Improving wear performance of wind turbine gearboxes using ionic liquids as additives of lubricants

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ABSTRACT
Wind resources are a proven source of clean, affordable and sustainable energy. Wind energy does not produce harmful pollution gases such carbon dioxide, sulphur dioxide, or other gases that have contributed to global warming. The wind energy industry has seen rapid growth within the last decade; however the cost of maintaining the turbines is a major drawback. Wind turbine gearboxes present one of the more challenging current practical tribological problems. Contact failures in gear and bearing components have been the source of costly repairs and downtime of the turbine's drivetrain and actuator. A potential solution to reduce contact failures in wind turbines and increase their lifespan, is the use of ionic liquids (IL) as lubricant or additives of lubricants. ILs have the ability to form stable ordered layers on the contact area between the materials, reducing friction and wear.
In this work, the wear behavior of trihexyltetradecylphosphonium bis(trifluoromethylsulfonyl) amide used as additive in two oils is studied and compared to commercially available, fully formulated lubricant. Lubricated disks of steel AISI 52100 mated with AISI 440C stainless steel balls are studied using a ball-on-flat reciprocating configuration under variable conditions of normal applied load and sliding frequency. The use of the IL as additive in a base oil reduce wear, particularly under the lowest frequency studied.

KEY WORDS: wear, ionic liquids, lubricants, steel-steel contact.

1.- INTRODUCTION
Wind is a proven source of clean, affordable and sustainable energy. Wind energy does not produce harmful pollution gases such carbon dioxide, sulfur dioxide, or other gases that have contributed to global warming. According to the American Wind Energy Association, "on average, each MWh of electricity generated in the U.S. results in the emission of 1,341 pounds of carbon dioxide (CO2), 7.5 pounds of sulfur dioxide (SO2) and 3.55 pounds of nitrogen oxides (NOx). Thus the 10 million MWh of electricity generated annually by U.S. wind farms represents about 6.7 million tons in avoided CO2 emissions, 37,500 tons of SO2 and 17,750 tons of NOx. This avoided CO2 equals over 1.8 million tons of carbon, enough to fill 180 trains, each 100 cars long, with each car holding 100 tons of carbon every year [1]." The wind energy industry has seen rapid growth within the last decade; however the cost of maintain the turbines is a major drawback. Wind turbine gearboxes present one of the more challenging current practical tribological problems. Contact failures in gear and bearing components have been the source of costly repairs and downtime of the turbine's drivetrain and actuator [2-4]. A potential solution to reduce contact failures in wind turbines and increase their lifespan, is the use of ionic liquids (ILs) as lubricant or additives of lubricants.

In the last decade, ILs have emerged as high-performance fluids due to their unique characteristics such as high thermal stability, non-volatility, non-flammability, high ionic conductivity, wide electrochemical window and miscibility with organic compounds. Also, ILs have the ability to form stable ordered layers and protective tribofilms [5-7] on the area between the two materials in contact, reducing friction and wear. ILs are salts with melting points lower than 100 ºC and are usually composed of an organic cation, typically containing nitrogen or phosphorus, and a weakly coordinating anion. The ability to modify the chemical and physical properties of the ILs by changing the anion-cation combination allows to tailor them for any particular application [8]. ILs are also considered as "green" solvents, since both the cation and anion can be chosen to be non-toxic [9, 10]. Recent literature has suggested potential for using room-temperature ionic liquids as lubricants [6, 8, 11, 12]; however, studies on the tribological performance of ILs as additives or neat lubricants for wind turbine applications are still very scarce.

In this work, the wear behavior of trihexyltetradecylphosphonium bis(trifluoromethylsulfonyl) amide used as additive in two oils is studied and compared to commercially available, fully formulated lubricant.

2.- EXPERIMENTAL DETAILS

AISI 52100 steel flat disks were tested in a ball-on-flat reciprocating (Figure 1) tribometer against AISI 440C steel balls (3 mm spherical radius, 690 hardness HV).The sliding time (60 min) and amplitude (10.5 mm) were kept constant for all tests.

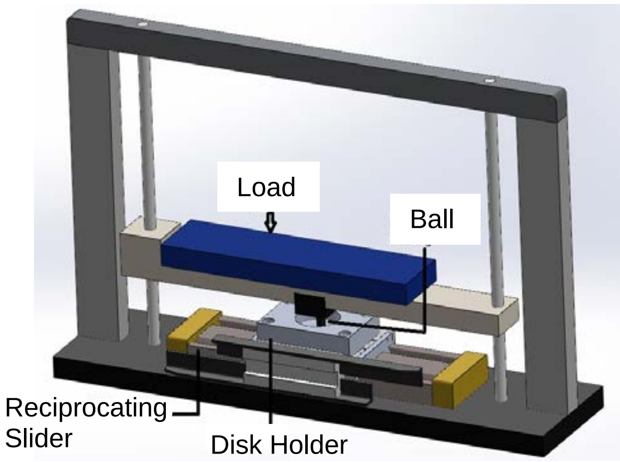


Figure 1. Ball-on-flat test configuration.

Trihexyltetradecylphosphonium bis(trifluoromethylsulfonyl) amide (Sigma-Aldrich, USA) is the IL used in this study. Lubricating mixtures were prepared by adding 2.5, 5, 10, 20 wt.% ratio of IL to a synthetic poly alpha olefin (Syton PAO-40) and 5 wt.% ratio of IL to a commercially available, fully formulated, wind turbine gearbox lubricant (Mobilgear SHC XMP 320). Before each test, steel disks were covered with 2 ml of the lubricant, and no additional lubricant was added during the test.

Wear was obtained after three tests under the same condition. Volume loss was determined by image analysis after 45 wear track width (W) measurements (Figure 2) for each test, according to Eq. 1 [13]:

$$Vf = Ls \cdot \left[Rf^{2} \arcsin\left(\frac{W}{2Rf}\right) - \left(\frac{W}{2}\right)(Rf - hf) \right] + \frac{\pi}{3}(3Rf - hf)$$

As can be seen in Figure 2, W is the wear width, Ls is stroke length and Rf is the radius of 440C steel ball.

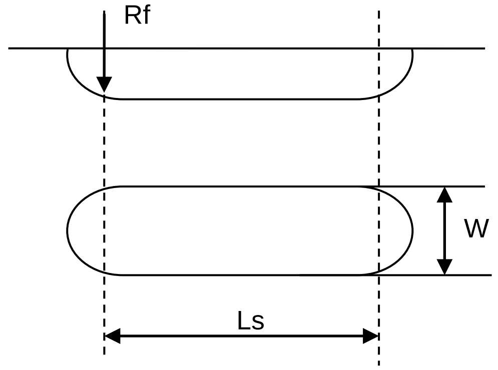


Figure 2. Schematic of a wear scar on a flat specimen against a spherical pin of radius Rf.

Optical micrographs were obtained using a Zeiss optical stereoscope and wear track profiles using a Taylor-Hobson profilometer.

3.- RESULTS AND DISCUSSION

3.1.- Effect of IL concentration

In order to study the effect of IL concentration in PAO, the following parameters were kept constant: sliding distance= 227 m, frequency= 3Hz and normal load= 23 N (max hertzian contact pressure = 1.85 Gpa). As shown in Figure 3, wear rate of steel disks is minimum when a ratio between 5-10 wt. % of IL is used in the synthetic poly alpha olefin (PAO). After increasing this ratio of IL in PAO, wear rate increases until reaching a maximum value when IL is used as neat lubricant. 5 wt. % of IL was the concentration selected to compare wear performance of ILs as additives in PAO and wind turbine oil.

Figure 4 shows the optical micrographs of worn surfaces after a test lubricated with IL as neat lubricant and 5wt.% IL in PAO. The milder wear regime when 5 wt. % IL is used as additive in PAO is evidenced by the absence of a real worn surface in some parts of the wear track, as only superficial scratches were observed (Figure 4b). When IL is used as neat lubricant a wider and deeper wear track was obtained as can been observed in Figure 4a.

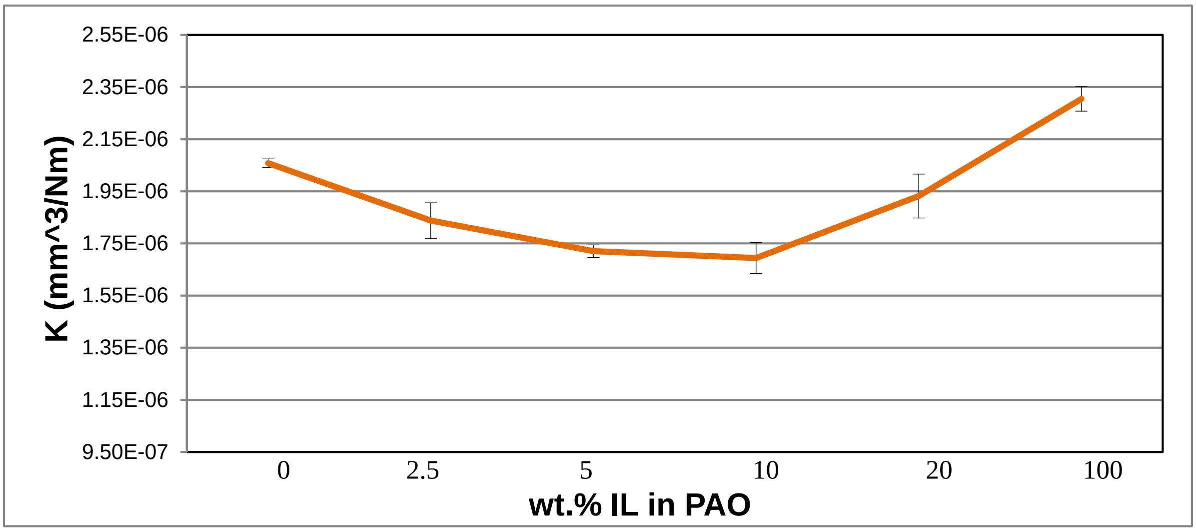
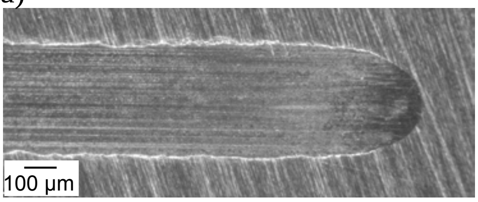


Figure 3. Schematic of a wear scar on a flat specimen against a spherical pin of radius Rf.

a)



b)

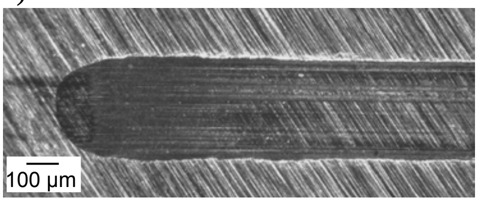


Figure 4. Optical micrographs of worn surfaces after a test (3Hz, 23 N, 227 m) lubricated with (a) 100 wt. % IL, (b) 5 wt. % IL in PAO.

3.1.- Effect of frequency

For this part of the study, normal load (23 N) and sliding time (1hr) were kept constant. PAO, 5 wt. % IL in PAO (PAO+5% IL), wind turbine gearbox oil (MG) and 5 wt. % IL in MG (MG+5%IL) were studied as a function of the sliding frequency. While under the highest frequency studied, no major differences (Figure 5) were found in the lubricating ability of the mixtures; at 1.5 Hz, the addition of 5 wt. % IL to PAO and MG reduced the wear rate of steel disk. Wear reductions of 31 % and 39 % with respect PAO were observed for PAO+5% IL and MG+5% IL respectively. It is interesting to notice that under the lowest frequency, PAO+5% IL showed a better lubricating ability than the commercially available, wind turbine gearbox lubricant (MG).

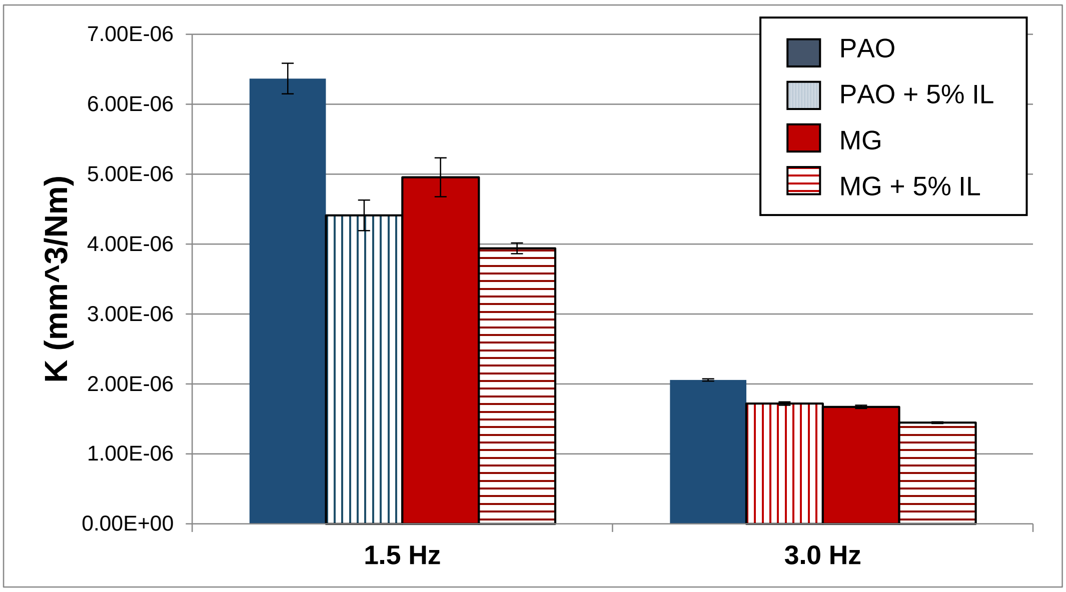


Figure 5. Wear rates of AISI 52100 steel disks against AISI 440C steel balls under lubrication (23 N, 1hr).

3.1.- Effect of normal load

Maintaining a constant frequency of 1.5 Hz and sliding distance of 454 m, the influence of the normal load on the lubricating ability of the oils was studied. As shown in Figure 5, wear rates under increasing normal loads, are always lower in the presence of the IL with respect to both oils without ILs (PAO and MG). This reduction is particularly important under the highest load (45 N), where the addition of 5wt. % IL in MG reduced one order the magnitude the wear rate of steel disk, with respect the commercially wind turbine gearbox lubricant. Under the loads studied, the lowest wear rate was always obtained on the steel disk lubricated with MG+5%IL. This suggests a synergistic effect of IL with the anti-wear additives included in the formulation of the gear oil, which is in agreement with previous studies [14].

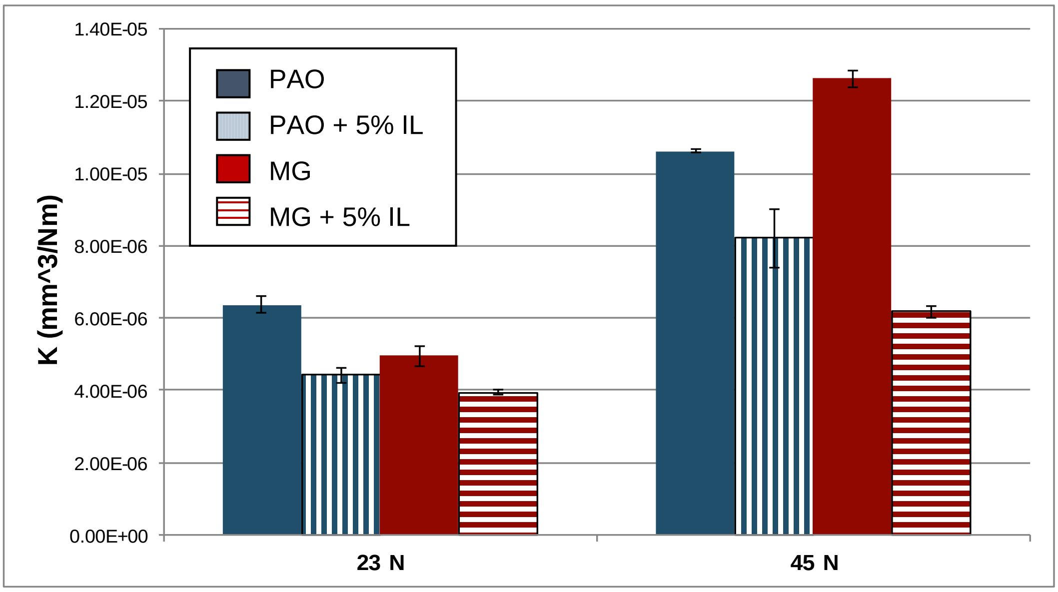


Figure 5. Wear rates of AISI 52100 steel disks against AISI 440C steel balls under lubrication (23 N, 1hr).

Figure 6 shows the wear track profiles on steels disk after a test using PAO and MG+5%IL as lubricants. As can be seen, both wear tracks show an area of material deformed plastically (Figure 6), but the area of wear loss is clearly smaller when MG+5%IL is used.

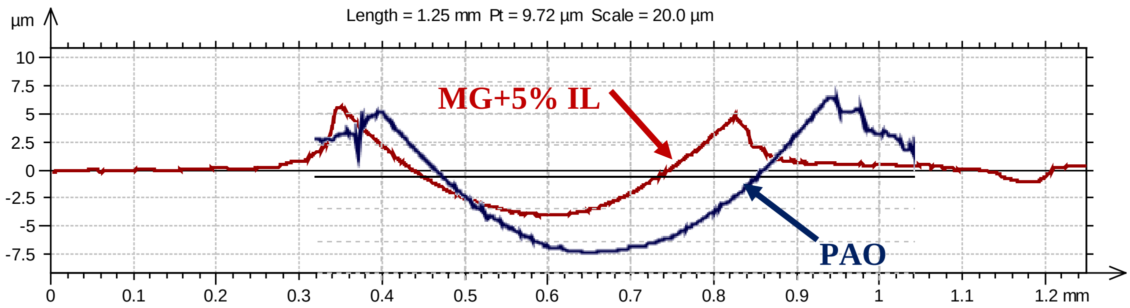


Figure 6. Wear track profiles on steel disks after a test lubricated with PAO and MG+5%IL (1.5 Hz, 454m, 45 N).

Figure 7 shows wear tracks on the steel disks after a test lubricated with PAO and MG+5%IL. From the figure, the wear track after a test lubricated with MG+5%IL is narrower and has a smoother appearance. In both cases, abrasion marks parallel to the sliding directions (Figures 7) show a component of abrasive wear which is more severe when the IL is not present. An important component of plastic deformation is also observed, particularly for PAO, where lateral plastic flow creates accumulation of material at the edges of the wear track (Figures 6 and 7).

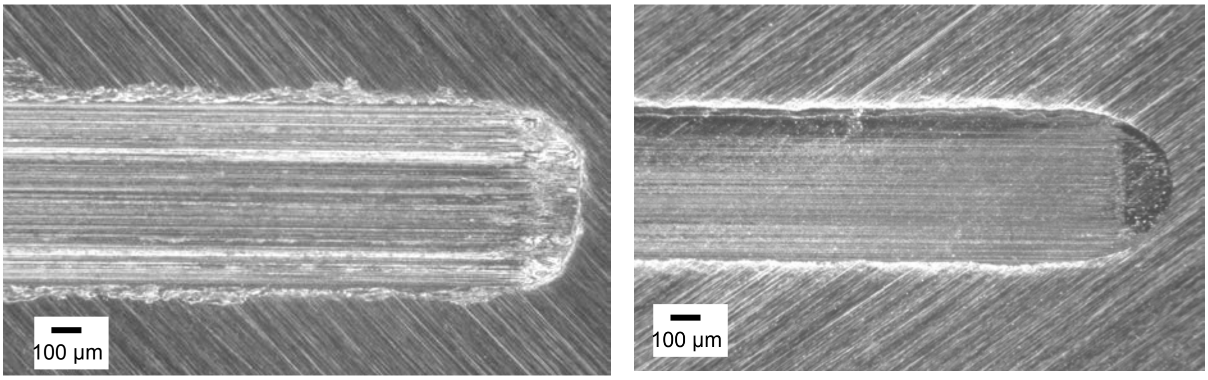


Figure 7. Optical micrographs of worn surfaces after a test (1.5 Hz, 454m, 45 N). lubricated with (a) PAO, (b) 5 MG+5%IL.

4.- CONCLUSION

This paper investigated the wear behavior of trihexyltetradecylphosphonium bis(trifluoromethylsulfonyl) amide used as additive in a synthetic oil and a wind turbine gearbox oil.

Wear rate of steel disks is minimum when a ratio between 5-10 wt. % of IL is used in the synthetic poly alpha olefin (PAO).

While under the highest frequency studied, no major differences were found in the lubricating ability of the mixtures; at 1.5 Hz, the addition of 5 wt. % IL to PAO and MG reduced the wear rate of steel disk 31 % and 39 % with respect PAO, respectively.

Under the highest load (45 N) studied, the addition of 5wt. % IL in MG reduced one order the magnitude the wear rate of steel disk with respect the commercially wind turbine gearbox lubricant. Under the loads studied, the lowest wear rate was always obtained on the steel disk lubricated with MG+5%IL. This suggests a synergistic effect of IL with the anti-wear additives included in the formulation of the gear oil.

ACKNOWLEDGEMENTS

The authors acknowledge financial support from New York State Pollution Prevention Institute (NYSP2I 2013)-Increasing the Reliability and Efficiency of Wind Turbines by Reducing Gearbox Friction and Wear.

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