



# Study on the conductive and tribological properties of copper sliding electrical contacts lubricated by ionic liquids

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## ABSTRACT

To reduce energy dissipation, improve reliability and lifetime of sliding electrical contact, ionic liquids (ILs) and multiply-alkylated cyclopentanes (MACs) were employed to lubricate copper sliding electrical contacts. Their physical properties, electrical contact resistance (ECR) and tribological properties were investigated in detail. Standard deviation was introduced to evaluate the stability of conductive and tribological behaviors. Results show that ILs not only greatly lower the COF, ECR and wear volumes, but also make them more stable as compared with MACs. Based on the characterization and analysis of the lubricants and worn surfaces, the conductive and tribological behaviors of different lubricants under current-carrying friction are related to the nature of the lubricants and the protective film generated on the worn surfaces.

## 1. Introduction

Nowadays, with the development of the electrification engineering, the number of sliding electrical connectors has increased dramatically [1]. Sliding electrical connector is known as the key element appearing in electromechanical equipment, such as electrical switch, high-speed railway and power transmission system and so forth, which performs the main functions of connecting, breaking and transmitting electrical energy or signal [2,3]. The performances of the sliding electrical connector have a critical influence on the reliability and lifetime of operating system and much work has been done in this field. In the past decades, the research is mainly focused on dealing with the sliding electrical contact materials to improve the conductive and tribological properties [4–6]. Although a series of metal-based self-lubricating materials are intensively studied, these problems are still exist [4–7].

Lubricants have been widely employed to reduce both friction and wear in industrial fields. However, different from the conventional operating conditions, when lubricants are applied in electromechanical equipment, some specific requirements are imposed. Besides excellent lubricity, lubricants should also have good conductivity, anti-corrosion and thermal stability [3,7]. Depending on the complex physical and chemical interaction, conventional lubricants could form protective film on the worn surfaces to decrease direct metal contact, thereby improving friction reduction and anti-wear abilities. However, the protective films including physical adsorption film and tribochemical reaction film generally have poor conductivity, which undoubtedly

increase the ECR [2,7]. Therefore, there is a continuous desire to seek a suitable lubricants with excellent conductivity and tribological properties to meet the requirements for lubricating sliding electrical contacts.

Recently, some groups have done some research about the conductive lubricants [7–9]. Huang et al. evaluated the ECR and tribological properties of the 1-ethyl-3-methylimidazolium tetrafluoroborate under current-carrying condition and found that the lubricant could reduce the ECR and improve the tribological properties [7]. However, the corrosion property of the lubricant was not evaluated. Corrosion usually leads to a sharp increase in ECR and causes the failure of the electrical connectors [10]. Ge et al. prepared a series of lubricating greases containing conductive nanoparticles such as carbon nanotubes, Cu, Ag etc [8,9]. Although the conductivity of the lubricating grease was increased, they only investigated the tribological properties under no current-carrying condition which does not match the actual operating conditions. In fact, current-carrying friction is much more complicated than traditional friction condition. Besides the above-mentioned, there are another three aspects that should be taken into consideration during the course of study. (1) The thermal stability of lubricant. The lubricant should have good thermal stability because a lot of Joule heat is usually generated in the electrical contact zones. (2) Characterization and analysis of the chemical compositions on the worn surfaces. The identification of the chemical compositions is critical to understanding the conductive and lubrication mechanisms. (3) The materials of the tested friction pairs. In general, owing to the relatively

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low cost and high conductivity, copper has been widely used to fabricate electrical connectors.

Ionic liquids (ILs) not only have excellent conductivity, but also possess outstanding lubricating ability. Moreover, ILs have good thermal stability, negligible vapor pressure and broad electrochemical potential window and so forth [11–13]. Therefore, ILs hold a great potential as promising lubricants to lubricate the sliding electrical contacts. However, till now, there is little knowledge about the conductive and tribological properties and related mechanisms analysis of the copper sliding electrical contacts lubricated by ILs.

In this work, two kinds of ILs including 1-butyl-3-methylimidazolium tetrafluoroborate (LB104) and 1-butyl-3-methylimidazolium hexafluorophosphate (LP104) were used as conductive lubricants to lubricate the copper sliding electrical contacts. Multiply-alkylated cyclopentanes (MACs) was employed as a contrastive lubricant because of the good thermal stability and tribological properties [14,15]. The thermal stability and corrosion resistance of the lubricants were evaluated, and the ECR and friction reduction and anti-wear abilities of the lubricants for copper sliding electrical contacts were investigated in detail. Owing to the fact that the stability of the ECR and friction has a crucial influence on the performances and service life of the sliding electrical contacts [16], therefore, standard deviations (SD) of the ECR and coefficient of friction were introduced to evaluate the stability. A larger standard deviation value means more unstable. In addition, due to the LB104 shows hydrophilicity, this work also investigated the effect of water on the conductive and tribological behaviors of LB104. After friction and wear test, the worn surfaces were characterized and analyzed by a scanning electron microscopy (SEM) and an X-ray photoelectron spectroscopy (XPS) to propose the possible conductive and tribological mechanisms.

## 2. Experimental details

### 2.1. Materials

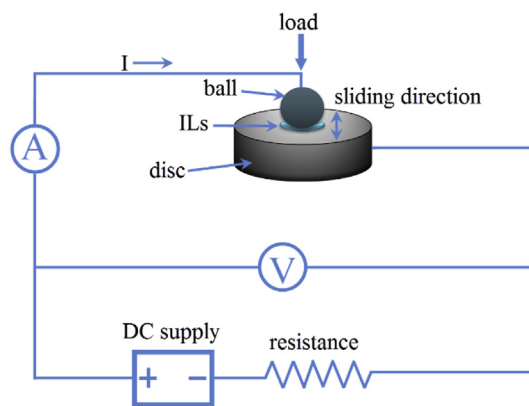
The MACs was provided by Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences (Lanzhou, China). 1-butyl-3-methylimidazolium tetrafluoroborate (LB104, 99%) and 1-butyl-3-methylimidazolium hexafluorophosphate (LP104, 99%) were purchased from J&K Scientific Ltd (Beijing, China). Table 1 gives the conductivity and kinematic viscosity of the lubricants. Acetone (analytical grade) was purchased from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China).

### 2.2. Characterization of the lubricants

Before test, the ILs (LB104 and LP104) have been dried under 60 °C for 24 h. The Fourier transform infrared spectra (FT-IR) of ILs were characterized using a FT-IR spectrometer (Thermo Fisher Scientific) in the wavenumber range of 4000–400 cm<sup>-1</sup>. The thermogravimetric analysis (TGA) of the lubricants were performed using a Q500 TGA (TA instruments) at a heating rate of 10 °C/min in flowing air. The corrosion test was conducted as following procedure. A piece of bright finish copper block was immersed in 40 ml of lubricants and heated at 150 °C for 24 h. At the end of the test, the copper block was washed with acetone and compared with the finish copper to evaluate the corrosion performance.

**Table 1**  
Conductivity and kinematic viscosity of the MACs and ILs.

| Sample                                   |        | MACs | LB104 | LP104 |
|------------------------------------------|--------|------|-------|-------|
| Conductivity (mS/cm)                     |        | 0    | 4.09  | 1.49  |
| Kinematic viscosity (mm <sup>2</sup> /s) | 40 °C  | 55.8 | 27.9  | 71.6  |
|                                          | 100 °C | 9.2  | 5.7   | 10.4  |



**Fig. 1.** Schematic diagram of the experimental device.

### 2.3. Tribological test under current-carrying friction

The tribological behaviors of lubricants under current-carrying friction were evaluated by a MFT-R4000 reciprocal friction and wear apparatus, which was designed by State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences (Lanzhou, China). Fig. 1 gives a schematic diagram of the experimental device. The DC supply can provide a stable voltage. The contact current and voltage measured on the contact monitored was in live time, and it was observed that the voltage was very stable and only the current changed in the real-time during the friction process. The copper ball (CuZn40; diameter, 5 mm; hardness, 120 Hv) slides reciprocally against the lower copper disc (27 mm × 25 mm; hardness, 82 Hv) at an amplitude of 5 mm, a frequency of 2 Hz, a normal load of 5/20 N under the applied voltage of 500/1500 mV. All the discs were polished with different grades of diamond paste to achieve a surface roughness of about 0.05 μm. The temperature and relative humidity were 25 °C and 30%, respectively. Before each test, the ball and disc were ultrasonically washed with acetone for 10 min and then about 0.5 g lubricant was introduced into the friction region. The contact current and coefficients of friction (COF) were recorded automatically by the tester.

After friction test, the resistance values calculated by Ohm's law represented the ECR values of friction pair for other resistance values were constant such as wires' and components'. The mean values ( $\bar{x}$ ) of the ECR and COF were calculated using equation (1):

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

The standard deviations (SD) of the ECR and COF were calculated using equation (2):

$$SD = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (2)$$

Where  $\bar{x}$  is the mean value,  $x_i$  is the instantaneous value,  $n$  is the number of the instantaneous values.

### 2.4. Surface analysis

After friction test, the discs were ultrasonically cleansed in acetone for 10 min. The wear volume was determined by a Micro-XAM 3D surface mapping microscopy profile meter. The morphologies of the worn surfaces were obtained by an EVO-18 SEM (Zeiss, Germany) under an accelerating voltage of 10 kv and a beam current of 7.5 nm. The chemical states of the characteristics elements on the worn surfaces were analyzed by a PHI-5702 multifunctional X-ray photoelectron spectroscopy (XPS, American Institute of Physics Electronic Company) with K-alpha irradiation as the excitation source. The diameter of the

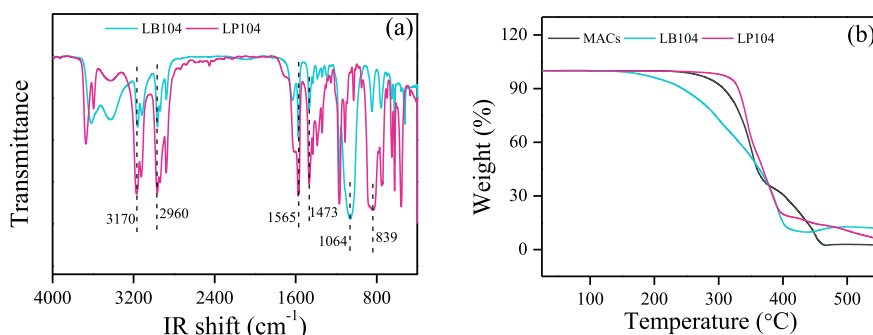


Fig. 2. FTIR and TGA curves of the samples.

spot size for XPS analysis was 300  $\mu\text{m}$ . A pass energy of 29.3 eV determined the binding energies of the target elements, with the resolution of about  $\pm 0.3$  eV, and the binding energy of carbon (C1s: 284.6 eV) as the reference.

### 3. Results

#### 3.1. Physicochemical properties of the lubricants

Fig. 2(a) gives the FTIR spectra of the ILs. LB104 has the peak of B-F stretching vibration at  $1064\text{ cm}^{-1}$  and LP104 has the peak of P-F stretching vibration at  $839\text{ cm}^{-1}$ . The peaks at  $1473$  and  $1565\text{ cm}^{-1}$  are originated from the C-N bands on imidazolium rings. The peaks at  $2960$  and  $3170\text{ cm}^{-1}$  belong to the N=C stretch vibrations and the H-C-C-H asymmetric stretch vibrations, respectively [17,18]. Fig. 2(b) gives the TGA curves of MACs and ILs. It is observed that the decomposition temperatures of MACs and LP104 are higher than  $280\text{ }^\circ\text{C}$ , indicating an excellent thermal stability. LB104 has a relatively low decomposition temperatures at about  $190\text{ }^\circ\text{C}$ . In some harsh cases, the temperature of the electrical contact region could reach  $150\text{ }^\circ\text{C}$  [19,20]. Herein, all the decomposition temperatures of lubricants are higher than  $150\text{ }^\circ\text{C}$ , which could meet the requirement.

Fig. 3 displays the pictures of the copper blocks after corrosion test. It can be seen that there is no obvious corrosion appearing on the copper blocks immersed in MACs and LB104. However, in a sharp contrast, the copper block immersed in LP104 was seriously corroded. This strong corrosive property of LP104 may have a crucial influence on the conductive and tribological performances of the sliding electrical contact.

#### 3.2. Tribological and conductive behaviors of the lubricants

In this work, the effect of changing the current direction on conductive and tribological behaviors was also investigated. It was found that changing current direction had no obvious influence on the conductive and tribological properties because the upper ball and lower disc all have good conductivity. When exchanging the polarity, it only changed the relative position of the ion adsorption film which were respectively consisted of anions and cations. Therefore, the tribological

tests shown in following sections all conducted under the same current direction (upper ball is positive electrode and the lower disc is negative electrode).

Fig. 4 (a) and (b) give the COF and ECR as a function of time and the corresponding SD values under a load of 5 N and a voltage of 500 mV at 2 Hz. It is noted that MACs had the COF and ECR up to 0.357 and  $39.093\text{ m}\Omega$  respectively, and the corresponding SD values were also higher than others. By a contrast, LB104 and LP104 not only greatly reduced the COF and ECR, but also made them more stable, indicating superior friction reduction and conductive abilities. Compared with LP104, although LB104 exhibited lower COF and ECR, the SD values of LB104 were a little higher than those of LP104. Fig. 4(c) gives the wear volumes on the copper discs lubricated by different lubricants. It is seen that LB104 and LP104 had much lower wear volumes than MACs, indicating a preferable anti-wear ability.

Fig. 5 presents the COF and ECR as a function of time and the corresponding SD values and the wear volumes under a load of 5 N and a voltage of 1500 mV. As shown in Fig. 5(a), LB104 and LP104 still exhibited low and stable COF and ECR as compared with MACs. Fig. 5(b) shows LB104 and LP104 had close SD values, indicating they all had good stability during the friction process. The wear volumes shown in Fig. 5(c) suggest that the anti-wear ability of the lubricants can be arranged as follows: LB104 > LP104 > MACs.

Fig. 6 shows the COF and ECR as a function of time and the corresponding SD values under a load of 20 N and a voltage of 1500 mV at 2 Hz. As shown in Fig. 6(a), the COF of MACs was about one time larger than that of LB104 and LP104, and the ECR of all the lubricants increased gradually during the first few minutes of the friction and then remained stable. Different from that LB104 and LP104 had close COF, the ECR of LB104 was much lower than that of LP104. Meanwhile, Fig. 6(b) indicates that the COF and ECR of LB104 were more stable than others. Fig. 6(c) gives the wear volumes lubricated by different lubricants. The lowest wear volume was obtained by LB104, indicating a superior anti-wear ability during the friction process.

Fig. 7 gives a tribological test with the voltage ranging from 0 to 1500 mV and at 5 N and 2 Hz. As shown in Fig. 7(a), MACs exhibited gradually increasing COF when the voltages rose from 0 to 1500 mV, which may be attributed to the Joule heat generated in the friction region. When the voltage was switched off, the COF of MACs gradually

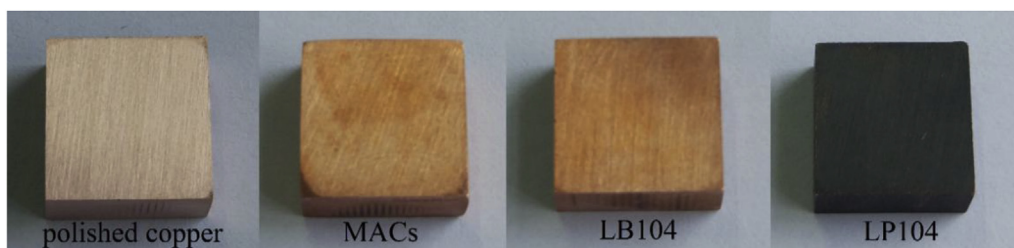


Fig. 3. Photos of the copper blocks (20 mm  $\times$  20 mm) after corrosion test.

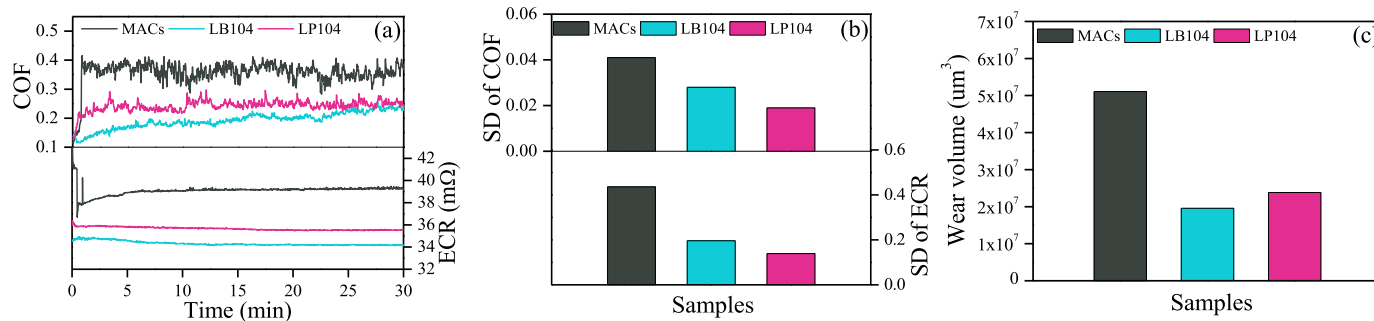


Fig. 4. (A) COF and ECR as a function of time and (b) SD values of COF and ECR and (c) wear volumes of the wear scars under a load of 5 N and a voltage of 500 mV at 2 Hz.

decreased. By a contrast, ILs exhibited different evolution of COF. The COFs with applied voltage are lower than those with no voltage, indicating the electrical enhanced ions adsorption film exhibited better tribological properties than the mixed ions adsorption film. It was also found that a peak immediately appeared in the curves of the COF at the moment of applying or switching voltage, and then the COF was gradually reduced. The formation of the peaks may be attributed to destroy of the mixed ions adsorption film caused by applying voltage. This results suggest that the influence of voltage on the ions is immediately generated. However, it needs to suffer a running-in period to form a stable electrical enhanced adsorption ions film. Observing the curves of ECR shown in Fig. 7 (b), it was also consistent with the evolution of COF. When the voltage was applied or changed, the ECR of ILs immediately dropped. The reason may be lie in that at the moment of changing voltage, the mixed ions adsorption film was destroyed and thus the direct contact between friction pair increased, which resulted in a drop in the ECR and an increase in COF. Moreover, it was found that the intensity of the peak in COF and the valley in ECR became weaker with the voltage increasing from 500 mV to 1500 mV. The reason may be ascribed to that a relatively sufficient electrical enhanced ions adsorption film had been formed on the worn surfaces at low voltage and the number of free ions that could be driven was reduced with the increasing voltage, therefore, increasing voltage had less effect on the conductive and tribological properties.

LB104 shows good hydrophilicity, therefore, this work further investigated the effect of water on the tribological and conductive properties of LB104 under a load of 5 N and a voltage of 1500 mV at 2 Hz. The concentration of water in LB104 was adjusted as 1%, 2% and 5% (mass fraction). As shown in Fig. 8, LB104 containing 1% or 2% water exhibited lower COF, ECR and wear volumes, indicating addition of small amount of water into LB104 could improve the conductive and tribological properties. The reason may be related to the changes in the conductivity, viscosity and tribochemical reactions induced by water, which will be discussed in detail in the following section 4.2.

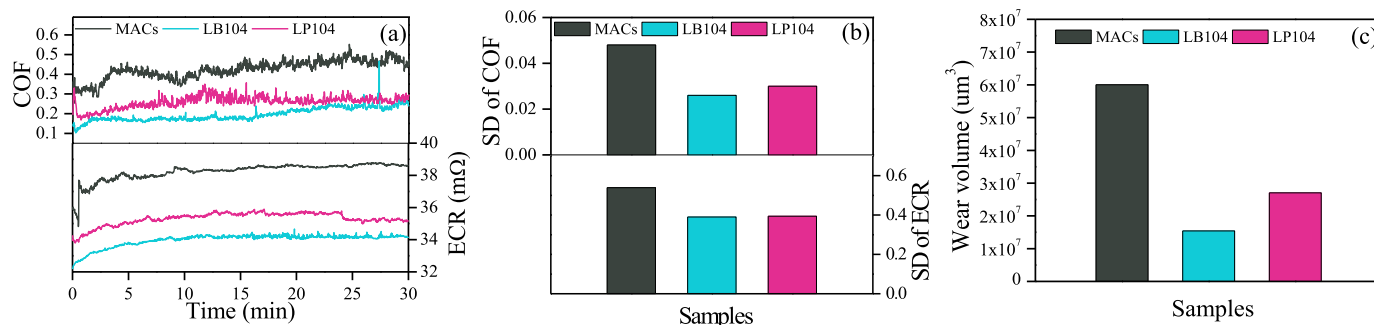


Fig. 5. (A) COF and ECR as a function of time and (b) SD values of COF and ECR and (c) wear volumes of the wear scars under a load of 5 N and a voltage of 1500 mV at 2 Hz.

### 3.3. Analysis of the worn surface

Fig. 9 gives the SEM morphologies of the worn surfaces on the copper discs to further compare the tribological properties. As shown in Fig. 9 (a) and (b), the worn surfaces lubricated by MACs was relatively wide and acquired a plenty of deep furrows and spalling, indicating severe wear occurred on this condition. When lubricated by LB104 (Fig. 9 c and d), not only the wear width was reduced, but also the worn surface became smoother, indicating an outstanding anti-wear ability. Fig. 9 (e) and (f) shows that although the wear width was reduced to some extent, some furrows still appeared on the worn surface lubricated by LP104. The SEM analysis shows that LB104 had the best anti-wear ability among all the lubricants.

To understand the conductive and lubrication mechanisms, XPS was employed to detect the chemical states of the characteristics elements including C1s, Cu2p, O1s, F1s, P2p, N1s and B1s on the worn surfaces lubricated by different lubricants. The XPS of C1s (Fig. 10 a) has a strong and symmetrical peak at 284.6 eV, which is identified as the carbon in air and is used as the reference. Fig. 10 (b) gives the XPS spectra of Cu2p on the worn surfaces lubricated by MACs and LB104. The XPS spectra of Cu2p has the peak of Cu2p<sub>3/2</sub> at 932.6 eV and the peak of Cu2p<sub>1/2</sub> at 952.4 eV, which are assigned to metallic Cu or Cu (I) [21,22]. Because metallic Cu and Cu (I) have similar binding energy, therefore it is hard to differentiate these two chemical states of copper on the basis of the Cu2p XPS spectra. However, Cu (I) is unstable and it can be oxidized easily to Cu (II) [22,23]. Further observing the Cu2p XPS spectra, there is no obvious peak of Cu (II) appearing at 933.9 eV [3,23]. Therefore, it can be inferred that the main substance of the worn surfaces lubricated by MACs and LB104 are still metallic copper. As for the worn surface lubricated by LP104, the XPS spectra of Cu2p is obviously different. As shown in Fig. 10 (c), besides the peaks at 932.6 and 952.4 eV, there are another two peaks at 934.2 and 936.6 eV. Combining the XPS spectra of F1s and P2p shown in Fig. 10 (e) and (f), it can be confirmed that copper fluoride and copper phosphate were generated on the worn surface lubricated by LP104 [17,24–26]. This result is

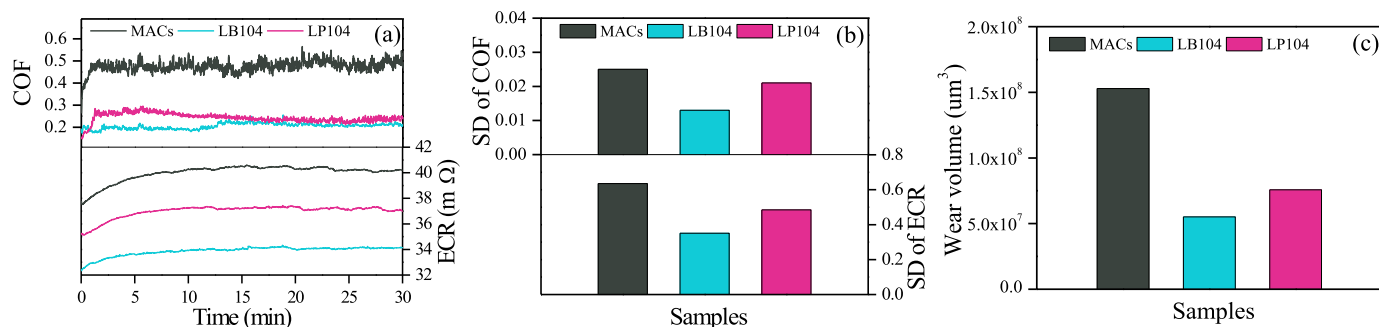


Fig. 6. (A) COF and ECR as a function of time and (b) SD values of COF and ECR and (c) wear volumes of the wear scars under a load of 20 N and a voltage of 1500 mV at 2 Hz.

also consistent with the corrosion result shown in Fig. 3. LP104 has a strong corrosive property and it can easily react with Cu. The O1s has the peak at 531.0 eV belonging to the C-O bonding [25]. The binding energies of N1s appearing at about 400.1 eV may belong to carbonitride and/or nitrogen oxide, and/or nitrogen doubled-bond compounds [27,28]. There is no obvious peak appearing at the XPS spectra of F1s and B1s lubricated by LB104, indicating that  $\text{BF}_4^-$  anion of LB104 did not react with Cu during the friction process. The XPS analysis suggests that a protective film is generated on the worn surfaces by complex physical adsorption and tribochemical reaction during the friction process, which is responsible for the enhanced friction reduction and anti-wear abilities as well as improved conductive capacity.

## 4. Discussion

### 4.1. Analysis of the conductive and lubrication mechanisms

The experimental characterizations suggest that LB104 and LP104 not only lower the COF, ECR and wear volume, but also make them more stable as compared with MACs. Three kinds of lubricants exhibited different conductive and tribological behaviors, which is attributed to the different intrinsic properties of lubricants. Based on the characterization and analysis, the conductive and lubrication mechanisms will be discussed in detail.

It is noted that MACs exhibited high and fluctuant COF and ECR as well as large wear volumes under all the tested conditions. XPS analysis suggests that metal oxides were not detected on the worn surface. Therefore, it can be inferred that the lubricity mainly depends on the physical adsorption film. During the current-carrying friction process, a non-negligible factor is Joule heat which may damage the physical adsorption film, resulting in high and fluctuant COF and large wear volume [2]. Especially, at 1500 mV, MACs exhibited higher COF, ECR and wear volume. As far as the conductive ability is concerned, although MACs prevents the worn surface from being oxidized and thus is beneficial to improve the conductivity, the lubricating oil film formed by MACs between the contact surfaces is generally recognized as an insulating layer which may impede the flow of current [2,7]. Thus, the

sliding electrical contact lubricated by MACs has a high ECR.

Compared with MACs, due to the outstanding conductivity and special properties, LB104 and LP104 significantly improve the conductive and tribological performances. Therein, the best conductive and tribological performances were obtained by LB104. The characterization and analysis suggest that the possible mechanisms for LB104 and LP104 are different. Regarding the possible conductive and lubrication mechanisms, two main factors should be taken into consideration: (a) the physical adsorption film generated by ILs ions, (b) the layer generated by chemical reactions between ILs and worn surfaces.

In general, as shown in Fig. 11 (a), the interfacial adsorption film generated by ILs on the worn surfaces is expected to be composed of mixed anions and cations [29]. However, as reported by the literature [30–32], the interaction between ILs ions and contact surface is greatly affected by applying a current. Depending on the polarity of the counterpart of the friction pairs, the interfacial adsorption film is dominated by anions or cations as shown in Fig. 11(b) [29]. Meanwhile, the amount of the ions at the contact interfaces is determined by the magnitude of the applied current. Higher current leads to a larger amount of ions [29,33]. Li et al. has reported that applying potential induced anions and cations to orient towards the worn surfaces such that the anions and the alkyl chains of imidazoilium cations could form a well-ordered ion layers, which could prevent the direct asperity contact to improve the tribological properties [34,35]. Therefore, LB104 and LP104 all could form a protective film on the worn surfaces to improve the tribological performances [29]. Meanwhile, due to the excellent conductivity, LB104 and LP104 existing in the interspace of the contact surfaces could transmit larger current than MACs, thereby enhancing the conductive performances. In addition, it was found that LB104 exhibited lower COF and ECR and wear widths than LP104. The reason may be related to the physicochemical properties including viscosity, conductivity and corrosion performance. According to the H-D equation [36], lubricant with a relatively high viscosity can form a thick lubricating film, which may exhibit better tribological properties. However, high viscosity can impede the movement of ions, which may have an adverse influence on the conductive and tribological properties under current-carrying friction. Herein, as shown in Table 1, LB104 has

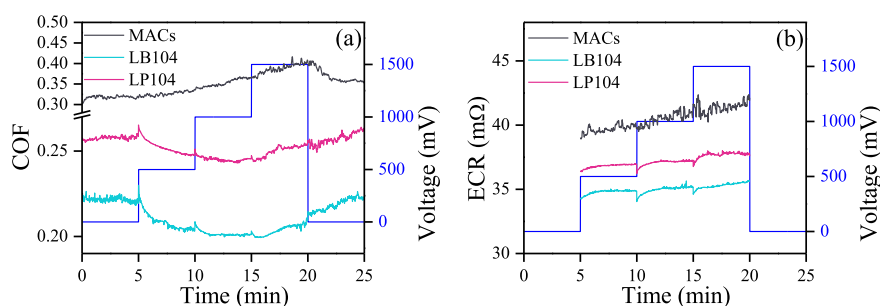


Fig. 7. (A) COF and (b) ECR of the lubricants as a function of time under the voltage ranging from 0 to 1500 mV and at 5 N and 2 Hz.

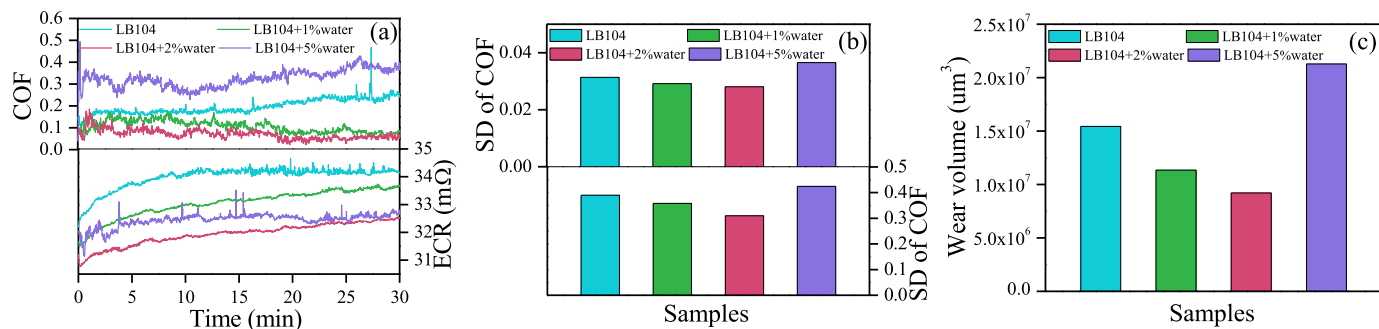


Fig. 8. (A) COF and ECR of LB104 in the absence and presence of water as a function of time and (b) SD values of COF and ECR and (c) wear volumes under a load of 5 N and a voltage of 1500 mV at 2 Hz.

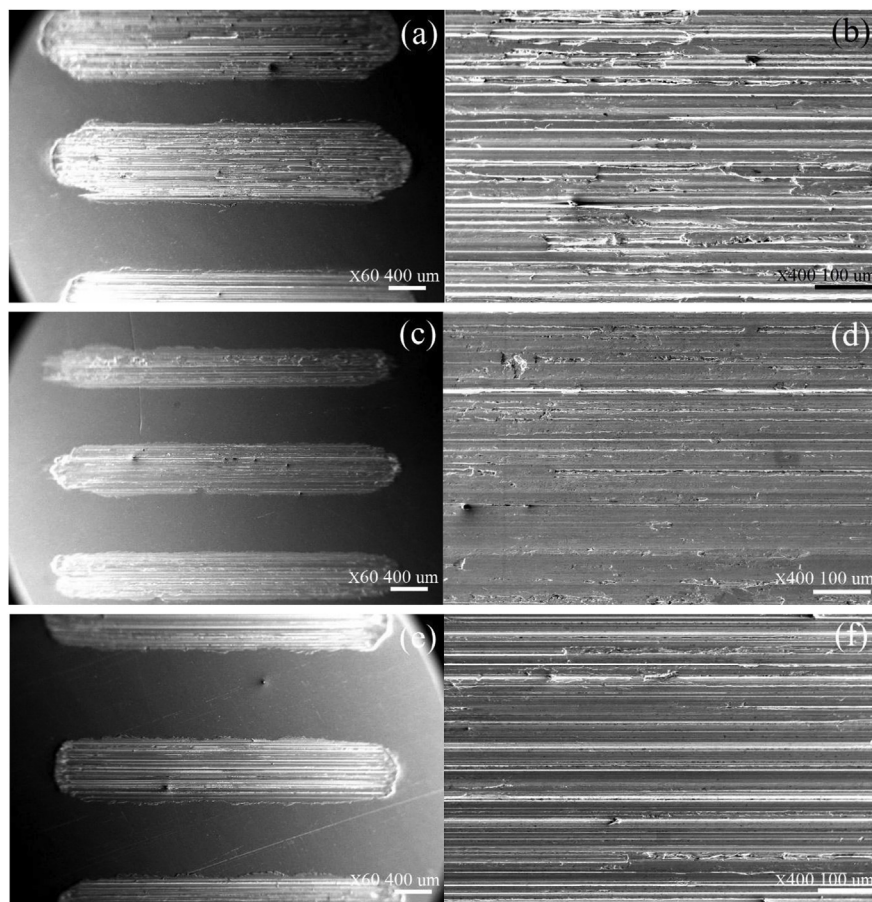


Fig. 9. SEM morphologies of the worn surfaces on the copper discs lubricated by (a) and (b) MACs, (c) and (d) LB104, (e) and (f) LP104 under a normal load of 20 N and a voltage of 1500 mV at 2 Hz.

a relatively lower viscosity and higher conductivity than LP104. Therefore, compared with LP104, LB104 could form a denser protective film on the worn surface during the current-carrying friction. Moreover, it has been reported that the ILs containing  $\text{PF}_6^-$  anion could cause serious corrosion (Fig. 3), which also results in high friction and wear [25,26,28].

Chemical effect as another factor significantly influences the conductive and tribological properties of different ILs. Observing the XPS spectra of Cu2p lubricated by LB104, it is similar to MACs that no obvious chemical reaction took place on the worn surface. Thus, the electrical enhanced adsorption ions film may be regarded as the main factor that influences the conductive and tribological properties during the friction process. However, the XPS analysis of the worn surface lubricated by LP104 indicates that tribochemical products including

copper fluoride and copper phosphate were generated during the friction process. These products are known as layers that may benefit the tribological properties whereas some literature also suggest that the serious corrosion caused by ILs, especially the ILs containing  $\text{PF}_6^-$ , which may damage the friction reduction and anti-wear abilities [17,25,26,28,37]. Based on the corrosion test and the tribological results, this work is more inclined to support the latter view. In addition, the tribochemical products generally have poor conductivity as compared with metal copper, which results in a high ECR. The above-mentioned analysis may be another reason that why LB104 exhibited better conductive performance and friction reduction and anti-wear abilities than LP104.

As shown in Fig. 4 (a) and (b), it was found that LB104 exhibited lower COF and ECR whereas its corresponding SD values were higher

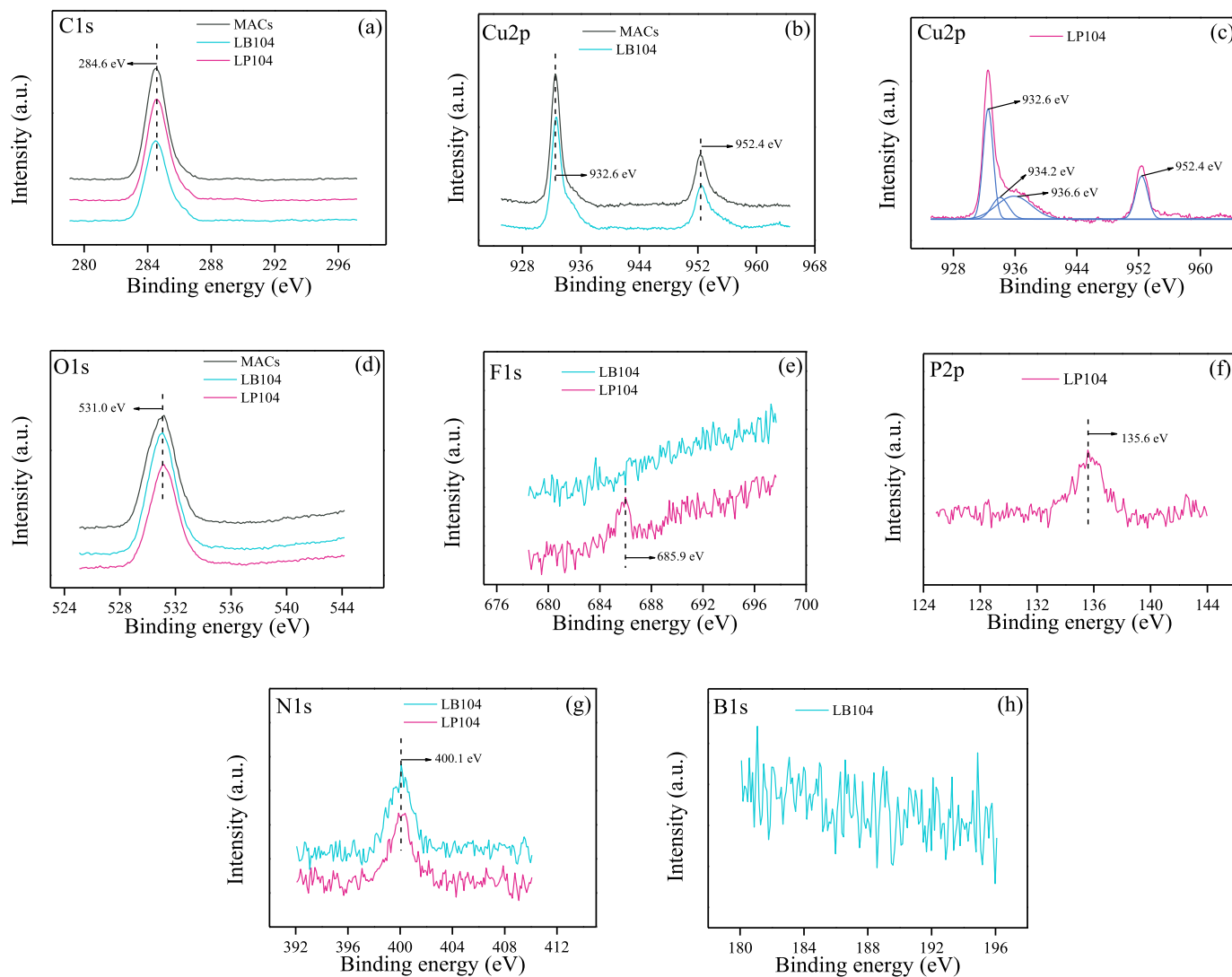


Fig. 10. X-ray photoelectron spectra of the elements (C1s, Cu2p, O1s, F1s, P2p, N1s and B1s) on the worn surfaces lubricated by MACs, LB104 and LP104 under a load of 20 N and a voltage of 1500 mV at 2 Hz.

than LP104. As above-mentioned that the lubricity of LB104 is mainly dependent on the physical adsorption film and the Joule heat could damage the lubricating film, therefore, LB104 has more fluctuant COF and ECR. However, as shown in Figs. 5 and 6, when the applied voltage increases, due to the higher conductivity and lower viscosity, more ions originating from LB104 could easily adsorb on the worn surface to form a denser electrical enhanced adsorption ions film, making the COF and

ECR lower and more stable as compared with LP104.

#### 4.2. Analysis of the effect of water on the conductive and tribological behaviors

Fig. 8 shows that LB104 containing 1% or 2% water exhibited lower COF, ECR and wear volumes. The reason may be ascribed to the

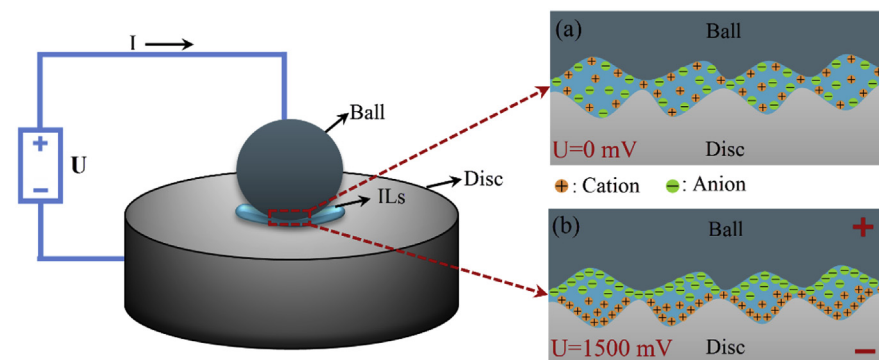


Fig. 11. Schematic diagram of the ILs lubrication in the absence and presence of an applied voltage (upper ball is positive electrode and the lower disc is negative electrode).

changes in the conductivity, viscosity and tribochemical reactions induced by water.

It has been reported that the conductivity of ILs increased first and then decreased with the increase of water [38,39]. A small amount of water can promote ionization of ILs and increase migration speed of ions, thereby improving the conductivity. However, too much water will greatly reduce ions concentration, resulting in a drop in conductivity [38,39]. Herein, LB104 containing 1%, 2% and 5% water have the conductivities of about 6.53, 9.27, 14.17 mS/cm which were determined by a DDSJ-308 A conductivity meter (Shanghai INESA & Scientific Instrument Co., Ltd.). Thus, more ions could be driven to form protective film and transmit current under LB104 containing water lubrication than under pure LB104 lubrication. The tribological tests (Fig. 8) also shows that LB104 + 5% water exhibited higher COF and wear volume than others. Although addition of water into ILs can improve the conductivity, it reduces the viscosity [38,39]. Under the lubrication of LB104 + 5% water, the reduced viscosity has a greater impact on the tribological properties than increased conductivity. Therefore, LB104 containing 5% water exhibited higher COF and wear volumes than others.

Another factor that need to be considered is the tribochemical reaction induced by water under the current-carrying friction. Referring to the literature reported by Souza and Islam [40,41], at 1500 mV, water in LB104 was underwent electrolysis to produce O<sub>2</sub> and H<sub>2</sub>. Water electrolysis may cause the friction zone to be in an oxygen-rich environment, resulting in oxides generated on the worn surface during friction process. Moreover, the addition of water also leads to hydrolysis of LB104, resulting in tribochemical products formed on the worn surfaces [42,43]. Observing Fig. 8, these complex chemical products were beneficial for the tribological properties because LB104 containing 1% or 2% water all exhibited gradually decreasing COF and lower wear volumes. The formation of the chemical products was also reflected by the evolution of ECR. During the 10–30 min of the friction, LB104 exhibited a stable ECR whereas LB104 containing 1% or 2% water had rising ECR, which suggests that complex chemical products were generated on the worn surfaces because chemical products generally had lower conductivity than pure copper. As for the LB104 + 5% water, Islam reported that the electrolysis voltage of water increases with the increasing concentration of water in LB104 [41]. Therefore, the effect of water electrolysis on the tribological and conductive behaviors is not obvious at 1500 mV. The factors that mainly influence the tribological and conductive behaviors of LB104 + 5% water are still the reduced viscosity.

## 5. Conclusions

ILs and MACs were employed as lubricants to lubricate the copper sliding electrical contacts, thereby reducing energy dissipation and improving reliability and service life. Their physical properties, conductive and tribological behaviors were investigated in detail. The conductive and lubrication mechanisms were explored and analyzed by SEM and XPS. The conclusions are summarized as follow:

- (1) TGA analysis suggests that all the lubricants have good thermal stability whereas corrosion test shows LP104 has a strong corrosive property.
- (2) Standard deviation could be introduced as a parameter to evaluate the stability of conductive and tribological behaviors during the friction process.
- (3) LB104 and LP104 not only greatly lower the COF, ECR and wear widths, but also make them more stable as compared with MACs under different applied loads and voltages.
- (4) The excellent conductive and tribological behaviors of ILs under current-carrying friction are attributed to their high conductivity and the complex protective film generated on the worn surfaces.
- (5) LB104 exhibited better conductive and tribological performances

than LP104 during the friction process, which is due to its higher conductivity, better anti-corrosion ability and the denser protective film formed on the worn surfaces.

- (6) LB104 containing 1% or 2% water exhibited better conductive and tribological behaviors, which may be attributed to the changes in conductivity and chemical reaction induced by water.

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## References

- [1] Song J, Schinow V. Correlation between friction and wear properties and electrical performance of silver coated electrical connectors. *Wear* 2015;330–331(330–331):400–5.
- [2] Chen J, Xia Y, Hu Y, Hou B. Tribological performance and conductive capacity of Ag coating under boundary lubrication. *Tribol Int* 2017;110:161–72.
- [3] Cao Z, Xia Y, Ge X. Conductive capacity and tribological properties of several carbon materials in conductive greases. *Ind Lubric Tribol* 2016;68(5):577–85.
- [4] Wang YA, Li JX, Yan Y, Qiao LJ. Effect of electrical current on tribological behavior of copper-impregnated metallized carbon against a Cu-Cr-Zr alloy. *Tribol Int* 2012;50(4):26–34.
- [5] Liu Y, Senturk BS, Mantese JV, Aindow M, Alpay SP. Electrical and tribological properties of a Ni-18%Ru alloy for contact applications. *J Mater Sci* 2011;46(20):6563–70.
- [6] Tu C, Chen Z, Xia J. Thermal wear and electrical sliding wear behaviors of the polyimide modified polymer-matrix pantograph contact strip. *Tribol Int* 2009;42(6):995–1003.
- [7] Huang W, Kong L, Wang X. Electrical sliding friction lubricated with ionic liquids. *Tribol Lett* 2017;65(1):17.
- [8] Ge XY, Xia YQ, Feng X. Influence of carbon nanotubes on conductive capacity and tribological characters of conductive greases. *J Tribol Trans ASME* 2015;138(1):011801.
- [9] Ge X, Xia Y, Shu Z, Zhao X. Conductive grease synthesized using nanometer ATO as an additive. *Friction* 2015;3(1):56–64.
- [10] Åsa KR, Jacobson S. Stationary loading, fretting and sliding of silver coated copper contacts - influence of corrosion films and corrosive atmosphere. *Tribol Int* 1997;30(3):165–75.
- [11] Liu W, Ye C, Gong Q, Wang H, Wang P. Tribological performance of room-temperature ionic liquids as lubricant. *Tribol Lett* 2002;13(2):81–5.
- [12] Minami I. Ionic liquids in tribology. *Molecules* 2009;14(6):2286–305.
- [13] Fan X, Wang L. Highly conductive ionic liquids toward high-performance space-lubricating greases. *ACS Appl Mater Interfaces* 2014;6(16):14660–71.
- [14] Leong JY, Satyanarayana N, Sinha SK. A tribological study of multiply-alkylated cyclopentanes and perfluoropolyether lubricants for application to Si-MEMS devices. *Tribol Lett* 2013;50(2):195–206.
- [15] Fan X, Li W, Li H, Zhu MH, Xia YQ, Wang JJ. Probing the effect of thickener on tribological properties of lubricating greases. *Tribol Int* 2018;118:128–39.
- [16] Huang ZY, Zhai HX, Li MQ, Liu XH, Zhou Y. Friction behaviors and effects on current-carrying wear characteristics of bulk Ti<sub>3</sub>AlC<sub>2</sub>. *Tribol Trans* 2014;57(2):300–7.
- [17] Cao Z, Xia Y, Chen C. Fabrication of novel ionic liquids-doped polyaniline as lubricant additive for anti-corrosion and tribological properties. *Tribol Int* 2018;120:446–54.
- [18] Fan X, Wang L. High-performance lubricant additives based on modified graphene oxide by ionic liquids. *J Colloid Interface Sci* 2015;452:98–108.
- [19] Trinh KE, Tsipenyuk A, Varenberg M, Rosenkranz A, Souza N, Mücklich F. Wear debris and electrical resistance in textured Sn-coated Cu contacts subjected to fretting. *Wear* 2015;344–345(4):86–98.
- [20] Park YW, Narayanan TSNS, Kang YL. Effect of temperature on the fretting corrosion of tin plated copper alloy contacts. *Wear* 2007;262(3):320–30.
- [21] Brust M, Bard AJ, Blass PM. Self-assembly of photoluminescent copper(I)-dithiol multilayer thin films and bulk materials. *Langmuir* 1997;13(21):5602–7.
- [22] Yu HL, Xu Y, Shi PJ, Xu BS, Wang XL, Liu Q. Tribological properties and lubricating mechanisms of Cu nanoparticles in lubricant. *T Nonfer Metal Soc* 2008;18(3):636–41.
- [23] Zhang C, Zhang S, Song S, Yang G, Yu L, Wu Z, Li X, Zhang P. Preparation and tribological properties of surface-capped copper nanoparticle as a water-based lubricant additive. *Tribol Lett* 2014;54(1):25–33.
- [24] Espinosa T, Sanes J, Jiménez AE, Bermúdez MD. Surface interactions, corrosion processes and lubricating performance of protic and aprotic ionic liquids with OFHC copper. *Appl Surf Sci* 2013;273(273):578–97.
- [25] Cai M, Liang Y, Zhou F, Liu W. Anticorrosion imidazolium ionic liquids as the additive in poly(ethylene glycol) for steel/Cu-Sn alloy contacts. *Faraday Discuss* 2012;156(30):147–57.
- [26] Liu X, Zhou F, Liang Y, Liu W. Benzotriazole as the additive for ionic liquid lubricant: one pathway towards actual application of ionic liquids. *Tribol Lett* 2006;23(3):191–6.



- [27] Cao Z, Xia Y. Synthesis and tribological properties of polyaniline functionalized by ionic liquids. *J Mater Sci* 2018;53(9):7060–71.
- [28] Cai M, Liang Y, Zhou F, Liu W. Tribological properties of novel imidazolium ionic liquids bearing benzotriazole group as the antiwear/anticorrosion additive in poly(ethylene glycol) and polyurea grease for steel/steel contacts. *ACS Appl Mater Interfaces* 2011;3(12):4580–92.
- [29] Dold C, Amann T, Kailer A. Influence of electric potentials on friction of sliding contacts lubricated by an ionic liquid. *Phys Chem Chem Phys* 2015;17(16):10339–42.
- [30] Hayes R, Warr GG, Atkin R. At the interface: solvation and designing ionic liquids. *Phys Chem Chem Phys* 2010;12(8):1709–23.
- [31] Gnahn M, Pajkossy T, Kolb DM. The interface between Au(1 1 1) and an ionic liquid. *Electrochim Acta* 2010;55(21):6212–7.
- [32] Li H, Rutland MW, Atkin R. Ionic liquid lubrication: influence of ion structure, surface potential and sliding velocity. *Phys Chem Chem Phys* 2013;15(35):14616–23.
- [33] Atkin R, Borisenko N, Drüschler M, el-Abedin SZ, Endres F, Hayes R, Huber B, Roling B. An in situ STM/AFM and impedance spectroscopy study of the extremely pure 1-butyl-1-methylpyrrolidinium tris(pentafluoroethyl)trifluorophosphate/Au(111) interface: potential dependent solvation layers and the herringbone reconstruction. *Phys Chem Chem Phys* 2011;13(15):6849–57.
- [34] Li H, Rutland MW, Atkin R. Ionic liquid lubrication: influence of ion structure, surface potential and sliding velocity. *Phys Chem Chem Phys* 2013;15(35):14616–23.
- [35] Li H, Wood RJ, Endres F, Atkin R. Influence of alkyl chain length and anion species on ionic liquid structure at the graphite interface as a function of applied potential. *J Phys Condens Matter* 2014;26(28):284115.
- [36] Dowson D, Higginson GR. *Elasto-hydrodynamic lubrication*. Oxford: Pergamon Press; 1977.
- [37] Cai M, Liang Y, Zhou F, Liu W. A novel imidazolium salt with antioxidation and anticorrosion dual functionalities as the additive in poly(ethylene glycol) for steel/steel contacts. *Wear* 2013;306(1–2):197–208.
- [38] Jarosik A, Krajewski SR, Lewandowski A, Radzinski P. Conductivity of ionic liquids in mixtures. *J Mol Liq* 2006;123(1):43–50.
- [39] Widegren JA, Saurer EM, Marsh KN, Magee JW. Electrolytic conductivity of four imidazolium-based room-temperature ionic liquids and the effect of a water impurity. *J Chem Thermodyn* 2005;37(6):569–75.
- [40] Souza RFD, Padilha JC, Gonçalves RS, Rault-Berthelot J. Dialkylimidazolium ionic liquids as electrolytes for hydrogen production from water electrolysis. *Electrochem Commun* 2006;8(2):211–6.
- [41] Islam MM, Okajima T, Kojima S, Ohsaka T. Water electrolysis: an excellent approach for the removal of water from ionic liquids. *Chem Commun (J Chem Soc Sect D)* 2008;42(42):5330–2.
- [42] Fan M, Song Z, Liang Y, Zhou F, Liu WM. Laxative inspired ionic liquid lubricants with good detergency and No corrosion. *ACS Appl Mater Interfaces* 2014;6(5):3233–41.
- [43] Uerdingen M, Treber C, Balsler M, Schmitt G, Werner C. Corrosion behaviour of ionic liquids. *Green Chem* 2005;7(5):321–5.