Tribol Lett (2017) 65:17
DOI 10.1007/s11249-016-0802-8

ORIGINAL PAPER

Electrical Sliding Friction Lubricated with Ionic Liquids

Wei Huang[1] · **Lingling Kong**[1] · **Xiaolei Wang**[1]

Received: 29 September 2016 / Accepted: 12 December 2016 / Published online: 20 December 2016

Abstract Lubrication is one of the most important methods for maintaining and improving the reliability of electric contact components. In view of the conductivity, the lubrication performances of ionic liquids under electric contact have been investigated by using a reciprocating sliding tribometer. Compared with dry friction condition, ionic liquids present an excellent lubrication property. Meanwhile, under the low-load condition, the contact resistance as well as electrical power consumption decreased obviously when lubricated with ionic liquids. And the stronger current strength it is, the higher coefficient and lower contact resistance it shows. The reason could be ascribed to the current-induced fracture of the ion-adsorbed film, especially those in the asperities. And the transformation of the direct contacts, in turn, affects the friction coefficient and contact resistance.

Keywords Ionic liquids · Electric contact · Friction · Contact resistance · Electrical power consumption

1 Introduction

Nowadays, with the development of electrification engineering, the phenomenon of current-carrying friction has widely appeared in electromechanical devices, such as electrical switches, integrated circuits, high-speed railway system and power transmission system of public tram. It is of practical concern to extend the lifetime of these electrical facilities. Though the metal-based self-lubricating materials are widely used in the case of electrical contact friction, the problems of the high friction coefficient and severe wear still exist [1–3]. Meanwhile, the arc erosions, which always tie with the electrical friction process, will further accelerate the failure of the friction pairs.

Lubrication reduces both friction and wear. Different from traditional working condition, there are specific requirements for the lubricants under the condition of electric contact. Besides the lubricity, the conductivity of the lubricant is one of the important. Although the conventional oil and grease can act to prevent direct contact between surfaces in relative mutual motion and thus reduce both the friction force and surface wear, the insulation characteristic may, no doubt, increase the contact resistance and the power consumption as well. Therefore, it is of a great challenge to seek a proper lubrication media with both excellent lubricity and conductivity for current-carrying circumstances.

Ionic liquids (ILs) are molten salts at relatively low temperature (below 100 °C) [4]. They possess a combination of unique characteristics, including negligible volatility, non-flammability, high thermal stability, low melting point, and these properties are highly desirable in lubrication [5, 6]. The application of ILs as lubricants in a diverse range of systems has found that these materials can show remarkable protection against wear and significantly reduce friction in the neat state [7]. In addition to the aforementioned properties, the ionic conductivity is also another important feature for ILs since they are salts formed by a weakly coordination anion and an organic cation. Several studies have shown that lubricity of the confined ILs was markedly affected by the application of external electric field (EEF) [8–10] and the reason is

✉ Wei Huang
huangwei@nuaa.edu.cn

[1] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Yudao street 29#, Nanjing 210016, China

attributed to the EEF-dependent composition of confined ion layers between the two surfaces.

A series of questions then arise: Can excellent lubricating behavior of ILs be achieved in the case of electrical contact friction? How about the relationship between the lubricity and the current intensity, and what is the difference of the electrical power consumption during the friction process with the lubrication of ILs and dry friction? Till now, there is little knowledge about this. In this paper, compared with dry friction condition, special attention was paid on the lubrication properties of ILs under electric contact. The efficiency of electrical power transmission was also taken into account.

2 Experimental Details

To evaluate the lubrication performances of ILs crossed by an electrical current, a reciprocating sliding tribometer (Sinto Scientific, Japan) was used. The tribopairs contain a commercial bearing ball of 10 mm in diameter and a reciprocating disk, which are both made of 304 stainless steel in consideration of its good corrosion resistance. The tests were conducted at a reciprocating frequency of 0.83 Hz and a stroke of 5 mm (average speed of 8.325 mm/s). Two normal loads of 1 and 5 N were used, corresponding to the initial Hertzian contact pressure of 454 and 776 MPa. In order to form a current circuit in the test system, a DC power supply was used and its one pole was kept in contact with the bearing ball and the other was fixed at the disk. The constant current ranging from 0 to 4 A was applied crossing the ILs lubrication film. A digital voltmeter was imposed between the ball and disk (see Fig. 1 inset), and the voltage data were recorded automatically during the whole test process. Thus, the variation of the "dynamic contact resistance" of the whole circuit (ball, ILs film and disk) can be predicted according to Ohm's law. And all the resistances measured in this paper contain the total value of the entire circuit.

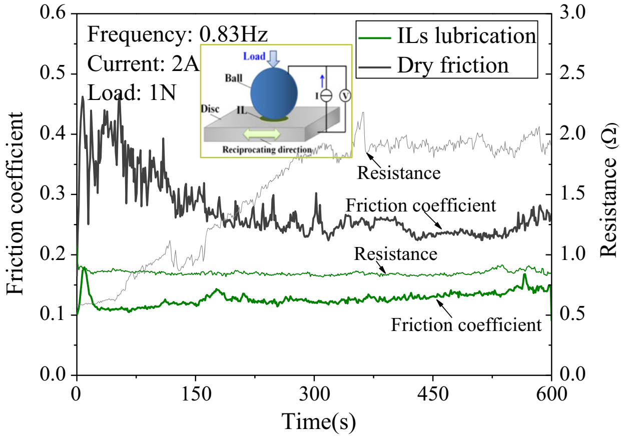

Fig. 1 Variations of friction coefficients and contact resistances with/without ILs lubrication at load of 1 N and current of 2 A (*inset* is the sketch of the reciprocating sliding tester)

Here, the ILs of 1-ethyl-3-methylimidazolium tetrafluoroborate (purity: 99.9%, viscosity: 41 MPa s, conductivity: 1.4 S/m and electrochemical window: 4.3 V) was chosen due to its high thermal stability and hydrophilic properties [11]. To avoid the decomposition, even at the highest current of 4 A, the voltage imposed across the ILs is about 0.5 V, which is much less than its electrochemical window. Before running the experiments, the specimens were cleaned with ethanol and acetone. The ILs were dried under vacuum ($<10^{-1}$ Pa) at 60 °C for 1 day. Each time, lubricant (8 μL) was placed between the ball and the disk, and the whole experiments were conducted at a temperature of 25 ± 2 °C.

3 Results

Figure 1 illustrates the typical evolution of friction coefficients lubricated with/without ILs at low load of 1 N and a current of 2 A. The corresponding variations of the contact resistance during the friction process are also shown in Fig. 1. It can be seen that a high friction coefficient of about 0.4 appeared at the beginning of the dry friction condition and it decreased gradually and remained relative stable at the value of 0.25 after a 300 s running-in process. On the contrary, the resistance increased continually in the primary stage and it maintained smoothly at the value of 1.8 Ω. However, the coefficient curve looks much smooth during the whole test process when lubricated with ILs. What is important is that no resistance increment is found and the finial resistance decreases 62% compared with dry friction condition.

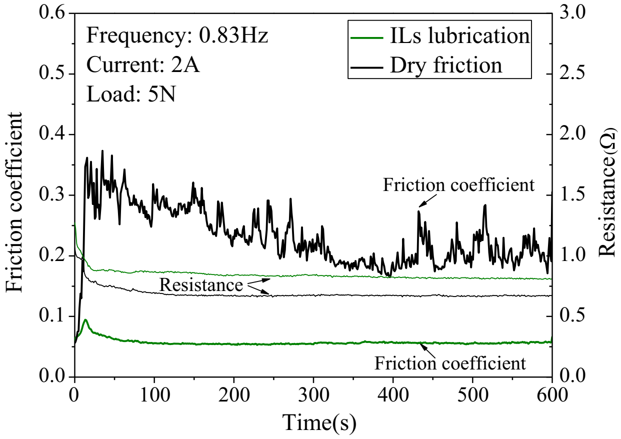

Fig. 2 Variations of friction coefficients and contact resistances with/without ILs lubrication at load of 5 N and current of 2 A

Figure 2 shows the evolution of friction coefficients and corresponding contact resistances lubricated with/without ILs at high load of 5 N. Compared with the 1 N condition, both of the friction coefficients present no obvious changes. However, the contact resistance at dry friction is going smoothly in general. In addition, the resistance under ILs lubrication is a little higher than that of the dry friction, which is different from the low-load condition (see Fig. 1).

Figure 3 presents the images of different interfacial phenomena at the load of 1 N during the friction process. As can be seen, the harsh light of the electric arc emerged under the dry friction condition and the electric arc disappeared when lubricated with ILs. At the higher load of 5 N, no arc was observed whether lubricated with ILs or not.

Figure 4 shows the SEM of the corresponding worn surfaces under dry and ILs lubrication conditions. As shown in Fig. 4a and b, the worn surfaces under dry friction are characterized by severe adhesion and plastic deformation. And the wear is even more serious at the low load of 1 N condition. Adhesion wears at dry frictions can be further verified by the images of the 3D morphologies (Fig. 4e, f). In addition, the wear scar becomes wider at the high load of 5 N. When lubricated with ILs, the wear scar narrows down obviously and no adhesive wear is found. The worn surfaces are quite smooth with narrow scratch lines parallel to the sliding direction (Fig. 4c, d). Meanwhile, according to the 3D images, the wear depth also increased with the increasing normal load. Based on the above comparison, it can be deduced that the tribopairs lubricated with ILs experienced a mild wear.

To have a clear picture on the influence of current, experiments at different current intensities were carried out at the load of 1 N since the electrical sliding friction lubricated with ILs under the low load presented significant superiorities, including the friction and contact resistance reduction. As shown in Fig. 5, the current-dependent behaviors confirm that the current intensity systematically affects the friction coefficient and resistance at both the dry and ILs-lubricated states. In the dry friction, the average coefficient is about 0.3 in the early stages. It decreased gradually and trended to be stable after applying a current of 2 A. With the increment in currents, the coefficient rose continuously as time went by and then reached a steady state again when revoking the current. For ILs lubrication, the initial coefficient is about 0.1, which is much less than the dry friction condition. And it increased ladder like with the corresponding increment in current intensities. As the current changed from 2 to 4 A, a significantly increase in coefficient appeared. While the finial coefficient reduced rapidly to the initial value at the moment the current returned to 0 A. Compared with friction coefficient, the resistances show an opposite trend with the enhancement of currents. At dry friction condition, the resistance dropped considerably from 3 Ω at the current of 1 A to 1Ω for the current of 4 A. With the increase in current, only a small variation of 0.3 Ω emerged for ILs lubrication.

Figure 6 presents the electrical power consumption of the entire circuit with/without ILs lubrication under three applied currents. It can be found that the electrical power consumptions at the two conditions both increase with the increment in currents. But the important thing is that the loss of electrical power under ILs lubrication is much smaller than that of the dry friction at the same value of current. Comparison with dry friction, the relative reductions in electrical power consumption under ILs lubrication reach to 40% at 1 A and to 80% at 4 A, which means that the reduction in electrical power consumption by ILs works much better at low-current situation. The result shows that at the low-load conditions, compared with dry friction, using ILs in the relatively moving parts of the electric contact system can effectively reduce electrical power consumption and then improve transfer efficiency.

4 Discussion

Electrical sliding friction is a common phenomenon in the conductive parts of electrical equipments, and the wear of the sliding pairs is the inter-superposition of mechanical

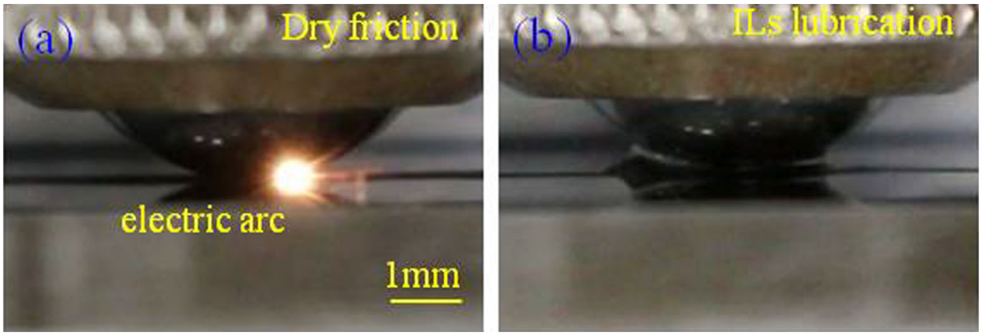

Fig. 3 Friction phenomena under dry and ILs lubrication conditions at the load of 1 N and current of 2 A

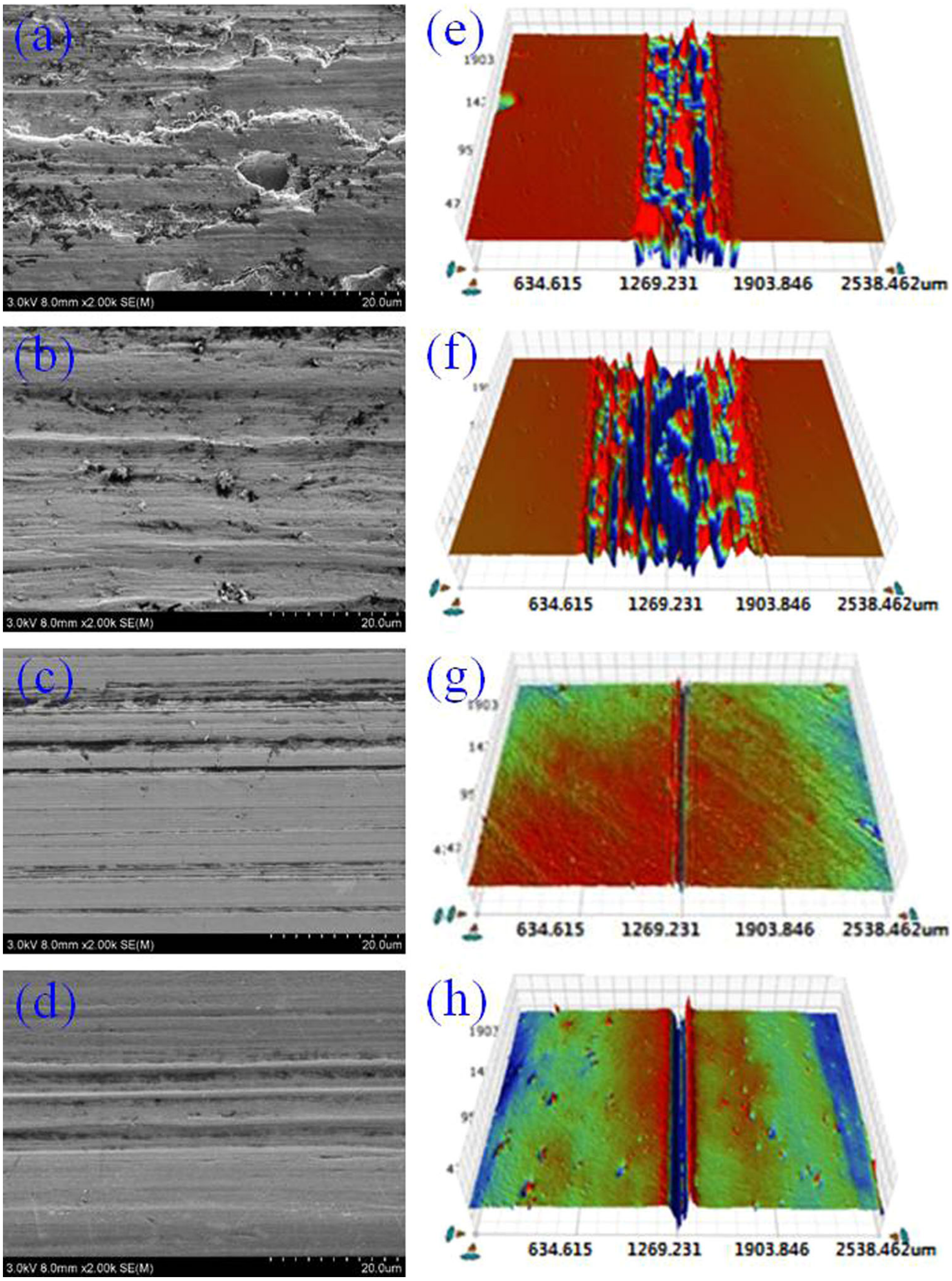

Fig. 4 SEM and 3D morphologies of wear tracks on disk: **a** and **e** dry friction at 1 N; **b** and **f** dry friction at 5 N; **c** and **g** lubricated with ILs at 1 N; **d** and **h** lubricated with ILs at 5 N

and electrical wear. How to extend the service life of the electrical facilities during the friction process is the crux of the matter. As shown in Fig. 1, the friction coefficient at the load of 1 N is much higher associated with electric arc discharge (see Fig. 3a), which is attributed to the poor contact and electrical breakdown [12]. Severe wear can be found on the disk surface (see Fig. 4a, e), and the wear mechanisms are mainly adhesive wear with arc erosion. According to Fig. 1, the mechanical energy consumed by friction (about 1–2 mW) is three orders of magnitude lower than that of the electrical power consumption. It means that the mechanical energy consumption plays no role in this experiment for heating in comparison with electrical energy consumption. Therefore, on the one hand, the Joule and arc in the contact area generated by electrical power consumption may lead to the material soften, which could be the dominated reason. On the other side, the accumulated thermal energy results in the fusion and gasification, which cause erosion pits and massive spalling on the worn surface [13]. The corresponding resistance increased gradually as shown in Fig. 1. It is known that the applied current went through the

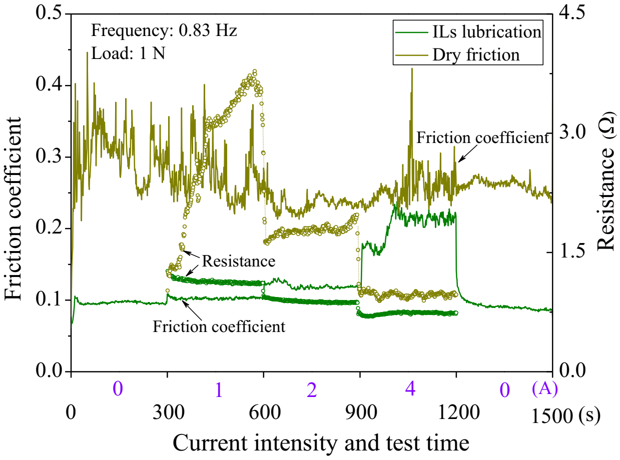

Fig. 5 Effect of current on the friction behavior and resistance with/without ILs lubrication (the current was changed every 300 s)

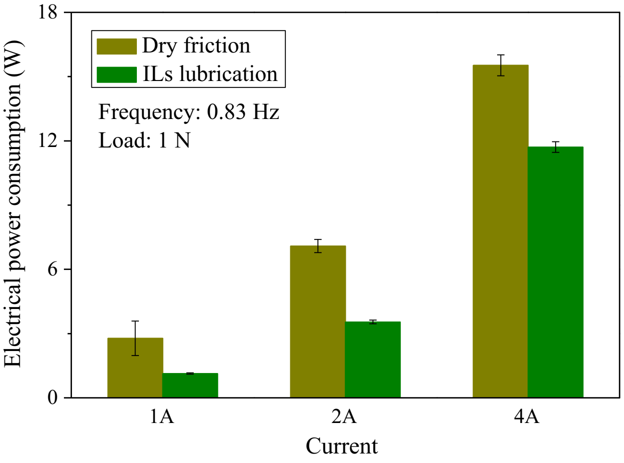

Fig. 6 Variations of electrical power consumption with/without ILs lubrication at different current conditions

friction pairs merely by the asperity microcontacts and the electrical contact area is only a very small portion of the nominal contact area. Therefore, the resistance rose greatly. In addition, due to the heat of arc discharge, the formation of metallic oxide film on the rubbing surfaces could lead to the higher resistance. After the running-in process, the friction tends to be stable, and the resistance becomes flatten. When the load increased to 5 N, the tribopairs maintain good contact, resulting in the stable contact resistance (see Fig. 2). Although the adhesion wear also appeared (see Fig. 4b, f), the wear degree has receded since no arc erosive happened.

Better lubricating behaviors were found under electric contact when lubricated with ILs (see Figs. 1, 2). For their unique dipolar structure, ILs can be easily adsorbed on the sliding surface, forming an effective boundary film to reduce friction and wear [14]. Meanwhile, no arc discharge occurred, which further confirmed the good contact state. As shown in Fig. 4c, d, g and h, the contact surfaces experience a mild wear and the existence of ILs effectively suppresses surface oxidation, which could be the main reason for the stable resistance. Besides, different from conventional oils that are electrically insulating, ILs can minimize and smooth the contact resistance between sliding surfaces because they are electrically conducting [12]. Due to the poor contact between the tribopairs at the low load of 1 N, the existence of ILs helps to improve the conductivity to achieve stable resistance, while for the high-load condition (see Fig. 2), the contact resistance in dry friction decreased compared with ILs lubrication. Since the electrical conductivity of ILs is much lower than that of the metal, the boundary film of ILs may increase the contact resistance under the good contact state between tribopairs.

The current intensity strongly affects the tribological performances at dry friction (see Fig. 5). Under the lower current of 1 A, for the corresponding current density in the contact center is much low and the effect of heat is weak. Therefore, the coefficients of dry friction presented no obvious change (see Fig. 5). However, the coefficient decreased obviously when the current of 2 A was applied. The reason could be attributed to an oxidation layer caused by arc discharge heat on the sliding surfaces [15, 16]. When the current intensity reached to 4 A, the high temperature in the contact areas could not be ignored, resulting in serious arc erosion and adhesive wear. On one side, the high temperature accelerates surface oxidation, which is possible to cause high contact resistance. However, either higher contact resistance or current may lead to the higher temperatures, so that the insulating layer decomposes or moves away during the sliding process. On the other side, high temperature can lead to metal soften and expansion, which may enlarge the real contact area of the couples [17]. As a consequence, the contact resistance decreases.

The current intensity may also have an impact on the structure of the boundary ILs film, which changes the contact mechanism of the tribopairs (see Fig. 7). It is known that the current has a tendency to breakdown the

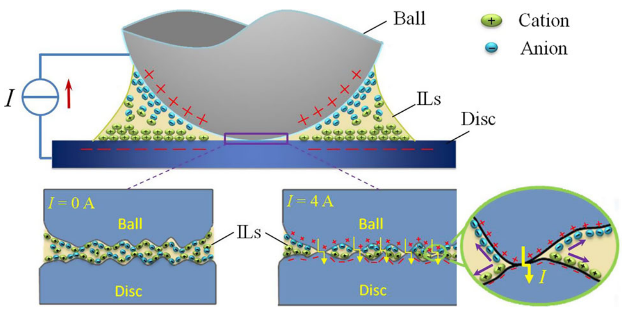

Fig. 7 Schematic of the ILs lubrication with/without an electric contact

lubrication film, which may lead to the asperity micro-contacts [17]. As the current improves, the adsorption layer of ions will first be driven away from the higher current areas (see Fig. 7, $I = 4$ A). Thus, the direct contacts between tribopairs increase, which results in the lower contact resistance. Besides the resistance, the growing contacts are also reflected in friction process. As shown in Fig. 5, the friction coefficients presented a step-like jump with the varied currents, which may be attributed to the soaring elastic–plastic deformations of the contact area. When switching off the current, the boundary film of the ions absorbing between tribopairs is reconstructed and the coefficients return to the initial one again, which further confirms the current effect.

Compared with dry friction, ILs lubrication yields a significant effect on electrical power consumption (see Fig. 6). The reasons can be divided into two aspects. First, in the absence of ILs, the heat sources caused by resistance as well as electric arc are the main factors of the high power loss. And the electrical power loss will rise with the increasing applied currents. Excellent lubrication performance of ILs deeply decreased electrical power consumption during the friction process, and the disappeared electric arc and mild wear are both the most favorable evidences (see Fig. 3, Fig. 4). For another, due to its electrical conductivity, ILs may effectively enlarge the area of contact regimes, which means that a smaller contact resistance will be produced. Thus, the total electrical power consumed by the resistance of the whole circuit declined.

5 Conclusion

The lubrication performances of ILs under electric contact have been investigated by using a reciprocating sliding tribometer. Experimental results indicate that, compared with dry friction, ILs have an excellent lubricating performance under both low- and high-load conditions. It is also found that, with a small load of 1 N, the contact resistance as well as electrical power consumption in the circuit drops to different extents. Besides, the lubricity of ILs is closely related to the current intensity and the stronger current intensity results in the higher friction coefficient and the lower contact resistance. It is supposed that the breakdown of the absorbed ion layers near the electrified contact interface could be the main reason.

Acknowledgements The authors are grateful for the support provided by the National Natural Science Foundation of China (No. 51475241).

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