

Sliding wear behaviors of Nomex fabric/phenolic composite under dry and water-bathed sliding conditions

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Abstract: A Nomex fabric/phenolic composite was prepared, and its tribological properties were evaluated under dry and water-bathed sliding conditions by a pin-on-disk tribometer. The resulting size of the friction coefficient for the Nomex fabric/phenolic composite in the study occurred in the following order: dry sliding condition > distilled water-bathed sliding condition > sea water-bathed sliding condition. The fabric composite's wear rate from high to low was as follows: distilled water-bathed sliding condition > sea water-bathed sliding condition > dry sliding condition. Under water-bathed sliding conditions, penetration of water into the cracks accelerated the composite's invalidation process, resulting in a higher wear rate. We also found that the extent of corrosion and transfer film formed on the counterpart pin significantly influenced the wear rate of the Nomex fabric composite. Discussion of the Nomex fabric composite's wear mechanisms under the sliding conditions investigated is provided on the basis of the characterization results.

Keywords: Nomex fabric/phenolic composite; friction and wear property; dry and water-bathed sliding condition

1 Introduction

Fabric-reinforced polymer composites display enhanced properties such as self-lubrication ability and excellent anti-wear compared with unreinforced polymer composites, metals, and alloys [1–3]. Therefore, fabric-reinforced polymer composites have been employed as bearing liners in aircrafts and construction materials for automobiles and pressure vessels [4–6], all of which typically undergo friction and wear. In recent decades, researchers have comprehensively studied the tribological behaviors and mechanisms of fabric-reinforced polymer composites under dry sliding conditions [7–10]. However, studies related to their tribological properties under water-lubricated conditions are relatively rare, despite the fact that fabric-reinforced

polymer composites will inevitably be used in rainy conditions, marine environment, and ultrahigh humidity environments whereby absorbed water molecules will affect their mechanical and tribological properties [11–14].

As a class of tribo-engineering materials, Nomex fabric-reinforced composites have various industrial applications. However, the friction and wear behavior of these composites under water-bathed sliding conditions have not yet been investigated with respect to their practical application. In this study, we systematically investigate the sliding wear behaviors of a Nomex fabric/phenolic composite under dry and water-bathed sliding conditions. We found the friction coefficient of the Nomex fabric composite under water-bathed sliding conditions to be much lower than that under dry a sliding condition. However, the wear rate for the Nomex fabric composite increased markedly under water-bathed sliding conditions compared with

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the rate measured under a dry sliding condition. In addition, we found that the Nomex fabric composite displayed different tribological behaviors when a distilled water-bathed sliding condition and sea water-bathed sliding condition were applied separately. These distinct tribological behaviors result from differences in the components of distilled water and sea water. This study provides a new avenue for basic research as well as real applications for fabric composites.

2 Experimental

2.1 Materials

Nomex fabric, knitted with the Nomex fibers from DuPont, has a plain weave with a weight/area ratio of 1.37 g/cm². Adhesive resin (204 phenolic resin) was provided by Shanghai Xing-guang Chemical Plant, China. The other chemicals of analytical grade were provided by Sinopharm Chemical Reagent Company and used as received.

Sea water was prepared according to ASTM D1141-98 standard [15], and its resultant composition is shown in Table 1.

2.2 Specimen preparation

The Nomex fabric was cleaned by a Soxhlet extractor in petroleum ether and ethanol in turn, and then dried in the oven. Next, the Nomex fabric was immersed in the adhesive diluted with the mixed solvent $V_{\text{acetone}}: V_{\text{ethanol}}: V_{\text{ethyl acetate}} = 1:1:1$ and then dried. We performed a series of repetitive immersions and coatings of Nomex fabric until the mass fraction of

Table 1 Chemical composition of sea water (The chlorinity of the sea water is 19.38; the pH is 8.20).

Compound	Concentration (g/l)
NaCl	24.53
MgCl ₂	5.20
Na ₂ SO ₄	4.09
CaCl ₂	1.16
KCl	0.695
NaHCO ₃	0.201
KBr	0.101
H ₃ BO ₃	0.027
SrCl ₂	0.025
NaF	0.003

fabric in the composite was about 70% ± 5%. Finally, the fabric composite was cut into pieces and affixed with the phenolic resin to an AISI-1045 steel disk (Φ 45 mm × 8 mm in size, with a surface roughness of 0.45 μm) and then cured at 180 °C for 2 h under a specific pressure.

2.3 Friction and wear tests

A Xuanwu-III pin-on-disk tribometer (see Fig. 1) was used to study the tribological properties of two fabric composite samples. In this pin-on-disk tester, a stationary steel pin slides against the fabric composite specimen on a rotating steel disk with or without water. The flat-ended AISI-1045 pin (diameter 2 mm) is secured to the load arm with a chuck. The distance between the center of the pin and the axis is 12.5 mm. The pin has two degrees of freedom over the disk: vertical, for normal load applications by direct contact with the disk, and horizontal for friction measurement. A load cell sensor connected to the pin measured the frictional torque during the friction test. Before each wear test, the frictional torque was tuned to zero. When a wear test started, the pin was rotated to certain angles, and the frictional torque was obtained using computer software.

Before each test, the pin was polished successively with 350, 700, and 900 grade water-proof abrasive papers to a surface roughness (Ra) of 0.15 μm, and then cleaned with acetone. The sliding wear tests were performed at room temperature, at loads between 60 MPa and 100 MPa, at a speed of 0.131 m/s, and over a 2 h period under dry and water-bathed sliding conditions. At the end of each test, the corresponding wear volume loss (V) of the composite was obtained by measuring the depth of the wear scar with a

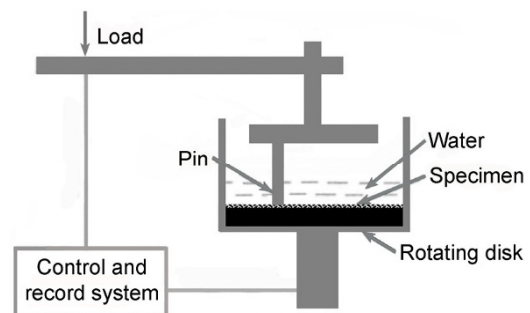


Fig. 1 Schematic diagram of pin-on-disc friction and wear tester.

micrometer (resolution 0.001 mm). The wear performance was expressed by the wear rate (ω , $\text{m}^3 (\text{N}\cdot\text{m})^{-1}$) as follows: $\omega = V \cdot (PL)^{-1}$, where V is the wear volume loss in m^3 , P is the load in Newtons, and L is the sliding distance in meters.

The friction coefficient, measured from the frictional torque in the load cell sensor, was obtained using a computer running friction-measure software. The contact temperature of the worn surface was monitored by a thermocouple positioned at the edge of the counterpart pin. Each experiment was carried out three times and the average value was used. The worn surfaces of the composites and the pins were analyzed using JSM-5600LV scanning electron microscopy (SEM). The chemical changes occurring on the counterpart pin under different conditions were analyzed on an ESCALAB 210 X-ray photoelectron spectroscopy (XPS).

3 Results and discussion

3.1 Tribological properties of Nomex fabric composite under different applied loads

The wear and friction behaviors of the Nomex fabric composite were measured under a dry sliding condition and distilled water-bathed/sea water-bathed sliding conditions, respectively. Variations in the friction coefficient and wear rate of the Nomex fabric composite with applied load under dry and water-bathed sliding conditions is illustrated in Fig. 2. The friction coefficient and temperature of the worn surface of the Nomex fabric composite under an applied load

of 25 MPa is plotted as a function of sliding time in Fig. 3. As shown in Figs. 2(a) and 3, under each applied load, the size of the friction coefficient and the worn surface temperature of the Nomex fabric composite occurs in the following order: dry sliding condition > distilled water-bathed sliding condition > sea water-bathed sliding condition. Under a load of 25 MPa, the friction coefficient of the Nomex fabric composite decreased from 0.602, measured under the dry sliding condition, to 0.285, under the distilled water-bathed sliding condition, and then to 0.204, under the sea water-bathed sliding condition. We believe that the lubricating effect of the water film between the sliding pin and the fabric composite contributed to the decrease in the friction force and friction coefficient [16, 17].

Figure 2(b) shows the change in wear rate of the Nomex fabric composite with applied load under dry and water-bathed sliding conditions. Under all the applied loads investigated, the degree of wear rate of the Nomex fabric composite occurred in the following order: distilled water-bathed sliding condition > sea water-bathed sliding condition > dry sliding condition. When a load of 25 MPa was applied, the wear rate of Nomex fabric composite clearly increased from $10.8 \times 10^{-14} \text{ m}^3 (\text{N}\cdot\text{m})^{-1}$, measured under dry sliding condition, to $45.8 \times 10^{-14} \text{ m}^3 (\text{N}\cdot\text{m})^{-1}$, under distilled water-bathed sliding condition, and to $23.9 \times 10^{-14} \text{ m}^3 (\text{N}\cdot\text{m})^{-1}$, under sea water-bathed sliding condition. In addition, study results show that the load-carrying capacity of the Nomex fabric composite under a sea water-bathed sliding condition is better than that under a distilled

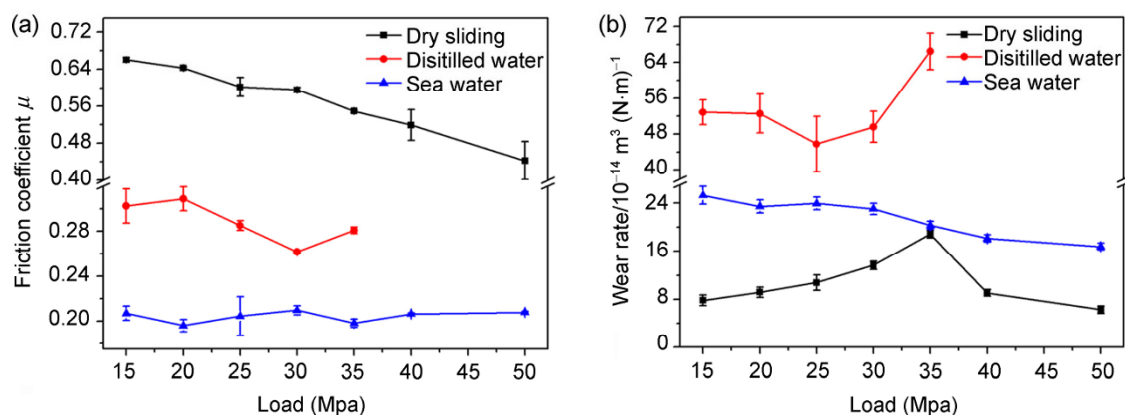


Fig. 2 The value of friction coefficient (a) and wear rate (b) of the fabric composite as a function of applied load. The sliding speed in the tests was 0.131 m/s.

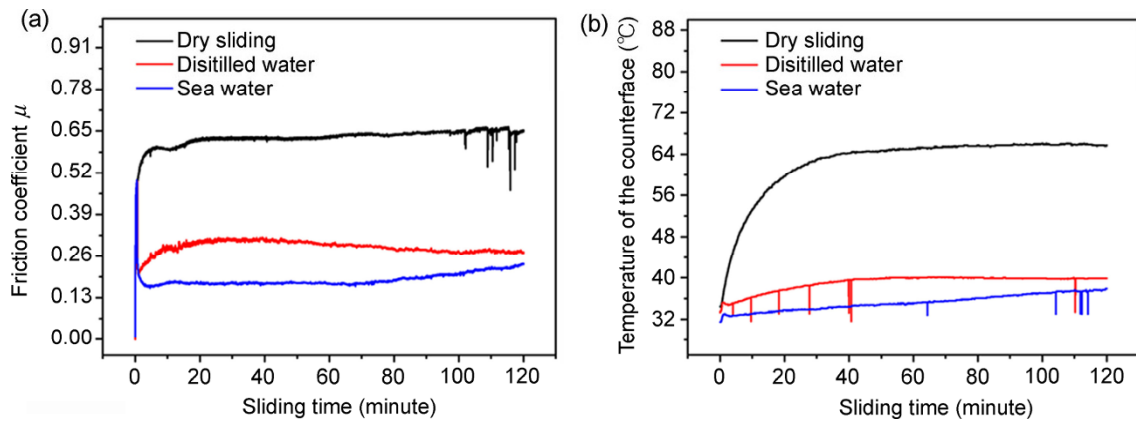


Fig. 3 The value of friction coefficient (a) and temperature of the counterface (b) of the fabric composite as a function of sliding time. The load and sliding speed in the tests were 25 MPa and 0.364 m/s, respectively.

water-bathed sliding condition, though the capacity of both are worse than that under a dry sliding condition. For instance, the wear rate of the Nomex fabric composite under 35 MPa was $18.9 \times 10^{-14} \text{ m}^3(\text{N}\cdot\text{m})^{-1}$, measured under a dry sliding condition, and $20.3 \times 10^{-14} \text{ m}^3(\text{N}\cdot\text{m})^{-1}$, measured under a sea water-bathed sliding condition. However, when the same load and sliding speed were applied, the Nomex fabric composite was worn out after sliding for 116 min under a distilled water-bathed sliding condition.

3.2 SEM images of the worn surface of the Nomex fabric composite

The absorption of water leads to damage of the interface in composites and a reduction in their mechanical and tribological properties. In a fabric composite, the penetration of water into the interface of its fiber and adhesive may cause them to debond. Accordingly, when the fabric composite is subjected to wear under distilled water-bathed/sea water-bathed sliding conditions, water inevitably penetrates into the micro cracks generated on the fabric composite's worn surface and the swelling effect also causes debonding of the fiber and adhesive [18, 19].

Figure 4 shows SEM images of the worn surfaces of the Nomex fabric composite tested under dry and water-bathed sliding conditions. The worn surface of a Nomex fabric composite tested under a dry sliding condition is smooth and flat (see Fig. 4(a)), and the magnified image suggests that no debonding or micro cracks existed on the worn surface. However, on the worn surface of the Nomex fabric composite tested

under a distilled water-bathed sliding condition, the abrasion of the phenolic resin was severe. During the sliding process, water penetrated into the fabric composite along micro cracks, resulting in the water-swollen phenolic resin having lower shear strength [18, 19]. Figures 4(b) and 4(e) show that a large area of phenolic resin has detached from the composite, due to the damage caused by the shearing force and pressure. Comparatively, the worn surface of the Nomex fabric composite tested under a sea water-bathed sliding condition was only mildly damaged (see Figures 4(c) and 4(f)). Figure 6(c) shows that a large area of the worn surface was smooth without patches of resin debris attached. Figure 4(f) also shows that only some of the micro cracks are not spread out. These results suggest that the Nomex fabric/phenolic composite is more durable under a sea water-bathed sliding condition than under a distilled water-bathed sliding condition.

3.3 Characterizations of the counterpart pin surface

The surface composition and morphology of the counterpart pins sliding against the Nomex fabric composites were also analyzed. Table 2 shows the content of the element on the counterpart pin surface. By analyzing the composition of the three counterpart pins tested under different sliding conditions, we found that the counterpart pin in the distilled water-bathed sliding condition caused the most serious erosion, as evidenced by the large Fe2p content (see Table 1). In the XPS spectra of Fe2p in the counterpart pin under a distilled water-bathed sliding condition,

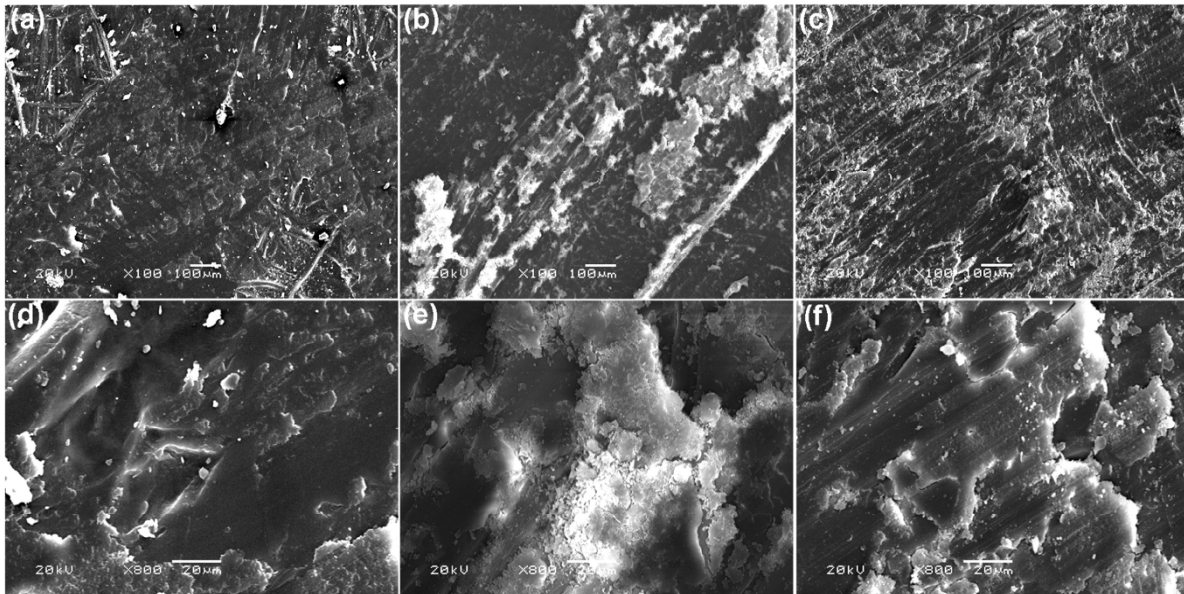


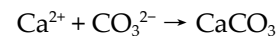
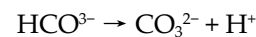
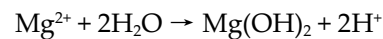
Fig. 4 SEM images of the worn surfaces for fabric composites tested under different sliding conditions: (a) Under dry sliding condition, (b) under distilled water-bathed sliding condition, and (c) under sea water-bathed sliding condition. (d), (e), and (f) are the magnified images of (a), (b), and (c), respectively. The applied load and sliding speed in the tests were 25 MPa and 0.131 m/s, respectively.

Table 2 Relative atomic concentration of worn surfaces of the steel pin Nomex fabric composite slid against under different conditions.

Wear condition	Atomic percent						
	C	N	O	Fe	Na	Mg	Ca
Ambient	58.75	4.255	33.505	3.54			
Distilled water	59.105	0.11	30.595	10.18			
Sea water	52.185	4.42	26.845	2.85	0.825	10.64	2.235

we attribute the peaks at 710.5 eV and 724 eV to Fe_2O_3 and the peak at 712.1 eV to FeSO_4 (see Fig. 5(a)). For the counterpart pin under the sea water-bathed sliding condition, we ascribe the peak at 712 eV to FeSO_4 (see Fig. 5(b)) [20]. That is, the oxidation of Fe was restrained under the sea water-bathed sliding condition, which may have contributed to the lower wear rate of the fabric composite under the sea water-bathed sliding condition than in the distilled water-bathed sliding condition. The XPS analysis of the counterpart pin under a sea water-bathed sliding condition indicates the presence of NaCl, CaCO_3 , and $\text{Mg}(\text{OH})_2$ deposits on the pin surface. As shown in Figs. 5(c), 5(d), and 5(e), the peaks at 1,072 eV, 49.94 eV, and 351 eV can be ascribed to NaCl, $\text{Mg}(\text{OH})_2$, and CaCO_3 deposits, respectively. The chemical reactions for the formation of NaCl, CaCO_3 , and $\text{Mg}(\text{OH})_2$ in the white film during

wear testing are as follows: [21]



After the sliding of the counterpart pin against the Nomex fabric composite under an ambient sliding condition scratches were detected and the transfer film was compact though discontinuous (Fig. 6(a)). When tested under a distilled water-bathed sliding condition, a rather thin and discontinuous transfer film can be seen on the counterpart pin, which has a high level of roughness and to which wear debris is attached. Eroded spots caused by the erosion of Fe were also detected (see Fig. 6(b)). We deduced that the cooling effect of water hindered the melting of the phenolic resin and inhibited the transfer and generation of wear debris on the sliding counterpart pin [22]. Under the sea water-bathed sliding condition, the surface of the counterpart pin after testing was much smoother and had no continuous covering of transfer film. However, a discontinuous white film was detected on the surface of the pin. We made the assumption that the white film was mainly composed of deposits of NaCl, CaCO_3 , and $\text{Mg}(\text{OH})_2$. As seen

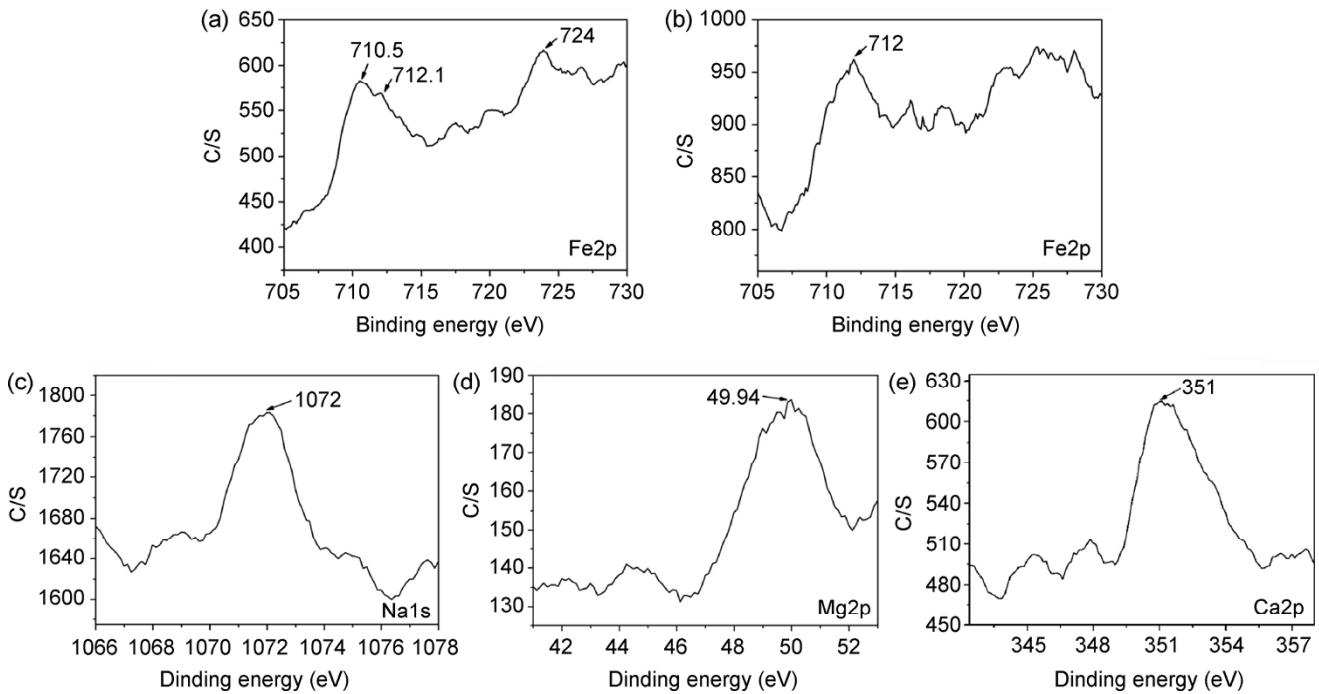


Fig. 5 XPS analysis of the counterpart pins sliding against fabric composites under different sliding conditions. Fe 2p XPS spectrum of the pin surface sliding against fabric composites under distilled water-bathed sliding condition (a); Fe 2p (b), Na 1s (c), Mg 2p (d), Ca 2p (e) XPS spectrum of the pin surface sliding against fabric composite under sea water-bathed sliding condition. The applied load and sliding speed in the tests were 25 MPa and 0.131 m/s, respectively.

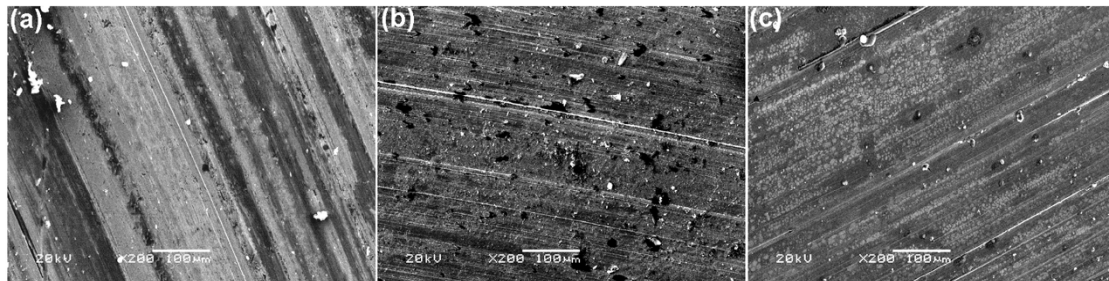


Fig. 6 SEM images of the counterpart pins sliding against fabric composites under different sliding conditions: (a) Under dry sliding condition, (b) under distilled water-bathed sliding condition, and (c) under sea water-bathed sliding condition. The applied load and sliding speed in the tests is 25 MPa and 0.131 m/s, respectively.

in Fig. 6(c), the NaCl, CaCO₃, and Mg(OH)₂ deposits were mainly along the grooves. We thus deduced that the grooves contributed to the deposition of NaCl, CaCO₃, and Mg(OH)₂ and these NaCl, CaCO₃, and Mg(OH)₂ deposits reduced the roughness of the pin surface. In addition, this film had a high resistance which could serve to isolate the steel surface from the corrosive medium, preventing Cl⁻ and O₂ from diffusing onto the surface of the steel, and thus reducing corrosion of the steel. Wang [21] et al. pointed out that a medium affects a polymer's tribological behavior

mainly through corrosion to the counterface and the wear rate of a polymer depends on the extent of corrosion to the counterface. Accordingly, the Nomex fabric composite exhibits a higher wear rate under a distilled water-bathed sliding condition than under a sea water-bathed sliding condition.

4 Conclusions

In this study, we investigated the tribological behaviors of a Nomex fabric/phenolic composite under dry and

water-bathed sliding conditions. We proposed that the penetration of distilled water/sea water induces damage to the mechanical properties of the Nomex fabric composite. Wear test results show that the wear resistance of the Nomex fabric/phenolic composite was much higher under a sea water-bathed sliding condition than under a distilled water-bathed sliding condition, owing to the NaCl, Mg(OH)₂, and CaCO₃ deposited on the pin surface. We conclude that the transfer film formed on the counterpart pin and extent of erosion to the pin were the two main factors determining the friction and wear properties of the fabric composites.

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