

FAP-anion ionic liquids used in the lubrication of a steel-steel contact

J.L. Viesca^{a,d,*}, A. García^a, A. Hernández Battez^{a,d}, R. González^{b,d}
R. Monge^a, A. Fernández-González^c, M. Hadfield^d

^aDepartment of Construction and Manufacturing Engineering, University of Oviedo, Asturias, Spain

^bDepartment of Marine Science and Technology, University of Oviedo, Asturias, Spain

^cDepartment of Physical and Analytical Chemistry, University of Oviedo, Asturias, Spain

^dSchool of Design, Engineering and Computing, Bournemouth University, UK

(*Email: viescajose@uniovi.es)

Abstract

This study compares the tribological behavior of two ionic liquids ([BMP][FAP] and [(NEMM)MOE][FAP]) used as oil additive for the lubrication of a steel-steel contact. Friction and wear experiments were performed using a HFRR test machine. Friction coefficient and electrical contact resistance (ECR) were measured during the tests and the wear surface was analysed by confocal microscopy and XPS. The tribological results showed that both ionic liquids used as additive decrease friction and wear but the [BMP][FAP] had a better performance than the [(NEMM)MOE][FAP] due to its higher reactivity with the steel.

Keywords: FAP-based ionic liquids, additives, lubricants, friction, wear.

1. Introduction

In recent years many efforts have been made in order to study the advantages of ionic liquids (ILs) as lubricants or additives [1]. The possible use of ionic liquids in lubrication is due to mainly their high thermal stabilities, wide range of viscosities (50-1500 mm²/s at 23°C), non-flammability, negligible volatility and controlled miscibility with organic compounds. On the other hand, ionic liquids with a huge range of properties can be obtained by changing the cation/anion combinations [2-3]. Therefore, ILs due to their tribological behavior, which are better than the one of synthetic, mineral or engine oils (frequently used in lubricated contacts), are a feasible alternative to substitute traditional additives or lubricants [4].

Among the several combinations of anionic and cationic moiety that have been considered, the tris(pentafluoroethyl)trifluorophosphate (FAP) has begun to be used in the formulation of ionic liquids [5]. The hydrolytic stability and hydrophobic character of FAP make this anion a good election to be used in lubrication.

González et al. [6] studied the use of the 1-butyl-1-methylpyrrolidinium tris(pentafluoroethyl)trifluorophosphate ionic liquid, [BMP][FAP], as 1 wt% additive to a PAO 6 (polyalphaolefin) and as pure lubricant in the lubrication of three coatings (CrN, DLC and TiN) obtained by the PVD technique. The wear and friction tests made showed that [BMP][FAP] used as additive only slightly decrease friction in comparison with the results of the pure base oil. However, the [BMP][FAP]

1 as pure lubricant significantly decreased the friction coefficient with regard to the base oil and the mixture
2 showing similar friction values for all the coatings. The surface analysis performed after the tribological
3 tests showed that the FAP- anion reacted up to 80% with TiN and DLC surface but the reaction did not
4 occur with the CrN coating.
5

6 Blanco et al. [7] tested the ethyl-dimethyl-2-methoxyethylammonium
7 tris(pentafluoroethyl)trifluorophosphate ionic liquid, [(NEMM)MOE][FAP], also as 1 wt% additive to a
8 PAO 6 for the lubrication of a CrN PVD coating. The tribological behavior of the mixture of PAO 6 and
9 [(NEMM)MOE][FAP] was compared to the traditional ZDDP added to the base oil in similar
10 concentration. In this case both additives greatly improved the antiwear and antifriction properties of the
11 base oil although ZDDP had the best performance. The [(NEMM)MOE][FAP] ionic liquid was also
12 tested as 1 wt% additive in the lubrication of TiN coating using again PAO 6 as base oil [8]. The use of
13 the ionic liquid as additive also improved the tribological behavior with regard to the use of the pure base
14 oil in the lubrication of this coating. On the other hand, Hernández Battez et al. [9] compared the use of
15 the [(NEMM)MOE][FAP] ionic liquid as neat lubricant and as additive (also PAO 6 was used as base oil)
16 in the lubrication of CrN, TiN and DLC coatings obtained by PVD. In general, the ionic liquid showed a
17 slight antifriction performance for all coatings when it was used as an additive in comparison with the
18 behavior of the pure base oil. However, when the ionic liquid was used as neat lubricant a significant
19 friction and wear reduction was obtained.
20

21 In this present study, the ionic liquids, ethyl-dimethyl-2-methoxyethylammonium
22 tris(pentafluoroethyl)trifluorophosphate, [(NEMM)MOE][FAP], and 1-butyl-1-methylpyrrolidinium
23 tris(pentafluoroethyl)trifluorophosphate, [BMP][FAP], have been considered. A proportion of 2 and 4
24 wt% additives to a mineral hydrocracking oil (M2) for a steel-steel contact have been studied.
25

26 **2. Experimental details**

27 Mineral Hydrocracked Oil (M2) used as base lubricant was kindly provided by Repsol, S.A. with a
28 density of 0.838 g/cm³ (ASTM D4052), a kinematic viscosity of 32.89 and 5.96 mm²/s (ASTM D445) at
29 40 and 100°C, respectively, and a viscosity index of 127 (ASTM D2270). The ionic liquids used in this
30 study (Table 1) were commercially available from Merck (Germany). Before the tribological tests the
31 ionic liquids were separately mixed with the base oil at concentrations of 2 and 4 wt% using an ultrasonic
32 probe for 5 minutes at 400 W and 50% of amplitude assuring that the temperature of the samples did not
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 reach 60°C. The stability of the mixtures was measured by light backscattering at room temperature
2 during 2 hours with data acquisition every 10 minutes. During the 2 hours test the blend remained
3 practically constant and no creaming phenomena was found. This results guarantee that the blend is
4 homogeneous during the tribological tests.
5

6
7 Reciprocating ball-on-disc wear tests were performed on a HFRR (a microprocessor-controlled
8 reciprocating friction and wear test system) machine from PCS Instruments using a load of 1.0 kg.
9 (corresponding to a maximum contact pressure of 1.42 GPa), temperature of 100°C, stroke length of 1
10 mm, frequency of 30 Hz and test duration of 60 minutes. In the tribological tests 6.0 mm diameter AISI
11 52100 steel balls with a surface finish (Ra) of less than 0.05 µm and a hardness of 58-66 HRC and discs
12 of AISI 52100 steel with a hardness of 190-210 HV and a surface finish (Ra) of less than 0.02 µm were
13 used as specimens. Before tribological tests all specimens were cleaned ultrasonically with toluene and
14 propinol for 5 min and dried with hot air. Three tests were undertaken for each lubricant sample in order
15 to give mean values of friction coefficient. The electrical contact resistance (ECR) was measured during
16 all tests for monitoring tribofilm formation.
17

18 After tribological test the specimens were cleaned by rinsing in propinol and air drying. Post tribological
19 experiment steps also included the wear volume determination by using a Leica DCM 3D confocal
20 microscope and worn surface analysis by XPS (X-ray photoelectron spectroscopy). XPS measurements
21 were taken under ultra-high vacuum conditions ($\leq 5 \cdot 10^{-9}$ mbar) using the K α Mg (1253.6 eV) at 200 W
22 and 13 kV. A Phoibos Hemispherical Energy Analyzer Series MDA5 was used to measure kinetic energy
23 from the electrons in a constant pass energy mode. High resolution spectra were taken using 30 eV as
24 pass energy and 0.1 eV as step size energy; a 2.5 mm diameter iris between detector and sample was used
25 to select the desired zone of the sample (inner part of the wear scar). The position of the C1s band of the
26 spurious carbon was used to check whether the spectrometer should be calibrated using a low energy
27 electron flood gun.
28

29 High resolution spectra of both Iron (at 2p_{3/2} band) and Fluorine (at 1s band) were taken in every sample.
30 Fe was selected as it is the main component of the steel of the sample, whereas fluorine was selected on
31 the basis of being the most abundant atom in the common anion of both ionic liquids (FAP) and also on
32 previous experience of the authors [6]. On the other hand, phosphorus was analysed in order to check the
33 presence of phosphates.
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 The analysis of the high resolution XPS spectra was performed using CasaXPS software. Curve fitting
2 was carried out using a Shirley-type baseline [10] and pseudovoigt curves (Product Gaussian (70%)-
3 Lorentzian (30%)). Levenberg-Marquardt algorithm was selected as optimization procedure.
4 Supplementary analysis using Simplex method was also performed with software developed by the
5 authors.
6
7
8
9

10 11 **3. Results and discussions**

12 The friction coefficient results from the tribological tests are shown in Fig. 1. In general, the addition of
13 both ionic liquids to the base oil (M2) decrease friction in comparison with the friction results of the neat
14 base oil. For both ionic liquids the highest friction reduction was obtained when the IL content was 4
15 wt%. However, the [BMP][FAP] ionic liquid showed improved tribological behaviour as an oil additive
16 than [(NEMM)MOE][FAP].
17
18
19
20
21
22
23

24 The evolution of the friction coefficient during the tribological tests using the pure base oil and the
25 mixtures with the [(NEMM)MOE][FAP] is observed as Fig. 2. The friction behavior can be clearly
26 related to the formation of tribofilm on worn surfaces which change the electrical contact resistance
27 (ECR) values. For the pure base oil the ECR is approximately zero and this corresponds to the highest
28 friction coefficient. On the other hand, when the ionic liquid was added to the base oil the ECR values
29 changed from zero and lower friction coefficient was observed for higher ECR values. The mixtures with
30 4 wt% of ionic liquid had the highest ECR results and then the lowest friction coefficient.
31
32
33
34
35
36
37
38

39 Fig. 3 shows the friction evolution of the tests made using the [BMP][FAP]. In this case the result is quite
40 similar to the [(NEMM)MOE][FAP] one. The highest and stable ECR values showed by the mixture with
41 4 wt% of ionic liquid also contributed to obtain the lowest and stable friction coefficient. However, it is
42 important to point out the fact that the [BMP][FAP] reacted more quickly with the wear surfaces
43 (tribofilm formation) and showed higher ECR values than the [(NEMM)MOE][FAP]. The influences of
44 the ionic liquid used as additives on the tribofilm formation and the improvement of antifricition and
45 antiwear behaviour have been studied in depth recently by Qu et al. [11].
46
47
48
49
50
51
52

53 This study also showed the antiwear properties of these ionic liquids used as additives, Fig. 4. Both used
54 ionic liquids concentration (2 and 4 wt%) decreased wear, but the higher concentration showed better
55 results. Similar to friction results, [BMP][FAP] improved the antiwear performance of the base oil more
56 than the [(NEMM)MOE][FAP] one. Fig. 5 shows the 2D image of the wear scar on the lower specimen
57
58
59
60
61
62
63
64
65

(disc) and it can be observed the best antiwear performance of [BMP][FAP] with regard to the [(NEMM)MOE][FAP] and also how the 4 wt% concentration is more effective than the 2 wt% one.

The variation on the concentration of [(NEMM)MOE] seems not to have a strong effect on the surface from the chemical point of view. The iron on the surface at both concentrations (2 and 4 wt%) has a very similar behaviour, with a strong main peak from iron (III) oxide at 710.8-710.9 eV [12-13] and a smaller peak at 712.6 belonging to FePO_4 [14]. Fluorine-Iron interactions can be appreciated in the 2 wt% [(NEMM)MOE][FAP] samples with a peak at 714.1 eV [12] too (Fig. 6). Fluorine content in the surface is low in both cases, although it is lower in the 4 wt% [(NEMM)MOE][FAP] samples (Fig.7). Curve fitting for fluorine shows two different species: the most abundant coming from FAP-anion (688.5 eV, 289.2 eV [5-6]) and a smaller band at 684.6–684.7 eV from the Fe–F interactions [12]. Phosphorus in both samples shows a peak at 133.7–133.8 eV coming from FePO_4 [15]. These results are summarized in Table 2.

Lubrication with [BMP][FAP] at 2 wt% concentration behaves very similarly to that with [(NEMM)MOE][FAP]. $\text{Fe}2p_{3/2}$ band appears at 710.8 eV, being due to iron (III) oxide with a small contribution at 712.8 eV arising from FePO_4 (Fig. 8). Fluorine concentration is too low, so Fe-F interactions are masked by FePO_4 and Fe_2O_3 . Even so, two different peaks at 684.5 and 690.5 eV can be detected for F1s. These bands are assignable to metallic fluorides and FAP-anion respectively. The presence of FePO_4 is confirmed checking the high resolution P2p XPS spectrum, showing a band at 133.5 eV assignable to iron (III) phosphate. When the concentration of the ionic liquid is increased to 4 wt%, the main difference is a stronger presence of fluorine on the surface, which can be appreciated also in the Fe2p band (with a very small component at 714.3 eV) together with the bands of Fe_2O_3 and FePO_4 (Fig. 9). The high resolution analysis of the F1s band indicates a similar situation to that from the 2 wt% [BMP][FAP] sample, with 50% of fluorine as Fe-F and 50% as unreacted FAP-anion. As in the previous cases, the presence of phosphate can be easily checked by analysing the P2p band, finding a peak at 133.6 eV. These results are summarized in Table 3.

In general the tribological behavior (antifricition and antiwear properties) of [BMP][FAP] was better than the [(NEMM)MOE][FAP] one. These improved results are related with the higher decomposition of the FAP⁻ anion and the reaction of fluorine with the wear surface. Similar results were obtained when these ionic liquids were tested as additives in the lubrication of two PVD coatings (TiN and DLC) [6,9,16]. With these two coatings, more than the 60% of fluorine (F) of the [BMP][FAP] ionic liquid was bound to

1 metals inside the wear scar, while the rest of fluorine remained as FAP- anion. On the other hand, the
2 tribological behavior of the [(NEMM)MOE][FAP] was better than the [BMP][FAP] one in the lubrication
3 of a CrN coating [6,9] because the former also reacted much more with the surface than the latter.
4
5
6
7

8 **4. Conclusions**

9

10 The use of [(NEMM)MOE][FAP] and [BMP][FAP] ionic liquids as additives to a mineral hydrocracked
11 oil (base oil) was studied in this work. Mixtures of the base oil with 2 and 4 wt% of ionic liquid was
12 tribologically tested and the worn surface was measured by confocal microscopy and analyzed by XPS.
13
14 The main results showed that both ionic liquids have antifriction and antiwear properties when they are
15 used as additives. The [BMP][FAP] showed better tribological behavior than the [(NEMM)MOE][FAP]
16 one. In both cases, higher content of ionic liquid in the mixture resulted in higher friction and wear
17 reduction. The friction behavior of the mixtures was related to the tribofilm formation and this fact was
18 evaluated by measuring the electrical contact resistance (ECR). As expected, higher ECR values resulted
19 in lower friction and wear.
20
21
22
23
24
25
26
27

28 The wear results were similar to the friction ones, being the mixtures with 4 wt% of ionic liquid the best
29 in both cases. The XPS analysis showed that the ionic liquid reacted with surfaces forming both
30 phosphates- and fluorine-iron compounds, but not at 100%, remaining certain percentage of FAP-anion.
31
32 The mixture with 4 wt% of [BMP][FAP] reacted with the surface much more than the other mixtures,
33
34 leading to the highest overall friction and wear reduction.
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2 **Acknowledgements**
3

4 The authors wish to express their thanks to the Ministry of Science and Innovation Spain, for supporting
5 this work within the framework of the research project WINDTRIB (DPI2010-18166). Similarly, they
6 thank the Ministry of Education, Culture and Sport for funding, within the program "*José Castillejo*", the
7 research stay of José Luis Viesca at Bournemouth University. They also thank the Government of the
8 Principality of Asturias and the University of Oviedo for funding the pre-doc grant program "*Severo*
9 *Ochoa*" and the research stay of Alberto Garcia at Imperial College London. The Unit of Photoelectron,
10 UV-Vis and FTIR spectroscopy from the Scientific-Technical Services at the University of Oviedo is also
11 acknowledged.
12
13
14
15
16
17
18
19
20
21

22 **References**
23

- 24
25 1. Bermúdez, M.D., Jiménez, A.E., Sanes, J., Carrión, F.J.: Ionic liquids as advanced lubricant fluids.
26 *Molecules* 14, 2888–2908 (2009)
27
28 2. Mistry, K., Fox, M.F., Priest, M.: Lubrication of an electroplated nickel matrix silicon carbide coated
29 eutectic aluminium–silicon alloy automotive cylinder bore with an ionic liquid as a lubricant additive.
30 *Proceedings of the Institution of Mechanical Engineers Part J: Journal of Engineering Tribology* 223,
31 563-569 (2009).
32
33 3. Jiménez, A.E., Bermúdez, M.D., Carrión, F.J., Martínez-Nicolás, G.: Room temperature ionic liquids
34 as lubricant additives in steel–aluminium contacts: Influence of sliding velocity, normal load and
35 temperature. *Wear* 261, 347-359 (2006).
36
37 4. Qu, J., Blau, P.J., Dai, S., Luo, H., Meyer III, H.M.: Ionic Liquids as Novel Lubricants and Additives
38 for Diesel Engine Applications. *Tribology Letters* 35, 181-189 (2009).
39
40 5. Minami, I., Kita, M., Kubo, T., Nanao, H., Mori, S.: The tribological properties of trifluorotris
41 (pentafluoroethyl) phosphate derived ionic liquids. *Tribol. Lett.* 30, 215-223 (2008)
42
43 6. González, R., Hernández Battez, A., Blanco, D., Viesca, J.L., Fernández-González, A.: Lubrication of
44 TiN, CrN and DLC PVD Coatings with 1-Butyl-1-Methylpyrrolidinium
45 tris(pentafluoroethyl)trifluorophosphate. *Tribol. Lett.* 40, 269–277 (2010)
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
7. Blanco, D., Hernández Battez, A., Viesca, J.L., González, R., Fernández-González, A.: Lubrication of CrN Coating With Ethyl-Dimethyl-2-Methoxyethylammonium Tris(pentafluoroethyl) Trifluorophosphate Ionic Liquid as Additive to PAO 6. *Tribol. Lett.* 41, 295–302 (2011)
8. Blanco, D., González, R., Hernández Battez, A., Viesca, J.L., Fernández-González, A.: Use of ethyl-dimethyl-2-methoxyethylammonium tris(pentafluoroethyl)trifluorophosphate as base oil additive in the lubrication of TiN PVD coating. *Tribol. Int.* 44, 645–650 (2011)
9. Hernández Battez, A., González, R., Viesca, J.L., Fernández-González, A., Hadfield, M.: Lubrication of PVD coatings with ethyl-dimethyl-2-methoxyethylammonium tris(pentafluoroethyl)trifluorophosphate. *Tribol. Int.* 58, 71–78 (2013)
10. D. A. Shirley, D.A.: High Resolution X-Ray Photoemission Spectrum of the Valence Bands of Gold. *Phys. Rev. B.* 5(12), 4709-4714 (1972)
11. Qu, J., Bansal, D.G., Yu, B., Howe, J.Y., Luo, H., Dai, S., Li, H., Blau, P.J., Bunting, B.G., Mordukhovich, G., Smolenski, D.J.: Antiwear Performance and Mechanism of an Oil-Miscible Ionic Liquid as a Lubricant Additive. *ACS Appl. Mater. Interfaces* 4, 997–1002 (2012)
12. Wagner, C.D., Riggs, W.M., Davis, L.E., Moulder, J.F., Muilenberg, G.E.: *Handbook of X-ray photoelectron spectroscopy*, Ed. Perkin-Elmer Corp. (1979).
13. Allen, G.C., Curtis, M.T., Hooper, A.J., Tucker, P.M.: X-ray photoelectron spectroscopy of iron-oxygen systems. *J. Chem. Soc., Dalton Trans.*, 1526 (1974)
14. Nemoshalenko, V.V., Didyk, V.V., Krivitskii, V.P., Senekevich, A.I.: Investigation of the atomic charges in iron, cobalt and nickel phosphides. *Zh Neorg. Khimii* 28, 2182 (1983)
15. Barbaux, Y., Dekiok, M., Le Maguer, D., Gengembre, L., Huchette, D., Grimblot, J.: Bulk and surface analysis of a Fe-P-O oxydehydrogenation catalyst. *Appl. Catalysis A* 90 (1), 51-60 (1992)
16. González, R., Hernández Battez, A., Viesca, J.L., Higuera-Garrido, A., Fernández-González, A.: Lubrication of DLC coatings with two tris(pentafluoroethyl)trifluorophosphate anion-based ionic liquids. *Tribol. Trans.* DOI:10.1080/10402004.2013.810319 (2013).

Table 1. Ionic liquids properties (provided by the supplier).

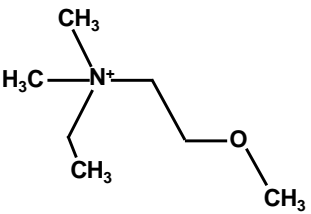
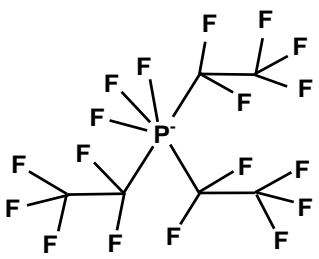
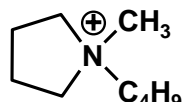
| Ionic Liquids | | | | | |
|---|-------|--|--|------------------------|----------------|
| Cation | Anion | IUPAC name | Purity (%) | Water content | Viscosity (cP) |
| [(NEMM)MOE] | [FAP] | ethyl-dimethyl-2-methoxyethylammonium tris(pentafluoroethyl)trifluorophosphate | >99 | <100 ppm (Karl Fisher) | 178 |
| [BMP] | [FAP] | 1-Butyl-1-methylpyrrolidinium tris(pentafluoroethyl)trifluorophosphate | >99 | <1 % (Karl Fisher) | 292 |
| Chemical structure | | | | | |
| Cations | | | Anion | | |
| $(\text{CH}_3)_2(\text{CH}_2\text{CH}_3)(\text{CH}_2\text{CH}_2\text{OCH}_3)\text{N}^+$ | | | $\text{F}_3(\text{C}_2\text{F}_5)_3\text{P}^-$ | | |
|  | | |  | | |
| [(NEMM)MOE] | | | [FAP] | | |
| $\text{C}_9\text{H}_{20}\text{N}$  | | | | | |
| [BMP] | | | | | |

Table 2. XPS results for samples lubricated with [(NEMM)MOE][FAP] at 2 and 4 wt%.

| | M2 + 2% [(NEMM)MOE][FAP] | M2 + 4% [(NEMM)MOE][FAP] |
|---------|---|---|
| Fe2p3/2 | 710.9 eV, 84%, Fe ₂ O ₃ | 710.8 eV, 73%, Fe ₂ O ₃ |
| | 712.6 eV, 12%, FePO ₄ | 712.6, 27%, FePO ₄ |
| | 714.4 eV, 4%, Fe - F ($\chi^2=0.5190$) | ($\chi^2=0.7473$) |
| F1s | 684.6 eV, 20%, Fe - F | 684.7 eV, 23%, Fe -F |
| | 688.5 eV, 80%, [FAP ⁻] ($\chi^2=0.5294$) | 689.2 eV, 77%, [FAP ⁻] ($\chi^2=0.4139$) |
| P2p | 133.7 eV, 100%, FePO ₄ ($\chi^2=0.9680$) | 133.8 eV, 100%, FePO ₄ ($\chi^2=0.5512$) |

Table 3. XPS results for samples lubricated with [BMP][FAP] at 2 and 4wt%.

| | M2 + 2% [BMP][FAP] | M2 + 4% [BMP][FAP] |
|---------|--|--|
| Fe2p3/2 | 710.8 eV, 90%, Fe ₂ O ₃ 712.8 eV, 10%, FePO ₄ ($\chi^2=0.5272$) | 710.8 eV, 77%, Fe ₂ O ₃ 712.6 eV, 20%, FePO ₄ 714.3 eV, 3%, Fe – F ($\chi^2=0.7440$) |
| F1s | 684.5 eV, 40%, Fe – F 690.5 eV, 60%, [FAP] ($\chi^2=1.0681$) | 684.4 eV, 50%, Fe – F 688.5 eV, 50%, [FAP] ($\chi^2=0.3747$) |
| P2p | 133.5 eV, 100%, FePO ₄ ($\chi^2=0.4250$) | 133.6 eV, 100%, FePO ₄ ($\chi^2=0.5658$) |

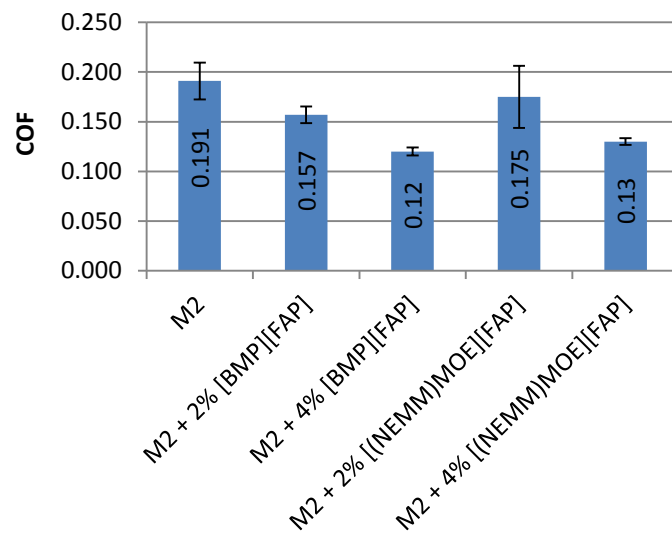


Fig. 1. Average friction coefficient.

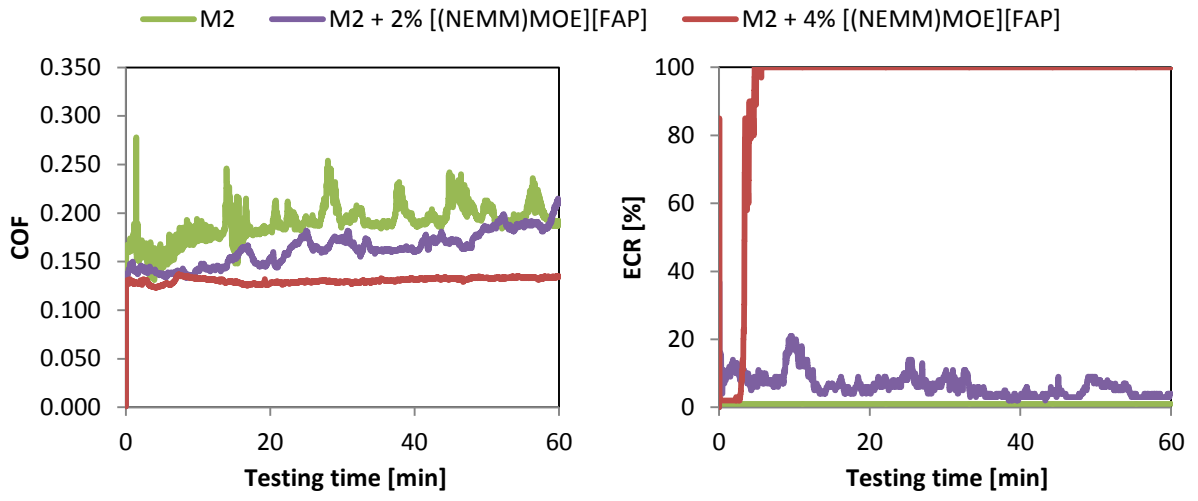


Fig. 2. Friction and ECR behaviour for [(NEMM)MOE][FAP].

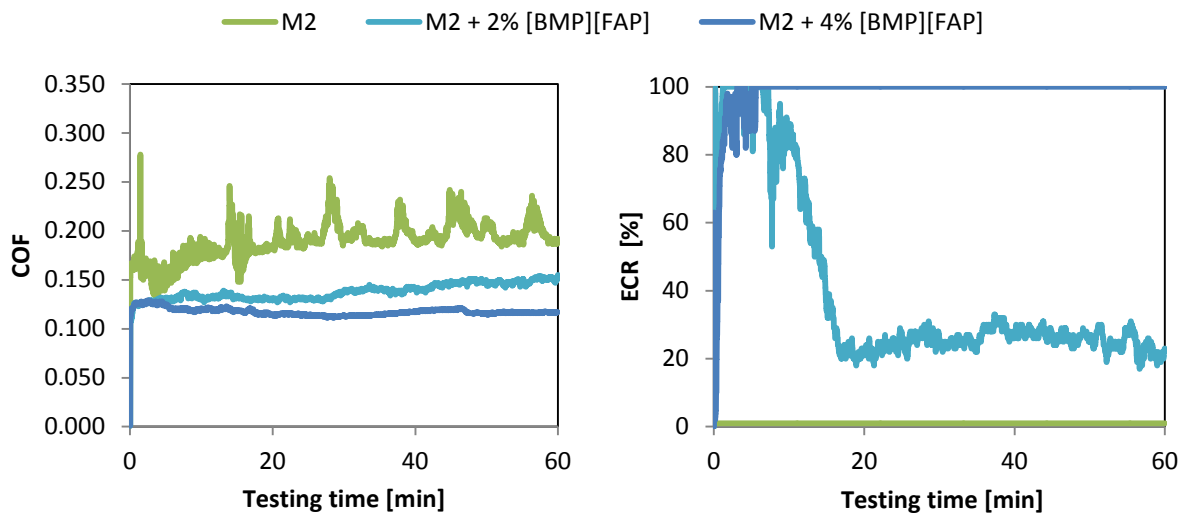


Fig. 3. Friction and ECR behaviour for [BMP][FAP].

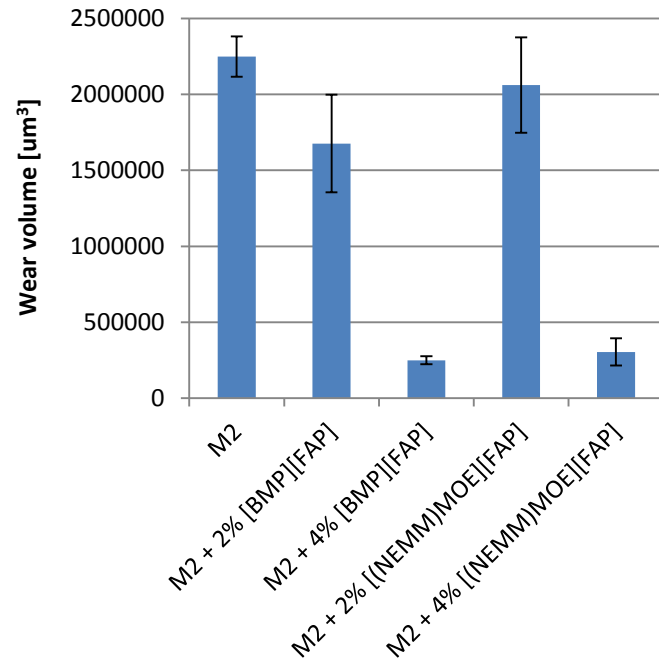


Fig. 4. Average wear volume.

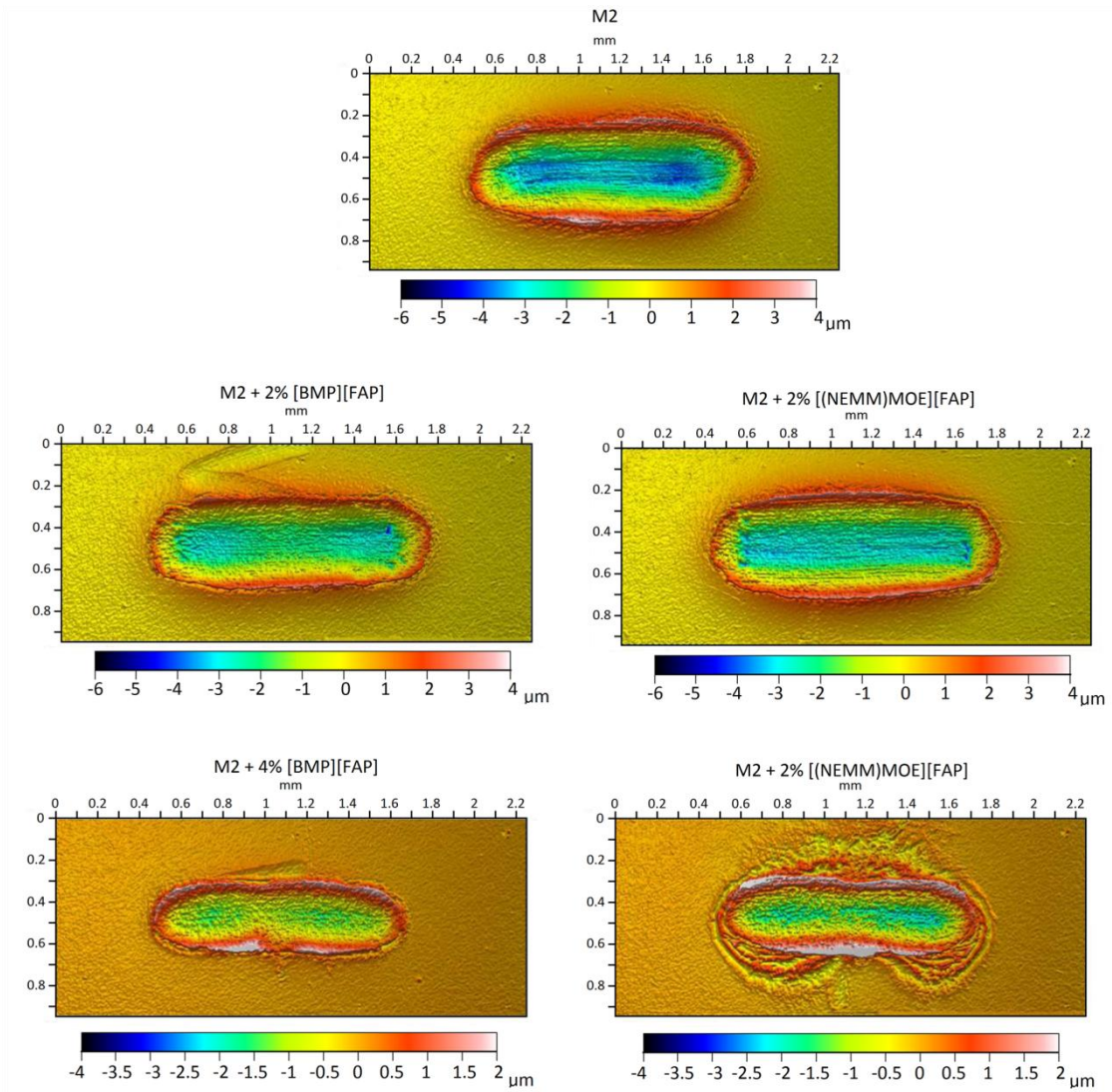


Fig. 5. 2D wear scar on the lower specimen (disc).

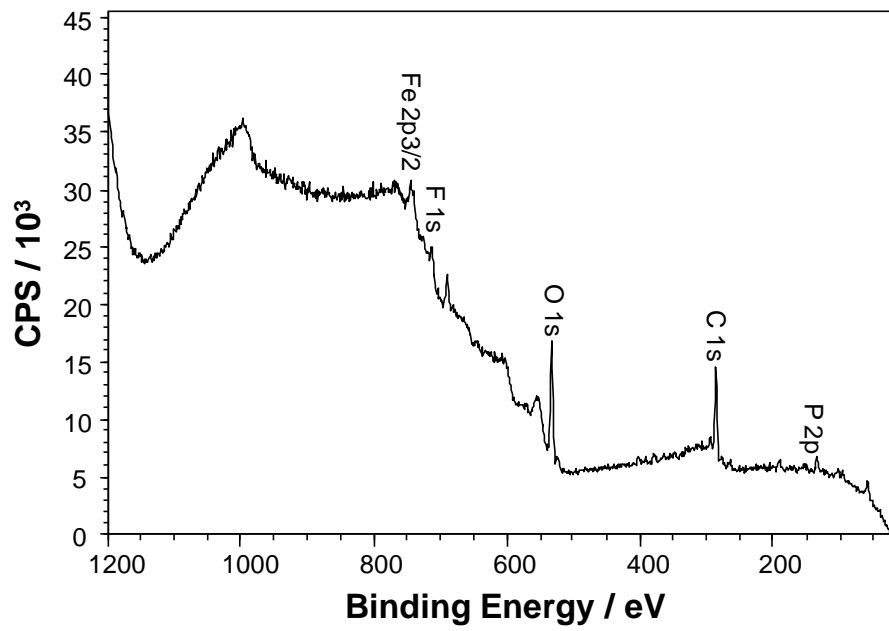


Fig. 6. Survey spectrum of M2 + 2wt% [(NEMM)MOE][FAP].

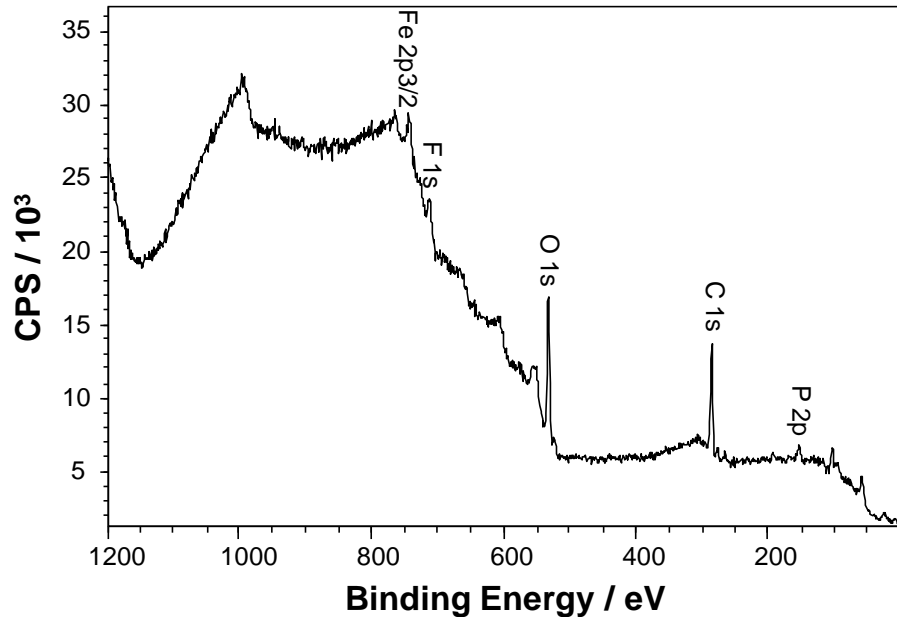


Fig. 7. Survey spectrum of M2 + 4wt% [(NEMM)MOE][FAP].

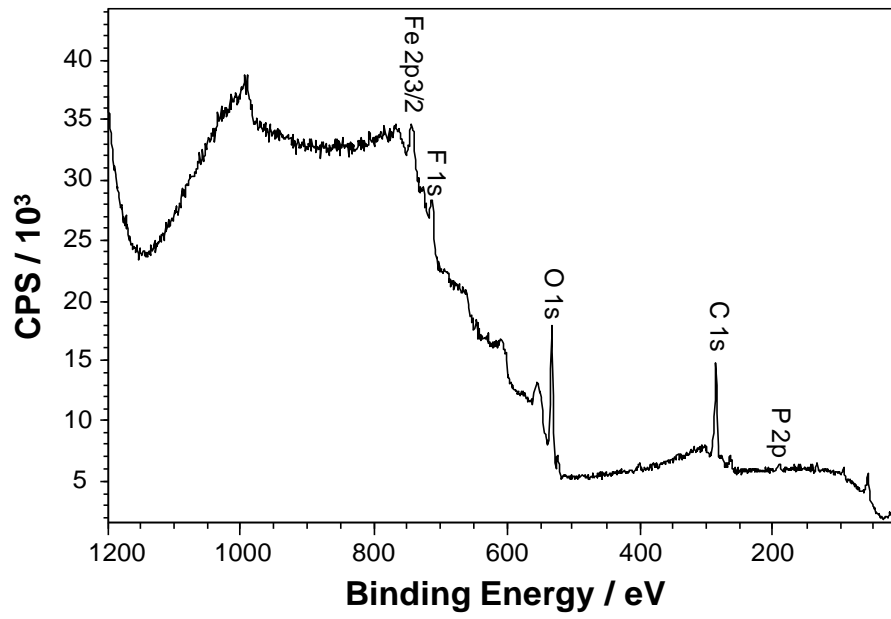


Fig. 8. Survey spectrum of M2 + 2wt% [BMP][FAP].

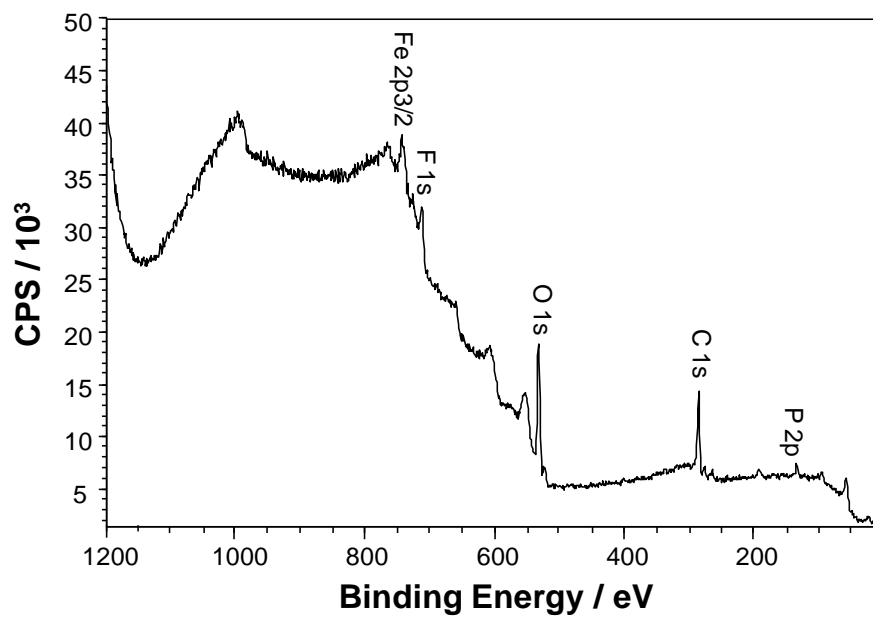


Fig. 9. Survey spectrum of M2 + 4wt% [BMP][FAP].