An Amino Acid Functionalized Ionic Liquid as A Multifunctional Lubricant Additive in Water-Glycerol

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Abstract: Water-glycerol as one promising alternative for mineral oil can be applied as a green lubricant but has poor lubricity and strong corrosivity. It is desirable to design multifunctional water soluble lubricant additives. Protic ionic liquids (PILs) show considerable potential due to their facile preparation and environmental friendliness. Herein, an eco-friendly PIL ([osar][mea]) was facilely prepared from an amino acid derivate and investigated its anticorrosion and lubrication performances in the glycerol solution. Furthermore, the wear traces were measured using SEM/EDS and XPS for exploring the lubrication mechanism. The prepared PIL can rapidly increase the corrosion inhibition ability of water-glycerol as its concentration increases over CMC, and the anion playing a key role in the light of DFT calculations. Furthermore, [osar][mea] can greatly enhance the lubrication capability especially of water-glycerol while its concentration in the glycerol solution exceed 3%. The lubricity reduced with the increasing load. By the means of using SEM/EDS and XPS evaluation of the wear traces, we can speculate the possible lubrication mechanism may be the presence of the [osar][mea] adsorption film and the tribofilm containing complex nitrogen compounds.

Key words: lubricant, water-glycerol, amino acid, PIL

1 Introduction

Traditional petroleum lubricants exhibit widespread applications in transportation vehicles, mining, electric power, metallurgy and other industrial fields and represent over 90% share of worldwide lubricant market1–3. They are derived from nonrenewable petroleum resources and display several drawbacks including high flammability, poor biodegradability and tendency to contaminate environment4–6.

Glycerol is an abundant green material obtained from biodiesel and can improve the fluidity in subzero and anti-depravation, it has been one of the most promising alternatives and used in metal working and hydraulic transmission7–9. Besides, water-glycerol as an aqueous lubricant exhibits several advantages like environment-friendliness, fire-resistance and excellent cooling ability. With energy exhaustion and environment deprivation, it has been one of the most promising alternatives and used in metal working and hydraulic transmission10–12. Nevertheless, water-glycerol’s disadvantages of poor lubricity and high corrosivity impede their extensive applications13, 14. Hence, there is a pressing need for green additives which can remarkably enhance anticorrosion and lubricating properties of water-glycerol.

Ionic liquids (ILs) exhibit enormous potential as lubricant additives for their unique physicochemical characteristics including high reactivity, sturdy surface adsorption and controllable structure15–18. Early studies focus on halogen-containing ILs which cause corrosion to metal in the presence of water and are only suitable for aqueous lubrication of non-metal materials19. Recently, a novel family of halogen-free ILs from amino acid, ricinoleic acid, organic phosphate and ibuprofen have been used as lubricant additives to improve tribology performances of aqueous lubricants20–24. However, there are still some problems such as complex preparation and environment compatibility.

In this study, an amino acid functionalized IL was prepared from a renewable biomaterial: N-oleoyl sarcosine. It belongs to protic ionic liquids (PILs) synthesized through proton transfer from a Brønsted acid to a Brønsted base and displays potential benefits including facile synthesis and environmental friendliness25. Current work focused on the applications of the PIL as a multipurpose additive for aqueous lubrication and probe its anticorrosion and lubri-
2 Experimental

2.1 Materials

Water-glycerol containing 50 wt% water was the base fluid. Glycerol (purity, 99.0%) and methylethanolamine (purity, 99%) were bought from Shanghai Macklin Biochemical Co., Ltd. N-oleylsarcosine (purity, 93.0%) was obtained from BASF SE (Shanghai, China).

Referring to the studies, the amino acid functionalized IL was acquired from neutralization of amine with eco-friendly amino acid derivate. Equimolar methylethanolamine was blended with N-oleylsarcosine and magnetically agitated at 70°C for two hours. The prepared PIL was coded as [osar][mea], and its synthesis route was depicted in Fig. 1. Its spectra of Fourier transform infrared (FTIR) and Proton nuclear magnetic resonance (1H NMR) were collected as follows.

FTIR spectrum of [osar][mea] is shown in Fig. 2. The broad peak at 3392 cm⁻¹ represents the -OH stretch from CH₂NH₂⁺; CH₃CH₂OH. The signals at 1603 cm⁻¹ and 1388 cm⁻¹ stand for the asymmetric and symmetric stretches of COO⁻ and there is almost no absorption peak at 1733 cm⁻¹ pointing to free –COOH, indicating the formation of the PIL.

1H NMR (600 MHz, DMSO-d₆, δ = 2.50) of [osar][mea] (s = singlet, d = doublet, t = triplet and m = multiplet): δ = 6.85 (s, 2H, NH₂⁺), δ = 5.32 (m, 2H, HC = CH), 3.56-3.60 (m, 2H, OCH₂), 2.92 (s, 2H, N-CH₃C = O), 2.83 (t, 2H, N-CH₃), 2.75 (s, 3H, N-CH₃), 2.45 (s, 3H, N-CH₃), 2.24 (t, 2H, O = CCH₂), 2.12 (m, 2H, = CCH₂), 1.99 (m, 2H, = CCH₂), 1.44 (m, 2H, CH₂), 1.35-1.09 (m, 20H, CH₂). The existence of NH₂⁺ implies the occurrence of proton transfer.

2.2 Analysis and tribological performance

The DMol3 module from Materials Studio software performs DFT calculations using CGA/BLYP functional with a DNP basis set to optimize the geometries of cation and anion of [osar][mea] and obtain the energies of their orbitals involving the highest occupied molecular orbit (HOMO) and the lowest unoccupied molecular orbit (LUMO).

The platinum ring detachment method was performed to determine the surface tension for different mass concentrations of [osar][mea] in water-glycerol solutions using a Q100 Surface tension meter. The test was conducted three times at 25°C, and the average value was calculated as the final result.

The based fluid was mixed with the [osar][mea] at different mass fractions (0%, 0.5%, 1.0%, 3.0% and 6.0%) to obtain the corresponding aqueous lubricants whose viscosities (40°C) are described in Table 1.

The anticorrosion characteristics of the aqueous lubricants were explored using cast iron chips test referring to DIN 51360 Part 2 method. The dry cast iron chips on round filter were wetted by the tested solution and stored at 25°C for 12 h. The rust spots on the filter were observed as the test result.

The tribology behavior of the water lubricants was studied using an Optimol Schwingung Reibung Verschleiss (SRV)-V tester. The test specimens were a 10 mm diameter AISI52100 steel ball and a 24 mm diameter AISI52100 steel disc. The tests in this work were performed for 30 min at 25°C and 125 N. The frequency and the amplitude were 50 Hz and 1 mm respectively. Tribology properties of 3.0% [osar][mea] were further investigated under different loads (50 N, 100 N and 125 N). According to the literature, all the friction tests are in the boundary lubrication regime. The wear volumes were determined by a non-contact 3D Optical Surface Profiler. The worn surfaces were assessed by a scanning electron microscopy with an energy dispersive X-ray spectroscopy (SEM/EDS) and an X-ray photoelectron spectrometry (XPS).
### Table 1 The viscosities (40°C) of the aqueous lubricants.

| Aqueous lubricant | Mass fraction of [osar][mea] / % | Viscosity / mPa·s |
|-------------------|---------------------------------|------------------|
| water-glycerol    | 0                               | 3.12 ± 0.11      |
| 0.5% [osar][mea]  | 0.5                             | 3.15 ± 0.12      |
| 1.0% [osar][mea]  | 1.0                             | 3.31 ± 0.15      |
| 3.0% [osar][mea]  | 3.0                             | 3.97 ± 0.18      |
| 6.0% [osar][mea]  | 6.0                             | 4.99 ± 0.22      |

3 Results and Discussions

3.1 Surface tension and corrosion inhibition

The surface tensions of water-glycerol with varying concentrations of [osar][mea] are indicated in Fig. 3. The surface tension firstly decreases quickly and subsequently increase slowly with the rising concentration. The critical micelle concentration (CMC) of [osar][mea] in water-glycerol can be speculated to approach 0.5% in that the surface tension falls to the valley of the curve as the concentration of [osar][mea] reaches 0.5%.

The results of corrosion test are presented in Fig. 4. If only small amount of [osar][mea] (less than 0.5%) is added to water-glycerol, the number and area of rust spots remains as large as water-glycerol. However the number and area of rust spots significantly decreases while the concentration of [osar][mea] exceeds 0.5%. Rust spot is absent when the concentration of [osar][mea] increases to 3%. The above results show the anticorrosion property of [osar][mea].

According to the DFT calculations, the energetic values of the HOMO and LUMO (\(E_h\) and \(E_l\)) for the cation and anion were deduced and listed in Table 2. The difference between \(E_h\) and \(E_l\) is defined as \(\Delta E\). As shown in Table 2, the anion of [osar][mea] display a smaller \(E_l\) and \(\Delta E\) than contrasted with the cation. Referring to the previous paper, the smaller \(E_l\) and \(\Delta E\) demonstrates the stronger adsorption and the higher inhibition efficiency. Accordingly, the anion of [osar][mea] predominate the inhibition efficiency. The corrosion inhibition of [osar][mea] may result from the adsorbed [osar][mea] film hindering water from contacting the metal surface. In addition, multilayer molecules begin to adsorb onto the surface and form a thicker adsorption film providing more excellent corrosion protection as the additive concentration increases over CMC.

3.2 Tribology properties

We studied the influence of the concentration of [osar][mea] on the tribology properties of water-glycerol. Figure 5a displays the mean friction coefficients and wear volumes of the base fluid with [osar][mea] at varying concentrations. Both the average friction coefficient and the wear volume significantly decreases after the blend of the glycerol solution with [osar][mea]. They decrease by 36.3% and 81.6% respectively when the concentration of [osar][mea] increases from 0% to 6%. However, there is no marked change in either the friction coefficient or the wear volume as the [osar][mea] concentration exceeds 3%. Moreover, the wear volume remains invariable with the rising concentration of [osar][mea] from 3% to 6%.

Fig. 3 Surface tension of different concentrations of [osar][mea].

Fig. 4 Cast iron chips test results at different concentrations of [osar][mea].
maybe because the adsorption amount of [osar][mea] on the contact surface has approaches or attains saturation when the concentration of [osar][mea] reaches 3%. The change of friction behavior with time was indicated in Fig. 5b. At the initial period of about 200 s in the friction process, the friction coefficient of 0.5% [osar][mea] stays at a low level of about 0.12 but quickly increases to as high level as that of the glycerol solution, because very low concentration of [osar][mea] has difficulty in forming a stable lubricating film. Each of the glycerol solutions with [osar][mea] undergoes a running-in stage. The running-in time increases by about three times when the concentration of [osar][mea] increases from 0.5% to 6%. A high friction stage occurs in the running-in process when the concentration of [osar][mea] exceeds 0.05%.

We further researched the tribological properties of 3% [osar][mea] at different loads. Figure 6a presents the dependence of varying loads on the mean friction coefficients and wear volumes. With the increase of load from 50 N to 125 N, the average friction coefficient nearly remains unchangeable, but the wear volume increases by about two times. The possible reason was proposed as follows. The increasing load remarkably decreases the thickness of lubrication film but increases the direct contact of asperities. Figure 6b presents the change of friction behavior with time at different loads. There is no obvious running-in stage in the friction process at 50 N. At higher load (100 N or 125 N), the running-in time increases to about 800 s, and there is a wide friction fluctuation at the initial stage. Evidently, it is unfavorable for [osar][mea] as water based
lubricant additive to construct a stable lubrication film.

3.3 Surface analyses

The geography and element construction of tribo-surfaces was measured using SEM/EDS. The SEM micrographs and EDS spectra are depicted in Fig. 7. At the high load (125 N), the base fluid causes a large wear scar, while the addition of 3% [osar][mea] makes the wear scar smaller and narrower, but there are still lots of wide cracks and deep grooves observed in the tribo-surface. As the load decreases from 125 N to 50 N, 3% [osar][mea] can afford better lubrication and result in a smaller and smoother worn surface where there are only several slight and shallow furrows especially at 50 N. In the EDS spectra, nitrogen as a characteristic element of the studied PIL is significantly detected only after the addition of [osar][mea] at the low load of 50 N, maybe because the lubricating film produced by [osar][mea] is easily destroyed at the high load (100 N and 125 N). Furthermore, the chemical construction of wear traces was evaluated by XPS and the spectrograms

![Fig. 7](image_url)

**Fig. 7** The SEM micrographs and EDS spectra of wear traces for the glycerol solution at 125 N (a, a', a''), 3% [osar][mea] at 125 N (b, b', b''), 3% [osar][mea] at 100 N (c, c', c'') and 3% [osar][mea] at 50 N (d, d', d'').

![Fig. 8](image_url)

**Fig. 8** XPS spectra of wear traces: C1s (a), O1s (b), Fe2p (c) and N1s (d).
are shown in the Fig. 8 (the C1s peak at 284.8 eV as calibration). The C1s peaks at 284.8-285.2 eV and 288.6 eV are attributed to C = C and C = O respectively\(^{38}\). The O1s peak at 531.3 eV and the Fe2p peak at 710.4 eV represent the formation of iron oxide\(^{38}\). The N1s peak at 400.2 eV only observed in the presence of[osar][mea]stands for the complex nitrogen compounds derived from[osar][mea] and appears more obvious with the decreasing load. Besides, the complex nitrogen compounds are considered to play a key role in the lubrication on the basis of the previous studies\(^{20, 24, 38-41}\). According to above surface analyses, the potential lubrication mechanism was speculated as follows. The adsorption film formed by[osar][mea] plays a key lubricating role at the initial friction stage, but it may be continually destroyed and reconstructed in the friction process. Meanwhile, the adsorbed[osar][mea]molecules may triboreact with the metal surface to promote the growth of the tribofilm containing complex nitrogen compounds. The adsorption film and the tribofilm may contribute to the excellent lubricity.

4 Conclusions

In the present work, an ecofriendly PIL was facilely synthesized from an amino acid derivate and applied as a multipurpose additive in water-glycerol. It can yield a remarkable improvement in the anticorrosion performance of water-glycerol while its concentration increases over 0.5%. Especially as the concentration of[osar][mea] reaches 3.0%, there is nearly no rust spot in the filter paper. DFT calculation deduced that the anion of[osar][mea] play a decisive role in the corrosion inhibition efficiency. Meanwhile, it can significantly improve the lubricity of water-glycerol, and the optimal concentration is 3.0%. Each of the aqueous lubricants undergoes a running-in period which prolongs with the increasing concentration of[osar][mea], and there is a high friction stage in the running-in time when the concentration exceeds 0.5%. Further investigation on the change of tribology behavior with load reveals that the antiwear and friction reducing abilities reduce with the increasing load. Based on the SEM/EDS and XPS analyses of worn surfaces, the stable lubrication film consisted of the adsorbed[osar][mea]film and the tribofilm containing complex nitrogen compounds.

References

1) Erdemir, A.; Ramirez, G.; Eryilmaz, O.L.; Narayanan, B.; Liao, Y.; Kamath, G.; Sankaranarayanan, S.K.R.S. Carbon-based tribofilms from lubricating oils. *Nature* 536, 67-71 (2016).
2) Saboya, R.M.A.; Cecilia, J.A.; García-Sancho, C.; Sales, A.V.; de Luna, F.M.T.; Rodríguez-Castellón, E.; Cavalcante, C.L. Synthesis of biolubricants by the esterification of free fatty acids from castor oil with branched alcohols using cationic exchange resins as catalysts. *Ind. Crop. Prod.* 104, 52-61 (2017).
3) Liu, S.B.; Saha, B.; Vlachos, D.G. Catalytic production of renewable lubricant base oils from bio-based 2-alkylfurans and enals. *Green Chem.* 21, 3606-3614 (2019).
4) Wang, Y.R.; Yu, Q.L.; Cai, M.R.; Shi, L.; Zhou, F.; Liu, W.M. Ibuprofen-based ionic liquids as additives for enhancing the lubricity and antimeal of water-ethylene glycol liquid. *Tribol. Lett.* 65, 55 (2017).
5) Panchal, T.M.; Patel, A.; Chauhan, D.D.; Thomas, M.; Patel, J.V. A methodological review on bio-lubricants from vegetable oil based resources. *Renew. Sust. Energ. Rev.* 70, 65-70 (2017).
6) Matiliunaite, M.; Paulauskiene, T. From concept to practice: manufacturing of bio-lubricants from renewable resources. *Biomass Convers. Bior.* 9, 353-361 (2019).
7) Shi, Y.J.; Minami, I.; Grahn, M.; Bjorling, M.; Larsson, R. Boundary and elastohydrodynamic lubrication studies of glycerol aqueous solutions as green lubricants. *Tribol. Int.* 69, 39-45 (2014).
8) Gonzalez, J.A.T.; Longinotti, M.P.; Corti, H.R. The viscosity of glycerol-water mixtures including the supercooled region. *J. Chem. Eng. Data* 56, 1397-1406 (2011).
9) Wichmann, H.; Stache, H.; Schmidt, C.; Winter, M.; Bock, R.; Herrmann, C.; Bahadir, M. Ecological and economic evaluation of a novel glycerol based biocide-free metalworking fluid. *J. Clean Prod.* 43, 12-19 (2013).
10) Liang, S.S.; Shen, Z.G.; Yi, M.; Liu, L.; Zhang, X.J.; Ma, S.L. In-situ exfoliated graphene for high-performance water-based lubricants. *Carbon* 96, 1181-1190 (2016).
11) Ye, X.Y.; Ma, L.M.; Yang, Z.G.; Wang, J.Q.; Wang, H.G.; Yang, S.R. Covalent functionalization of fluorinated graphene and subsequent application as water-based lubricant additive. *ACS Appl. Mater. Interfaces* 8, 7483-7488 (2016).
12) Li, X.; Wang, Z.K.; Dong, G.N. Preparation of nanoscale liquid metal droplet wrapped with chitosan and its tribological properties as water-based lubricant additive. *Tribol. Int.* 148, 106349 (2020).
13) Zhang, C.L.; Zhang, S.M.; Yu, L.G.; Zhang, Z.J.; Wu, Z.S.; Zhang, P.Y. Preparation and tribological properties of water-soluble copper/silica nanocomposite as a water-based lubricant additive. *Appl. Surf. Sci.* 259, 824-830 (2012).
14) Tang, J.Z.; Chen, S.Q.; Jia, Y.L.; Ma, Y.; Xie, H.M.; Quan, X.; Ding, Q. Carbon dots as an additive for improving performance in water-based lubricants for amorphous
15) Kaneko, K.; Akamatsu, M.; Sakai, K.; Sakai, H. Adsorption of hydrophilic amine-based protic ionic liquids on iron-based substrates. *J. Oleo Sci.* 70, 333-339 (2021).

16) Gabler, C.; Tomastik, C.; Brenner, J.; Pisarova, L.; Dörr, N.; Allmaier, G. Corrosion properties of ammonium based ionic liquids evaluated by SEM-EDX, XPS and ICP-OES. *Green Chem.* 13, 2869-2877 (2011).

17) Zhou, Y.; Qu, J. Ionic liquids as lubricant additives: a review. *ACS Appl. Mater. Interfaces* 9, 3209-3222 (2017).

18) Zheng, G.L.; Ding, T.M.; Huang, Y.X.; Zheng, L.; Ren, T.H. Fatty acid based phosphite ionic liquids as multifunctional lubricant additives in mineral oil and refined vegetable oil. *Tribol. Int.* 123, 316-324 (2018).

19) Cai, M.R.; Yu, Q.L.; Liu, W.M.; Zhou F. Ionic liquid lubricants: When chemistry meets tribology. *Chem. Soc. Rev.* 49, 7753-7818 (2020).

20) Wang, Y.R.; Yu, Q.L.; Cai, M.R.; Zhou, F.; Liu, W.M. Halide-free PN ionic liquids surfactants as additives for enhancing tribological performance of water-based liquid. *Tribol. Int.* 128, 190-196 (2018).

21) Zheng, D.D.; Wang, X.B.; Zhang, M.; Liu, Z.G.; Ju, C. Anticorrosion and lubricating properties of a fully green lubricant. *Tribol. Int.* 130, 324-333 (2019).

22) Fan, M.J.; Du, X.; Ma, L.; Wen, P.; Zhang, S.; Dong, R.; Sun, W.J.; Yang, D.S.; Zhou, F.; Liu, W.M. In situ preparation of multifunctional additives in water. *Tribol. Int.* 130, 317-323 (2019).

23) Yang, D.S.; Du, X.; Li, W.Q.; Han, Y.Y.; Ma, L.; Fan, M.J.; Zhou, F.; Liu, W.M. Facile preparation and tribological properties of water-based naphthalene dicarboxylate ionic liquid lubricating additives. *Tribol. Lett.* 68, 1-11 (2020).

24) Yang, Z.Q.; Sun, C.F.; Zhang, C.Y.; Zhao, S.J.; Cai, M.R.; Liu, Z.L.; Yu, Q.L. Amino acid ionic liquids as anticorrosive lubricating additives for water and their environmental impact. *Tribol. Int.* 153, 106663 (2021).

25) Greaves, T.L.; Drummond, C.J. Protic ionic liquids: evolving structure-property relationships and expanding applications. *Chem. Rev.* 115, 11379-11448 (2015).

26) Mu, L.W.; Shi, Y.J.; Ji, T.; Chen, L.; Yuan, R.X. et al. Ionic grease lubricants: Proton triethanolamine oleic acid and aprotic choline oleic acid. *ACS Appl. Mater. Interfaces* 8, 4977-4984 (2016).

27) Shi, Y.J.; Larsson, R. Non-corrosive and biomaterials protic ionic liquids with high lubricating performance. *Tribol. Lett.* 63, 1 (2016).

28) Gruzdev, M.S.; Shmuikler, L.E.; Kudryakova, N.O.; Kolker, A.M.; Sergeeva, Y.A; Safonova, L.P. Triethanolamine-based protic ionic liquids with various sulfonic acids: Synthesis and properties. *J. Mol. Liq.* 242, 838-844 (2017).

29) Kreivaitis, R.; Gumbyte, M.; Kupcinskas, A.; Kazancev, K.; Makareviciene, V. Investigating the tribological properties of PILs derived from different ammonium cations and long chain carboxylic acid anion. *Tribol. Int.* 141, 105905 (2020).

30) Determination of corrosion preventing characteristics of cooling lubricants mixed with water. DIN 51360 Part 2.

31) Shi, Y.J.; Minami, I.; Grahn, M.; Björling, M.; Larsson, R. Boundary and elastohydrodynamic lubrication studies of glycerol aqueous solutions as green lubricants. *Tribol. Int.* 69, 39-45 (2014).

32) Negm, N.A.; El Farargy A.F.M.; Halim E.A.A.; El Boudy S.; Ahmed A.I. Novel bio-based nonionic surfactants: synthesis, surface activity and corrosion inhibition efficiency against aluminum alloy dissolution in acidic media. *J. Surfact. Deterg.* 17, 1203-1211 (2014).

33) Yuce, A.O.; Mert, B.D.; Kardaş, G.; Yazıcı, B. Electrochemical and quantum chemical studies of 2-amino-4-methyl-thiazole as corrosion inhibitor for mild steel in HCl solution. *Corros. Sci.* 83, 310-316 (2014).

34) Tawfik S.M.; Abd Elaal, A.A.; Aiad, I. Three gemini cationic surfactants as biodegradable corrosion inhibitors for carbon steel in HCl solution. *Res. Chem. Intermed.* 42, 1101-1123 (2016).

35) Sulek, M.W.; Wasielski, T. Influence of critical micelle concentration (CMC) on tribological properties of aqueous solutions of alkyl polyglycosides. *Tribol. Trans.* 52, 12-20 (2009).

36) Zheng, G.L.; Zhang, G.Q.; Ding, T.M.; Xiang, X.Z.; Li, F. et al. Tribological properties and surface interaction of novel water-soluble ionic liquid in water-glycol. *Tribol. Int.* 116, 440-448 (2017).

37) Su, T.; Song, G.J.; Zheng, D.D.; Ju, C.; Zhao, Q. Facile synthesis of protic ionic liquids hybrid for improving antiwear and anticorrosion properties of water-glycol. *Tribol. Int.* 153, 106660 (2021).

38) Fan, M.J.; Zhang, C.Y.; Guo, Y.N.; Zhang, R.R.; Lin, L.B. et al. An Investigation on the friction and wear properties of perfluorooctane sulfonate ionic liquids. *Tribol. Lett.* 63, 11 (2016).

39) Dong, R.; Wen, P.; Zhang, S.; Zhang, C.Y.; Sun, W.J. et al. The synthesis and tribological properties of dicarboxylic acid ionic liquids. *Tribol. Int.* 114, 132-140 (2017).

40) Dong, R.; Yu, Q.L.; Bai, Y.Y; Wu, Y.; Ma, Z.F. et al. Towards superior lubricity and anticorrosion performances of proton-type ionic liquids additives for water-based lubricating fluids. *Chem. Eng. J.* 383, 123201 (2020).

41) Dong, R.; Bao, L.Y.; Yu, Q.L.; Wu, Y.; Ma, Z.F. et al. Effect of electric potential and chain length on tribologi-
cal performances of ionic liquids as additives for aqueous systems and molecular dynamics simulations. *ACS Appl. Mater. Interfaces* **12**, 39910-39919 (2020).

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