POWER LOSS OF FZG GEARS LUBRICATED WITH WIND TURBINE GEAR OIL USING IONIC LIQUID ADDITIVE

Carlos M.C.G. Fernandes[1(*)],Antolin Hernandez Battez[2,3], Rubén González[4,3], Raquel Monge[5], José L. Viesca[2,3], Alberto García[2], Ramiro C. Martins[1], Jorge H.O. Seabra[6]
[1]INEGI, Universidade do Porto, Campus FEUP, Rua Dr. Roberto Frias 400, 4200-465 Porto, Portugal
[2]Department of Construction and Manufacturing Engineering, University of Oviedo, Asturias, Spain
[3]Faculty of Science and Technology, Bournemouth University, UK
[4]Department of Marine Science and Technology, University of Oviedo, Asturias, Spain
[5]Engineering Division, CELLS – ALBA Synchrotron Light Facility, Barcelona, Spain
[6]FEUP, Universidade do Porto, Campus FEUP, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal

ABSTRACT
This work presents a study of the tribological behaviour of a mineral fully-formulated wind turbine gear oil additised with [BMP][NTf_2] ionic liquid. The target application are the wind turbine gearboxes, thus the fully formulated oil with and without ionic liquid additive was tested in a rolling bearings test rig to measure the thrust rolling bearing torque loss and was also tested in a FZG gear test rig to measure the gears torque loss at operating conditions similar to the observed in a wind turbine gearbox.
The results show that a wind turbine gear oil additised with ionic liquid can reduce the torque loss and improve the gearbox efficiency while producing less wear particles as observed in the oil analysis.
KEY WORDS: friction, wear, ionic liquids, lubricants.

1.- INTRODUCTION
Reduction of CO_2 emissions is one of the most important concerns in today's society due to the climate change. Wind energy has been playing an important role on the electricity generation, especially during the last years, with the emergence of new designs of wind turbines with increasing size and output power. For large wind turbines, the low rotor speed makes necessary the usage of multiple stage gearboxes, in order to multiply the speed for the adequate rotating speed of the generator [1].
Approximately 30% of the energy losses in wind turbine gearboxes are caused by the rolling bearings. However, at high operation torque the friction losses between the meshing teeth are the main source of power loss. These energy losses depend on the rheological and film forming properties of the gear oil [2, 3, 4, 5].
Fernandes *et al.* [6] measured the torque loss in a FZG gearbox lubricated with five commercial fully-formulated gear oils with ISO VG 320, obtaining substantial differences in the torque loss behaviour for each lubricant.
One of the most important challenges of the industry consists in improve tribological behaviour of mechanical transmissions, and for this objective, the research of high performance gearbox oils using new additives is one of the most promising approaches. Ionic liquids have been proposed many times as oil additives in the development of novel high performance lubricants [7]. Ionic liquids (ILs) are molten salts at room temperature, composed by organic or inorganic anions and cations. ILs are used in the lubrication of several mechanical contacts in vacuum applications [8]

due to their main properties: low vapour pressure, thermal and chemical stability, high thermal and electrical conductivity and tuneable properties.

Ye *et al.* [9] published the first research work on the use of ILs on lubrication showing the good tribological properties of different imidazolium-based ILs for various material contacts in pure sliding conditions. Different material pairs such as steel/steel, steel/SiO_2, steel/aluminium, steel/copper, steel/Si(100), steel/sialon, steel/titanium, sialon/Si_3N_4 and steel-PVD coatings (TiN, DLC and CrN) have been explored using different cations (pyridinium, imidazolium, phosphonium and ammonium) combined with anions such as hexafluorophosphate (PF_6), tetrafluoroborate (BF_4), CF_3SO_3, $(C_2F_5)_3PF_3$ (or FAP) and $(CF_3SO_2)_2N$ (or NTf_2) [10, 11, 12, 13, 14, 15, 16, 17, 18, 19] [20, 21, 22, 23, 24, 25, 26].

The most frequently anions studied in the tribology literature are PF_6 and BF_4. However, their tendency to produce HF (very corrosive) and hydrolytic instability have been reported [26]. A new type of ILs using the FAP anion (manufactured by Merck KGaA [27]) shows a better hydrolytic stability. Several review papers [28, 29, 30, 31] have explained the advantages of using ILs in lubrication, their oxidative and thermal stability, tribochemical reactions and tribological properties. ILs can be used as neat lubricants, or as additive to base or formulated oils. The use of ILs as pure lubricant presents the problem of the high cost of ILs compared with any mineral or synthetic hydrocarbon oils. The use of ILs as additive in oil is a cheaper solution, but could present a problem of low solubility in non-polar oils [32].

The wear and friction behaviour of ILs as oil additive or as neat lubricant have been studied using different mineral and synthetic base oils [26, 32, 33, 34]. The use of ILs as additional additives of fully formulated oils needs to be studied in depth. The combined effect of the IL with another existing oil additives has been studied by Qu *et al.* [35] reporting the improved performance of SAE 5W-30 engine oil using a phosphonium-based ionic liquid with concentration of 5 wt%. Greco *et al.* [36] obtained similar results using 1 wt% of nanocolloidal boron nitride as additive in fully formulated wind turbine gearbox oil.

Monge *et al.* [37] have studied the friction and wear behaviour of two [NTf_2] anion-based ionic liquids used as additive to two fully formulated (polyalphaolefin- and mineral-based) wind turbine gear oils, using ball on plate reciprocating tests. Results indicated a slightly friction reduction; however the use 5 wt% of both ILs improved the wear performance of the gear oils under all test conditions employed.

Based on the good anti friction behaviour, hydrophobicity and hydrolytic stability of the [NTf_2] anion reported by Minami *et al.* [15, 29], the current work studies using a new approach the tribological performance of the best mixture found in [37], the [BMP][NTf_2] ionic liquid (1-butyl-1-methylpyrrolidinium bis (trifluoromethylsulfonyl)imide) used as additive to a mineral-based fully formulated wind turbine gear oil. The study is based on the power loss of FZG gear tests. The wear protection provided by the addition of the ionic liquid is also studied. The present work is part of the work previously published in [38] where rolling bearing tests and gear wear tests were performed.

2.- LUBRICANTS

A commercial ISO VG 320 fully formulated mineral-based gear oil (MINR) was tested in this work. This oil is widely used in wind turbine gearboxes and in a previous work [37] it was tested with and without ionic liquids in its composition using a different tribological approach. The chemical composition and rheological properties was previously determined by Fernandes *et al.* [2, 3, 4, 5, 6] and are displayed in Table 1.

Table 1. Physical and chemical properties of wind turbine gear oil.

Parameter	**Unit**	**MINR**
Base Oil	[-]	Mineral
Chemical composition		
Zinc (Zn)	[ppm]	0.9
Magnesium (Mg)	[ppm]	0.9
Phosphorus (P)	[ppm]	354.3
Calcium (Ca)	[ppm]	2.5
Boron (B)	[ppm]	22.3
Sulphur (S)	[ppm]	11200
Physical properties		
ρ @ 15 ˚C	[g/cm^3]	0.902
ν @ 40 ˚C	[cSt]	319.22
ν @ 70 ˚C	[cSt]	65.81
ν @ 100 ˚C	[cSt]	22.33
VI	[-]	85

1-butyl-1-methylpyrrolidinium bis (trifluoromethylsulfonyl) imide, [BMP][NTf$_2$], provided by (Io-Li-Tec), was used as additive in this paper. The main properties of this ionic liquid are shown in Table 2, including the molecular structure.

Before each experimental test, ionic liquid at 5 wt% was blended with the mineral oil, using a mechanic mixer for 10 minutes and controlling the temperature of the samples at 70 ˚C.

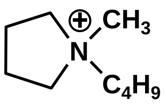
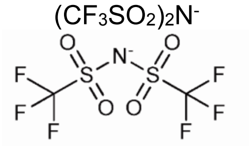
The corrosion activity, thermogravimetric performance and rheological properties of the mixture was previosuly studied in [37]. On the one hand, the surface analysis by optical microscopy, SEM and EDS after testing did not show corrosion activity. On the other hand, the thermogravimetric analysis (TGA) made to the blend and the gear oil without ionic liquid showed that thermal stability (decomposition temperature of around 230 ˚C) was not improved with the addition of the ionic liquid. Finally, the addition of the ionic liquid resulted in a small increase in viscosity and viscosity index of the blend with regard to the gear oil without ionic liquid. All these results meet some of requirements established by DIN 51517 Part 3; however, for a commercial use, further analysis should be done in order to verify all the standard requirements and possible interactions of the ionic liquid with other lubricant additives.

Table 2. Main properties and molecular structure of the ionic liquid.

Ionic Liquid							
Cation	**Anion**	**IUPAC name**	**Purity (%)**	**Density (g/cm^3)***	**Viscosity (mm^2/s)***		**Viscosity Index***
				15 ˚C	**40 ˚C**	**100 ˚C**	
[BMP]	[NTf$_2$]	1-Butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide	>99	1.40	28.826	6.228	174

*****Measured in a SVM 3000 Stabinger viscometer (ASTM D7042, D2270)

Molecular structure

Cation	Anion
$C_9H_{20}N$  [BMP]	$(CF_3SO_2)_2N^-$  [NTf$_2$]

3.- POWER LOSS AND WEAR ON FZG GEARS

3.1.- Test rig

The FZG test machine used in this work is presented in the Figure 3. The FZG machine is a gear test rig operating with a static torque in a power recirculating concept [42]. The drive gearbox (3) connects the test pinion (1) and wheel (2) through two shafts. The test pinion shaft is separated into two parts by the load clutch (4). One part of the clutch can be locked using the locking pin (5), while in the other part of the clutch different static torques can be applied using the load lever and dead weights (6).
The torque loss (T_L) was measured using a torque transducer (ETH Messtechnik DRDL II) integrated in the FZG test rig, as shown in Figure 1. A sensor interface (ValuemasterBase) is used by the system to communicate with a computer using an Ethernet port. The software and hardware of torque cell allows measuring and recording the torque with a sampling rate between 1 Hz and 1000 Hz.
The temperatures of the test were measured using eight different thermocouples located in different points of the machine.
Type C gear with a face width of 40 mm was assembled in the FZG drive gearbox while a type C gear with face width of 14 mm was assembled in the test gearbox.
Table **3** displays the main dimensions of both gears.

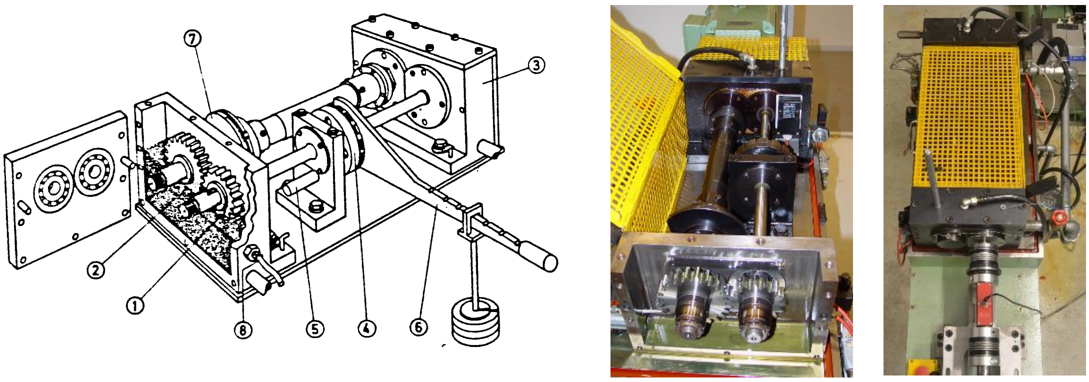


Figure 1. FZG gear test rig

Table 3. Gear geometric properties.

Gear type	type C40		type C14	
Property	Pinion	Wheel	Pinion	Wheel
Number of teeth	16	24	16	24
Module [mm]	4.5			
Centre distance [mm]	91.5			
Pressure angle [˚]	20			
Working pressure angle [˚]	22.44			
Helix angle [˚]	0			
Contact path [mm]	19.0987			
Face width [mm]	**40**		**14**	
Addendum modification [/]	+0.1817	+0.1715	+0.1817	+0.1715
Addendum diameter [mm]	82.64	118.54	82.64	118.54
Transverse contact ratio ε_α [/]	1.44			
Overlap contact ratio ε_β [/]	0			
Material	20MnCr5			
Ra [μm]	0.7		≈ 0.5	

3.2.- Test conditions and test procedure

Three input speeds and four load stages were performed in FZG test campaign. The operating conditions used in the torque loss tests are displayed in Table 4. The tangential speed, the power circulating in the system, the tangential force transmitted by the gears, the radial forces on the rolling bearings and the Hertzian pressure in the gears are also included.

The slave gearbox was oil jet lubricated with an oil flow of 3 l/min at 80 ˚C always with MINR oil without ionic liquids. The test gearbox was dip lubricated with 1 l of the candidate oils (MINR or MINR+5% IL) at 80 ˚C.

The test procedure can be summarized as follows:

1. Run load stage Ki at each rotational speed n_i condition (Table 4) during 4 h according to the test sequence presented in Figure 4 and:
   - Register the assembly working temperatures.
   - Continuous torque measurement with a sample rate of 1 Hz.
2. Repeat procedure till the highest load stage (K9).

The values reported for torque loss and temperature are the average of the last 30 min of operation (only the steady state operating conditions are considered for the average calculation). Between each oil test, the gearboxes were flushed with solvent.

Table 4. Operating conditions.

Load stage	Torque [Nm]	Wheel Speed [rpm]	v_t [m/s]	Power [W]	F_{bn} [N]	F_r [N]	${p_0}^{C14}$ [MPa]	${p_0}^{C40}$ [MPa]
K1	4.95	200	1.1	103.7	98	49.5	188	111
		400	2.3	207.3				
		1200	6.8	622.0				
K5	104.97	200	1.1	2198.5	2069	1049	511	865
		400	2.3	4396.9				
		1200	6.8	13190.9				
K7	198.68	200	1.1	4161.2	3915	1986	704	1189
		400	2.3	8322.4				
		1200	6.8	24967.2				
K9	323.27	200	1.1	6770.4	6371	3231	898	1517
		400	2.3	13540.9				
		1200	6.8	40622.7				

3.3.- Torque loss results

The total torque loss measurements for all the test conditions performed with C40 gears assembled on drive gearbox and C14 on test gearbox are presented in Table 5. It is important to mention that the slave gearbox was always lubricated under oil jet lubrication with MINR. The total torque loss was previously measured with C40 gears installed in both the test and drive gearboxes and presented in Table 6 (procedure presented in [6]).

The torque loss of the test gearbox (${T_L}^{C14}$) is then given by equation (2).

$$ {T_L}^{C14} = {T_L}^{C40+C14} - \frac{{T_L}^{C40+C40}}{2} \quad (1) $$

Table 5. Total torque loss measured on FZG test machine for the oils tested ($T_L^{C40+C14}$).

Wheel speed	Load stage	MINR	MINR+IL
200	K1	1.34	1.30
	K5	3.17	3.30
	K7	6.22	4.87
	K9	8.64	7.93
400	K1	1.55	1.53
	K5	3.22	3.38
	K7	6.10	4.77
	K9	8.31	7.49
1200	K1	2.22	2.19
	K5	3.65	3.75
	K7	6.15	4.92
	K9	8.11	7.09

Table 6. Total torque loss measured on FZG test rig for MINR with C40 gears in both test and drive gearboxes ($T_L^{C40+C40}$).

Wheel speed	Load stage	MINR
200	K1	1.15
	K5	3.69
	K7	5.88
	K9	8.88
400	K1	1.49
	K5	3.76
	K7	5.73
	K9	8.53
1200	K1	2.14
	K5	4.22
	K7	5.80
	K9	8.08

Figure 2a) displays the torque loss measured for load stage K1 at the input speeds of 200, 400 and 1200 rpm. MINR and MINR+5% IL had very similar torque loss for all operating speeds which means that no substantial changes are found for a no-load condition. These torque losses are mainly generated by load independent losses.
Figure 2b) displays the torque loss for load stage K5. MINR and MINR+5% IL promoted similar experimental torque losses. However, MINR+5% IL generated slightly higher torque loss.
The torque loss for the load stage K7 is displayed in Figure 2c). The MINR + 5% IL promoted a reduction in the total torque loss of around 1 Nm, which corresponds to a torque loss reduction of around 20%.
The torque loss measurements for load stage K9 are presented in Figure 2d). The MINR + 5% IL promoted a reduction in torque loss between 8% and 12%, depending on the rotational speed in comparison with the mineral oil.
These experimental results clearly show that the Ionic Liquid has a positive effect in the reduction of the torque loss in comparison with the original lubricant, MINR.

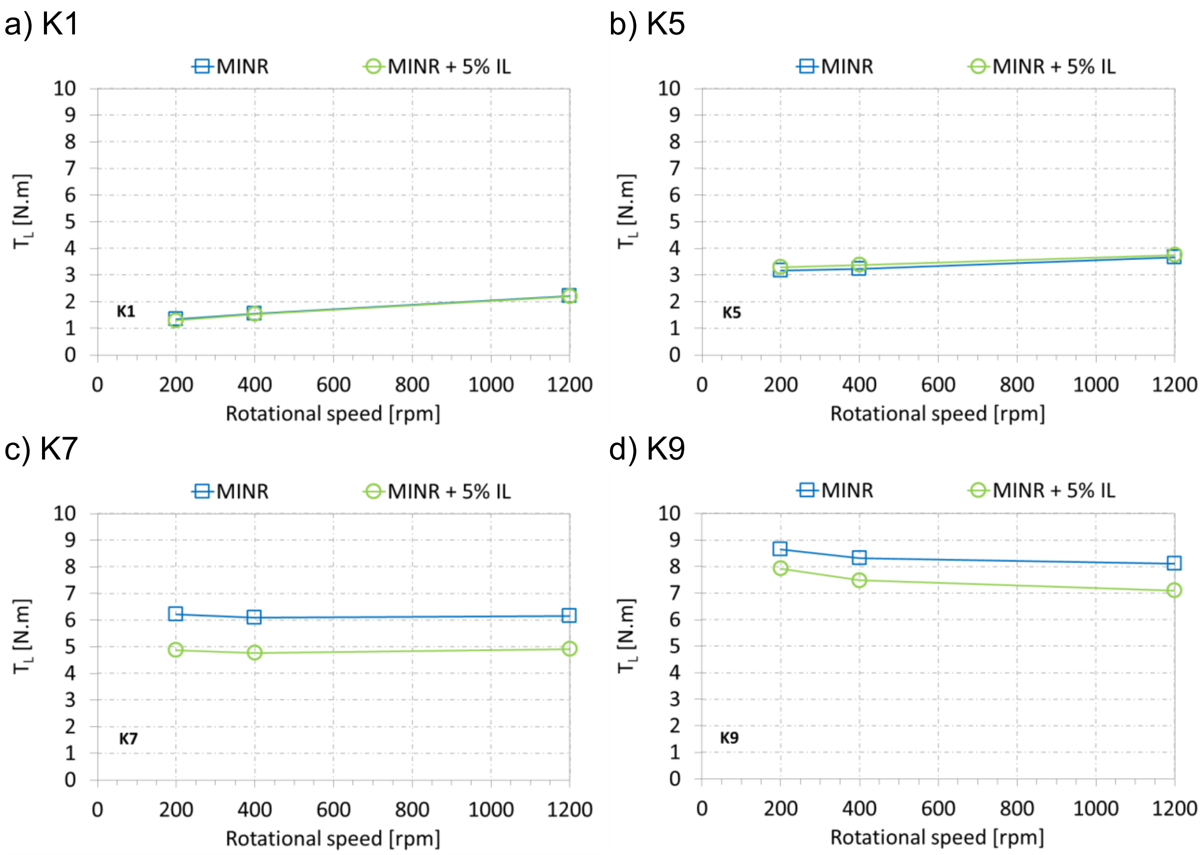


Figure 2.Total torque loss (T_L) in function of load and speed.

3.4.- Wear of FZG gears

The wear of the gears during the power loss tests was monitored using different techniques like mass loss, surface roughness and oil analysis.

Mass loss

Before and after power loss test campaign, the gear pinion was weighted. For each oil a new gear set was used. The mass loss is presented in Table 7 and it is clear that no substantial difference was found.

Table 7. Mass loss [mg] of the pinion after power loss test.

Number of Cycles× 1000	MINR	MINR + 5% IL
1944	10	9

Surface Roughness

The Surface evolution has been accessed using 2D and 3D Surface texture evaluations with a Hommelwerk T8000 device. Three measurements in two different teeth were performed both on pinion and wheel in radial direction. Table 8 displays the average values of the six measurements. No substantial differences were found during the power loss tests.

Oil analysis

The protection against wear provided by MINR and MINR + 5% IL is also compared through oil analysis. The analysis of the wear particles contained in the lubricant gives

quite good indication about the wear of lubricated parts, since those particles in a closed box have origin in the contacting parts.
The lubricant samples, collected after each power loss test, were analysed by Direct Reading Ferrography in order to measure the ferrometric parameters DL (large wear particles index) and DS (small wear particles index). The values of DL and DS are then used to evaluate the concentration of wear particles index - CPUC and the severity of wear particles index - ISUC, defined by equations (2) and (3), respectively.

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

$$\mathrm{ISUC} = \frac{DL^2-DS^2}{d^2} \quad (3)$$

Table 8. Roughness parameters of the tooth Surface in radial direction.

Oil		Condition	Ra	Rq	Rz	Rmax
MINR	pinion	New	0.46	0.58	3.17	4.05
		Power loss	0.35	0.47	2.68	4.18
	wheel	New	0.61	0.78	4.21	4.98
		Power loss	0.42	0.57	3.24	4.42
MINR+IL	pinion	New	0.53	0.67	3.60	4.37
		Power loss	0.37	0.47	2.44	2.94
	wheel	New	0.53	0.68	3.79	4.46
		Power loss	0.34	0.44	2.34	2.76

The results clearly show that the concentration of wear particles is higher in the test with MINR, indicating a larger amount of particle generation. The wear severity is also larger for the MINR lubricant, indicating that the wear particle are also larger than that found with MINR+5% IL.

Table 9. Ferrometric indexes.

Oil	DL	DS	CPUC	ISUC
MINR	37.4	3.3	407	1.4×10^5
MINR+5%IL	20.3	6.1	264	3.7×10^4

4.- CONCLUSIONS

The use of [BMP][NTf_2] ionic liquid as 5 wt% additive in a mineral-based fully formulated wind turbine gear oil was analysed under different testing conditions in this work. The blend tested before under a ball-on-plate reciprocating configuration had showed slight friction reduction behavior with regard to the gear oil without ionic liquid but a clear wear reduction performance. Now, using another tribological approach with FZG power loss tests, some conclusions can be drawn: the addition of the ionic liquid to the mineral-based fully formulated gear oil promoted lower power loss in FZG tests, though the small friction reduction of the blend with regard to the non-containing IL sample verified in a previous work. At the same time the results suggest lower wear severity when using the ionic liquid as additive.

ACKNOWLEDGEMENTS

The authors thank to the Ministry of Science and Innovation (Spain) and to the Foundation for the Promotion in Asturias of the Applied Scientific Research and

Technology (FICYT) for supporting this research within the framework of the Research Projects WINDTRIB (DPI2010-18166) and GRUPIN14-023, respectively.
The authors thank to Repsol S.A. that provided the wind turbine gear oil.
The authors gratefully acknowledge the funding supported by: National Funds through Fundação para a Ciência e a Tecnologia (FCT), under the project EXCL/SEM-PRO/0103/2012; COMPETE and National Funds through Fundação para a Ciência e a Tecnologia (FCT), under the project Incentivo/EME/LA0022/2014; Quadro de Referência Estratégico Nacional (QREN), through Fundo Europeu de Desenvolvimento Regional (FEDER), under the project NORTE-07-0124-FEDER-000009 - Applied Mechanics and Product Development; without whom this work would not be possible.

REFERENCES

[1] P. M. Marques, C. M. Fernandes, R. C. Martins and J. H. Seabra, "Efficiency of a gearbox lubricated with wind turbine gear oils," *Tribology International* , vol. 71, no. 0, pp. 7-16, 2014.

[2] C. M. Fernandes, R. C. Martins and J. H. Seabra, "Friction torque of thrust ball bearings lubricated with wind turbine gear oils," *Tribology International,* vol. 58, no. 0, pp. 47-54, 2013.

[3] C. M. Fernandes, R. C. Martins and J. H. Seabra, "Friction torque of cylindrical roller thrust bearings lubricated with wind turbine gear oils," *Tribology International,* vol. 59, pp. 121-128, 2013.

[4] C. M. Fernandes, P. M. Amaro, R. C. Martins and J. H. Seabra, "Torque loss in thrust ball bearings lubricated with wind turbine gear oils at constant temperature," *Tribology International* , vol. 66, no. 0, pp. 194-202, 2013.

[5] C. M. Fernandes, P. M. Amaro, R. C. Martins and J. H. Seabra, "Torque loss in cylindrical roller thrust bearings lubricated with wind turbine gear oils at constant temperature," *Tribology International,* vol. 67, no. 0, pp. 72-80, 2013.

[6] C. M. Fernandes, R. C. Martins and J. H. Seabra, "Torque loss of type C40 FZG gears lubricated with wind turbine gear oils," *Tribology International,* vol. 70, no. 0, pp. 83-93, 2013.

[7] V. Totolin, I. Minami, C. Gabler and N. Dorr, "Halogen-free borate ionic liquids as novel lubricants for tribological applications," *Tribology International,* vol. 67, no. 0, pp. 191-198, 2013.

[8] S. Stolte, S. Steudte, O. Areitioaurtena, F. Pagano, J. Thöming, P. Stepnowski and A. Igartua, "Ionic liquids as lubricants or lubrication additives: An ecotoxicity and biodegradability assessment," *Chemosphere,* vol. 89, no. 9, pp. 1135-1141, 2012.

[9] C. Ye, W. Liu, Y. Chen and L. Yu, "Room-temperature ionic liquids: a novel versatile lubricant," *Chem. Commun.,* pp. 2244-2245, 2001.

[10] H. Kamimura, T. Kubo, I. Minami and S. Mori, "Effect and mechanism of additives for ionic liquids as new lubricants," *Tribology International* , vol. 40, no. 4, pp. 620-625, 2007.

[11] L. Weng, X. Liu, Y. Liang and Q. Xue, "Effect of tetraalkylphosphonium based ionic liquids as lubricants on the tribological performance of a steel-on-steel system," *Tribology Letters,* vol. 26, no. 1, pp. 11-17, 2007.

[12] A.-E. Jimenez and M.-D. Bermudez, “Imidazolium ionic liquids as additives of the synthetic ester propylene glycol dioleate in aluminium/steel lubrication,” *Wear,* vol. 265, no. 5-6, pp. 787-798, 2008.

[13] A.-E. Jimenez and M.-D.-D. Bermudez, “Ionic liquids as lubricants for steel/aluminum contacts at low and elevated temperatures,” *Tribology Letters,* vol. 26, no. 1, pp. 53-60, 2007.

[14] S. Lawes, S. Hainsworth, P. Blake, K. Ryder and A. Abbott, “Lubrication of Steel/Steel Contacts by Choline Chloride Ionic Liquids,” *Tribology Letters,* vol. 37, no. 2, pp. 103-110, 2010.

[15] I. Minami, M. Kita, T. Kubo, H. Nanao and S. Mori, “The Tribological Properties of Ionic Liquids Composed of Trifluorotris(pentafluoroethyl) Phosphate as a Hydrophobic Anion,” *Tribology Letters,* vol. 30, no. 3, pp. 215-223, 2008.

[16] A. Jimenez and M. Bermudez, “Ionic Liquids as Lubricants of Titanium-Steel Contact. Part 2: Friction, Wear and Surface Interactions at High Temperature,” *Tribology Letters,* vol. 37, no. 2, pp. 431-443, 2010.

[17] H. Kondo, “Protic Ionic Liquids with Ammonium Salts as Lubricants for Magnetic Thin Film Media,” *Tribology Letters,* vol. 31, no. 3, pp. 211-218, 2008.

[18] R. Gonzalez, A. Hernandez Battez, D. Blanco, J. Viesca and A. Fernandez-Gonzalez, “Lubrication of TiN, CrN and DLC PVD Coatings with 1-Butyl-1-Methylpyrrolidinium tris(pentafluoroethyl)trifluorophosphate,” *Tribology Letters,* vol. 40, no. 2, pp. 269-277, 2010.

[19] D. Blanco, A. Battez, J. Viesca, R. Gonzalez and A. Fernandez-Gonzalez, “Lubrication of CrN Coating With Ethyl-Dimethyl-2-Methoxyethylammonium Tris(pentafluoroethyl)Trifluorophosphate Ionic Liquid as Additive to PAO 6,” *Tribology Letters,* vol. 41, no. 1, pp. 295-302, 2011.

[20] J. Viesca, A. H. Battez, R. Gonzalez, T. Reddyhoff, A. T. Perez and H. Spikes, “Assessing boundary film formation of lubricant additivised with 1-hexyl-3-methylimidazolium tetrafluoroborate using ECR as qualitative indicator,” *Wear,* vol. 269, no. 1-2, pp. 112-117, 2010.

[21] D. Blanco, R. Gonzalez, A. H. Battez, J. Viesca and A. Fernandez-Gonzalez, “Use of ethyl-dimethyl-2-methoxyethylammonium tris (pentafluoroethyl) trifluorophosphate as base oil additive in the lubrication of TiN PVD coating,” *Tribology International,* vol. 44, no. 5, pp. 645-650, 2011.

[22] A. H. Battez, R. Gonzalez, J. Viesca, A. Fernandez-Gonzalez and M. Hadfield, “Lubrication of PVD coatings with ethyl-dimethyl-2-methoxyethylammonium tris(pentafluoroethyl)trifluorophosphate,” *Tribology International ,* vol. 58, no. 0, pp. 71-78, 2013.

[23] J. Viesca, A. Garcia, A. Hernandez Battez, R. Gonzalez, R. Monge, A. Fernandez-Gonzalez and M. Hadfield, “FAP -- Anion Ionic Liquids Used in the Lubrication of a Steel/Steel Contact,” *Tribology Letters,* vol. 52, no. 3, pp. 431-437, 2013.

[24] R. Gonzalez, A. H. Battez, J. L. Viesca, A. Higuera-Garrido and A. Fernandez-Gonzalez, “Lubrication of DLC Coatings with Two Tris(pentafluoroethyl)trifluorophosphate Anion-Based Ionic Liquids,” *Tribology Transactions,* vol. 56, no. 5, pp. 887-895, 2013.

[25] A. Garcia, R. Gonzalez, A. H. Battez, J. Viesca, R. Monge, A. Fernandez-Gonzalez and M. Hadfield, "Ionic liquids as a neat lubricant applied to steel/steel contacts," *Tribology International ,* vol. 72, no. 0, pp. 42-50, 2014.

[26] J. Qu, J. Truhan, S. Dai, H. Luo and P. Blau, "Ionic liquids with ammonium cations as lubricants or additives," *Tribology Letters,* vol. 22, no. 3, pp. 207-214, 2006.

[27] C. Yao, W. R. Pitner and J. L. Anderson, "Ionic Liquids Containing the Tris(pentafluoroethyl)trifluorophosphate Anion: a New Class of Highly Selective and Ultra Hydrophobic Solvents for the Extraction of Polycyclic Aromatic Hydrocarbons Using Single Drop Microextraction," *Analytical Chemistry,* vol. 81, no. 12, pp. 5054-5063, 2009.

[28] F. Zhou, Y. Liang and W. Liu, "Ionic liquid lubricants: designed chemistry for engineering applications," *Chem. Soc. Rev.,* vol. 38, pp. 2590-2599, 2009.

[29] I. Minami, "Ionic Liquids in Tribology," *Molecules,* vol.14, no 6, pp.2286-2305, 2009.

[30] M. Palacio and B. Bhushan, "A Review of Ionic Liquids for Green Molecular Lubrication in Nanotechnology," *Tribology Letters,* vol.40, no.2, pp. 247-268, 2010.

[31] M.-D. Bermúdez, A.-E. Jiménez, J. Sanes and F.-J. Carrión, "Ionic Liquids as Advanced Lubricant Fluids," *Molecules,* vol. 14, no. 8, pp. 2888-2908, 2009.

[32] J. Qu, H. Luo, M. Chi, C. Ma, P. J. Blau, S. Dai and M. B. Viola, "Comparison of an oil-miscible ionic liquid and ZDDP as a lubricant anti-wear additive," *Tribology International,* vol. 71, no. 0, pp. 88-97, 2014.

[33] G. Mordukhovich, J. Qu, J. Y. Howe, S. Bair, B. Yu, H. Luo, D. J. Smolenski, P. J. Blau, B. G. Bunting and S. Dai, "A low-viscosity ionic liquid demonstrating superior lubricating performance from mixed to boundary lubrication," *Wear,* vol. 301, no. 1-2, pp. 740-746, 2013.

[34] J. Qu, P. Blau, S. Dai, H. Luo and H. I. Meyer, "Ionic Liquids as Novel Lubricants and Additives for Diesel Engine Applications," *Tribology Letters,* vol. 35, no. 3, pp. 181-189, 2009.

[35] J. Qu, D. G. Bansal, B. Yu, J. Y. Howe, H. Luo, S. Dai, H. Li, P. J. Blau, B. G. Bunting, G. Mordukhovich and D. J. Smolenski, "Antiwear Performance and Mechanism of an Oil-Miscible Ionic Liquid as a Lubricant Additive," *ACS Applied Materials & Interfaces,* vol. 4, no. 2, pp. 997-1002, 2012.

[36] A. Greco, K. Mistry, V. Sista, O. Eryilmaz and A. Erdemir, "Friction and wear behaviour of boron based surface treatment and nano-particle lubricant additives for wind turbine gearbox applications," *Wear ,* vol. 271, no. 9-10, pp. 1754-1760, 2011.

[37] R. Monge, R. González, A. H. Battez, A. Fernández-González, J. Viesca, A. García and M. Hadfield, "Ionic liquids as an additive in fully formulated wind turbine gearbox oils," *Wear,* Vols. 328-329, pp. 50-63, 2015.

[38] C. M. Fernandes, A. H. Hernandes, R. González, R. Monge, J. L. Viesca, A. García, R. C. Martins and J. H. Seabra, "Torque loss and wear of FZG gears lubricated with wind turbine gear oils using an ionic liquid as additive," *Tribology International,* no. 0, 2015.