Journal of Molecular Liquids 382 (2023) 122013

Contents lists available at ScienceDirect

Journal of Molecular Liquids

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

Phosphonium-based ionic liquids as grease additives in rolling bearing tests

M. Bartolomé [a,*], D. Gonçalves [b], A. García Tuero [c], R. González [a,d], A. Hernández Battez [c,d], J.H. O. Seabra [e]

[a] Department of Marine Science and Technology, University of Oviedo, Blasco de Garay, s/n, 33203 Gijón, Spain
[b] INEGI, Universidade do Porto, Faculdade de Engenharia, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal
[c] Department of Construction and Manufacturing Engineering, University of Oviedo, Pedro Puig Adam, s/n, 33203 Gijón, Spain
[d] Faculty of Science & Technology, Bournemouth University, Poole BH12 5BB, United Kingdom
[e] FEUP, Universidade do Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal

ARTICLE INFO

Keywords:
Phosphonium ionic liquids
Additive
Greases
Rolling bearings
Friction torque
Wear

ABSTRACT

Two phosphonium-derived ionic liquids: trihexyltetradecylphosphonium bis(2-ethylhexyl)phosphate (IL1) and trihexyltetradecylphosphonium tricyanomethanide (IL2) were used as additives in lithium complex- (G1) and anhydrous calcium-based (G2) greases at 5 wt%. Friction torque and wear tests were performed using a modified four-ball machine for testing rolling bearings in order to determine the friction and wear reducing properties of these grease samples in a real component. The IL2 improved the friction reduction performance of both greases, especially G1. Both ILs improved the antiwear behaviour of grease G2. Grease G2 showed higher oxidation and thermal ageing levels than G1, but the addition of the ILs, IL2 in particular, improved this issue.

1. Introduction

Lubricating greases are the most commonly used lubricants in rolling bearings. More than 90% of rolling bearings are sealed for life, and they use grease to ensure lubrication [1], as its semi-solid state makes it much less likely to leak out from the bearing [2]. Mineral oils and triglycerides are commonly used as base oils, although synthetic oils are required for some applications. Among synthetic oils, poly-alpha-olefins (PAO), perfluoropolyalkylether fluids (PFPE), polyalkylene glycols, silicones and synthetic esters are generally used. The substances most commonly used to thicken the grease are: soap thickeners, simple or complex; inorganic thickeners such as clay, silica or polyurea; and mixed soap thickeners comprised of several cations. Grease lubrication with synthetic base oils is most often used for bearing applications in extreme environments, but many synthetic base oils are not compatible with soap thickeners, so teflon, polyurea, clay or fumed silica thickening systems must be used to form grease lubricants [1].

Since 2001, ionic liquids (ILs) have been widely studied as lubricant additives, but most of the research on this topic involves liquid lubricants [3,4]. The ILs can be grouped according to different properties, such as the cation or anion on which they are based and their miscibility in organic compounds, among others. ILs that are immiscible in non-polar hydrocarbon oils were used as additive in earlier research [5–24]. Despite their immiscibility, they can enhance friction and wear reduction. Further research was carried out into oil-soluble phosphonium cation-based ILs [25–50] and ammonium cation-based ILs [11,18,50–61], as additives in lubricant oils or organic compounds. Several ILs based on imidazolium and pyrrolidinium cations, which are only miscible in base oils of a polar nature, have been studied [11,38,57,58,62–74]. ILs have also been studied as additives in water-based fluids, an environmentally friendly alternative to petroleum oil-based lubricants, especially in fire-resistant hydraulic fluids and metal-working fluids [75–85].

From 2010 onwards, researchers started to study the use of ILs as additives in lubricant greases [85–89], showing them to possess good antiwear and friction reduction properties. In these studies, standard tribological tests (pin-on-disk, ball-on-disk, four-ball or reciprocating configurations) were used to test the influence of the ILs on the tribological properties of greases. Polyurea grease was additised with five different alkyl imidazolium ILs at 1 wt% [85] and with imidazolium bearing a benzotriazole group at 2 wt% [87]. The authors found that the 1 wt% alkyl imidazolium IL additives performed better at high temperature conditions, while imidazolium bearing a benzotriazole group, at a concentration of 2 wt%, had excellent friction reduction and antiwear performance. Wang et al. [86] tested a lithium lubricating grease based on a polyalphaolefin (PAO 10) additised with three phosphonium

* Corresponding author.
E-mail address: bartolomemarlene@uniovi.es (M. Bartolomé).

https://doi.org/10.1016/j.molliq.2023.122013
Received 4 November 2022; Received in revised form 30 March 2023; Accepted 2 May 2023
Available online 7 May 2023

ILs at 5 wt%. The results showed that the friction-reducing and antiwear properties were enhanced in all cases. More recently, Ploss et al. [88] tested four non-halogenated ILs containing the trihexyl(tetradecyl) phosphonium cation as an additive in polypropylene (PP) and lithium complex (LiX) greases at concentrations of 2–10 wt%. In this case, a reduction in wear of up to 60% and in traction of up to 40% were found.

Although the main use of lubricant greases is in rolling bearings, few studies have described the performance of greases in this practical application [90–97]. Some of these studies explored topics like lubrication film thickness, wear or friction [90–92]; while others were focused on power loss, heating or lifetime [93–97]. None of them dealt with the performance of greases additised with ILs in practical applications (e.g., rolling bearings).

In previous works [89,98], thermal conductivity, thermal stability and tribological performance of two greases (lithium complex- and anhydrous calcium-based) were studied using three phosphonium-based ILs as additives: trihexyltetradecylphosphonium bis(2-ethylhexyl) phosphate, $[P_{6,6,6,14}][BEHP]$ (designated as IL1); trihexyltetradecylphosphonium tricyanomethanide, $[P_{6,6,6,14}][TCM]$ (designated as IL2); and trihexyltetradecylphosphonium decanoate, $[P_{6,6,6,14}][DEC]$ (designated as IL3). Rheology, lubricant film thickness and friction behaviour experiments were also carried out. The results showed improvements in friction reduction and lubricant film thickness for some of the mixtures [89]. Meanwhile, the higher friction and wear reductions were obtained with the use of $[P_{6,6,6,14}][BEHP]$ and $[P_{6,6,6,14}][TCM]$. Now, this work aims to determine how the additivation of the above-mentioned greases with these two better-performing ILs affect friction torque and wear in a real component (bearing) tested under real operating conditions (rolling/sliding motion). In addition, greases were analysed after tribological tests with FTIR and ferrometry.

2. Methodology

2.1. Greases and ionic liquids

Two non-additised greases (lithium complex-, G1, and anhydrous calcium-based, G2) provided by Axel Christiernsson International and two ILs (trihexyltetradecylphosphonium bis(2-ethylhexyl)phosphate or $[P_{6,6,6,14}][BEHP]$, coded as IL1, and trihexyltetradecylphosphonium tricyanomethanide or $[P_{6,6,6,14}][TCM]$, coded as IL2) provided by IOLITEC GmbH were used in this work. The chemical formulae and structures of these ILs are shown in Table 1. The physicochemical properties of the greases and the mixing procedure of the base greases and the ILs at 5 wt% were described in [89]. Apart from the non-additised greases, only the 5 wt% IL mixtures were tested in this work, as their performance was much better than that of greases with 2 wt% of ILs in previous tests.

2.2. Rolling bearing assembly and test procedures

Rolling bearing tests were conducted in a modified Cameron-Plint TE 82/7752 four-ball machine (Fig. 1) to study the tribological behaviour of the greases and their mixtures with ILs in a real component. For this purpose, the four-ball arrangement was replaced by a rolling bearing assembly on which different bearing tests can be performed and friction torque measurements can be obtained at different test temperatures. This procedure allows the performance of tests under rolling/sliding conditions, which correspond with the real operating conditions of bearings. A complete explanation of the development of this procedure can be found in references [93–95,99–101]. This test performed on a full bearing configuration is better than the well-known 4-ball test (ASTM D2266), which simulates smearing under pure sliding and is not relevant for rolling bearings, so the bearing and grease industry recommend full bearing tests [102].

During the test, the bearing was under a constant axial load (P) of approximately 7000 N, which was applied from bottom to top using a dead weight system. An electric motor was used to set the different test speeds as needed. The power was transmitted to the rolling bearing shaft with a belt-pulley arrangement, so that it rotates the upper bearing track, while the lower track was fixed to the housing. A KISTLER® 9339A (Kistler Group, Winterthur, Switzerland) piezoelectric reaction torque cell, coupled to the housing, was used to measure the friction torque.

A thrust ball bearing (TBB) reference 51107 from SKF (Sweden) was chosen for testing, and a new one was used for each test. This rolling bearing has 21 rolling elements of 6 mm of diameter, and the raceways have a mean diameter of 43.5 mm.

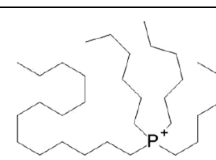
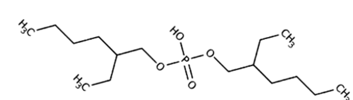
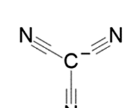
Two different rolling bearing tests were performed:

- Friction torque tests: a short test performed at constant load and temperature, where the friction torque is measured at different rotational speeds;
- Wear tests: a long test (3 × 24 h) performed at constant load, temperature and rotational speed. After the test, the roughness of the lower raceway was analysed, as well as the mass loss of the rolling bearing. A grease sample was collected after the test for evaluation by FTIR and Ferrometry.

2.2.1. Friction torque tests

These tests started with a period of 15 h, during which testing was performed at the established axial load of 7000 N, at a temperature of 50 °C in the bearing, and at 500 rpm rotational speed, to allow running-in and churning / grease distribution. To reach and maintain the temperature, an external thermal bath was used as described by Marques et al. [104]. After the churning period, the temperature in the rolling bearing was set at 80 °C and the rotational speed was reduced to 250 rpm. Once the temperature stabilized, after about two hours, the

Table 1
Chemical structure and empirical formula of the ionic liquids.

Ionic liquid	Cation	Anion
Trihexyltetradecylphosphonium bis(2-ethylhexyl)phosphate $[P_{6,6,6,14}][BEHP]$ Empirical formula: $C_{48}H_{102}O_4P_2$ Designation: IL1		Bis(2-ethylhexyl)phosphate 
Trihexyltetradecylphosphonium tricyanomethanide $[P_{6,6,6,14}][TCM]$ Empirical formula: $C_{36}H_{68}N_3P$ Designation: IL2		Tricyanomethanide 

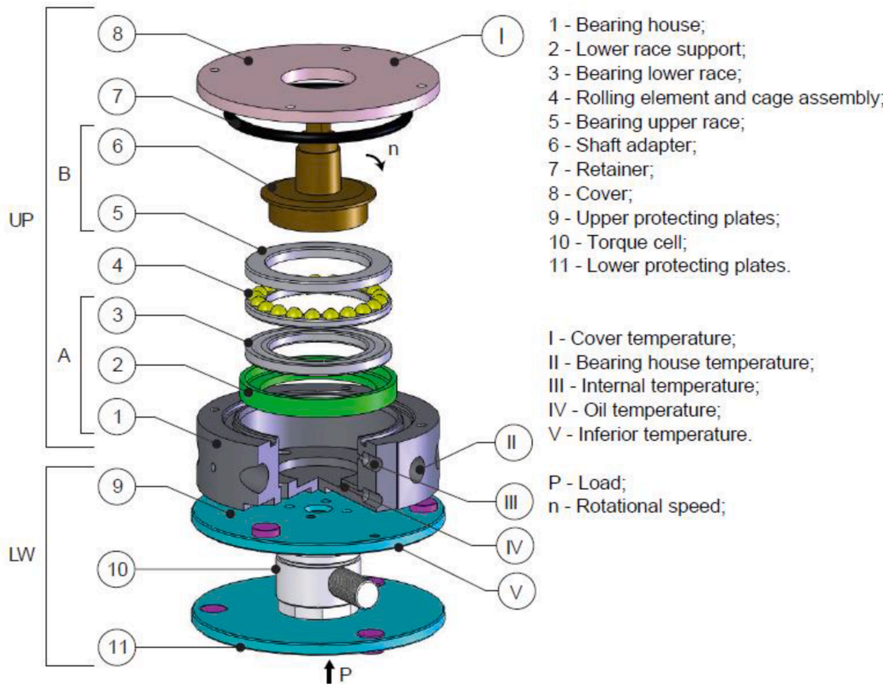


Fig. 1. Schematic diagram of rolling bearing assembly [103].

frictional torque was measured. Then the speed was increased to 750 rpm until the temperature stabilized (about 1 h) and friction torque was measured again. Finally, the speed was increased to 1500 rpm and the torque measured one last time after the temperature had stabilized. At each speed step, five friction torque measurements were taken and then averaged. 2 mL of grease was used to lubricate the rolling bearings (which corresponds to approximately 30% of the rolling bearińgs free volume). For each grease, the test was performed twice.

2.2.2. Wear tests

Wear tests were performed in the same device used in the friction torque tests. In these tests, the rolling bearing operated for 3 days (72 h), at constant load (7000 N), constant temperature (80 °C) and constant rotational speed (250 rpm). To increase the severity of the tests, three balls were removed from each bearing, which put the maximum hertzian pressure at 2.5 GPa. The operating conditions were chosen in order to promote boundary lubrication conditions.

The mass loss of each rolling bearing was measured on a scale with a precision of 0.001 mg. In addition, the infrared spectra of each grease before and after the wear tests were obtained on an Agilent Cary 630 FTIR device, using an ATR (Attenuated Total Reflectance) accessory to determine molecular alterations in the greases due to thermal aging. All the spectra shown in this work were taken directly from the device's software without smoothing, and a very good reproducibility was achieved. All spectra were normalized to the same peak's height at 1460 cm^{-1} [105], allowing the comparison between the relative height of the sample spectra. After each test, a grease sample was also analysed by Direct Reading Ferrography, obtaining the DS (wear particles <5 μm) and DL (wear particles >5 μm) parameters. The severity of wear particles index (ISUC) and the concentration of wear particles index (CPUC), defined by the Eqs. (1) and (2), were calculated from these parameters [106].

$$ISUC = \frac{(DL^2 - DS^2)}{d^2} \quad (1)$$

$$CPUC = \frac{(DL + DS)}{d} \quad (2)$$

where d is the dilution of the grease sample.

The roughness of the lower (fixed) racetrack of each rolling bearing was measured by interferometry using a BRUKER NPFLEX. A total area of 1.5 × 1.5 mm was collected. Although it is not possible to measure the roughness profiles at exactly the same position before and after test, the data collection was performed in the same region, which was assured by marking the bearing ring before the tests.

As it is possible to observe in the Fig. 2, the raceway is curved in the (y) direction. This curvature was removed and then the surface roughness (Ra) was determined according to ISO 4287, filtering the data with a Gaussian filter with a cut-off length of 0.25 mm. The roughness results were analyzed in the rolling direction (x) only because the curvature removal might show misleading results in the filtered roughness profile in the y direction.

3. Results and discussion

3.1. Rolling bearing tests

3.1.1. Friction torque results

The frictional torque of the TBB lubricated with the above-mentioned greases is shown in Fig. 3. The values represent the mean of two replicates performed for each lubricant mixture. The greases without IL (G1 and G2) showed the highest friction torque values, which were similar and approximately constant under the tested speeds. Grease G1 additised with IL2 showed the lowest values of friction torque, these being more significant at the lowest speed. The mixture of grease G1 with IL1 showed friction torque values similar to neat G1, always bearing in mind the uncertainty of the measurements. Furthermore, IL2 also conferred better friction reduction properties when mixed with grease G2, while the mixture of G2 + IL1 showed friction torque values that were similar to those of grease G2 at the tested speeds.

3.1.2. Wear results

Fig. 4 shows the wear results from the tests performed with all the lubricant samples. The addition of both ILs to grease G1 increased wear, but the wear values were very small and the differences observed between samples are within the combined uncertainties of the bearing test

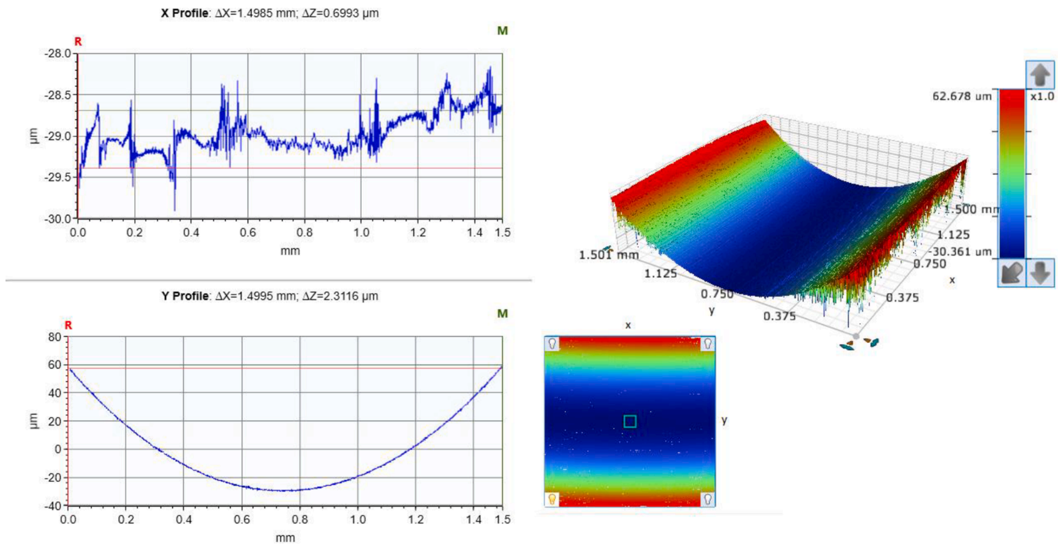


Fig. 2. Roughness of the bearing surface in the perpendicular (y) and longitudinal (x) directions of movement.

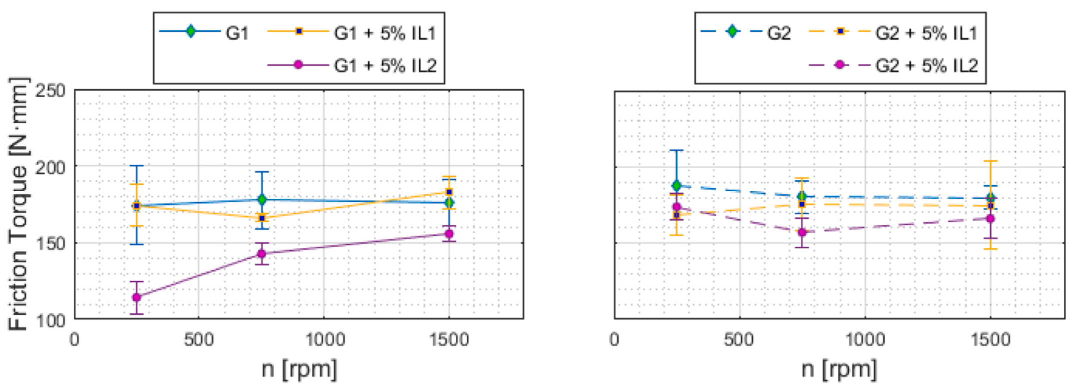


Fig. 3. Friction torque for the different blends of G1 (left) and G2 (right).

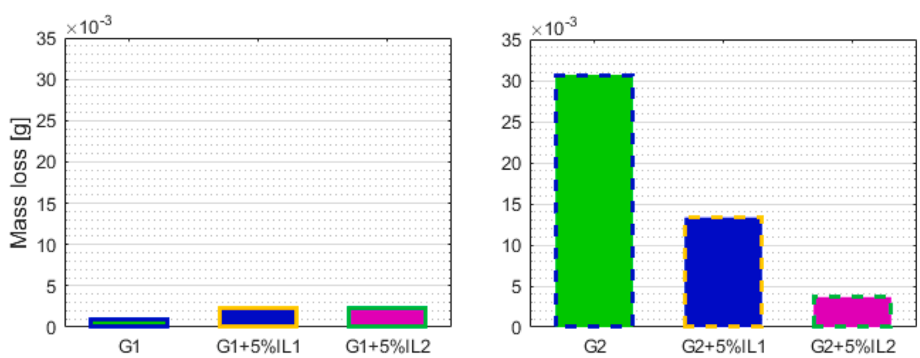


Fig. 4. Mass loss for the different blends of grease G1 (left) and grease G2 (right).

and the mass measurement. However, the addition of the ILs to grease G2 decreased wear considerably in all cases.

These results were different to those reported in [98], where the same lubricant samples were tested under pure sliding motion with both four-ball (constant speed) and reciprocating (variable speed) tests. In such cases, wear decreased with the addition of the ILs to the grease (G1) in both tribological tests, while wear increased in the case of grease G2 in the four-ball tests. On the other hand, friction behaved differently with the addition of the ILs to grease G1 (increased) and to grease G2 (decreased). Although the antiwear behaviour found in that case was correlated with the presence of phosphorus on the wear surface, the results obtained in this study could be related to the different motion configuration (rolling/sliding), where the sliding is typically 5% [102]. The tribological improvement not only depends on the concentration and chemistry of the IL but on the tribosystem also, as was stated by Zhou et al. [3].

The extreme complexity of grease lubrication is closely related to the high number of variables involved (base oil viscosity/nature, additive package, thickener type and/or content, consistency, etc.) and the numerous performance requisites (low friction, low and high temperature properties, improved oil bleeding, etc.) [102]. In fact, Gonçalves et al. [107] found that greases showing better performances in single contact tests can provide worse wear protection or rolling bearing life. In this study, the tests were performed after the churning or fully flooded film thickness period. Then, the bleeding period took place, where the bearing is mainly lubricated by the base oil or the mixture base oil-IL, and the film thickness decreases, which is known as the starvation phenomenon. This phenomenon occurs due to the lack of replenishment or the insufficient filling of the inlet region of the lubricated contact, which can decrease the lubricant film thickness by around 75% with respect to the values of the fully flooded film thickness [108], resulting in a lower load carrying capacity, asperity contacts taking place, and the appearance of wear mechanisms, like scuffing [109]. Under normal operation and depending on the initial grease volume and distribution, the lubricated contacts can starve due to several causes: side flow, centrifugal effects, surface tension, oil bleeding from the grease and evaporation [107]. In addition, lubricant loss may be caused by oxidation, polymerization, evaporation, centrifugal force induced thin film flow or droplet formation in the outlet of the contacts [110].

Table 2 shows the ferrometric parameters and indexes. In general, the number of wear particles larger than 5 μm was higher than those smaller than 5 μm. Grease G2 without IL had the highest *CPUC* and *ISUC* values, indicating that the use of this grease resulted in higher wear. The wear reduction found when IL2 was added to grease G2 can also be observed in the ferrometric parameters and index values shown in Table 2. However, grease G1 showed smaller values for both the *CPUC* and *ISUC* indexes than its mixtures with the ILs, corresponding with the wear results reported in Fig. 4.

Fig. 5 shows the average roughness evaluated in the rolling direction for all the 12 tests. It is possible to observe that the initial roughness is slightly different between the new bearings (average of 0.082 μm with a standard deviation of 0.008 μm) so instead of comparing just the final roughness value after the tests between samples, it is more suitable to analyze the difference relative to the initial roughness for each sample.

From Fig. 5 it is clear that the roughness increased after the testing for all samples, due to the severe operating conditions, namely boundary lubrication (3 days running at 250 rpm, 80 °C and 2.5 GPa). However, and despite the differences in the initial roughness of each bearing, it is also possible to observe that the increase of roughness after the wear test is higher for all G2 greases, particularly for the neat G2. Given that grease G1 and grease G2 are formulated with a base oil of the same nature, the differences in the variation of the roughness should be due to the slight smaller viscosity of the base oil used in grease G2 and the influence it might have on lubricant film generation. This was shown in the film thickness tests reported in [89], where grease G1 showed generally higher lubricant film thickness.

It is also interesting to notice that the addition of both ionic liquids improve the antiwear behaviour for grease G2, but this does not happen to grease G1. Nevertheless, it is clear that between the greases with ionic liquids, the ones which contain IL2 show a better behavior (smaller roughness increase) than those containing IL1. The reason for this behavior cannot be inferred from the tests performed in this work, but the results reported in [35,67] support that ionic liquids generate tribofilms on the metallic surfaces contributing to the reduction of friction and improving the antiwear behaviour [98].

Table 2
Ferrometric parameters and indexes.

Grease sample	DL	DS	CPUC × 10^{-3}	ISUC × 10^{-6}
G1	7.4	4.9	0.123	0.003
G1 + 5% IL1	46.5	18.2	0.647	0.183
G1 + 5% IL2	57.2	24.3	0.815	0.268
G2	119.8	79.8	19.960	79.840
G2 + 5% IL1	77.4	49.8	12.720	35.107
G2 + 5% IL2	25.3	11.8	3.710	5.009

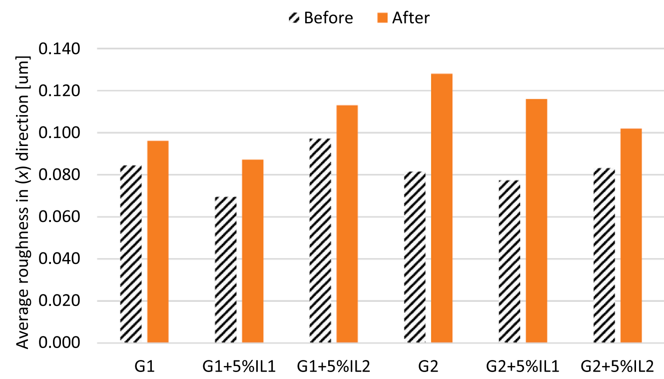


Fig. 5. Surface roughness of the rolling bearing before and after the wear tests.

Fig. 6 shows the variation of the average roughness (Ra) of the bearing raceways in the rolling direction versus the mass loss of the rolling bearing. According to Fig. 6, the greater the mass loss, the higher is the increase in roughness. Only the bearing lubricated with the mixture G1 + 5%IL1 broke that tendency, but the difference with the G2 + 5%IL2 counterpart was minimum (about 10^{-3} g of mass loss and 2% of variation of Ra, which is within the uncertainties of the wear test and the mass loss measurement).

Cen and Lugt [111] reported that the only relevant physical property that determines the film thickness, and thus the probability of asperity contacts and wear, in the early lifetime of a grease is the base oil viscosity, and not the bleed rate or any grease rheological properties. Considering that the greases G1 and G2 were formulated with base oils of similar viscosities, their original consistency and yield stress are also similar [89], and were studied under the same testing conditions, their different antiwear behavior could be related to oxidation. Changes on EHL film over long times, which are related to tribological behaviour, are given by mechanical and chemical degradation [102]. Chemical degradation is primarily given by oxidation, and also by evaporation, although other phenomena occur such as acid formation, thermo-oxidative degradation of the thickener and the base oil, varnish and sludge formation, etc. The oxidation of the base oil and thickener are not

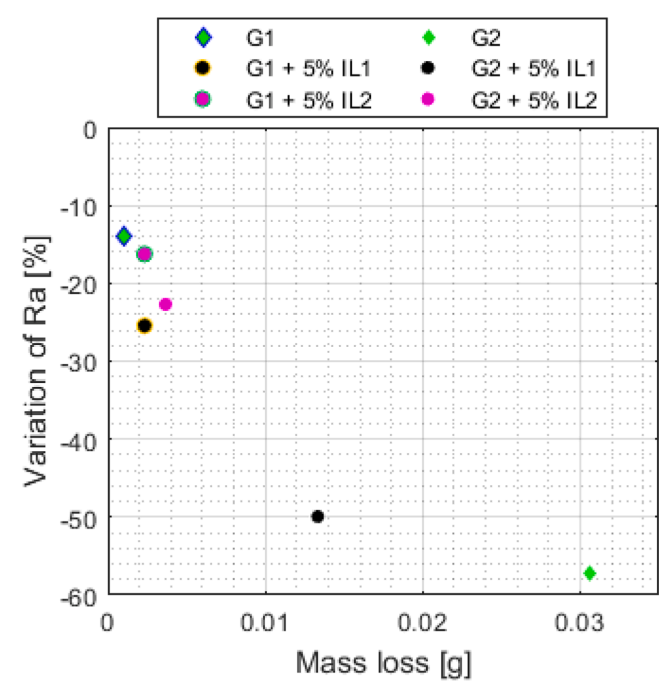


Fig. 6. Variation of surface roughness $\left(\frac{Ra_{before} - Ra_{after}}{Ra_{before}}\right)$ in the rolling direction.

fully independent problems. However, studies on grease thickener oxidation are rare and most oxidation research has been made on lubricating oils, being generally accepted that their corresponding results can be applied to lubricating greases [1]. Fig. 7 shows the FTIR spectra of the fresh grease (before wear testing) and the used grease (after the wear test, with the suffix "a"). From comparison of the spectra, it is clear that the calcium-based grease (G2) seems to be more sensitive to oxidation than the lithium-based grease (G1), due to its higher peak around 1750 cm^{-1} and also a clear offset in the whole fingerprint region (1800–650 cm^{-1}). The G1-containing samples also show some oxidation, but much less than their G2 counterparts. The oxidation level was diminished with the addition of IL2 to both G1 and G2 greases, and IL2 confers higher resistance to aging/oxidation than IL1. The higher improvement on thermal stability of these greases with the addition of the IL2 was also reported in a previous work [98], which is related to evaporation and hence to chemical degradation. The fact that anhydrous calcium soap greases (G2) can be used up to temperatures of 110 °C, while the operating temperature range of the lithium complex greases (G1) is between −30 °C and 140 °C [1], explains the higher contribution of the ILs on the wear protection properties of the grease G2 (Fig. 4) and the better tribological behavior of the grease G1. In summary, these data may explain the worse antiwear protection of grease G2 and its mixtures with the ILs. In addition, the polar nature of the oxidation products increase the polarity of the grease over time, which lead to an increase of water absorption from the air [112,113]. This phenomenon can cause corrosion impacting negatively in the grease wear protection.

4. Conclusions

Friction torque and wear tests in a real component (bearing) were carried out to evaluate the tribological behaviour of two greases (lithium complex- and anhydrous calcium-based) additised separately with two phosphonium-based cation ILs. The mass and roughness variations of the bearing were evaluated, and the greases were analysed after wear tests with FTIR and ferrometry. The main conclusions of this study are the following:

- IL2 improved the friction reduction performance of both greases, with the lowest friction torque value in the case of grease G1.
- The addition of both ILs to grease G1 resulted in a slight wear increase, while the addition of the ILs to grease G2 improved its antiwear performance, especially in the case of IL2.
- The ferrometric results were in concordance with the mass loss (wear) results. Furthermore, in general the decrease in surface roughness of the bearing raceways was also closely related to wear.
- Regarding oxidation and thermal aging, the FTIR spectra showed higher oxidation of grease G2 than grease G1, and the addition of IL2 provided higher resistance to oxidation than IL1 in both greases.
- The different tribological behaviour of the tested ILs is probably related to their antioxidant action. The exact mechanism taking place is unclear, but these ILs might be a suitable additive for grease G2 in bearing applications.

CRediT authorship contribution statement

M. Bartolomé: Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **D. Gonçalves:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **A. García Tuero:** Validation, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization. **R. González:** Conceptualization, Methodology, Resources, Data curation, Writing – review & editing, Visualization, Supervision. **A. Hernández Battez:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **J.H.O. Seabra:** Conceptualization, Methodology,

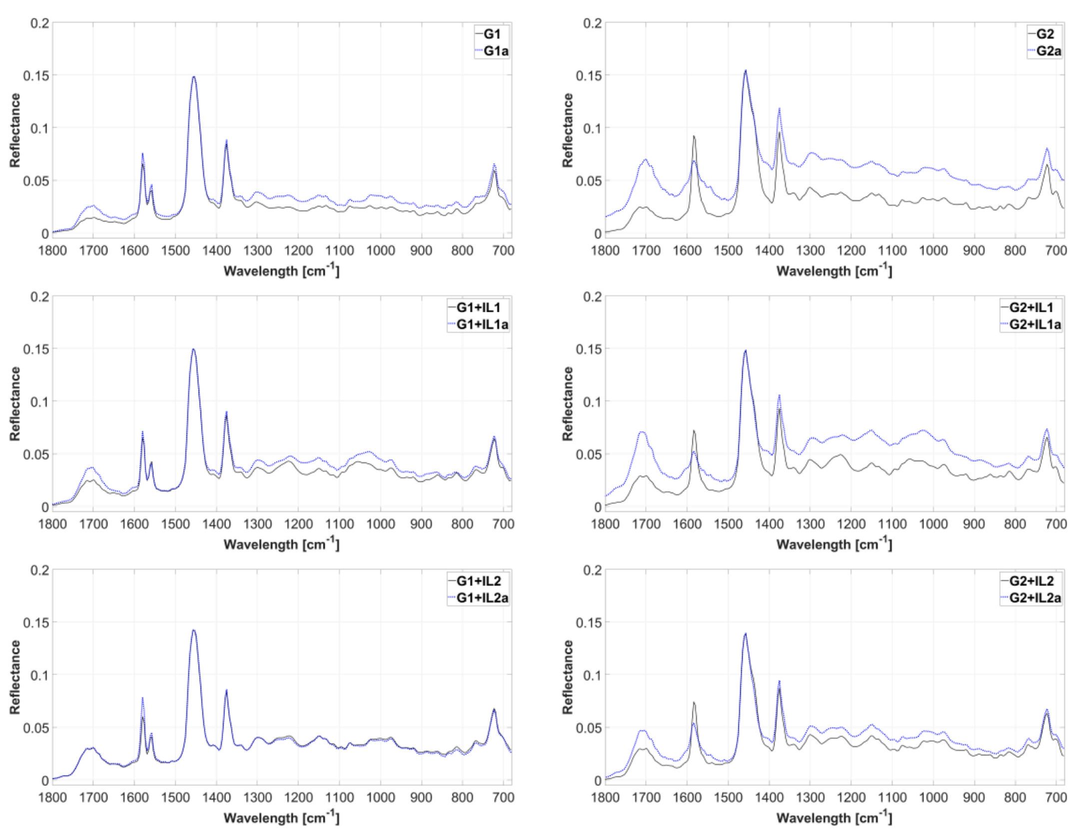


Fig. 7. FTIR spectra of the grease samples before and after tests.

Validation, Formal analysis, Resources, Data curation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors acknowledge the following national and foreign institutions and company for supporting this work: Principality of Asturias, Spain (grant number: IDI/2018/000131), Ministry of Science, Innovation and Universities, Spain (grant number: CAS19/00290 – the research stay of Marlene Bartolome at Porto University, Portugal) and Axel Christiernsson International AB, Sweden (grease supplier).

References

[1] P.M. Lugt, Grease Lubrication in Rolling Bearings, A John Wiley & Sons, Ltd., 2013.
[2] Y. Zhou, P.M. Lugt, On the application of the mechanical aging Master Curve for lubricating greases to rolling bearings, Tribol. Int. 141 (2020), 105918, https://doi.org/10.1016/j.triboint.2019.105918.
[3] Y. Zhou, J. Qu, Ionic liquids as lubricant additives: a review, ACS Appl. Mater. Interfaces 9 (2017) 3209–3222, https://doi.org/10.1021/acsami.6b12489.
[4] M. Cai, Q. Yu, W. Liu, F. Zhou, Ionic liquid lubricants : when chemistry meets tribology, R. Soc. Chem. (2020) 7753–7818, https://doi.org/10.1039/d0cs00126k.
[5] P. Iglesias, M.D. Bermúdez, F.J. Carrión, G. Martínez-Nicolás, Friction and wear of aluminium-steel contacts lubricated with ordered fluids-neutral and ionic liquid crystals as oil additives, Wear 256 (2004) 386–392, https://doi.org/10.1016/S0043-1648(03)00442-3.
[6] A.E. Jiménez, M.D. Bermúdez, F.J. Carrión, G. Martínez-Nicolás, Room temperature ionic liquids as lubricant additives in steel-aluminium contacts: influence of sliding velocity, normal load and temperature, Wear 261 (2006) 347–359, https://doi.org/10.1016/j.wear.2005.11.004.
[7] M. Cai, Y. Liang, M. Yao, Y. Xia, F. Zhou, W. Liu, Imidazolium ionic liquids as antiwear and antioxidant additive in poly(ethylene glycol) for steel/steel contacts, ACS Appl. Mater. Interfaces 2 (2010) 870–876, https://doi.org/10.1021/am900847j.
[8] D. Blanco, R. González, A. Hernández Battez, J.L. Viesca, A. Fernández-Gonzlez, Use of ethyl-dimethyl-2-methoxyethylammonium tris(pentafluoroethyl) trifluorophosphate as base oil additive in the lubrication of TiN PVD coating, Tribol. Int. 44 (2011) 645–650, https://doi.org/10.1016/j.triboint.2011.01.004.
[9] D. Blanco, A.H. Battez, J.L. Viesca, R. González, A. Fernández-González, Lubrication of CrN coating with ethyl-dimethyl-2-methoxyethylammonium tris (pentafluoroethyl)trifluorophosphate ionic liquid as additive to PAO 6, Tribol. Lett. 41 (2011) 295–302, https://doi.org/10.1007/s11249-010-9714-1.
[10] C. Zhang, S. Zhang, L. Yu, P. Zhang, Z. Zhang, Z. Wu, Tribological behavior of 1-methyl-3-hexadecylimidazolium tetrafluoroborate ionic liquid crystal as a neat lubricant and as an additive of liquid paraffin, Tribol. Lett. 46 (2012) 49–54, https://doi.org/10.1007/s11249-012-9917-8.
[11] V. Pejaković, M. Kronberger, M. Mahrova, M. Vilas, E. Tojo, M. Kalin, Pyrrolidinium sulfate and ammonium sulfate ionic liquids as lubricant additives for steel/steel contact lubrication, Proc. Inst. Mech. Eng. Part J J. Eng. Tribol. 226 (2012) 923–932, https://doi.org/10.1177/1350650112448978.
[12] M. Kronberger, V. Pejaković, C. Gabler, M. Kalin, How anion and cation species influence the tribology of a green lubricant based on ionic liquids, Proc. Inst. Mech. Eng. Part J J. Eng. Tribol. 226 (2012) 933–951, https://doi.org/10.1177/1350650112459012.
[13] R. González, A.H. Battez, J.L. Viesca, A. Higuera-Garrido, A. Fernández-González, Lubrication of DLC coatings with two tris(pentafluoroethyl)trifluorophosphate anion-based ionic liquids, Tribol. Trans. 56 (2013) 887–895, https://doi.org/10.1080/10402004.2013.810319.
[14] J.L. Viesca, A. García, A. Hernández Battez, R. González, R. Monge, A. Fernández-González, et al., FAP anion ionic liquids used in the lubrication of a steel-steel contact, Tribol. Lett. 52 (2013) 431–437, https://doi.org/10.1007/s11249-013-0226-7.
[15] N.V. Pogodina, T. Amann, C. Dold, E. Metwalli, P. Müller-Buschbaum, A. Kailer, et al., Triborheology and orientational dynamics of ionic liquid crystals, J. Mol. Liq. 192 (2014) 118–126, https://doi.org/10.1016/j.molliq.2013.09.022.
[16] R. Monge, R. González, A. Hernández Battez, A. Fernández-González, J.L. Viesca, A. García, et al., Ionic liquids as an additive in fully formulated wind turbine gearbox oils, Wear 328–329 (2015) 50–63, https://doi.org/10.1016/j.wear.2015.01.041.
[17] A.E. Jiménez, M.D. Bermúdez, P. Iglesias, F.J. Carrión, G. Martínez-Nicolás, 1-N-alkyl -3-methylimidazolium ionic liquids as neat lubricants and lubricant additives in steel-aluminium contacts, Wear 260 (2006) 766–782, https://doi.org/10.1016/j.wear.2005.04.016.
[18] J. Qu, J.J. Truhan, S. Dai, H. Luo, P.J. Blau, Ionic liquids with ammonium cations as lubricants or additives, Tribol. Lett. 22 (2006) 207–214, https://doi.org/10.1007/s11249-006-9081-0.
[19] J. Sanes, F.J. Carrión, A.E. Jiménez, M.D. Bermúdez, Influence of temperature on PA 6-steel contacts in the presence of an ionic liquid lubricant, Wear 263 (2007) 658–662, https://doi.org/10.1016/j.wear.2006.11.034.
[20] A.E. Jiménez, M.D. Bermúdez, Imidazolium ionic liquids as additives of the synthetic ester propylene glycol dioleate in aluminium-steel lubrication, Wear 265 (2008) 787–798, https://doi.org/10.1016/j.wear.2008.01.009.
[21] J. Qu, P.J. Blau, S. Dai, H. Luo, H.M. Meyer, Ionic liquids as novel lubricants and additives for diesel engine applications, Tribol. Lett. 35 (2009) 181–189, https://doi.org/10.1007/s11249-009-9447-1.
[22] M. Yao, Y. Liang, Y. Xia, F. Zhou, Bisimidazolium ionic liquids as the high-performance antiwear additives in poly(ethylene glycol) for steel-steel contacts, ACS Appl. Mater. Interfaces 1 (2009) 467–471, https://doi.org/10.1021/am800132z.
[23] A.H. Battez, R. González, J.L. Viesca, D. Blanco, E. Asedegbega, A. Osorio, Tribological behaviour of two imidazolium ionic liquids as lubricant additives for steel/steel contacts, Wear 266 (2009) 1224–1228, https://doi.org/10.1016/j.wear.2009.03.043.
[24] A. Schneider, J. Brenner, C. Tomastik, F. Franek, Capacity of selected ionic liquids as alternative EP/AW additive, Lubr. Sci. 22 (2010) 215–223, https://doi.org/10.1002/ls.120.
[25] J. Qu, D.G. Bansal, B. Yu, J.Y. Howe, H. Luo, S. Dai, et al., Antiwear performance and mechanism of an oil-miscible ionic liquid as a lubricant additive, ACS Appl. Mater. Interfaces 4 (2012) 997–1002, https://doi.org/10.1021/am201646k.
[26] B. Yu, D.G. Bansal, J. Qu, X. Sun, H. Luo, S. Dai, et al., Oil-miscible and non-corrosive phosphonium-based ionic liquids as candidate lubricant additives, Wear 289 (2012) 58–64, https://doi.org/10.1016/j.wear.2012.04.015.
[27] Y. Zhou, J. Dyck, T.W. Graham, H. Luo, D.N. Leonard, J. Qu, Ionic liquids composed of phosphonium cations and organophosphate, carboxylate, and sulfonate anions as lubricant antiwear additives, Langmuir 30 (2014) 13301–13311, https://doi.org/10.1021/la5032366.
[28] A. Westerholt, M. Weschta, A. Bösmann, S. Tremmel, Y. Korth, M. Wolf, et al., Halide-free synthesis and tribological performance of oil-miscible ammonium and phosphonium-based ionic liquids, ACS Sustain. Chem. Eng. 3 (2015) 797–808, https://doi.org/10.1021/sc500517n.
[29] M. Anand, M. Hadfield, J.L. Viesca, B. Thomas, A. Hernández Battez, S. Austen, Ionic liquids as tribological performance improving additive for in-service and used fully-formulated diesel engine lubricants, Wear 334–335 (2015) 67–74, https://doi.org/10.1016/j.wear.2015.01.055.
[30] Y. Zhou, D.N. Leonard, H.M. Meyer, H. Luo, J. Qu, Does the use of diamond-like carbon coating and organophosphate lubricant additive together cause excessive tribochemical material removal? Adv. Mater. Interfaces 2 (2015) 1500213, https://doi.org/10.1002/admi.201500213.
[31] Z. Wang, J. Chang, W. Wu, Synergistic effects of phosphate ionic liquids and octadecylaminen-oleoyl sarcosinate as lubricating grease additives, Lubr. Sci. 31 (2019) 127–136, https://doi.org/10.1002/ls.1454.
[32] J. Grace, S. Vysochanska, J. Lodge, P. Iglesias, Ionic liquids as additives of coffee bean oil in steel-steel contacts, Lubricants 3 (2015) 637–649, https://doi.org/10.3390/lubricants3040637.
[33] W.C. Barnhill, H. Gao, B. Kheireddin, B.L. Papke, H. Luo, B.H. West, et al., Tribological bench and engine dynamometer tests of a low viscosity SAE 0W–16 engine oil using a combination of ionic liquid and ZDDP as anti-wear additives, Front. Mech. Eng. 1 (2015) 12, https://doi.org/10.3389/fmech.2015.00012.
[34] R. González, M. Bartolomé, D. Blanco, J.L. Viesca, A. Fernández-González, A. H. Battez, Effectiveness of phosphonium cation-based ionic liquids as lubricant additive, Tribol. Int. 98 (2016) 82–93, https://doi.org/10.1016/j.triboint.2016.02.016.
[35] V. Sharma, N. Doerr, P.B. Aswath, Chemical-mechanical properties of tribofilms and their relationship to ionic liquid chemistry, RSC Adv. 6 (2016) 22341–22356, https://doi.org/10.1039/c6ra01915c.
[36] H. Li, A.E. Somers, P.C. Howlett, M.W. Rutland, M. Forsyth, R. Atkin, Addition of low concentrations of an ionic liquid to a base oil reduces friction over multiple length scales: a combined nano- and macrotribology investigation, Phys. Chem. Chem. Phys. 18 (2016) 6541–6547, https://doi.org/10.1039/c5cp07061a.
[37] A.E. Somers, B. Khemchandani, P.C. Howlett, J. Sun, D.R. Macfarlane, M. Forsyth, Ionic liquids as antiwear additives in base oils: Influence of structure on miscibility and antiwear performance for steel on aluminum, ACS Appl. Mater. Interfaces 5 (2013) 11544–11553, https://doi.org/10.1021/am4037614.
[38] D. Blanco, R. González, J.L. Viesca, A. Fernández-González, M. Bartolomé, B. A. Hernández, Antifriction and antiwear properties of an ionic liquid with fluorine-containing anion used as lubricant additive, Tribol. Lett. (2017), https://doi.org/10.1007/s11249-017-0846-4.
[39] L. Zhu, G. Zhao, X. Wang, Investigation on three oil-miscible ionic liquids as antiwear additives for polyol esters at elevated temperature, Tribol. Int. 109 (2017) 336–345, https://doi.org/10.1016/j.triboint.2016.10.032.
[40] S.A.S. Amiril, E.A. Rahim, Z. Embong, S. Syahrullail, Tribological investigations on the application of oil-miscible ionic liquids additives in modified Jatropha-

based metalworking fluid, Tribol. Int. 120 (2018) 520–534, https://doi.org/10.1016/j.triboint.2018.01.030.

[41] J. Hansen, M. Björling, I. Minami, R. Larsson, Performance and mechanisms of silicate tribofilm in heavily loaded rolling/sliding non-conformal contacts, Tribol. Int. 123 (2018) 130–141, https://doi.org/10.1016/j.triboint.2018.03.006.

[42] Q. Yu, Y. Wang, G. Huang, Z. Ma, Y. Shi, M. Cai, et al., Task-specific oil-miscible ionic liquids lubricate steel/light metal alloy: a tribochemistry study, Adv. Mater. Interfaces 5 (2018) 1800791, https://doi.org/10.1002/admi.201800791.

[43] S. Zhang, L. Hu, D. Qiao, D. Feng, H. Wang, Vacuum tribological performance of phosphonium-based ionic liquids as lubricants and lubricant additives of multialkylated cyclopentanes, Tribol. Int. 66 (2013) 289–295, https://doi.org/10.1016/j.triboint.2013.06.012.

[44] J. Qu, H. Luo, M. Chi, C. Ma, P.J. Blau, S. Dai, et al., Comparison of an oil-miscible ionic liquid and ZDDP as a lubricant anti-wear additive, Tribol. Int. 71 (2014) 88–97, https://doi.org/10.1016/j.triboint.2013.11.010.

[45] W.C. Barnhill, J. Qu, H. Luo, H.M. Meyer, C. Ma, M. Chi, et al., Phosphonium-organophosphate ionic liquids as lubricant additives: Effects of cation structure on physicochemical and tribological characteristics, ACS Appl. Mater. Interfaces 6 (2014) 22585–22593, https://doi.org/10.1021/am506702u.

[46] B. Khemchandani, A. Somers, P. Howlett, A.K. Jaiswal, E. Sayanna, M. Forsyth, Phosphonium-organophosphate ionic liquids as lubricant additives: effects of cation structure on physicochemical and tribological characteristics, Tribol. Int. 77 (2014) 171–177, https://doi.org/10.1016/j.triboint.2014.04.016.

[47] I. Otero, E.R. López, M. Reichelt, M. Villanueva, J. Salgado, J. Fernández, Ionic liquids based on phosphonium cations As neat lubricants or lubricant additives for a steel/steel contact, ACS Appl. Mater. Interfaces 6 (2014) 13115–13128, https://doi.org/10.1021/am502980m.

[48] Cai Z. bing, H.M. Meyer, C. Ma, M. Chi, H. Luo, J. Qu, Comparison of the tribological behavior of steel-steel and Si3N4-steel contacts in lubricants with ZDDP or ionic liquid, Wear 319 (2014) 172–183, 10.1016/j.wear.2014.08.002.

[49] D. Qiao, H. Wang, D. Feng, Tribological performance and mechanism of phosphate ionic liquids as additives in three base oils for steel-on-aluminum contact, Tribol. Lett. 55 (2014) 517–531, https://doi.org/10.1007/s11249-014-0377-1.

[50] R. Gusain, S. Dhingra, O.P. Khatri, Fatty-acid-constituted halogen-free ionic liquids as renewable, environmentally friendly, and high-performance lubricant additives, Ind. Eng. Chem. Res. 55 (2016) 856–865, https://doi.org/10.1021/acs.iecr.5b03347.

[51] P.K. Khatri, C. Joshi, G.D. Thakre, S.L. Jain, Halogen-free ammonium-organoborate ionic liquids as lubricating additives: the effect of alkyl chain lengths on the tribological performance, New J. Chem. 40 (2016) 5294–5299, https://doi.org/10.1039/c5nj02225h.

[52] G. Huang, Q. Yu, Z. Ma, M. Cai, W. Liu, Probing the lubricating mechanism of oil-soluble ionic liquids additives, Tribol. Int. 107 (2017) 152–162, 10.1016/j.triboint.2016.08.027.

[53] J.L. Viesca, M.T. Mallada, D. Blanco, A. Fernández-González, J. Espina-Casado, R. González, et al., Lubrication performance of an ammonium cation-based ionic liquid used as an additive in a polar oil, Tribol. Int. 116 (2017) 422–430, https://doi.org/10.1016/j.triboint.2017.08.004.

[54] T. Espinosa, J. Sanes, A.E. Jiménez, M.D. Bermúdez, Protic ammonium carboxylate ionic liquid lubricants of OFHC copper, Wear 303 (2013) 495–509, https://doi.org/10.1016/j.wear.2013.03.041.

[55] M. Fan, D. Yang, X. Wang, W. Liu, H. Fu, DOSS- Based QAILs: As both neat lubricants and lubricant additives with excellent tribological properties and good detergency, Ind. Eng. Chem. Res. 53 (2014) 17952–17960, https://doi.org/10.1021/ie502849w.

[56] R. Gusain, R. Singh, K.L.N. Sivakumar, O.P. Khatri, Halogen-free imidazolium/ammonium-bis(salicylato)borate ionic liquids as high performance lubricant additives, RSC Adv. 4 (2014) 1293–1301, https://doi.org/10.1039/c3ra43052a.

[57] R. Gusain, P. Gupta, S. Saran, O.P. Khatri, Halogen-free bis(imidazolium)/bis(ammonium)-di[bis(salicylato)borate] ionic liquids as energy-efficient and environmentally friendly lubricant additives, ACS Appl. Mater. Interfaces 6 (2014) 15318–15328, https://doi.org/10.1021/am503811t.

[58] X. Fu, L. Sun, X. Zhou, Z. Li, T. Ren, Tribological study of oil-miscible quaternary ammonium phosphites ionic liquids as lubricant additives in PAO, Tribol. Lett. 60 (2015) 1–12, https://doi.org/10.1007/s11249-015-0596-0.

[59] R. Gusain, O.P. Khatri, Halogen-free ionic liquids: effect of chelated orthoborate anion structure on their lubrication properties, RSC Adv. 5 (2015) 25287–25294, https://doi.org/10.1039/c5ra03092g.

[60] W.C. Barnhill, H. Luo, H.M. Meyer, C. Ma, M. Chi, B.L. Papke, et al., Tertiary and quaternary ammonium-phosphate ionic liquids as lubricant additives, Tribol. Lett. 63 (2016) 1–11, https://doi.org/10.1007/s11249-016-0707-6.

[61] M. Taher, F.U. Shah, A. Filippov, P. De Baets, S. Glavatskih, O.N. Antzutkin, Halogen-free pyrrolidinium bis(mandelato)borate ionic liquids: some physicochemical properties and lubrication performance as additives to polyethylene glycol, RSC Adv. 4 (2014) 30617–30623, https://doi.org/10.1039/c4ra02551b.

[62] M. Mahrova, F. Pagano, V. Pejakovic, A. Valea, M. Kalin, A. Igartua, et al., Pyridinium based dicationic ionic liquids as base lubricants or lubricant additives, Tribol. Int. 82 (2015) 245–254, https://doi.org/10.1016/j.triboint.2014.10.018.

[63] S. Qian, X. Chen, L. Liu, Q. Li, Tribological properties of the castor oil affected by the additive of the ionic liquid [HMIM]BF4, J. Tribol. 138 (2016), https://doi.org/10.1115/1.4031081.

[64] V. Pejaković, C. Tomastik, N. Dörr, M. Kalin, Influence of concentration and anion alkyl chain length on tribological properties of imidazolium sulfate ionic liquids as additives to glycerol in steel-steel contact lubrication, Tribol. Int. 97 (2016) 234–243, https://doi.org/10.1016/j.triboint.2016.01.034.

[65] L. Zhu, Q. Zhao, X. Wu, G. Zhao, X. Wang, A novel phosphate ionic liquid plays dual role in synthetic ester oil: from synthetic catalyst to anti-wear additive, Tribol. Int. 97 (2016) 192–199, https://doi.org/10.1016/j.triboint.2015.12.047.

[66] A. Fernández-González, M.T. Mallada, J.L. Viesca, R. González, R. Badía, A. Hernández-Battez, Corrosion activity and solubility in polar oils of three bis (trifluoromethylsulfonyl) imide/bis(trifluoromethylsulfonyl) amide ([NTf_2]) anion-based ionic liquids, J. Ind. Eng. Chem. 56 (2017) 292–298, https://doi.org/10.1016/j.jiec.2017.07.022.

[67] A.H. Battez, N. Rivera, D. Blanco, P. Oulego, J.L. Viesca, R. González, Physicochemical, traction and tribofilm formation properties of three octanoate-, laurate- and palmitate-anion based ionic liquids, J. Mol. Liq. 284 (2019) 639–646, https://doi.org/10.1016/j.molliq.2019.04.050.

[68] H. Zhang, Y. Xia, M. Yao, Z. Jia, Z. Liu, The influences of methyl group at C2 position in imidazolium ring on tribological properties, Tribol. Lett. 36 (2009) 105–111, https://doi.org/10.1007/s11249-009-9465-z.

[69] M. Cai, Y. Liang, F. Zhou, W. Liu, A novel imidazolium salt with antioxidation and anticorrosion dual functionalities as the additive in poly(ethylene glycol) for steel/steel contacts, Wear 306 (2012) 197–208, https://doi.org/10.1016/j.wear.2012.09.001.

[70] D. Jiang, L. Hu, D. Feng, Tribological properties of crown-type phosphate ionic liquid as additive in poly(ethylene glycol) for steel/steel contacts, Ind. Lubr. Tribol. 65 (2013) 202–208, https://doi.org/10.1108/00368791311311204.

[71] D. Jiang, L. Hu, D. Feng, Tribological properties of crown-type phosphate ionic liquids as lubricating additives in rapeseed oils, Lubr. Sci. 25 (2013) 195–207, https://doi.org/10.1002/ls.1199.

[72] Z. Song, M. Cai, Y. Liang, M. Fan, F. Zhou, W. Liu, In situ preparation of anti-corrosion ionic liquids as the lubricant additives in multiply-alkylated cyclopentanes, RSC Adv. 3 (2013) 21715–21721, https://doi.org/10.1039/c3ra42092b.

[73] Z. Song, M. Fan, Y. Liang, F. Zhou, W. Liu, Lithium-based ionic liquids: In situ-formed lubricant additive only by blending, Tribol. Lett. 49 (2013) 127–133, https://doi.org/10.1007/s11249-012-0046-1.

[74] B.A. Omotowa, B.S. Phillips, J.S. Zabinski, J.M. Shreeve, Phosphazene-based ionic liquids: synthesis, temperature-dependent viscosity, and effect as additives in water lubrication of silicon nitride ceramics, Inorg. Chem. 43 (2004) 5466–5471, https://doi.org/10.1021/ic049483o.

[75] B.S. Phillips, J.S. Zabinski, Ionic liquid lubrication effects on ceramics in a water environment, Tribol. Lett. 17 (2004) 533–541, https://doi.org/10.1023/B:TRIL.0000044501.64351.68.

[76] M. Fan, X. Du, L. Ma, P. Wen, S. Zhang, R. Dong, et al., In situ preparation of multifunctional additives in water, Tribol. Int. 130 (2019) 317–323, https://doi.org/10.1016/j.triboint.2018.09.020.

[77] L. Ge, L. Chen, R. Guo, Microstructure and lubrication properties of lamellar liquid crystal in Brij30/[Bmim]PF 6/H 2O system, Tribol. Lett. 28 (2007) 123–130, https://doi.org/10.1007/s11249-007-9256-3.

[78] G. Xie, S. Liu, D. Guo, Q. Wang, J. Luo, Investigation of the running-in process and friction coefficient under the lubrication of ionic liquid/water mixture, Appl. Surf. Sci. 255 (2009) 6408–6414, https://doi.org/10.1016/j.apsusc.2009.02.029.

[79] T. Espinosa, M. Jimenez, J. Sanes, A.E. Jimenez, M. Iglesias, M.D. Bermudez, Ultra-low friction with a protic ionic liquid boundary film at the water-lubricated sapphire-stainless steel interface, Tribol. Lett. 53 (2014) 1–9, https://doi.org/10.1007/s11249-013-0238-3.

[80] Y. Wang, Q. Yu, M. Cai, L. Shi, F. Zhou, W. Liu, Ibuprofen-based ionic liquids as additives for enhancing the lubricity and antiwear of water-ethylene glycol liquid, Tribol. Lett. 65 (2017) 55, https://doi.org/10.1007/s11249-017-0840-x.

[81] G. Zheng, G. Zhang, T. Ding, X. Xiang, F. Li, T. Ren, et al., Tribological properties and surface interaction of novel water-soluble ionic liquid in water-glycol, Tribol. Int. 116 (2017) 440–448, https://doi.org/10.1016/j.triboint.2017.08.001.

[82] Y. Wang, Q. Yu, Z. Ma, G. Huang, M. Cai, F. Zhou, et al., Significant enhancement of anti-friction capability of cationic surfactant by phosphonate functionality as additive in water, Tribol. Int. 112 (2017) 86–93, https://doi.org/10.1016/j.triboint.2017.03.034.

[83] Y. Wang, Q. Yu, M. Cai, L. Shi, F. Zhou, W. Liu, Synergy of lithium salt and non-ionic surfactant for significantly improved tribological properties of water-based fluids, Tribol. Int. 113 (2017) 58–64, https://doi.org/10.1016/j.triboint.2016.10.035.

[84] Y. Wang, Q. Yu, M. Cai, F. Zhou, W. Liu, Halide-free PN ionic liquids surfactants as additives for enhancing tribological performance of water-based liquid, Tribol. Int. 128 (2018) 190–196, https://doi.org/10.1016/j.triboint.2018.07.018.

[85] M. Cai, Z. Zhao, Y. Liang, F. Zhou, W. Liu, Alkyl imidazolium ionic liquids as friction reduction and anti-wear additive in polyurea grease for steel/steel contacts, Tribol. Lett. 40 (2010) 215–224, https://doi.org/10.1007/s11249-010-9624-2.

[86] Z. Wang, J. Chang, C. Cai, Tribological performance of phosphonium ionic liquids as additives in lithium lubricating grease, Lubricants 6 (2018) 23, https://doi.org/10.3390/lubricants6010023.

[87] M. Cai, Y. Liang, F. Zhou, W. Liu, Tribological properties of novel imidazolium ionic liquids bearing benzotriazole group as the antiwear/anticorrosion additive in poly(ethylene glycol) and polyurea grease for steel/steel contacts, ACS Appl. Mater. Interfaces 3 (2011) 4580–4592, https://doi.org/10.1021/am200826b.

[88] M. Ploss, Y. Tian, S. Yoshikawa, R. Westbroek, J. Leckner, S. Glavatskih, Tribological performance of non-halogenated phosphonium ionic liquids as additives to polypropylene and lithium-complex greases, Tribol. Lett. 68 (2020) 1–13, https://doi.org/10.1007/s11249-019-1240-1.

[89] M. Bartolomé, D. Gonçalves, A.G. Tuero, R. González, A.H. Battez, J.H.O. Seabra, Greases additised with phosphonium-based ionic liquids - Part I: rheology, lubricant film thickness and Stribeck curves, Tribol. Int. 156 (2021), 106851, https://doi.org/10.1016/j.triboint.2020.106851.

[90] H. Cen, P.M. Lugt, G. Morales-Espejel, On the film thickness of grease-lubricated contacts at low speeds, Tribol. Trans. 57 (2014) 668–678, https://doi.org/10.1080/10402004.2014.897781.

[91] G.E. Morales-Espejel, P.M. Lugt, H.R. Pasaribu, H. Cen, Film thickness in grease lubricated slow rotating rolling bearings, Tribol. Int. 74 (2014) 7–19, https://doi.org/10.1016/j.triboint.2014.01.023.

[92] T. Cousseau, B. Graça, A. Campos, J. Seabra, Friction and wear in thrust ball bearings lubricated with biodegradable greases, Proc. Inst. Mech. Eng. Part J J. Eng. Tribol. 225 (2011) 627–639, https://doi.org/10.1177/1350650110397261.

[93] D. Gonçalves, T. Cousseau, A. Gama, A.V. Campos, J.H.O. Seabra, Friction torque in thrust roller bearings lubricated with greases, their base oils and bleed-oils, Tribol. Int. 107 (2017) 306–319, https://doi.org/10.1016/j.triboint.2016.11.041.

[94] T. Cousseau, B. Graça, A. Campos, J. Seabra, Friction torque in grease lubricated thrust ball bearings, Tribol. Int. 44 (2011) 523–531, https://doi.org/10.1016/j.triboint.2010.06.013.

[95] D. Gonçalves, S. Pinho, B. Graça, A.V. Campos, J.H.O. Seabra, Friction torque in thrust ball bearings lubricated with polymer greases of different thickener content, Tribol. Int. 96 (2016) 87–96, https://doi.org/10.1016/j.triboint.2015.12.017.

[96] T. Cousseau, B.M. Graça, A.V. Campos, J.H.O. Seabra, Influence of grease rheology on thrust ball bearings friction torque, Tribol. Int. 46 (2012) 106–113, https://doi.org/10.1016/j.triboint.2011.06.010.

[97] T. Cousseau, B.M. Graça, A.V. Campos, J.H.O. Seabra, Influence of grease formulation on thrust bearings power loss, Proc. Inst. Mech. Eng. Part J J. Eng. Tribol. 224 (2010) 935–946, https://doi.org/10.1243/13506501JET724.

[98] A. García Tuero, M. Bartolomé, D. Gonçalves, J.L. Viesca, A. Fernández-González, J.H.O. Seabra, et al., Phosphonium-based ionic liquids as additives in calcium/lithium greases, J. Mol. Liq. 338 (2021), 116697, https://doi.org/10.1016/J.MOLLIQ.2021.116697.

[99] T. Cousseau, B. Graça, A. Campos, J. Seabra, Experimental measuring procedure for the friction torque in rolling bearings, Lubr. Sci. 22 (2010) 133–147, https://doi.org/10.1002/ls.115.

[100] C.M.C.G. Fernandes, P.M.P. Amaro, R.C. Martins, J.H.O. Seabra, Torque loss in thrust ball bearings lubricated with wind turbine gear oils at constant temperature, Tribol. Int. 66 (2013) 194–202, https://doi.org/10.1016/j.triboint.2013.05.002.

[101] C.M.C.G. Fernandes, R.C. Martins, J.H.O. Seabra, Friction torque of cylindrical roller thrust bearings lubricated with wind turbine gear oils, Tribol. Int. 59 (2013) 121–128, https://doi.org/10.1016/j.triboint.2012.05.030.

[102] P.M. Lugt, Modern advancements in lubricating grease technology, Tribol. Int. 97 (2016) 467–477, https://doi.org/10.1016/j.triboint.2016.01.045.

[103] N. Acar, J.M. Franco, E. Kuhn, D.E.P. Gonçalves, J.H.O. Seabra, Tribological investigation on the friction and wear behaviors of biogenic lubricating greases in steel-steel contact, Appl. Sci. 10 (2020) 1477, https://doi.org/10.3390/app10041477.

[104] P.M.T. Marques, R.C. Martins, J.H.O. Seabra, Experimental measurement of rolling bearing torque loss in a modified Four-Ball machine: an improved setup, Lubr. Sci. 32 (2020) 245–259, https://doi.org/10.1002/ls.1499.

[105] S. Hurley, P.M. Cann, H.A. Spikes, Thermal degradation of greases and the effect on lubrication performance, Tribol. Ser. 34 (1998) 75–83, https://doi.org/10.1016/S0167-8922(98)80063-1.

[106] T. Hunt, Handbook of Wear Debris Analysis and Particle Detection in Liquids, Springer, Netherlands, 1993.

[107] D.E.P. Gonçalves, A.V. Campos, J.H.O. Seabra, An experimental study on starved grease lubricated contacts, Lubricants 6 (2018) 82, https://doi.org/10.3390/lubricants6030082.

[108] H. Cen, P.M. Lugt, Film thickness in a grease lubricated ball bearing, Tribol. Int. 134 (2019) 26–35, https://doi.org/10.1016/j.triboint.2019.01.032.

[109] G. Poll, et al., Starved lubrication in rolling contacts-a review, Bearing World J. 4 (2019) 69–81.

[110] H. Cen, P. Lugt, Effect of start-stop motion on contact replenishment in a grease lubricated deep groove ball bearing, Tribol. Int. 157 (2021), 106882, https://doi.org/10.1016/j.triboint.2021.106882.

[111] H. Cen, P.M. Lugt, Replenishment of the EHL contacts in a grease lubricated ball bearing, Tribol. Int. 146 (2020), 106064, https://doi.org/10.1016/j.triboint.2019.106064.

[112] S. Hurley, Fundamental Studies of Grease Lubrication in Elastohydrodynamic Contacts, University of London, Imperail College of Science, Technology and Medicine, UK, 2000. PhD Thesis.

[113] L. Salomonsson, G. Stang, B. Zhmud, Oil/thickener interactions and rheology of lubricating greases.STLE, Tribol. Trans. 50 (2007) 302–309.