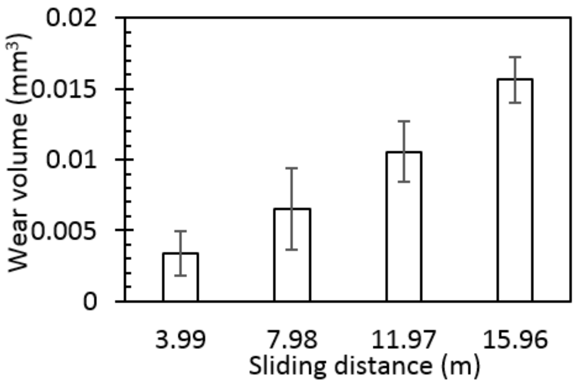

Figure 4. Wear volume obtained at different sliding distances by micro-abrasion tests using slurry.

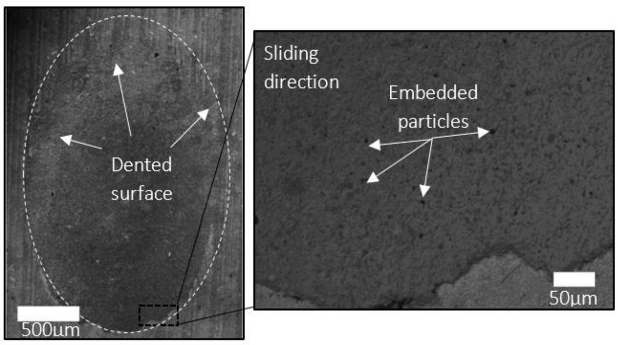

Figure 5. Example of SEM image from a wear scar produced by using slurry for 200 cycles.

All the scars produced by micro-abrasive wear exhibited similar wear patterns. The wear scar shows many embedded particles on the overlaying, which may be caused by the high embeddability of the coating. Besides, several indentations can be seen in the scar. The indentations and SiC embedment in the JB sample were produced by rolling and tumbling of the abrasive particles due to the ball sliding [6, 8, 29]. They are the main characteristics of rolling abrasion that can be considered as the predominant wear mechanism. Rolling abrasion mechanism is typically produced at large concentrations of hard particles at high contact pressures [37]. The accumulation and embedment of sic particles in the scar was confirmed by conducting EDS analysis.

Wear produced by using clean oil

The comparison of wear volumes obtained using clean oil at 25 and 100°C can be seen in Fig. 6. It can be seen a significant difference of wear volume obtained at both temperatures. It is attributed to the considerable oil viscosity reduction at 100°C, generating more reduced lubricating films conductive to more severe lubricated sliding wear.

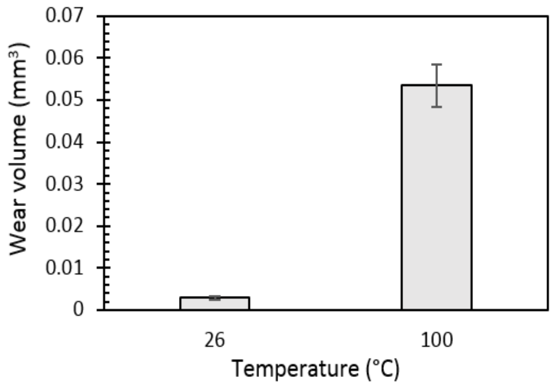

Figure 6. Wear volume by using clean oil

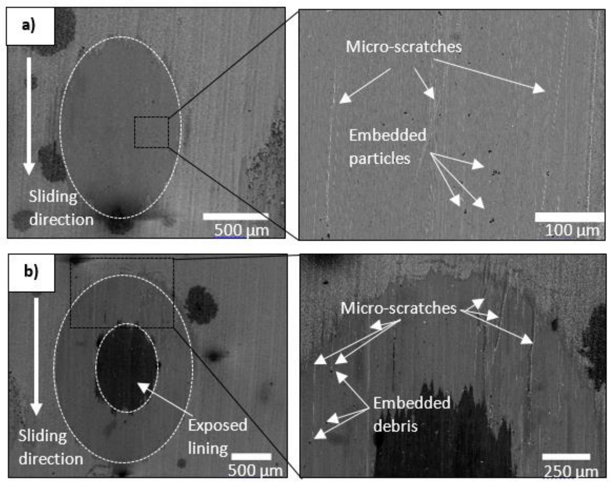

Figure 7. Example of a SEM image from a wear scar obtained by using clean oil at: a) 26 °C, b) 100 °C.

An example of a wear crater produced by using clean oil at both temperatures can be seen in Figures 7a-b. In contrast with the scars produced by micro-abrasion, the scars produced by using clean oil did not showed indentations, but they showed a shiny appearance produced mainly by polishing due to lubricated sliding wear. In addition, some micro-scratches were identified in the scar. They can be ascribed to three-body abrasion produced by wear particles detached from the JB by wear or two-body abrasion caused by large asperities of the ball. The wear produced at 25°C was evidently less severe than that produced at 100°C. It can be also seen in Figs. 7a-7b. The test at 25°C only generated wear on the overlaying (Fig. 7a) while the test at 100°C causes perforation of the overlaying generating wear on the lining material too (Fig. 7b).

Micro-abrasive oily wear

The comparison of wear volumes of scars produced using oil contaminated with different SiC concentrations are shown in Figures 8a-b. The plots present the evolution of wear volume with SiC concentration at 26 and 100°C, respectively. Figure 8a suggests that the lowest wear volume was obtained using a SiC concentration of 160 mg/kg at 26°C while Figure 8b suggests that the lowest wear volume was produced using a concentration of 120 mg/kg at 100°C.

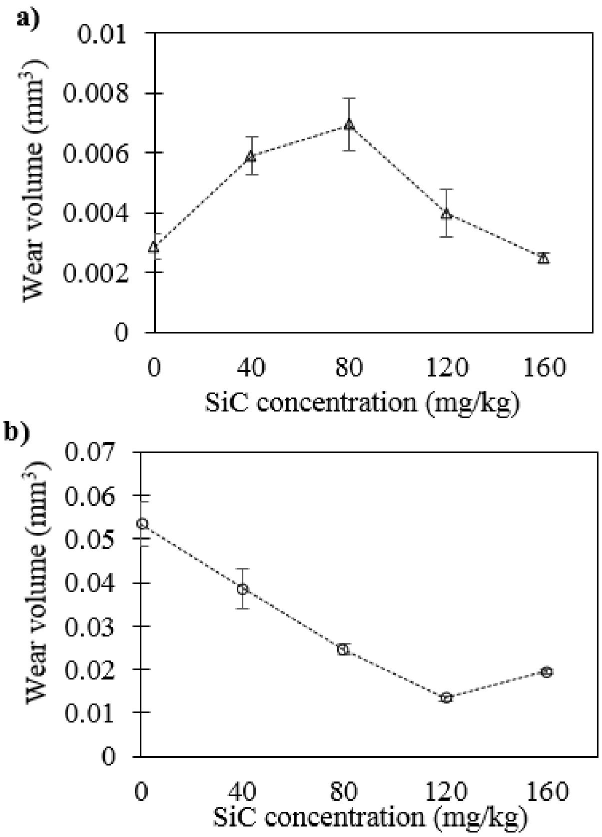

Figure 8. Wear volumes obtained from the micro-abrasive oily tests at: a) 25°C; b) 100°C.

In both Figures, the wear volume tended to decrease at high SiC concentrations in the oil. This phenomenon can be attributed to the formation of a layer made of many embedded SiC particles in the scar promoting a mechanical wear protection that decrease abrasive wear on the JB's surface.

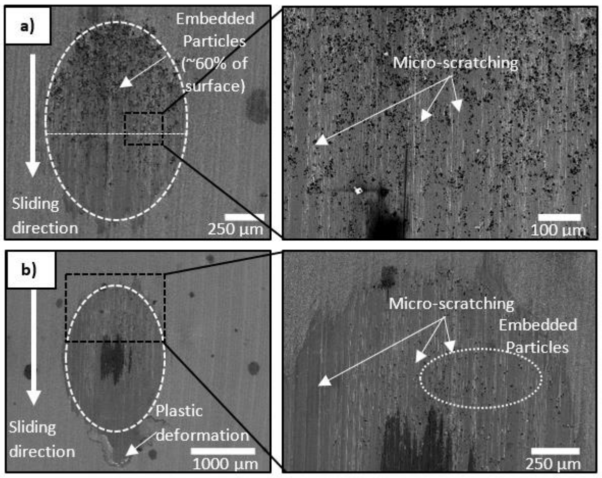

Figure 9. SEM image of wear scar of the micro-abrasive oily test using a SiC concentration of 80 mg/kg at; a) 26°C; b) 100°C.

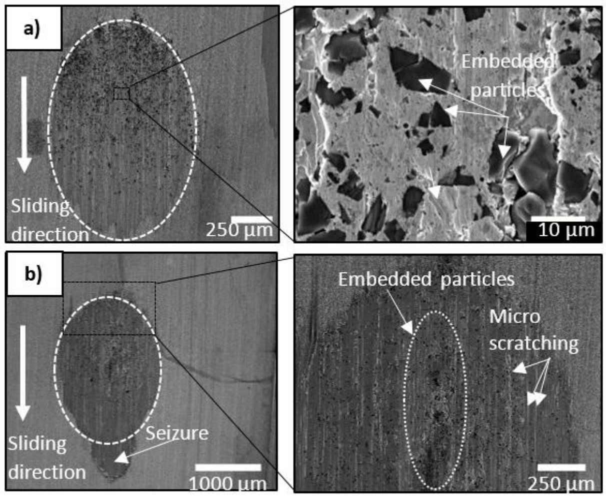

Figure 10. Example of a SEM image of wear scar obtained by a micro abrasive oily test using a SiC concentration of 160 mg/kg at: a) 26°C; b) 100 °C.

It is evidenced in Figures 9a-9b and 10a-10b where a lot of SiC particles were embedded on almost 60% of the JB sample's surface by using EDS analysis. SiC embedment and micro-scratching were the main wear patterns identified in all the scars. The highest wear volume was exhibited by the clean oil at 100°C and it was decreased with the increase in SiC concentration, as it can be seen in Figure 9b. It suggests that two-body abrasion generated by oily sliding wear is more critical than three-body abrasion for this coating. It means that the soft coating helps to reduce wear in the presence of debris, but it is very susceptible to wear by boundary lubrication situations.

3.2 DAMAGE ON THE STEEL BALL SURFACE

The wear produced in the ball by using clean oil was minimal, even it was not visible. In contrast, it was found that micro-abrasion produced in the JB samples by using both slurry and contaminated oil, in particular, at high SiC concentrations, caused severe damage on the steel ball surface.

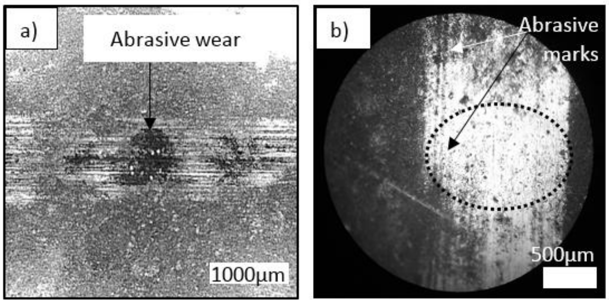

Figure 11. Examples of optical micrographs from a wear track on the ball surface produced by using: a) 80 mg/kg of SiC concentration; b) 160 mg/kg of SiC concentration.

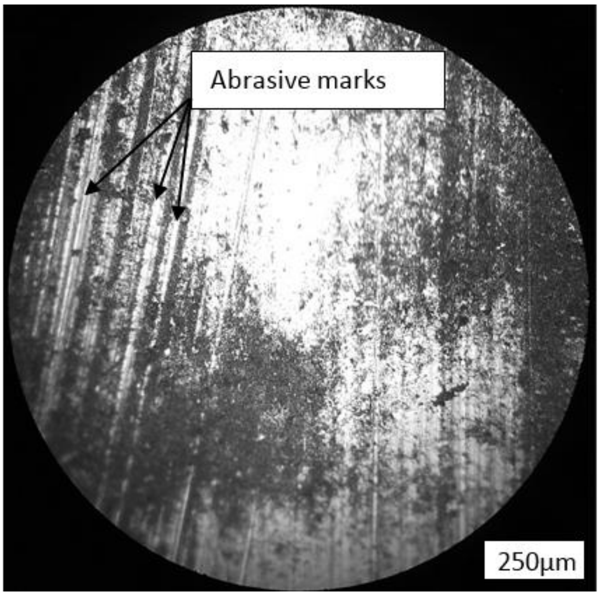

Figure 12. Example of an optical micrograph from a wear track produced on the steel ball surface using the contaminated oil sample at a SiC concentration of 160 mg/kg.

It generates wear tracks with visible abrasive marks, as it can be seen in Figures 11a-11c and 12. The most critical damage to the ball was produced by using slurry. However, contaminated oil at the higher SiC concentrations (80 to 160 mg/kg) generated significant wear tracks in the ball surface.

Pitting, grooving, ploughing and polishing were the main wear patterns exhibited at high SiC concentrations. These wear patterns can be considered as severe for shafts in actual applications.

Overall, the JB tested could prevent wear caused by debris in the oil but it may be very susceptible to be damaged by boundary lubrication situation such as engine start-stop, misalignments, overheating, etc., decreasing the JB's life and promoting premature failures. Although limiting wear by debris in JBs could be considered as positive, the embedment of debris in the soft coating can accelerate significantly wear in shafts. It perhaps generates more severe failures involving not only the JBs but also the shafts.

4. CONCLUSIONS

According to the findings in this work, it can be stated that clean oil generated higher wear than oil contaminated with SiC particles at different concentrations under boundary lubrication conditions. Also, the wear volumes were reduced even more with the increase in SiC concentration in the oil.

A layer of SiC particles was generated on the scars produced by using contaminated oil by embedment of many particles in the soft coating. It acted as protective layer for wear of the coating reducing wear volumes. However, the protective layer for the coating resulted as aggressive for the steel ball since the ball surface exhibited significant wear with severe abrasive marks.

The predominant wear mechanisms in JB samples tested with clean oil were slight abrasive marks and polishing meanwhile with oil contaminated with SiC particles exhibited patterns such as much particles embedment, micro-scratches, rolling abrasion and polishing.

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REFERENCES

[1] P.R.N. Childs, Journal bearings. In Mechanical Design Engineering Handbook, Elsevier Ltd, Butter worth Heinemann, United Kingdom, 2014, http://dx.doi.org/10.1016/B978-0-08-097759-1.00005-8.

[2] H. Singh, S.S. Sen, Wear in hydrodynamic journal bearings: a review, Int. J. Mod. Eng. Res., Vol. 4, No. 8, pp. 45–57, 2014.

[3] A. Vencl, A. Rac, Diesel engine crankshaft journal bearings failures: case study, Eng. Fail. Anal. Vol. 44, pp. 217–228, 2014, doi: 10.1016/j.engfailanal.2014.05.014

[4] Y. H.e, Z. Zhao, T. Luo, X. Lu, J. Luo. Failure analysis of journal bearing used in turboset of a power plant. Mater Des, Vol. 52, pp. 923–931, 2013.

[5] I. Hutchings, P. Shipway, 6 - Wear by hard particles, Editor(s): Ian Hutchings, Philip Shipway, Tribology (Second Edition), Butterworth-Heinemann, 2017, Pages 165-236, ISBN 9780081009109.

[6] J. Sep, A. Kucaba-Pietal, Experimental testing of journal bearings with two-component surface layer in the presence of an oil abrasive contaminant, Wear, Vol. 249, pp. 1090–1095, 2001.

[7] GK. Nikas. A state-of-the-art review on the effects of particulate contamination and related topics in machine-element contacts. Proc Inst Mech Eng Part JJ Eng Tribol, Vol. 224, pp. 453–479, 2010.

[8] MM. Khonsari, ER. Booser. Effect of contamination on the performance of hydrodynamic bearings. Proc Inst Mech Eng Part J J Eng Tribol., Vol. 220, pp. 419–428, 2006.

[9] M.H. Jones, Wear debris associated with diesel engine operation, Wear, Vol. 90, pp. 75– 88, 1983.

[10] Y. Zhang , J. Mao & Y. Xie, Engine Wear Monitoring with OLVF, Tribology Transactions, Vol. 54, No. 2, pp. 201-207, 2001, DOI: 10.1080/10402004.2010.534838

[11] H. Wu, Q. Bi, S. Zhu, J. Yang, W. Liu. Friction and wear properties of Babbitt alloy 16-16-2 under sea water environment, Tribol Int, Vol. 44, pp. 1161–7, 2011.

[12] AR. Lashin, M. Mossa, A. El-Bediwi, M. Kamal. Study of some physical properties of the rapidly solidified Sn–Sb–Cu–Zn alloys. Mater Des, Vol. 43, pp. 322–6, 2013.

[13] A. Zeren. Embeddability behaviour of tin-based bearing material in dry sliding. Mater Des, Vol. 28, pp. 2344–50, 2007.

[14] D. Zhang, J. K.L. Ho, G. Dong, H. Zhang, M. Hua. Tribological properties of Tin-based Babbitt bearing alloy with polyurethane coating under dry and starved lubrication conditions, Tribology International, Vol. 90, pp. 22-31, 2015, doi: 10.1016/j.triboint.2015.03.032

[15] A.E. Bravo, H.A. Durán, V.H. Jacobo, A. Ortiz, R. Schouwenaars, Towards new formulations for journal bearing alloys, Wear, Vol. 302, Iss. 1–2, pp. 1528-1535, 2013, doi: 10.1016/j.wear.2013.01.040.

[16] E. Rabinowicz: The Determination of the Compatibility of Metals Through Static Friction Tests, ASL E Transactions, Vol. 14, No. 3, pp. 198–205.

[17] Q. Wang & H. S. Cheng, A Mixed Lubrication Model for Journal Bearings with a Thin Soft Coating—Part I: Contact and Lubrication Analysis, Tribology Transactions, Vol. 38, No. 3, pp. 654-662, 1995, DOI: 10.1080/10402009508983455

[18] E. Feyzullahoglu, A. Zeren, M. Zeren. Tribological behaviour of tin-based materials and brass in oil lubricated conditions. Mater Des, Vol. 29, pp. 714–20, 2008.

[19] D. Tabor, The frictional properties of some white metal bearing alloys: the role of the matrix and the hard particles. J Appl Phys, Vol. 16, pp. 325–37, 1945.

[20] B.S. Ünlü. Investigation of tribological and mechanical properties of metal ¨ bearings. Bull Mater Sci, Vol. 32, pp. 451–7, 2009.

[21] M.Ö. Bora, O. Coban, T. Sinmazcelik, V. Günay, M. Zeren, Instrumented indentation and scratch testing evaluation of tribological properties of tin-based bearing materials. Mater Des, Vol. 31, pp. 2707–15, 2010.

[22] K.S. Pondicherry, F. Grün, I. Gódor, R. Bertram, M. Offenbecher, Applicability of ring-on-disc and pin-on-plate test methods for Cu–steel and Al–steel systems for large area conformal contacts, Lubr. Sci., Vol. 25, pp. 231–247, 2013, doi: 10.1002/ls.1187.

[23] F. Summera, F. Grüna, J. Schiffera, I. Gódora, I. Papadimitriou. Tribological study of crank

shaft bearing systems: comparison of forged steel and cast iron counterparts under start–stop operation, Wear, Vol. 338–339, pp. 232–241, 2015, doi: 10.1016/j.wear.2015.06.022.
[24] E. Feyzullahoglu, N. Sakiroglu, The wear of aluminium-based journal bearing materials under lubrication, Mater. Des., Vol. 31, pp. 2532–2539, 2010, doi: 10.1016/j.matdes.2009.11.037.
[25] H. Singh, M.S. Sethi, O.S. Bhatia, Wear rate analysis of hydrodynamic journal bearing in different conditions, Int. J. Mod. Eng. Res. Vol. 4, No. 10, pp. 60–69, 2014.
[26] D.E. Sander, H. Allmaier. Starting and stopping behavior of worn journal bearings. Tribology International, vol. 127, pp. 478-488, 2018, doi: 10.1016/j.triboint.2018.06.031
[27] X. Wang, L. Zhou, M. Huang, X. Yue, Q. Xu. Numerical investigation of journal misalignment on the static and dynamic characteristics of aerostatic journal bearings, Measurement, Vol. 128, pp. 314-324, 2018.
[28] J. Sep, L. Tomczewski, L. Galda, A. Dzierwa, The study on abrasive wear of grooved journal bearings, Wear, Vol. 376–377, pp. 54-62, 2017, doi: 10.1016/j.wear.2017.02.034.
[29] W. Daniel, Gebretsadik, J. Hardell, B. Prakash: Embeddability behaviour of some Pb-free engine bearing materials in the presence of abrasive particles in engine oil, Tribology - Materials, Surfaces & Interfaces, 2019, DOI: 10.1080/17515831.2019.157445
[30] L.I. Farfán-Cabrera, E.A. Gallardo-Hernández. Wear evaluation of journal bearings using an adapted micro-scale abrasion tester, Wear, Vol. 376-377, pp. 1841–1848, 2017.
[31] R.I. Trezona, I.M. Hutchings. Three-body abrasive wear testing of soft materials, Wear, Vol. 225–229, pp. 205–214, 1999, doi: 10.1016/S0043-1648(99) 00183-0.
[32] D.N. Allsopp, R.I. Trezona, I.M. Hutchings, The effects of ball surface condition in the micro-scale abrasive wear test, Tribol. Lett. Vol. 5, No. 4, pp. 259–264, 1998, doi: 10.1023/A:1019178716408.
[33] K.L. Rutherford, I.M. Hutchings, Theory and application of a micro-scale abrasive wear test, J. Test. Eval., Vol. 25, pp. 250–260, 1997, doi: 10.1520/ JTE11487J
[34] B.J. Hamrock, S.R. Schmid, B. Jacobson, Fundamentals of fluid film lubrication, Second Edition, Mercel Dekker Inc, New York, pp. 504–538, 2004.
[35] R.S. Fein, High pressure viscosity and EHL pressure-viscosity coefficient, In Tribology Data Handbook, CRC Press, Boca Raton, Fla, pp. 3–33, 1997.
[36] I.M. Hutchings, Tribology, friction and wear of engineering materials, First edition, Butterworth-Heinemann, pp. 58–73, 1992.
[37] K. Adachi, I.M. Hutchings, Wear mode-mapping for the micro-scale abrasion test, Wear, Vol. 255, pp. 23–29, 2003.