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Lubrication Performance and Mechanism of Electrostatically Charged Alcohol Aqueous Solvents with Aluminum–Steel Contact

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Abstract: Alcohol aqueous solvents were prepared by individually adding n-propanol, isopropanol, 1,2-propanediol, and glycerol to deionized water for use as lubricants for the electrostatic minimum quantity lubrication (EMQL) machining of aluminum alloys. The tribological characteristics of those formulated alcohol solvents under EMQL were assessed using a four-ball configuration with an aluminum–steel contact, and their static chemisorption on the aluminum surfaces was investigated. It was found that the negatively charged alcohol lubricants (with charging voltages of -5 kV) resulted in 31% and 15% reductions in the coefficient of friction (COF) and wear scar diameter (WSD), respectively, in comparison with those generated using neutral alcohol lubricants. During the EMQL, static charges could help dissociate the alcohol molecules, generating more negative ions, which accelerated the chemisorption of those alcohol molecules on the aluminum surfaces and thereby yielded a relatively homogeneous-reacted film consisting of more carbon and oxygen. This lubricating film improved the interfacial lubrication, thus producing a better tribological performance for the aluminum alloys. The results achieved from this study will offer a new way to develop high-performance lubrication technologies for machining aluminum alloys.

Keywords: alcohols; electrostatic minimum quantity lubrication; aluminum–steel contact; friction and wear

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1. Introduction

Owing to their low density, high specific strength, atmospheric corrosion resistance, and good electrical and thermal conductivity [1,2], aluminum alloys have been widely used in aerospace and automobile manufacturing [3,4]. However, problems such as the sticking phenomenon and built-up edges are prone to occur in the cutting process of the aluminum alloy due to its low hardness and high plasticity, which may negatively affect the machining quality of the workpiece [5]; the transfer of aluminum to steel in the aluminum–steel system is easy to occur in the aluminum–steel system, resulting in various degrees of damage on the surface of the aluminum parts, and even serious failure of the friction pair [6,7]. Therefore, in order to meet the requirements of the machining precision of aluminum parts and address the problems of quick-wear and the difficult lubrication of the aluminum–steel contact, it is crucial to realize the high-efficiency lubrication of aluminum alloys.

In the study of aluminum alloy lubrication, alcohols are well-known as highly effective anti-friction and anti-wear additives [8,9]. Montgomery [10] and Hironaka [11] studied the wear behavior of an aluminum–steel system under boundary lubrication conditions. It was discovered that functional groups, such as the hydroxyl groups in the alcohol compounds, can react with the aluminum surface to produce amorphous substances (aluminum complexes or salts), which may form sufficient adsorption films. Hotten [12] and Wan et al. [13] found that diol compounds are efficient boundary lubricants, which may react with the aluminum to form five- or six-element complexes for lubrication, and they also pointed out that the molecular structure has an important influence on the lubrication. Hu et al. [9,14] investigated the lubrication performance of a series of alcohols. The results showed that alcohols can significantly improve the lubrication state of the aluminum surface, whether it is a long chain or a short chain. The generation of an organic aluminum alkoxide on the aluminum alloy surface to produce continuous boundary films serves as the lubrication mechanism, thus lessening or avoiding wear. Its anti-wear ability and load-carrying capacity were affected by the chain length, hydroxyl number, and concentration.

Kajdas proposed the negative-ion-radical mechanism (NIRAM) based on the theory of exoelectron emission to explain the lubrication mechanism of alcohols during friction [15,16], and this hypothesis was subsequently supported by much research [17–19]. They believed that the tribochemical reaction between the alcohols and aluminum was primarily initiated by electrons. During the friction, the electrons emitted from the aluminum surface cause the dissociation of the alcohol molecules to form negative ions and free radicals and, finally, form an anti-friction and anti-wear protective layer on the metal surface. Inspired by the NIRAM, we assumed that when the lubricating fluids are charged by an external electric field, a large number of electrons will play a facilitating role in generating more negative ions or free radicals and enhancing the film-forming chemical reaction at the friction interface.

Electrostatic minimum quantity lubrication (EMQL) uses a high-voltage electrostatic electrode to contact-charge lubricants and produces charged mists under compressed air that are sprayed into the machining area for lubrication and cooling. The research showed that [20,21] the lubricant droplets carry electrostatic charges as the atomization of the charged lubricant, and their charge-to-mass ratio [22] sharply rises with the increase of the charging voltage's absolute value; the particle size of the lubricating oil droplets decreased and was more uniformly distributed after the charging. The wettability, penetration, and deposition of the lubricant were all optimized. This technology has demonstrated excellent lubrication performance in the cutting of difficult-to-machine materials, such as stainless steel and titanium alloy [23,24], compared to the conventional minimum quantity lubrication (MQL). Previous research mainly focused on the analysis of the changes in the physical properties of the droplets after charging, but the impacts of the electrostatic interaction on the interfacial chemical reactions were rarely involved.

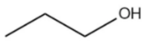
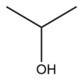
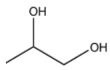
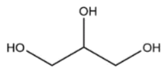
In this study, four short-chain alcohols were selected as lubricants, and the lubricants were contact-charged by high-voltage electrodes (EMQL was used as the charging method). Firstly, the tribological properties of the charged alcohols in the aluminum–steel system were investigated. Secondly, the impacts of the various molecular structures on the friction-reduction and wear-resistance properties were explored by evaluating the lubricating performance of the four alcohols and the corrosion tendency of the aluminum in different alcohol solutions. Finally, the lubrication mechanism of the charged alcohols was analyzed through the static reaction experiment of the alcohol with the aluminum, in combination with the surface morphology and element distribution of the aluminum ball-wear scar after the friction. To improve the machining performance and lubrication efficiency of aluminum alloys, the study findings may be applied in these fields.

2. Materials and Methods

2.1. Preparation of the Lubricants

Four analytically pure alcohols were chosen: n-propanol, isopropanol, 1,2-propanediol, and glycerol (purchased from Sinopharm Chemical Reagent Co., Ltd., Shanghai, China). The properties of the alcohols are shown in Table 1. The effect of the hydroxyl position on the friction and wear of the aluminum was studied by n-propanol and isopropanol, and the effect of the hydroxyl number was studied by n-propanol/isopropanol, 1,2-propanediol, and glycerol. Alcohols must be diluted with neutral solvents to lessen their reactivity since they easily corrode aluminum substrates [25,26]. The final alcohol lubricants were formulated at a volume concentration of 25% (25% alcohol and 75% deionized water).

Table 1. Properties of alcohols.

Alcohol	Formula	Molecular Mass	Boiling Point (°C)	Viscosity at 20 °C (mPa·s)
n-Propanol		60.1	97	2.256
Isopropanol		60.1	83	2.038
1,2-Propanediol		76.1	195	60.5
Glycerol		92.1	290	1412

2.2. Tribological Testing

The four-ball friction tests were conducted by an MMW-1 multi-specimen test system (Jinan Shijin Group Co., Ltd., Jinan, China). The upper friction pair consisted of a GCr15 steel ball, and the lower friction pair were three 1060 aluminum balls (the diameters were all 12.7 mm). The friction tester was grounded (as shown in Figure 1). The test conditions were as follows: loads of 12, 24, and 49 N; rotational speeds of 50, 150, and 250 r/min; the EMQL system was used for drip lubrication (air pressure: 0 MPa, flow rate: 20 mL/h, and the charging voltage, −5 kV); the test time was 20 min. The friction coefficient was recorded by the computer in real-time, and three parallel tests were conducted for each group. After the test, the test balls were removed and ultrasonically cleaned with petroleum ether for 10 min, and the wear scar diameters of the aluminum balls under various lubrication conditions were measured with a VW-6000 optical microscope (Keyence, Osaka, Japan). SEM and EDS (EVO18, Zeiss, Oberkochen, Germany) were used to observe and analyze the morphology and elemental composition of the worn surfaces of the aluminum balls.

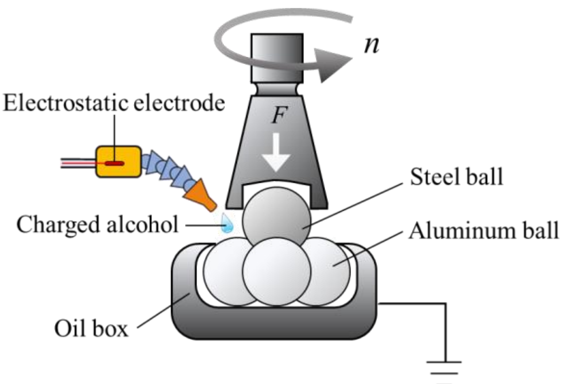


Figure 1. Schematic of the four-ball test.

2.3. Static Reaction Experiment

The static reaction tests of the aluminum plates and alcohols were carried out. The test device is shown in Figure 2. We selected 1060 aluminum plates (10 mm × 10 mm × 1 mm), and the alcohol solutions were n-propanol, isopropanol, 1,2-propanediol, and glycerol aqueous solutions, with a volume concentration of 25%. The aluminum plate was heated by an oil bath at 25 °C, 75 °C, or 140 °C for 30 min. The alcohol solutions were dropped on the surface of the aluminum plate by EMQL, with a flow rate of 20 mL/h and charging voltages of 0 kV and −5 kV. The surfaces of the aluminum plates were polished to mirrors before the experiment. After the experiment, the aluminum plates were ultrasonically cleaned in anhydrous ethanol for 10 min to remove the residual of the physical adsorption solution. SEM/EDS (EVO18, Zeiss, Oberkochen, Germany) was used to observe and analyze the morphology and element content of the reaction film on the aluminum plate surface.

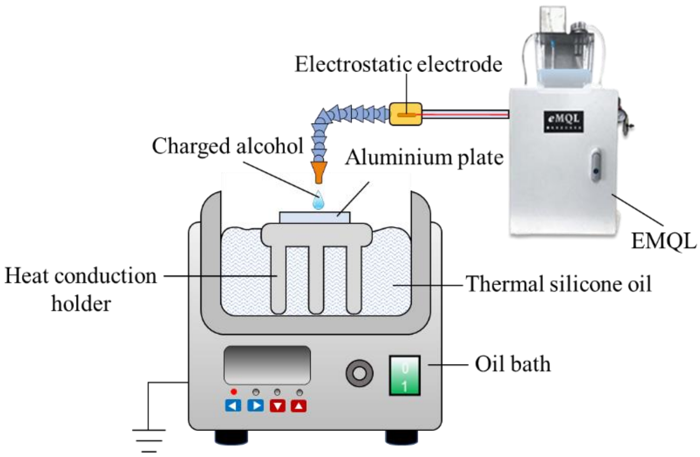


Figure 2. Diagram of static reaction device.

2.4. Electrochemical Polarization Test

A CH1760E electrochemical workstation (Shanghai Chenhua Instrument Co., Ltd., Shanghai, China) was used for the electrochemical polarization test (Figure 3). It consisted of a three-electrodes system; the working electrode was a 1060 pure aluminum plate (Φ 14 mm $\times$ 2 mm), the reference electrode was a calomel electrode, and the auxiliary electrode was a platinum electrode. The working electrode was immersed in four kinds of a 25% alcohol solution (n-propanol, isopropanol, 1,2-propanediol, and glycerol), and the self-corrosion potential of the aluminum plate was measured by the Tafel curve. Each test group was divided into three groups, and the average value was taken as the corrosion potential.

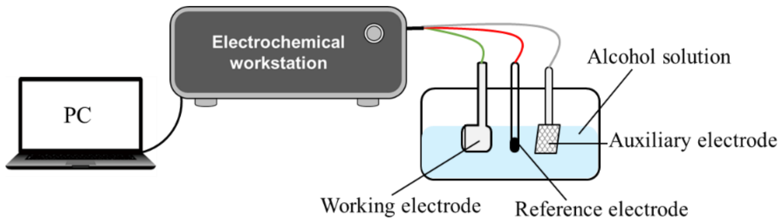


Figure 3. Diagram of electrochemical polarization test.

3. Results and Discussion

3.1. Tribological Performance

3.1.1. Lubrication Performance of Charged Alcohol Lubricants

Figure 4 shows the average COF and WSD as a function of the load under the lubrication conditions of the charged and uncharged four alcohol solutions. It can be seen that the COF and WSD lubricated by the charged four alcohol solutions are lower than those by the uncharged solutions at all loads. The largest reduction among them in the COF is around 31% (glycerol, 49 N), and the highest reduction in the WSD is about 12%, i.e., the wear volume is reduced by nearly 30% (n-propanol, 49 N). According to the findings, charging may effectively enhance the anti-friction and anti-wear properties of alcohol solutions. Since the adsorption capacity of alcohol molecules is enhanced after charging, it is easier to form protective lubricating films on the friction surface, thus avoiding the direct contact of the aluminum–steel friction pair.

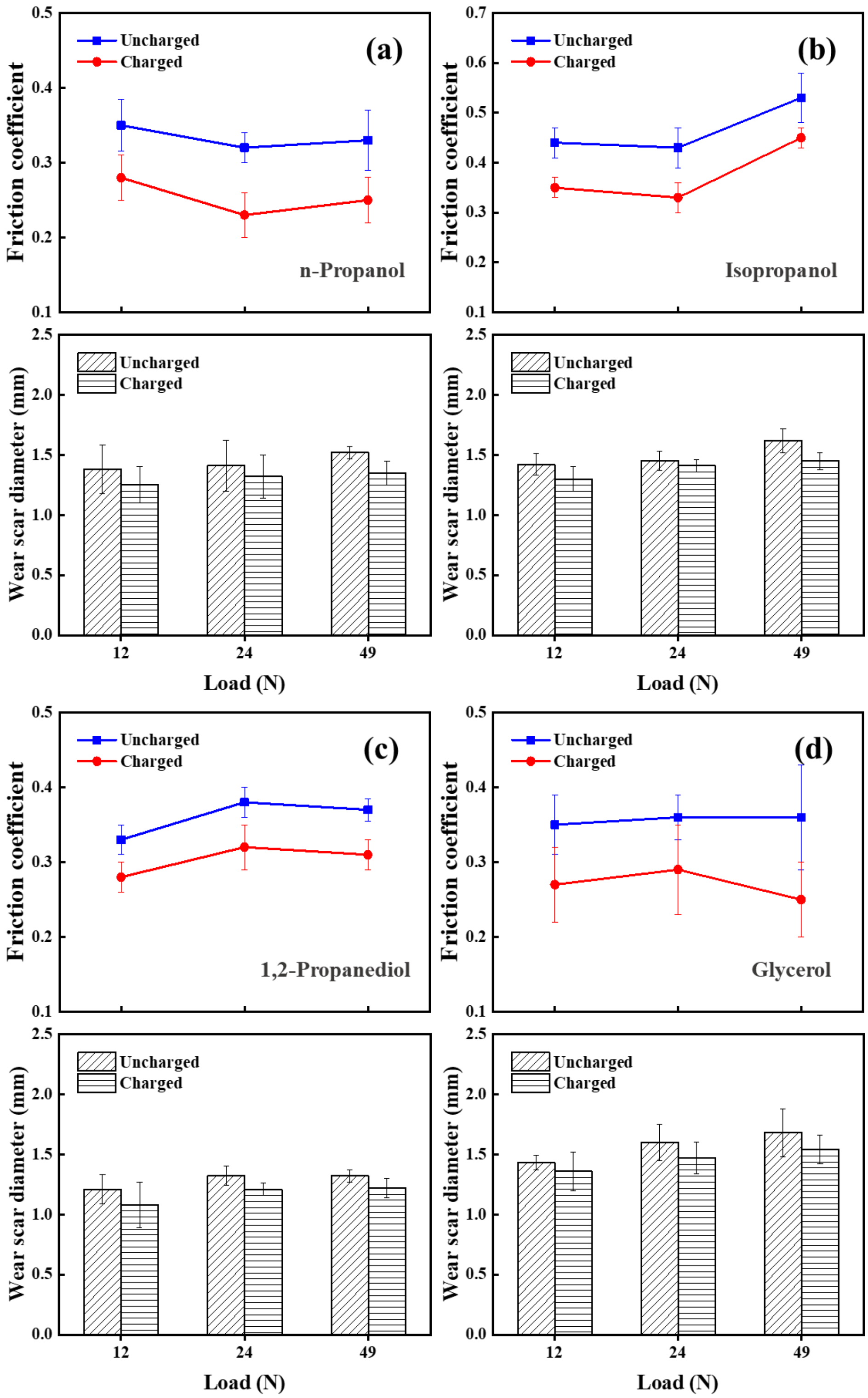


Figure 4. Comparison of the COF and WSD lubricated by charged and uncharged (**a**) n-propanol, (**b**) isopropanol, (**c**) 1,2-propanediol, and (**d**) glycerol under different loads (rotational speed: 150 r/min).

The average COF and WSD lubricated by the four alcohols, both charged and uncharged, at different rotational speeds are shown in Figure 5. The charged alcohol solutions exhibit good tribological properties at various rotational speeds. Among them, when the rotational speed is 150 r/min, the COF of the charged glycerol decreases by approximately 30%, and when the rotational speed is 50 r/min, the WSD of 1,2-propanediol reduces by about 15%, i.e., the wear volume decreases by nearly 36%. This demonstrates that when four kinds of alcohol solutions are charged, the lubrication performances of the aluminum–steel friction pair are improved.

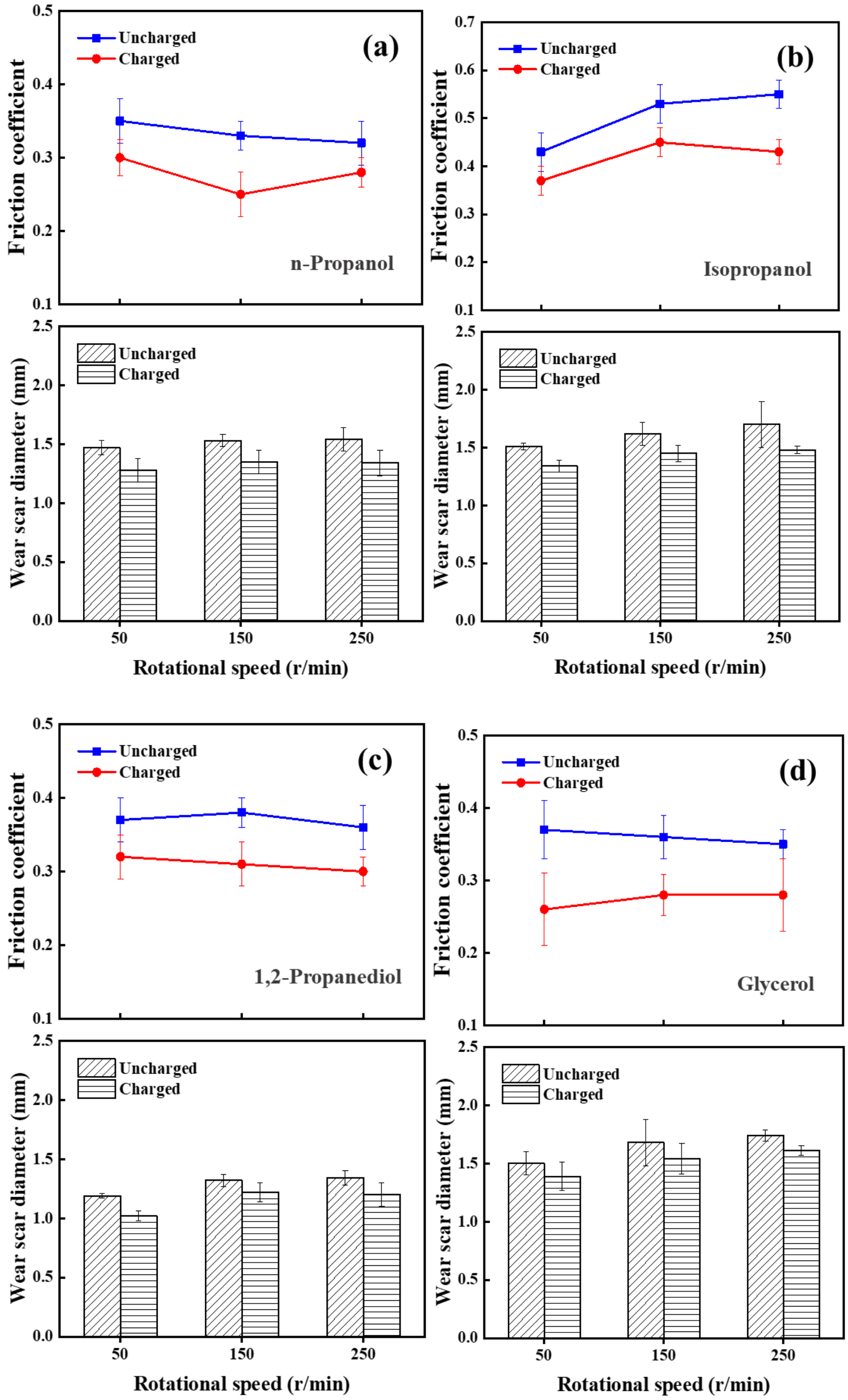


Figure 5. Comparison of the COF and WSD lubricated by charged and uncharged (**a**) n-propanol, (**b**) isopropanol, (**c**) 1,2-propanediol, and (**d**) glycerol under different rotational speeds (load: 49 N).

3.1.2. Comparison of Four Alcohols' Lubrication Performance

Figure 6 shows the COF of the aluminum–steel contact lubricated by the four alcohol solutions under different loads and speeds. As can be observed, the order of the COF is:

n-propanol < glycerol < 1,2-propanediol < isopropanol. Among them, isopropanol has the largest COF, with a large gap compared to the other three alcohols. Although the average COF of the glycerol solution is small, the real-time COF curve fluctuates considerably (Figure 7), indicating that its lubrication stability is poor.

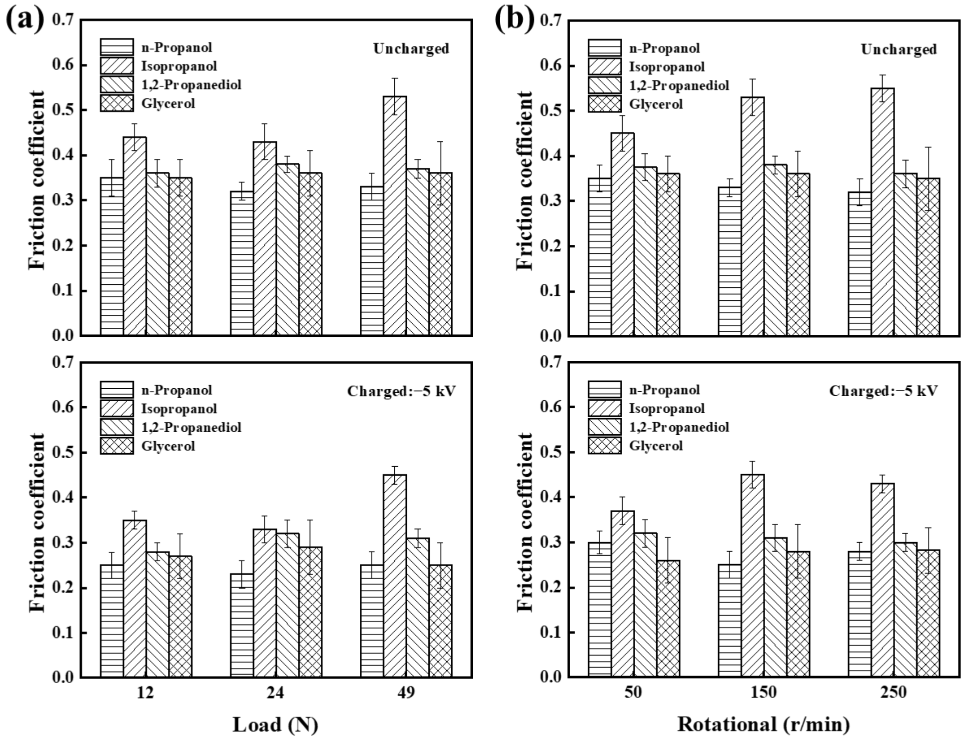


Figure 6. COF lubricated by four alcohol solutions under different (**a**) loads (speed is 150 r/min) and (**b**) rotational speeds (load is 49 N).

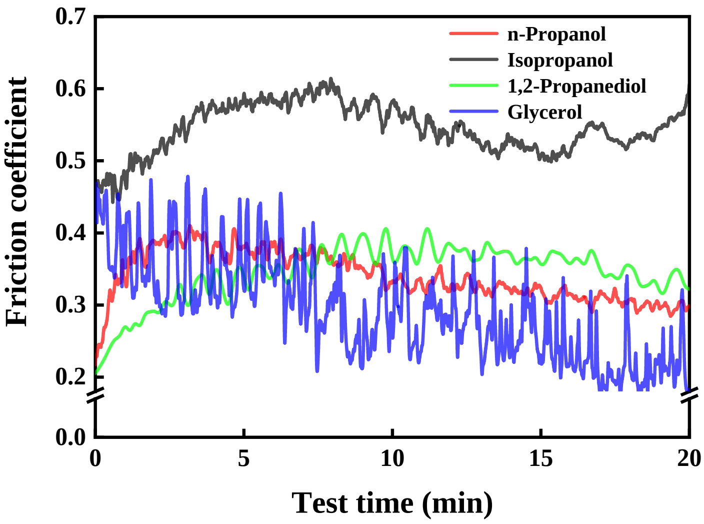


Figure 7. COF curves of aluminum–steel friction pairs with time (uncharged; load: 49 N; rotational speed: 250 r/min).

Figure 8 compares the WSD on the surface of the aluminum balls lubricated by the four alcohol solutions under different loads and rotational speeds. The order of the wear scar diameter is: 1,2-propanediol < n-propanol < isopropanol < glycerol. 1,2-Propanediol has the smallest WSD, which is significantly lower than that of the other alcohols and shows better anti-wear performance. The most severe wear is seen with glycerol, which corresponds to its poor stability. A large amount of flaking debris is generated as a result of the severe wear, causing remarkable fluctuations in the COF [27,28] and worse lubrication performance.

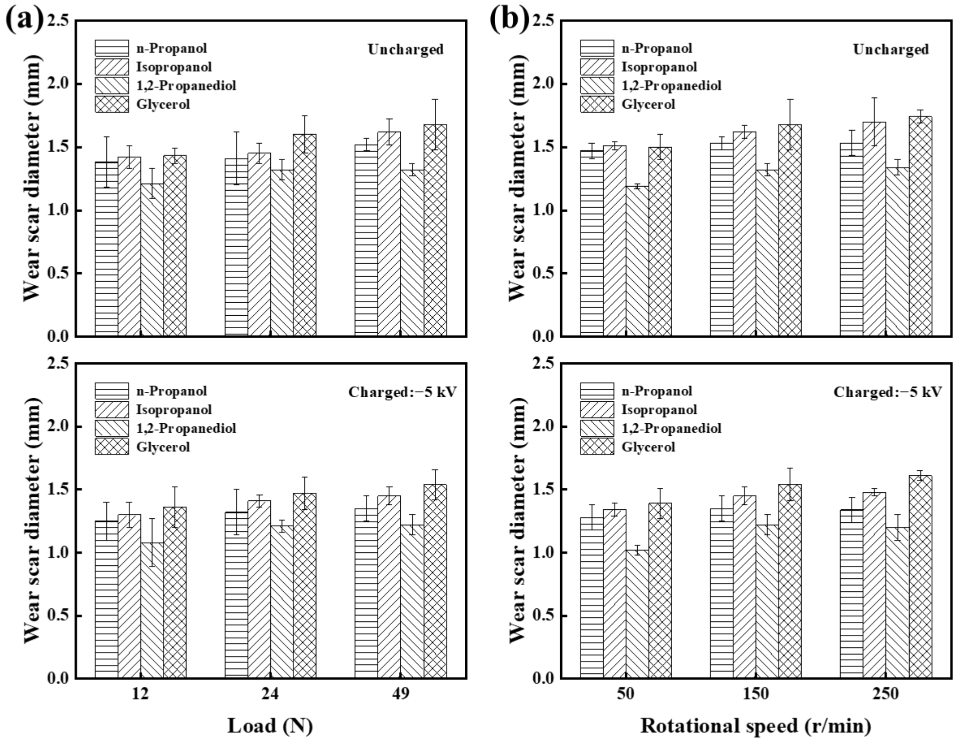


Figure 8. The WSD lubricated by four alcohol solutions under different (**a**) loads (speed is 150 r/min) and (**b**) rotational speeds (load is 49 N).

Glycerol, which has a unique polyhydroxy structure, possesses the strongest adsorption capability among the four alcohols [29]. Theoretically, it can form a more durable chemisorption film with the aluminum surface, which can effectively prevent the transfer and adhesion of the aluminum and shows high anti-wear and bearing performance. Glycerol did not, however, exert excellent lubrication performance in our study. It is speculated that the aluminum matrix may have experienced over-corrosion owing to the higher concentration of the glycerol solution. The self-corrosion potential of the aluminum in the four alcohol solutions was measured to judge the corrosion tendency of the aluminum in different alcohol solutions. As can be seen in Figure 9, glycerol has the largest negative potential values, suggesting that aluminum loses electrons easier, i.e., it is more easily corroded.

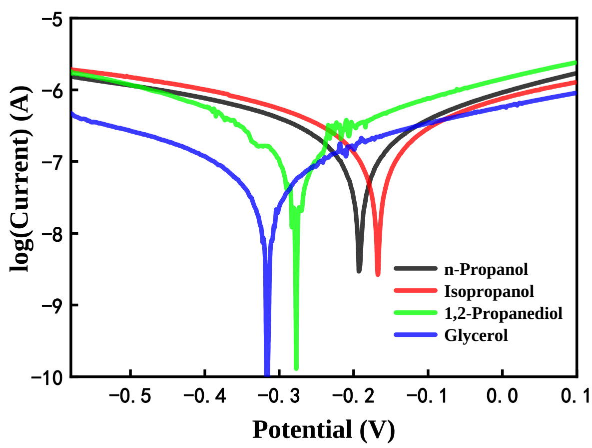


Figure 9. Polarization characteristic curve of aluminum plate in 25% of four alcohol solutions.

The self-corrosion potential of the aluminum plate is −0.251 V when the concentration of glycerol is lowered to 10% (as shown in Figure 10). Compared to a 25% concentration, the corrosion resistance has increased. Additionally, the COF curve fluctuates slightly, and the aluminum ball's WSD decreases by about 19% (Figure 11). The lubrication stability and anti-wear capacity of glycerol increase as its concentration decreases. It is concluded that the over-corrosion of glycerol on the aluminum matrix at a 25% concentration affects its lubrication performance and results in inadequate anti-friction and anti-wear performance.

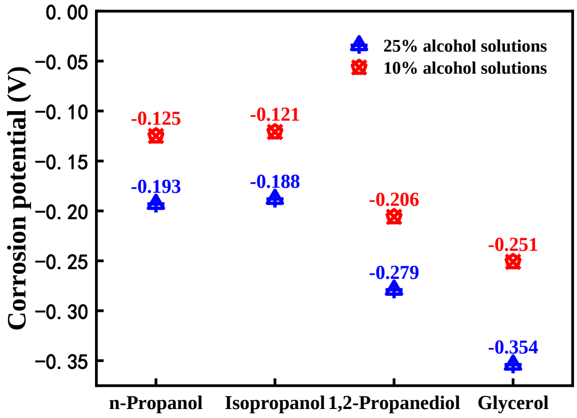


Figure 10. Corrosion potential of aluminum plate in four alcohol solutions.

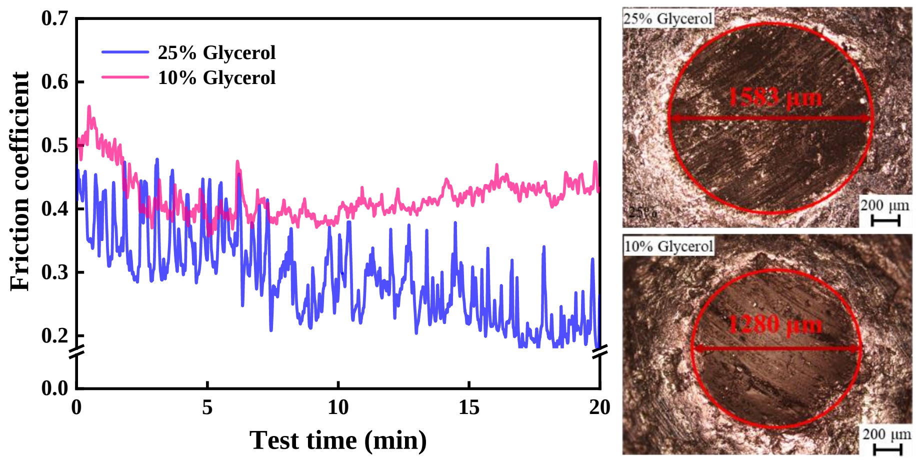
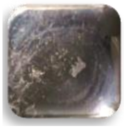
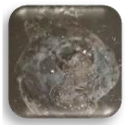


Figure 11. The COF and wear scar morphology under 10% and 25% glycerol lubrication (uncharged; load: 49 N; rotational speed: 250 r/min).

3.2. Static Reaction Experiment Results

Table 2 shows the image of the reaction films on the aluminum plate surface following the static reaction experiment. It can be seen that, at ambient temperature, there is no adsorption film on the aluminum plate surface when the solution is uncharged; the white adsorption films are visible on the local area of the aluminum plate surface after the treatment of the four alcohol solutions with a high voltage electrostatic charge. The SEM morphology and EDS energy spectrum of the reaction film area on the aluminum plate surface after the charged isopropanol treatment were analyzed (as shown in Figure 12). Some deposits may be observed on the aluminum plate surface. C and O elements are present in this substance. So, obviously, charging stimulates the adsorption of the alcohol molecules, which form relatively stable compounds on the aluminum surface.

Table 2. Static reaction films on aluminum plate surface.

	25 °C		75 °C		140 °C	
	Uncharged	**Charged**	**Uncharged**	**Charged**	**Uncharged**	**Charged**
n-Propanol						
Isopropanol						
1,2-Propanediol						
Glycerol						

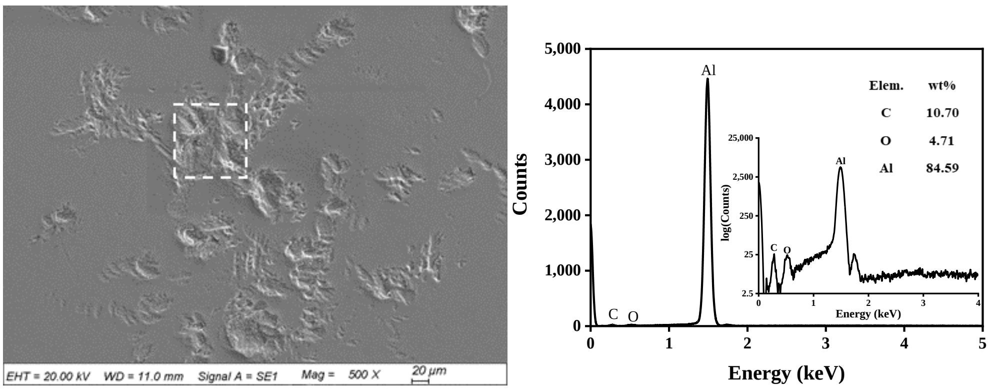


Figure 12. SEM and EDS of the aluminum plate surface after charged isopropanol static reaction (at room temperature: 25 °C).

The surface of the aluminum plate is covered with a film at 75 °C, whether charged or not. However, the surface film is not obvious when glycerol is used, indicating that the chemical interaction between glycerol and aluminum is negligible at 75 °C. When the temperature is raised to 140 °C, a reaction film appears on the aluminum plate surface (Table 2), indicating that glycerol can react with aluminum.

Figure 13 depicts the aluminum plate surface's SEM picture and EDS energy spectrum, detected within the dashed boxed areas after three different types of treatment. Compared with the untreated aluminum plate, the surface of the aluminum plate is covered with a reaction film after the n-propanol static reaction treatment, and the content of the C and O elements rises, suggesting that the reaction film might be an organic film or an oxide film. Meanwhile, the surface film is dense, and the surface scan reveals fewer black holes following the charged n-propanol treatment than in the uncharged, demonstrating a uniform distribution of the C and O elements. The percentages of C and O increase by around 9.8% and 61.9%, respectively, according to energy spectrum analysis. This indicates that the chemical activity of the alcohols can be effectively boosted by charging.

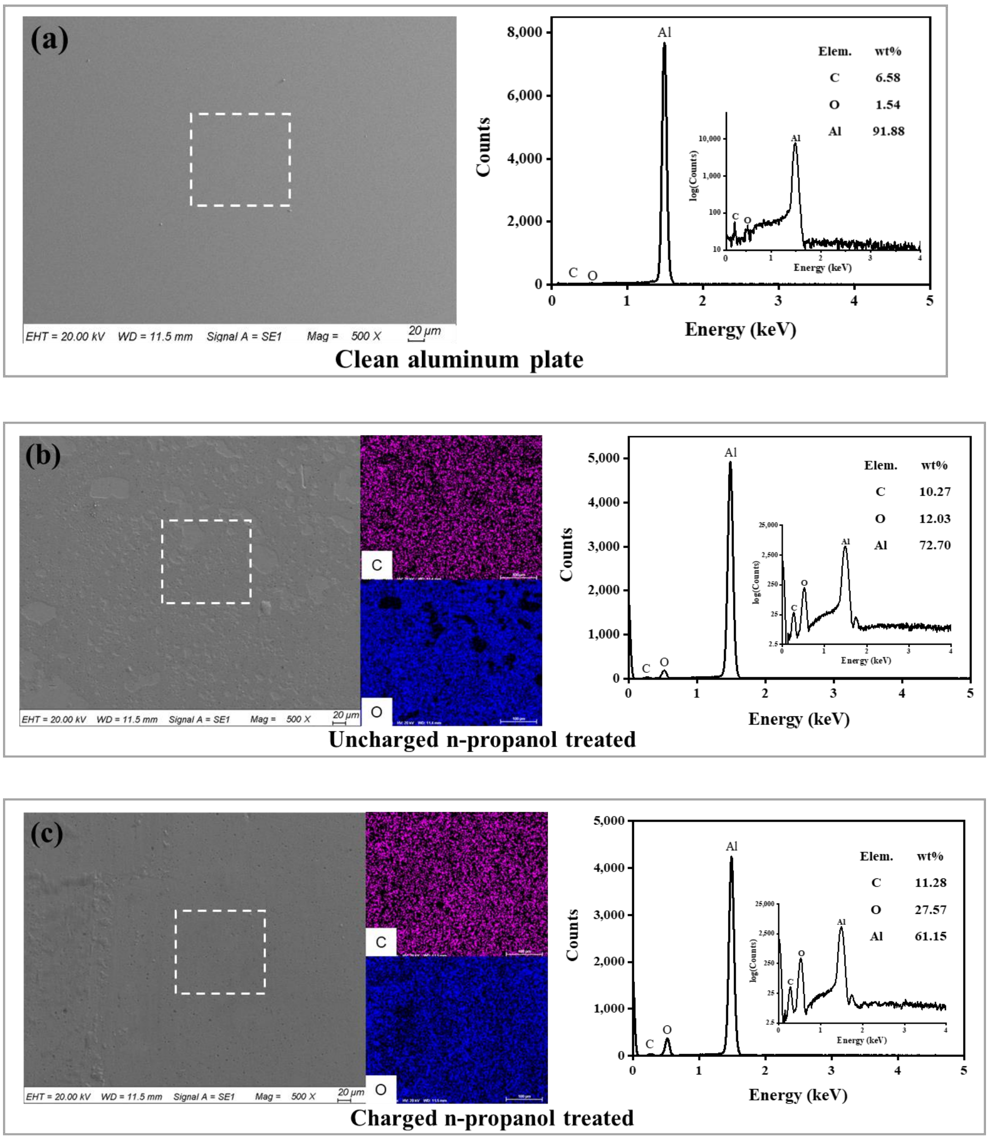


Figure 13. SEM and EDS of aluminum plate surface after (**a**) untreated, (**b**) uncharged n-propanol-treated, and (**c**) charged n-propanol-treated (75 °C heating).

It can be seen from Table 3 that the C and O content all increased after the four alcohol solutions were charged, compared to uncharged, which proves that charging promotes the reactivity between alcohol and aluminum, and thus promotes the formation of a reaction film. In contrast to other alcohols, n-propanol and 1,2-propanediol have higher C and O contents, and the rise in the C and O content is more pronounced after charging, which is consistent with their better anti-friction and anti-wear performance.

Table 3. Element content of aluminum surface after four alcohols' static reaction (75 °C heating).

Alcohols / Content %	n-Propanol		Isopropanol		1,2-Propanediol		Glycerol	
	Uncharged	Charged	Uncharged	Charged	Uncharged	Charged	Uncharged	Charged
C	10.27	11.28	6.13	12.88	11.07	16.28	7.89	15.02
O	17.03	127.57	10.82	9.67	4.28	17.91	2.86	5.89
Al	72.70	61.15	83.05	77.45	84.65	65.81	89.25	79.09

3.3. Lubrication Mechanism of Alcohol with Different Molecular Structures

The four alcohols with different molecular structures exerted different effects on the lubrication of the aluminum, according to the tribological testing and static reaction experiment.

The effect of the molecular structure on the anti-friction properties was analyzed. It showed that a three-layer carbon chain structure is formed when n-propanol adsorbs to the friction surface (Figure 14a). This multi-layer structure may better separate the steel–aluminum friction pair and achieves lower COFs in the four alcohol solutions. 1,2-propanediol possesses a two-layer carbon chain structure, while a five-membered ring structure is stably adsorbed, and the COF is likewise low. Isopropanol has only one hydroxyl group and performs poor adsorption despite forming a two-layer carbon chain structure on the friction surface (Figure 14b). Since the adsorption film is thin, the friction increases.

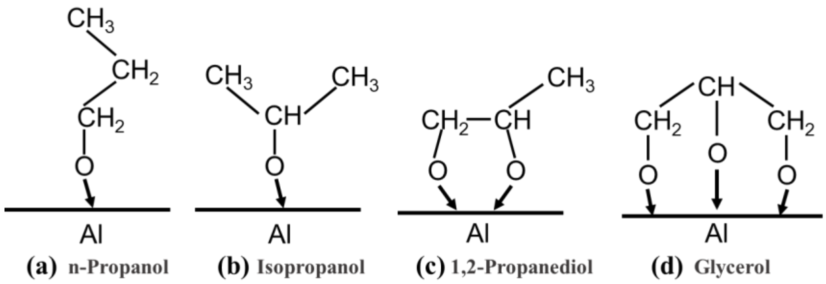


Figure 14. Chemisorption model of alcohols on aluminum surface during friction. (**a**) n-propanol, (**b**) isopropanol, (**c**) 1,2-propanediol, (**d**) glycerol.

By analyzing the influence of the molecular structure on the anti-wear properties, it can be concluded that 1,2-propanediol containing two hydroxyl groups forms a bidentate bond with the aluminum atom on the surface (Figure 14c). The stable five-membered ring structure [12,13] efficiently prevents the transfer of aluminum to steel and provides good anti-wear properties. Although glycerol with three hydroxyl groups might produce stronger adsorption (Figure 14d), Igari et al. [30] found that alcohol with this structure has a great impact on the aluminum wear when hydroxyl groups exist at both ends of the lubricant molecule. Glycerol exhibits the highest amount of wear among the four alcohols, which is attributed to its corrosive wear on the aluminum matrix at high concentrations.

3.4. Lubrication Mechanism of Charged Alcohols

In order to investigate the lubrication mechanism of the charged alcohols, n-propanol and 1,2-propanediol, which exhibit preferable anti-friction and anti-wear properties, were selected for further analysis. The wear scar morphology and the EDS energy spectrum of the aluminum ball surface after tribological tests with n-propanol and 1,2-propanediol lubrication are depicted in Figures 15 and 16. Deposits can be seen on the surface of the wear scar (the darker regions in the figures), demonstrating that the alcohol molecules build a protective film on the aluminum surface through physical and chemical adsorption or a reaction during the friction and have effective lubrication. At the same time, energy spectrum analysis revealed the presence of C and O components in the wear scar, with a very high concentration of O, which indicates that the surface film is dominated by the oxide film. This may be because the organic aluminum compounds are soft, shearable, and generally sacrificial layers [31] produced by the reaction of the alcohol and aluminum. The internal C-O chain is eventually broken by the action of the high shear force, leaving just alumina and its hydrate [32]. This viewpoint can be confirmed by the results of the static reaction experiment (Section 3.2). The surface films produced by the static interaction between the alcohol and aluminum are mostly organic films and oxide films without high shear forces, as shown in Table 2 by the slight differences in the C and O contents of the surface films.

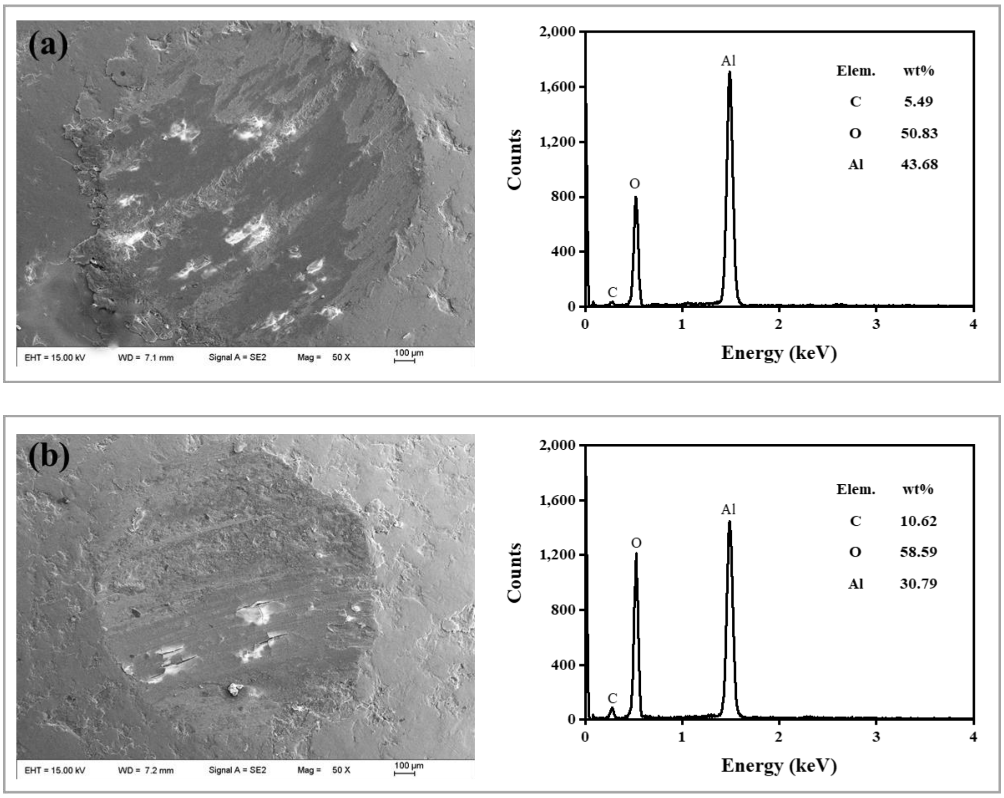


Figure 15. SEM and EDS of aluminum ball surface under (**a**) uncharged n-propanol lubrication and (**b**) charged n-propanol lubrication (load: 49 N; rotational speed: 150 r/min).

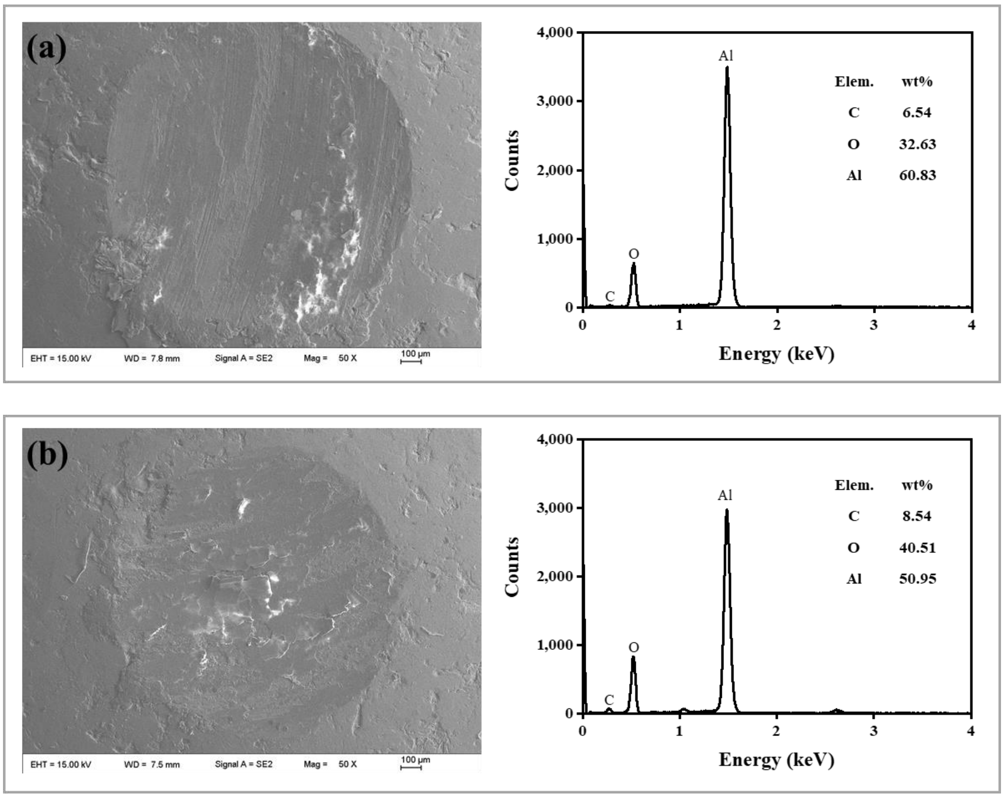


Figure 16. SEM and EDS of aluminum ball surface under (**a**) uncharged 1,2-propanediol lubrication and (**b**) charged 1,2-propanediol lubrication (load: 49 N; rotational speed: 150 r/min).

Comparing the impacts of uncharged and charged on alcohol lubrications, it is discovered that the wear scar is larger, with visible flaking and adhesion, surrounded under uncharged conditions (as illustrated in Figures 15a and 16a), which is mainly adhesive wear. This may be due to the low adsorption strength of the lubricants on the friction surface, which desorbs at a specific temperature [33] and cannot lubricate the surface properly, resulting in direct contact with some surfaces. Furthermore, because aluminum material is relatively soft, friction can cause plastic deformation on its surface. Adhesion points will be formed, accompanied by an instantaneously high temperature. When the alcohol is charged, the wear scar decreases, and its surrounding area becomes smooth and flat, with nearly no adhesion (as shown in Figures 15b and 16b). The energy spectrum shows that the percentages of C and O on the surface rise in comparison to the uncharged (n-propanol: 93.4%, 15.3%; 1,2-propanediol: 30.6%, 24.1%). It indicates that charging improves the lubrication performance of the alcohols. This might be because the reactivity between the alcohol and aluminum is enhanced after charging, and a high-strength chemical reaction film is easier to form on the friction surface. This film plays a sacrificial protective role, effectively preventing direct contact between the metal surfaces and reducing or avoiding the adhesion phenomenon, thereby reducing surface wear.

According to the Hard and Soft Acids and Bases (HSAB) theory [34] and the NIRAM, the reason why alcohols effectively lubricate the aluminum surface is that compounds with polar functional groups (e.g., alcohols) are hard bases, which are simple to adsorb to fresh hard acid surfaces (e.g., aluminum). There are several tribochemical reactions that occur during the friction process [35,36], including surface oxidation, high-energy nascent surface or abrasive particle catalysis [37], exoelectron emission, the oxidation and degradation of lubricating oil molecules, and local temperature rise. Among them, the interaction between the emitted electrons and alcohol molecules induces the dissociation of the alcohol molecules to form negative ions and radicals, which adsorb on the positive charge spots on the surface to produce an organometallic chemisorption film. The dehydrogenation reaction may take place since the C-H chain in alcohol breaks under a variety of catalytic, high-temperature, and oxidation conditions. This may cause intermolecular crosslinking and the formation of a network polymer film to protect the friction surface. If the shear strength is too high, the chemical bonds of organometallic compounds will break, and inorganic films (such as Al_2O_3) will be produced. The protective films will ultimately be destroyed by friction and wear, and then new organic and inorganic films will be produced. It is a dynamic process.

The above process demonstrates that the electron is very important for the reaction between alcohol and aluminum. However, the electron only originated from the friction process when general alcohols were employed as lubricants. The alcohols' lubrication effectiveness may not be completely utilized for aluminum—a material with weak exoelectron emission intensity [38,39]. By introducing electrostatic technology, the alcohol solutions are charged with negative high-voltage static electricity before entering the friction area, and a large number of electrons trigger the dissociation of alcohol molecules to generate negative ions and radicals. Alcohol molecules are, once more, ionized when they come into contact with friction-induced exoelectrons. Then, more negative ions on the aluminum surface will participate in chemical adsorption, thus forming a thicker lubricating film.

The lubrication mechanism of the charged alcohols has been analyzed using n-propanol as an example (Figure 17). Firstly, the alcohol molecules are dissociated to produce negative ions under the action of the electrons induced by charging and friction. Subsequently, the negative ions are chemisorbed to positive charge sites on the aluminum surface, forming an adsorption film. Molecular cross-linking may also take place simultaneously, generating an easily sheared network polymer film that effectively prevents direct contact between the aluminum–steel and lowers the friction. Finally, the C-O bonds break and generate free radicals under the influence of the high shear. The residual O reacts with the Al to create Al_2O_3—a thin, hard, and dense oxide film that provides an anti-wear effect.

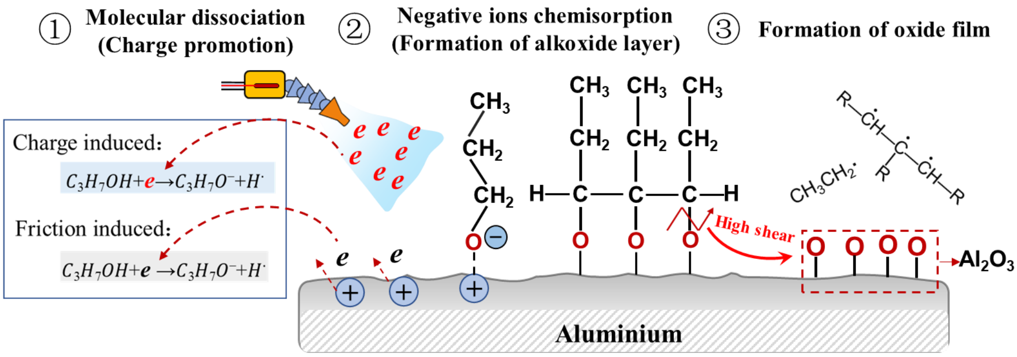


Figure 17. Lubrication model of charged n-propanol.

4. Conclusions

In this paper, the effects of charged alcohol lubricants on the lubrication performance of aluminum and its mechanism were analyzed. Based on the NIRAM, the lubrication characteristics of EMQL technology were studied from the perspective of the chemical reaction film. The following conclusions can be drawn:

(1) Compared with the uncharged case, the COF of the charged four alcohols decreased by about 31% at the highest, and the WSD was reduced by up to 15%. The lubrication performance of n-propanol and 1,2-propanediol was superior to that of the other alcohols;

(2) The static reaction experiment demonstrated that, following alcohol charging, the aluminum plate's surface film had a uniform morphology, the content of C and O grew noticeably, and the molecular structure had a certain impact on the content of C and O;

(3) The tribological properties of aluminum–steel friction pairs under alcohol lubrication were affected by the alcohols' molecular structures. The highest anti-friction performance was provided by n-propanol, which formed a three-layer carbon chain structure after its adsorption, and the best anti-wear performance was offered by 1,2-propanediol, which formed a stable five-membered ring structure on the aluminum surface;

(4) The lubrication mechanism of the charged alcohols was that the introduction of electrostatic technology enhanced the dissociation of the alcohol molecules to produce more negative ions. Numerous negative ions were chemisorbed onto the positive charge sites on the aluminum surface to form an easy shear protective film (the organic aluminum compounds), and then some chemical bonds of the organic aluminum compounds could be broken by the high shear force. Finally, organic aluminum compounds and inorganic aluminum oxide films were formed on the aluminum surface.

The effect of charged alcohol aqueous solvents on the lubrication performance of aluminum was investigated, in this work, using a particular alcohol concentration. In order to improve the practical application value of this research, subsequent work will focus on adding alcohol to the cutting fluid and charging the cutting fluid to evaluate its cutting performance and find the optimum additive concentration.

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