

Friction and wear behaviors of steel wire ropes sliding against drum flanges in offshore drilling hoisting systems

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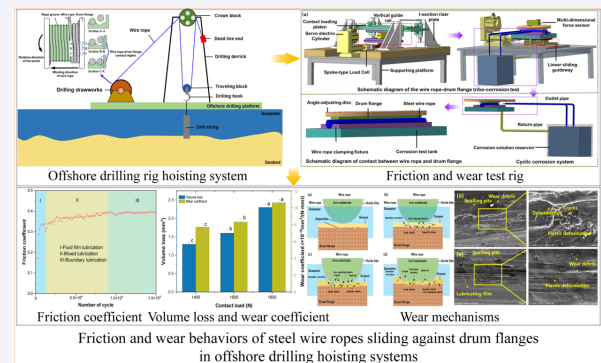
ABSTRACT: The time-dependent mechanical behavior of hoisting wire ropes on offshore drilling platforms can cause repeated contact and relative sliding between the steel wire rope and the drum flange during interlayer transition. In marine service environments, seawater exposure and lubrication conditions may further influence the tribological behavior of the rope–flange contact pair, thereby affecting the load-bearing safety of the hoisting system. In this study, friction and wear tests were performed on a steel wire rope–drum flange contact pair using a custom-built test rig. The effects of cycle number, environmental condition, contact load, and friction frequency on the friction coefficient, wear scar profile, volume loss, wear coefficient, and wear morphology were systematically investigated. Wear evolution and damage mechanisms were characterized by manual strand disassembly, three-dimensional profilometry, and scanning electron microscopy. The results show that the friction coefficient increases rapidly at the initial stage, then rises gradually, and finally fluctuates around a steady state with increasing cycle number. The steady-state friction coefficient decreases with increasing contact load and friction frequency. In contrast, the wear width, wear depth, maximum cross-sectional failure area, volume loss, and wear coefficient increase with cycle number and frictional parameters. The wear severity under different environmental conditions follows the order of air > seawater > grease + seawater > grease. These findings provide a basis for understanding the degradation behavior and optimizing maintenance strategies of steel wire rope–drum flange contact pairs in offshore drilling hoisting systems.

KEYWORDS: offshore drilling rig; hoisting steel wire rope; drum flange; friction and wear; marine environment; lubrication condition

1 Introduction

As global energy consumption continues to rise and readily accessible onshore oil and gas reserves are progressively depleted, offshore hydrocarbon exploration and production have become increasingly important for addressing the global energy supply challenge. Offshore drilling rigs constitute essential equipment for deep-sea oil and gas exploitation, and steel wire rope acts as the principal load-bearing element in the rig hoisting system. Failure of this component may lead to serious safety risks and a marked decline in the reliability of deep-sea hydrocarbon exploration and development [1, 2]. In practical operation, the hoisting rope is

arranged in multiple layers on the drawwork drum. The outermost rope layer departs from the drum at a specified fleet angle toward the fast-line sheave, subsequently passes around the crown block and traveling block, and is finally anchored at the deadline tie-down [3, 4]. The lifting and lowering motions of the drill string are therefore completed by the spooling-in and spooling-out processes of the drum, as illustrated in Fig. 1. The hoisting system is subjected to extremely demanding operating conditions, such as fast-line rope velocities as high as 20 m/s, maximum hook loads reaching 900 t, derrick heights up to 60 m, and sheave numbers up to 15. During service, acceleration and deceleration during start-stop stages, rope spooling on the drum,



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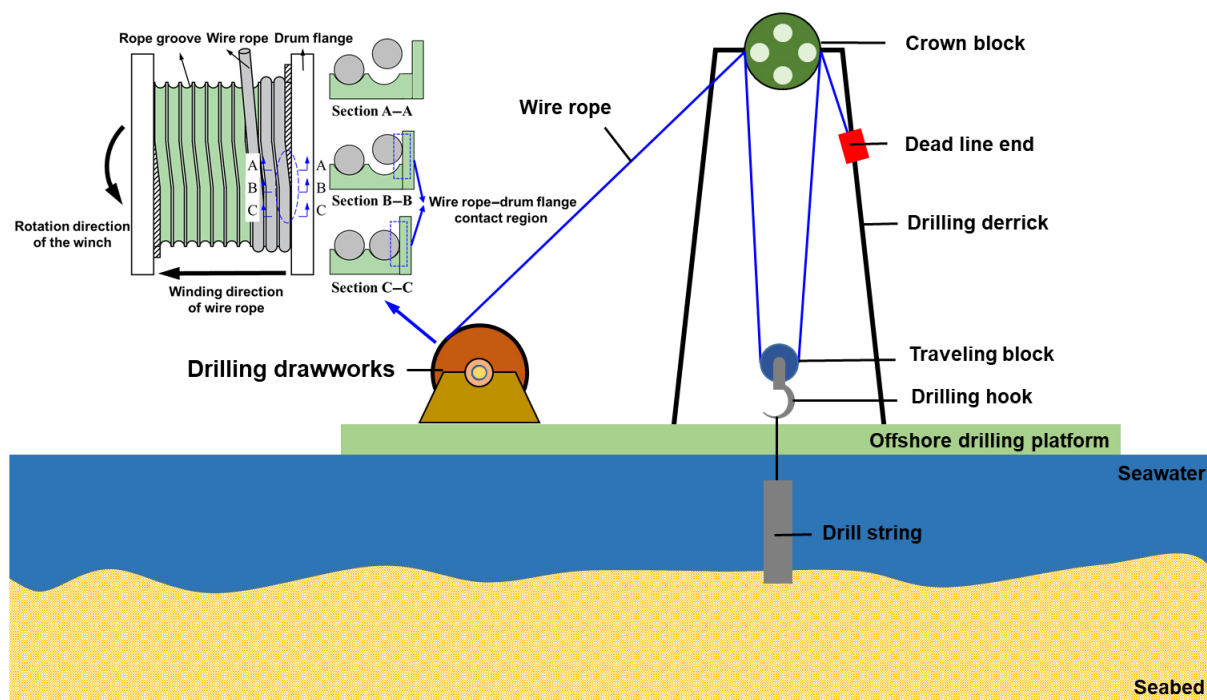


Fig. 1 The offshore drilling rig hoisting system.

layer-to-layer transition of the multilayer wound rope, and low-frequency vibration of the drawworks can readily generate complex time-varying dynamic responses in the wire rope. These responses may bring the rope into contact with the drum flange and induce relative sliding during interlayer transitions, thereby producing considerable friction and wear at the rope-drum flange contact interface. Meanwhile, offshore drilling platforms are continuously exposed to aggressive marine environments, particularly in marine atmospheric zones and splash zones [5, 6]. The hoisting wire rope therefore experiences repeated wet-dry cycles, abundant moisture, sustained oxygen replenishment, and high chloride ion concentrations, all of which promote general corrosion. When surface corrosion interacts with mechanical wear, severe tribo-corrosion occurs at the rope-drum flange interface. The resulting coupled damage may cause wire breakage, intense abrasive wear, and even strand fracture, ultimately weakening the load-bearing safety of the wire rope and impairing the service reliability of the offshore drilling rig hoisting system [7]. Hence, a clear understanding of the friction and wear behavior of wire ropes in offshore drilling rigs is of great significance for improving their load-bearing safety and maintaining the operational integrity of deep-sea oil and gas exploration and development.

Existing studies on steel wire ropes have mainly focused on corrosion-induced mechanical degradation, tribo-corrosion-fatigue damage, fretting wear, and the effects of service parameters on friction and wear behavior [1, 7–10]. Regarding corrosion-related mechanical degradation, Yang et al. [11] used accelerated electrochemical corrosion tests to study the monotonic tensile and hysteretic behaviors of $6 \times 19S + IWR$ wire ropes with different corrosion degrees and analyzed how seawater corrosion affects their macroscopic mechanical properties and fracture characteristics. Molnár et al. [12] further investigated the degradation of the mechanical properties of wire ropes and individual steel wires in corrosive environments by means of salt solution corrosion experiments. Ma et al. [13] proposed a time-dependent formula for predicting the uniform corrosion degree based on accelerated electrochemical corrosion tests and

examined the corrosion behavior and mechanical deterioration of stressed high-strength steel wires in acidic environments. Zhang et al. [14] combined corrosion-fatigue tests on 48 high-strength steel wires with numerical analysis to reveal the influence of corrosion pit geometry and spatial distribution on the stress concentration factor. Chang et al. [15] investigated the friction, wear, and residual strength properties of steel wire ropes with different corrosion types. Their results showed that corrosion significantly affected the friction coefficient, temperature rise, anti-wear performance, and residual bearing capacity of the rope and that seawater corrosion produced noticeable degradation in both wear resistance and mechanical performance. For tribo-corrosion and fretting wear, Wang et al. [2, 7] investigated the bending tribo-corrosion-fatigue damage of wire ropes under different fatigue loads, temperatures, and crossing angles, revealing the coupled relationships among tribological behavior, electrochemical corrosion response, and fatigue damage. Zhang et al. [16] studied the tribo-corrosion behavior of steel wires in wire ropes under alkaline conditions and clarified the evolution of the corrosion rate, friction coefficient, and material loss with friction cycles. Using a self-developed wire tribo-corrosion-fatigue tribometer, Wang et al. [17–19] further examined the roles of fatigue load, contact load, and relative slip amplitude in the tribo-corrosion-fatigue degradation of steel wires. Imran et al. [20] incorporated electrochemical corrosion into a finite element model for steel wire fretting wear and analyzed fretting wear behavior in the corrosive environment of mine hoisting systems. Huang et al. [21] experimentally evaluated the friction, wear, and mechanical property degradation of helically contacting steel wires under acidic, seawater, and alkaline media, as well as under time-varying corrosion conditions. Guo et al. [22] established a corrosion-fatigue coupled model to describe the full life cycle and crack propagation mechanisms of cables in marine environments. The influence of operational dynamics and contact parameters has also been widely examined. Zhang et al. [23] studied vibratory wear and performance degradation of mine winding hoisting wire ropes and demonstrated the synergistic effects of vibration conditions, lubrication states, and mineral dust environments.

Chang et al. [24] analyzed wire rope friction and wear under different contact parameters using a wire rope tribometer, indicating that wear zone distribution and wear depth are critical to the mechanical performance of wire ropes. Peng et al. [25] investigated the winding friction and wear of $6 \times 19 + FC$ wire ropes in low-temperature environments and found that oil–water lubrication significantly decreased the friction coefficient, wear area, and wear depth compared with dry friction, while the wear mechanism was strongly dependent on temperature. Chen et al. [26] developed a model for the interwire wear evolution of wire rope strands under cyclic bending loading by considering both frictional contact and relative sliding. Their results showed that wear appears only in regions outside the neutral layer where contact and sliding coexist, extends along the normal direction of the core–wire contact line, and reaches its maximum depth between the neutral layer and the outermost position of the bent strand. Cruzado et al. [27, 28] demonstrated that contact pressure increases the interwire wear coefficient, whereas larger crossing angles intensify the surface wear of steel wires. These studies provide an important basis for understanding wire rope degradation, but the friction and wear behavior of offshore drilling hoisting wire ropes under rope–drum flange contact and marine service conditions still require further investigation.

To address the limitations of previous studies, which mainly examined mine hoisting ropes, suspension bridge cables, or wire–wire and rope–sheave contacts under simplified environmental conditions, this study focuses on the rope–drum flange contact of offshore drilling hoisting ropes during multilayer winding and interlayer transition. Particular emphasis is placed on the coupled influence of seawater and grease lubrication because the corresponding friction and wear mechanisms remain insufficiently understood and constrain the reliability assessment and maintenance optimization of offshore drilling hoisting systems. A custom-built reciprocating test rig was therefore employed to reproduce the contact and sliding behavior between a steel wire rope and a drum flange under controlled environmental and mechanical conditions. Based on this platform, the effects of cycle number, contact load, friction frequency, and environmental medium were analyzed in terms of friction coefficient, wear profile, wear volume, wear coefficient, and worn surface morphology. These experimental results are expected to clarify the degradation behavior of the rope–drum flange contact pair and provide engineering guidance for improving the service reliability and maintenance strategy of offshore drilling hoisting systems.

2 Experimental details

2.1 Experimental materials

The test wire rope was selected following the requirements of the

industry standard SY/T 6666-2017 (Recommended Practice for Selection and Maintenance of Wire Ropes for Use in the Petroleum and Natural Gas Industries). Specifically, a right-hand lang lay bright steel wire rope with a $6 \times 19 + IWS$ configuration, which is commonly applied in petroleum drilling winches, was used as the test specimen, as illustrated in Fig. 2. The corresponding structural and mechanical parameters of the wire rope are summarized in Table 1. Referring to Ref. [29], the drum flange was fabricated from Q355 steel, and its chemical composition is reported in Table 2.

2.2 Test rig and parameters

The custom-designed friction and wear test apparatus was composed primarily of a tension sensor, a servo electric cylinder, a cyclic corrosion system, and a contact fixture for the steel wire rope–drum flange pair. This apparatus was capable of performing friction and wear tests on wire ropes under different environmental conditions, including air, seawater, grease + seawater mixture, and pure grease. It also allowed the frictional parameters, such as contact load and friction frequency, to be adjusted according to the test requirements, as illustrated in Fig. 3. The sliding specimens were cut from the steel wire rope to a length of 300 mm, whereas the counterpart specimens were custom-made drum flange samples with a length of 400 mm. Prior to the experiments, the contact surfaces of both specimens were carefully cleaned by repeatedly wiping them with anhydrous ethanol to eliminate residual oil, rust, and other contaminants. After cleaning, the specimens were naturally dried at room temperature and sealed until use. For each test, the pretreated wire rope specimen was first firmly installed in a dedicated fixture inside the corrosion tank using bolts. The corrosion tank was attached to a movable base plate and driven by a servo electric cylinder, whose reciprocating linear motion produced cyclic reciprocating sliding of the wire rope under the prescribed experimental parameters. The drum flange specimen was fastened to an angle-adjusting disc, which was connected to the loading plate through a multidimensional force sensor. A constant contact load between the wire rope and the drum flange was generated by placing standard weights with predetermined masses on the loading plate. In combination with the vertical guide rail assembly, this loading configuration ensured that the normal load was applied steadily and accurately along the normal direction of the contact interface, thereby avoiding eccentric loading. The reciprocating motion was controlled by a programmable servo controller, through which the stroke, sliding speed, and total number of cycles of the servo electric cylinder were preset. Thus, the reciprocating sliding amplitude and frequency of the wire rope could be precisely regulated, generating stable relative sliding between the wire rope and the drum flange. At the same time, the

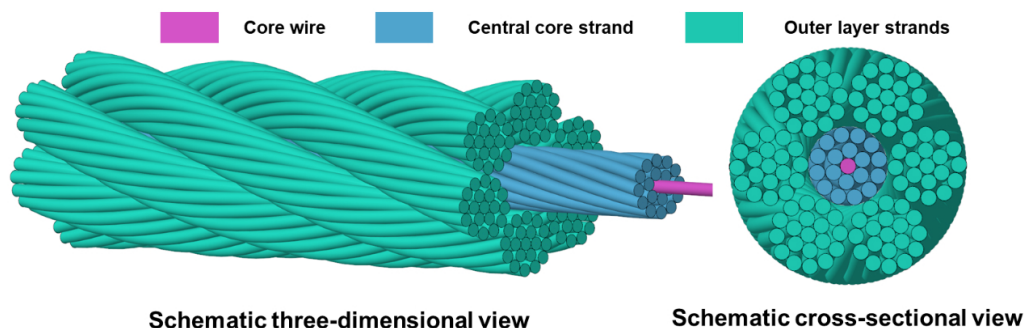


Fig. 2 Structure diagram of the experimental steel wire rope.

cyclic corrosion system continuously sprayed the frictional contact region with the selected corrosive medium through an atomizing nozzle at a specified flow rate, thereby initiating the reciprocating sliding wear process under corrosive media between the sliding

Table 1 Structural parameters of wire rope

Parameter	Value
Diameter (mm)	13
Lay length (mm)	78
Nominal tensile strength (MPa)	1,770
Minimum breaking force (kN)	106

Table 2 Chemical composition of the drum flange

Chemical component	(wt%)
C	≤ 0.24
Si	≤ 0.55
Mn	≤ 1.6
P	≤ 0.035
S	≤ 0.035
Cr	≤ 0.30
Ni	≤ 0.30
Cu	≤ 0.40

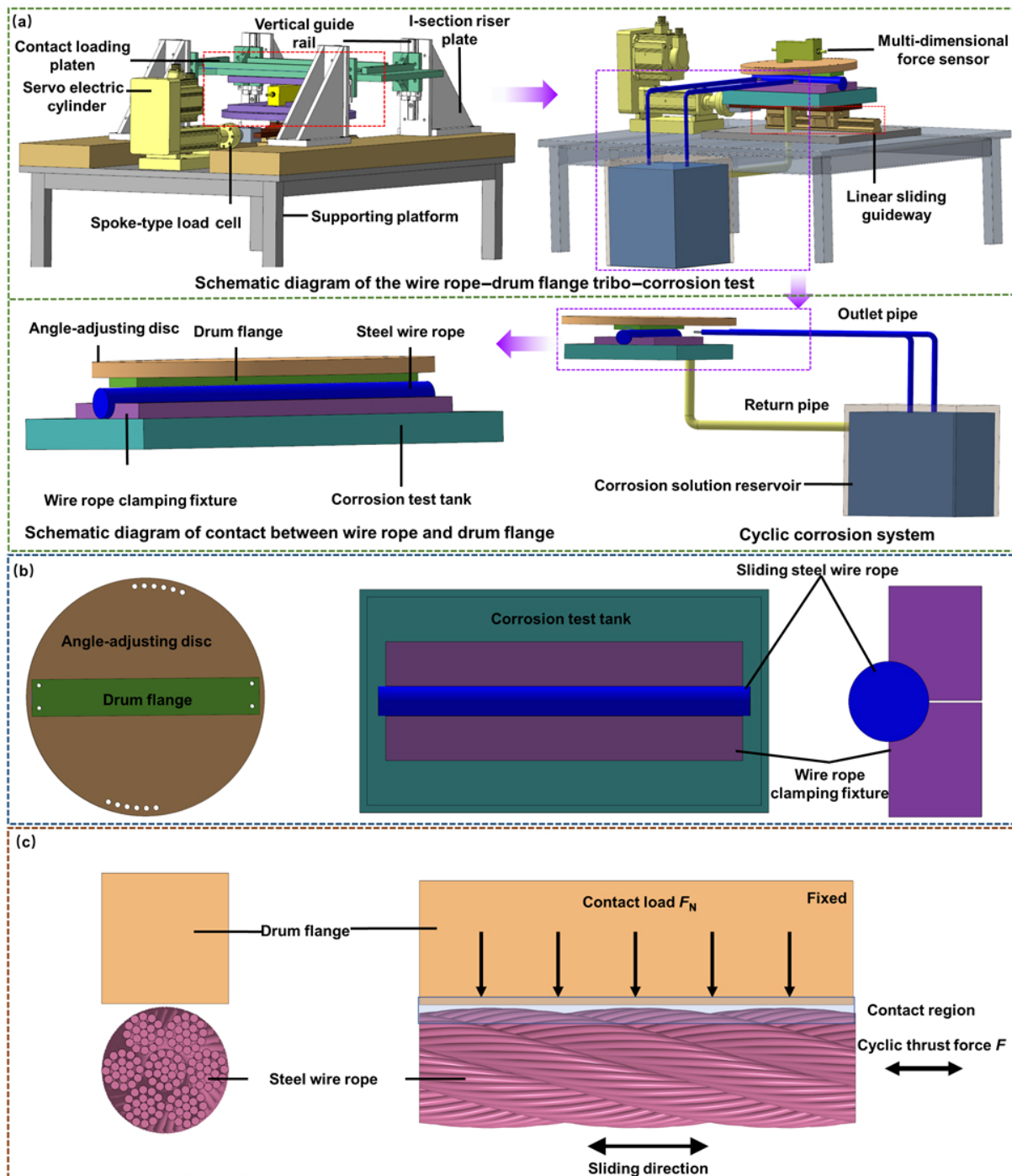


Fig. 3 The friction and wear test rig. (a) Structural diagram of test rig, (b) schematic diagram of the clamping and installation of steel wire rope and drum flange specimens, (c) diagram of working principle of the wire rope–drum flange contact pair.

wire rope and the drum flange. During the experiment, the normal contact load and tangential friction force were monitored in real time using a multidimensional force sensor. The collected signals were synchronously transferred to a host computer via a data acquisition system for recording and storage and were subsequently used to determine the friction coefficient of the wire rope.

The corrosive medium used in this study was artificial seawater, which was prepared in strict compliance with ASTM D1141-98 (2003) and the Chinese National Standard GB/T 15748-2013. A specialized lithium-based grease, IRIS 550, designed for the service and maintenance of steel wire ropes, was adopted as the lubricating medium. Its main performance parameters are presented in Table 3. In this work, the typical operating conditions were represented by a coupled seawater–grease environment, under which the contact load, friction frequency, and sliding amplitude were set to 1,600 N, 4 Hz, and 5 mm, respectively. A series of friction and wear experiments were carried out based on the single-factor control variable method. For the analysis of mechanical parameter effects, the environmental condition was fixed as grease + seawater, and the reciprocating sliding amplitude was kept constant at 5 mm. Under these conditions, the normal contact load was individually adjusted to 1,400, 1,600, and 1,800 N, while the friction frequency was varied as 2, 3, and 4 Hz. These parameter settings were used to clarify the effects of contact load and friction frequency on the friction and wear characteristics of the steel wire rope–drum flange contact pair. In addition, environmental effects were evaluated by maintaining the baseline mechanical parameters at 1,600 N, 4 Hz, and 5 mm. Four representative service environments, including air, seawater, grease + seawater, and pure grease, were then established to compare the friction and wear responses of the steel wire rope in different media. The complete experimental matrix is given in Table 4, and the detailed calculation process is described in the Electronic Supplementary Material (ESM).

2.3 Data processing and calculation methods

The experimental design included three independent replicates for each testing condition to ensure data reliability and reproducibility. All quantitative outcomes, namely, friction coefficient, wear width, wear depth, cross-sectional failure area, wear volume, and wear coefficient, were statistically summarized as the mean $\pm$ standard deviation (SD). One-way analysis of variance (ANOVA) was employed to determine whether significant differences existed among different groups, and Tukey's post hoc test was subsequently used for multiple comparison analysis. The results with $p < 0.05$ were considered

statistically significant. The error bars in the figures correspond to the standard deviations obtained from the three independent replicate measurements.

2.3.1 Friction coefficient

The friction coefficient of the steel wire rope–drum flange contact pair was calculated based on Eq. (1). During the test, a multidimensional force sensor was employed to acquire the force signals along the Z -axis and X -axis simultaneously, enabling accurate determination of the normal contact force F_N and the tangential friction force F_t . Within each cycle of the friction force signal, multiple valid data points were chosen for calculation, and the corresponding cycle-averaged friction coefficient was obtained using Eq. (1) [19, 30]. Subsequently, the average friction coefficients at predetermined cycle intervals were extracted. Based on these values, the variation curve of the friction coefficient between the steel wire rope and the drum flange was plotted.

$$\frac{F_t}{F_N} = \mu \quad (1)$$

where F_t is the tangential friction force, N; F_N is the normal contact load, N; and μ is the friction coefficient.

2.3.2 Wear profiles of worn wire

To quantitatively characterize the wear damage of the steel wire rope, a measurement procedure combining manual strand disassembly and microscopic wear scar analysis was adopted. Because of the special helical geometry of the wire rope, the relative sliding between the steel wire rope and the drum flange generally produced approximately elliptical wear scars on the surfaces of individual outer-strand wires (Fig. 4(a)). After testing, the wires in the worn region were sequentially separated by manual strand disassembly, and the dimensions of the wear scars on each wire were measured using an ultradepth-of-field digital microscope. The wire with the most severe wear was selected as the representative specimen for subsequent wear profile measurement and wear mechanism analysis. The measurement procedure for the maximum wear width was as follows. First, the wear scar on a single worn wire was uniformly divided into five segments along the axial direction. Second, five characteristic measurement points were arranged within each segment. Third, each point was measured five times, and the arithmetic mean was calculated to reduce measurement uncertainty. Finally, the maximum value among the arithmetic means of the five segments was regarded as the maximum wear width of the worn wire.

Using the measured maximum wear width L , together with the wire radius r ($r = OB$) shown in Fig. 4(b), the maximum wear depth h and cross-sectional failure area S were obtained using Eqs. (2)–(4) [17].

$$\alpha = \arcsin \frac{L}{2r} \quad (2)$$

$$h = r - \sqrt{r^2 - \frac{1}{4}L^2} \quad (3)$$

$$S = \alpha r^2 - \frac{1}{2}Lr \cos \alpha \quad (4)$$

where L represents the wear width ($L = AC$); r denotes the radius of the wire ($r = OA = OC$); h indicates the maximum wear depth ($h = BD$); α denotes the angle between OC and OD ; and S represents the maximum cross-sectional failure area ($S = S_{ABCD}$).

Table 3 Physical properties of IRIS 550 grease

Property	Appearance	Dropping point	Flash point	Brittleness point	Operating temperature range
Value	Pale yellow	$\geq 220^\circ\text{C}$	$\geq 220^\circ\text{C}$	-55°C	$(-30) - 140^\circ\text{C}$

Table 4 Experimental parameters

Parameter	Value
Environmental condition	Air, seawater, grease + seawater, and grease
Contact load F_N (N)	1,400, 1,600, and 1,800
Slip amplitude (mm)	5
Friction frequency f (Hz)	2, 3, and 4
Number of cycles N	5×10^4 , 1×10^5 , 1.5×10^5 , 2×10^5 , and 2.5×10^5

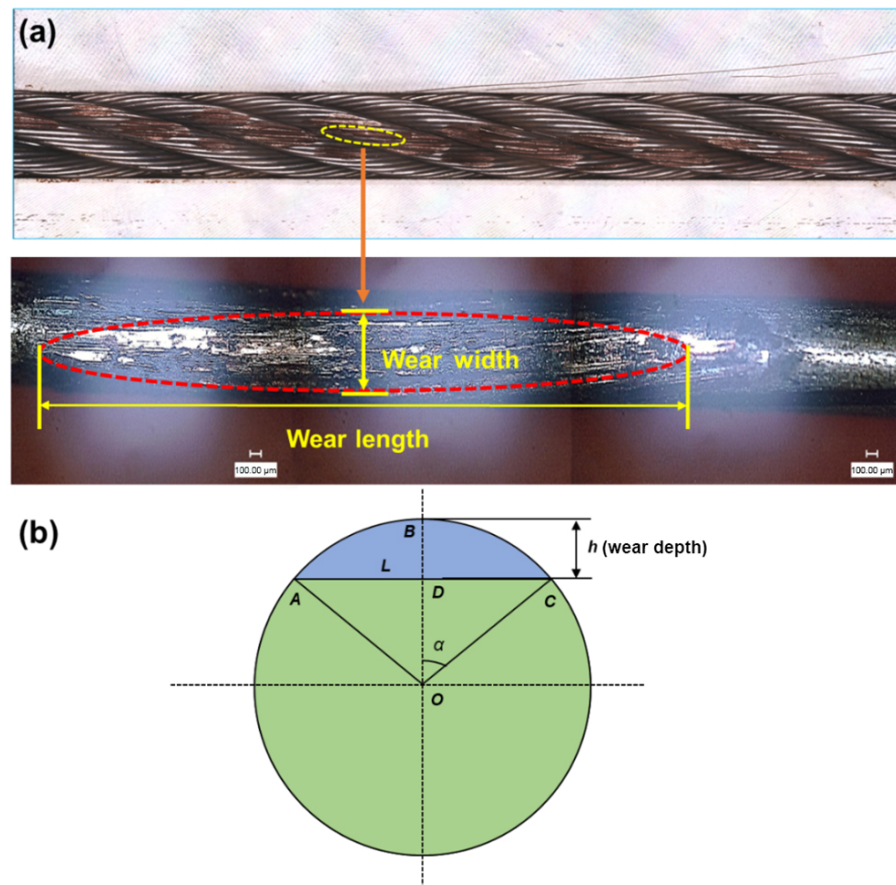


Fig. 4 Wear scar morphology and cross-sectional schematic of the worn wire. (a) Wear scar morphology, (b) schematic diagram of the worn wire cross-section.

2.3.3 Wear volume and wear coefficient

To determine the wear mass and wear volume of the steel wire rope, the worn wires were first obtained by manual strand disassembly after the test. Because grease and corrosion products could adhere to the wire surface and penetrate into the rope interior, the worn steel wires were ultrasonically cleaned with kerosene and alcohol and then dried before weighing. The total mass of these cleaned worn wires was measured using a high-precision balance with an accuracy of 1‰ and was denoted as m_1 . Subsequently, unworn steel wires with the same number and length were cut and cleaned under the same procedure, and their mass was measured as the reference value m_2 . The wear mass was calculated as the difference between m_2 and m_1 , and the wear volume was finally obtained using Eq. (5) [19].

$$\Delta V = \frac{m_2 - m_1}{\rho} \quad (5)$$

where ρ is the density of wires, 7.83 g/cm³.

To assess the wear performance of the steel wire rope material, the wear coefficient was introduced as a quantitative indicator. It characterizes the wear volume of the steel wire rope corresponding to the unit local slip and unit contact load during frictional sliding, and its value was determined using Eq. (6) [4].

$$K = \frac{V}{2 \cdot F_N \cdot \Delta x \cdot N} \quad (6)$$

where V denotes the wear volume, mm³; K represents the wear coefficient; F_N is the contact load, N; Δx is the relative slip amplitude, mm; and N is the total number of cycles.

2.3.4 Maximum wear depth of wire rope

The wear profile and micromorphology of the steel wire rope

were characterized following a cleaning–profiling–quantification procedure. First, ultrasonic cleaning was performed to eliminate wear debris and other contaminants from the specimen surface. Subsequently, a 3D profilometer was used to examine the surface damage profile of the steel wire rope and to obtain the radial cross-sectional profile. Finally, the maximum wear depth was quantified as the height difference h between the radial cross-sectional profiles measured before and after wear, as illustrated in Fig. 5 [2].

3 Friction and wear behavior under typical working conditions

3.1 Friction coefficient

As shown in Fig. 6, the friction coefficient of the steel wire rope–drum flange contact pair under typical working conditions evolves in three characteristic stages with increasing cycle number. In the first stage, the friction coefficient remains low, indicating that the interface is effectively separated by a grease-rich lubricating layer. This layer reduces metal-to-metal asperity contact and partly prevents artificial seawater from directly attacking the metallic substrate [2, 7]. As reciprocating sliding proceeds, repeated extrusion and seawater ingress gradually destroy the integrity of the grease film and weaken its load-bearing capacity. The resulting local film rupture increases asperity contact at the interface, which explains the rapid rise in the friction coefficient during the transition stage. The transition stage is accompanied by the continuous generation and redistribution of wear debris, oxide particles, residual grease, and corrosion products at the contact interface [31]. These interfacial products alter the friction response through debris entrainment, third-body formation, film degradation, and local surface damage. After

prolonged cycling, the friction coefficient tends to stabilize rather than increase continuously. This phenomenon suggests that a dynamic equilibrium has been established among grease film rupture, debris formation, debris removal, and compaction of third-body layers [32]. Consequently, the friction coefficient enters

the steady-state stage and fluctuates within a narrow range around a stable value.

3.2 Wear morphology

Figure 7 demonstrates that increasing the number of cycles significantly intensifies the surface damage of the steel wire rope. The initially localized microcontact wear scars progressively propagate and coalesce, causing the wear-damaged region to expand continuously. This evolution is accompanied by a roughened surface and distinct ploughing/furrowing features, indicating that abrasive action becomes increasingly pronounced during repeated sliding. The worn wires also exhibit a broader spatial distribution and a higher degree of damage as the number of cycles increases. As shown in Fig. 8, the maximum wear depth increases markedly from approximately 0.33 mm at 5.0×10^4 cycles to 1.58 mm at 2.5×10^5 cycles, with a net increment of 1.25 mm. This increase in wear depth and damaged area is closely related to the coupled action of cyclic mechanical loading and seawater-induced corrosion. Repeated cyclic shear stress damages the interfacial lubricating film and surface oxide layer, exposing the

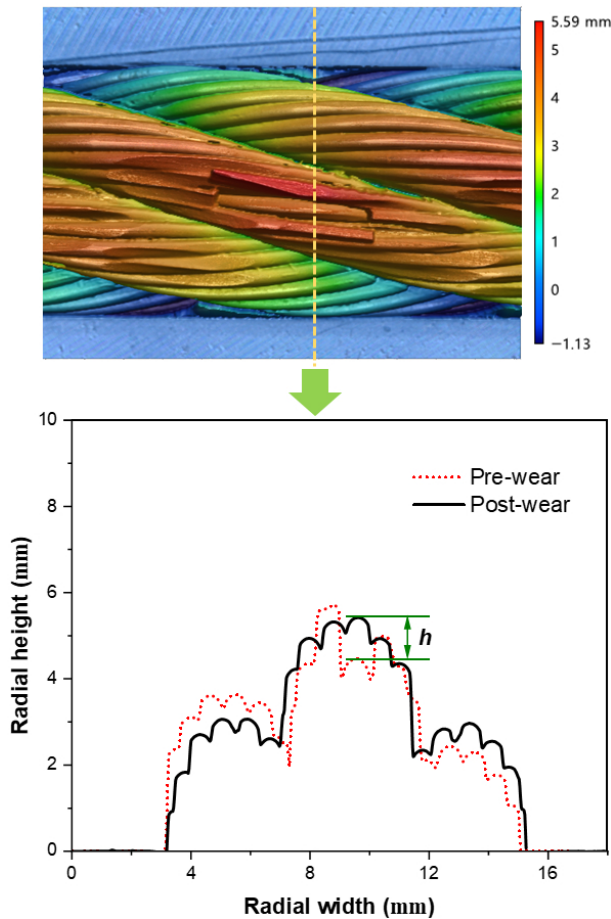


Fig. 5 3D surface topography and corresponding wear profiles of the worn wire ropes.

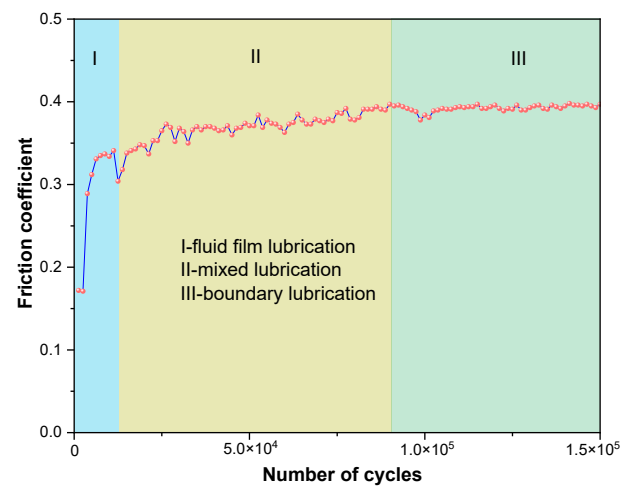


Fig. 6 Evolution curves of the friction coefficient under typical working conditions.

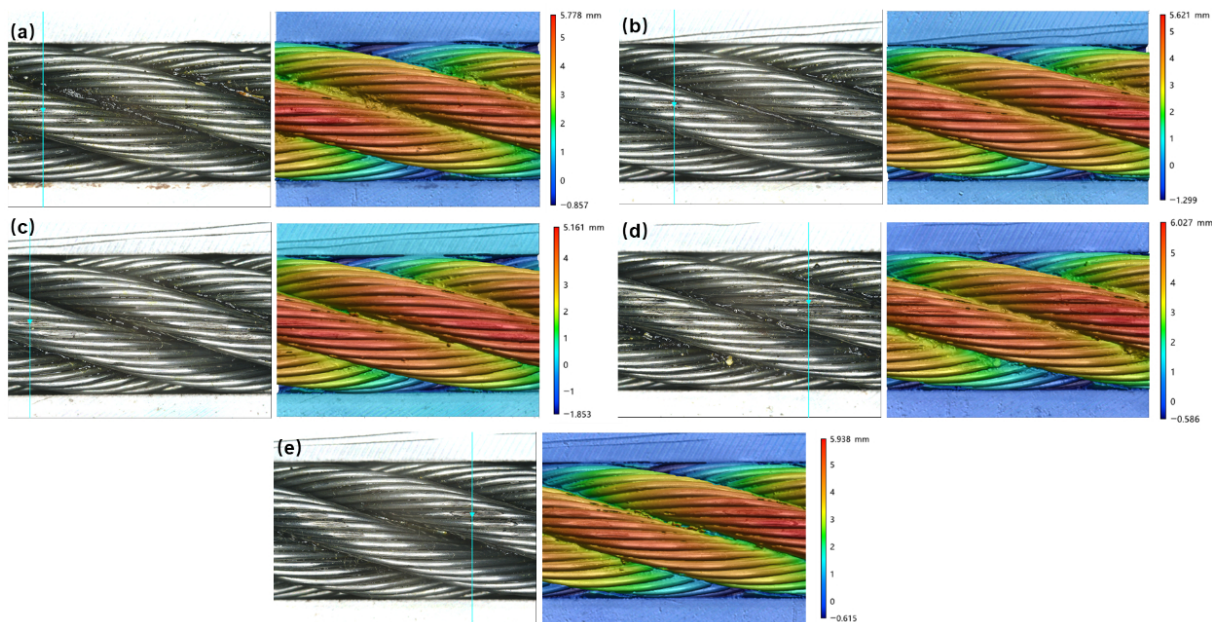


Fig. 7 Wear morphology of the steel wire rope: (a) $N = 5 \times 10^4$, (b) $N = 1 \times 10^5$, (c) $N = 1.5 \times 10^5$, (d) $N = 2 \times 10^5$, (e) $N = 2.5 \times 10^5$.

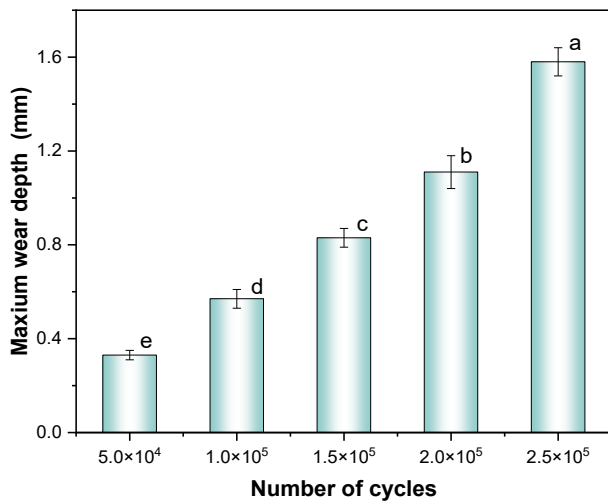


Fig. 8 Maximum wear depth of wire rope. Error bars represent standard deviations from three independent repeated tests. Different lowercase letters indicate statistically significant differences among groups according to one-way ANOVA followed by Tukey's post hoc test ($p < 0.05$).

substrate and promoting further wear propagation. In artificial seawater, chloride ions accelerate localized oxide film breakdown and trigger pitting corrosion. The corrosion pits formed on the worn surface intensify the local stress concentration and facilitate surface damage accumulation under reciprocating sliding [33–35]. Sulfate ions may further modify the corrosion behavior by influencing electrolyte conductivity, adsorption at the interface, and corrosion product transformation [36, 37]. Therefore, the wear evolution with increasing cycle number can be attributed to the combined effects of mechanical ploughing, lubricating-film degradation, oxide-film rupture, and corrosion-assisted damage.

3.3 Wear profile and cross-sectional failure area

Figure 9 reveals that the wear profile of the most severely worn wire becomes progressively deeper and wider as the cycle number increases. At 5×10^4 cycles, the wear width and wear depth are 487 and 86 μm , respectively. After 2.5×10^5 cycles, these two parameters increase to 585 and 128 μm , corresponding to increases of 20.1%

and 48.8%, respectively, compared with the initial 5×10^4 cycle conditions. The much higher growth rate of wear depth than wear width (**Fig. 10(a)**) indicates that material removal is more pronounced along the depth direction. This behavior is associated with the elliptical stress distribution of the line-contact pair, in which the highest stress is concentrated near the contact center. Under repeated high-frequency shear and hydrostatic stresses, the central metal matrix is more susceptible to plastic deformation, microcrack initiation, and crack propagation. Meanwhile, chloride ions in artificial seawater preferentially penetrate damaged oxide films and attack the exposed steel substrate at stress concentration sites. The resulting corrosion pits intensify the local stress concentration and become preferential locations for crack initiation and material detachment during reciprocating sliding. Therefore, the depth-direction wear rate exceeds the lateral expansion rate of the wear scar. The evolution of the cross-sectional failure area further confirms the accumulation of damage with increasing cycle number. As shown in **Fig. 10(b)**, when the cycle count rises from 5.0×10^4 to 2.5×10^5 , the cross-sectional failure area increases to $51.8 \times 10^{-3} \text{ mm}^2$, which is 77.4% higher than that at the initial stage and follows an approximately linear growth trend. At the early stage of testing, the grease film separates the metal surface from the seawater medium and reduces the interfacial stress, thereby inhibiting frictional wear. With prolonged cycling, however, high-frequency reciprocating shear and high-pressure extrusion progressively damage the grease structure, consume the lubricating medium, and weaken the protective interface. The direct exposure and contact of the metal matrix then increase continuously. At the same time, reciprocating shear repeatedly ruptures the oxide layer and removes loosely adhered corrosion products, exposing the fresh steel substrate to the seawater-containing environment. Metallic debris, oxide fragments, and corrosion products generated during this process are entrained into the interface and act as third-body abrasives, which further accelerate material loss. Overall, the increase in wear depth and cross-sectional failure area results from the coupled effects of contact stress concentration, lubricant film degradation, oxide-film rupture, chloride-induced localized corrosion, and third-body abrasion.

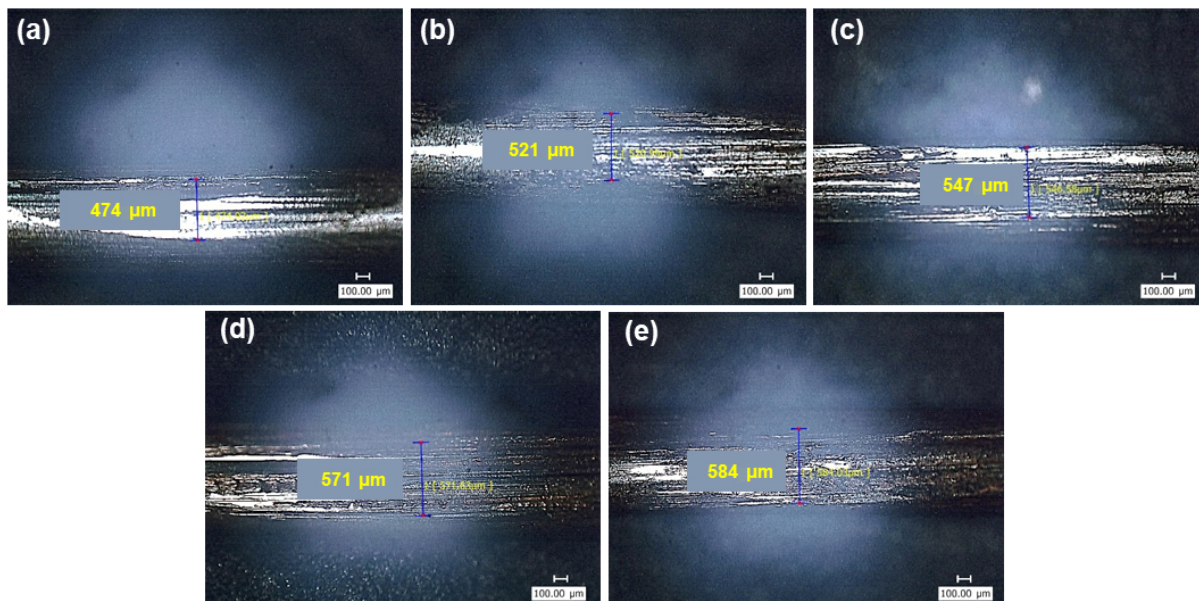


Fig. 9 Profile of wear scars of the most severely worn wire: (a) $N = 5 \times 10^4$, (b) $N = 1 \times 10^5$, (c) $N = 1.5 \times 10^5$, (d) $N = 2 \times 10^5$, (e) $N = 2.5 \times 10^5$.

3.4 Wear mechanisms

The wear evolution under seawater–grease mixed lubrication indicates that the steel wire rope–drum flange interface undergoes a typical corrosion-assisted wear process controlled by the coupling of mechanical damage and electrochemical degradation. As schematically shown in Fig. 11, the grease-rich interfacial layer initially separates the contact pair and reduces direct metallic contact, so friction mainly occurs at local asperities. With continued reciprocating sliding, cyclic shear progressively disrupts the lubricant film and native oxide layer. The damaged protective layer allows chloride ions in the seawater medium to reach the exposed steel substrate, causing localized corrosion and corrosion pit formation. These corrosion pits weaken the surface layer and act as stress concentration sites, thereby promoting microcrack initiation and propagation under repeated sliding. Simultaneously, fractured asperities, metallic debris, and oxide debris are entrained into the interface and act as third-body abrasives, which accelerates material removal. The coupling mechanism can be described as a self-reinforcing wear–corrosion cycle. Mechanical wear strips remove lubricant films, oxide layers, and corrosion products, exposing fresh steel surfaces with high electrochemical

activity. These newly exposed surfaces are more susceptible to chloride-induced dissolution. Conversely, corrosion-assisted degradation reduces the integrity and load-bearing capacity of the surface layer, making it more vulnerable to ploughing, delamination, spalling, and crack growth. Under alternating stress and corrosive attack, microcracks preferentially initiate at the bases of corrosion pits. As abrasive ploughing and corrosive dissolution proceed together, initial pits develop into larger delaminated and spalled regions. In the final stage, accumulated corrosion products, continuous chloride ingress, cyclic stress, and electrochemical dissolution of the matrix jointly intensify the damage. Therefore, the final degradation state is controlled by a multimechanism interaction among abrasive wear, adhesive wear, corrosion fatigue, and corrosion-assisted degradation, resulting in severe corrosion-assisted wear of the steel wire rope matrix.

The microscopic observations in Fig. 12 confirm this mechanism evolution. At $N = 5 \times 10^4$ cycles, the worn surface shows corrosion pits, wear pits, debris accumulation, and material delamination (Fig. 12(a)). The damage morphology is dominated by the coupling of corrosion and adhesive wear; therefore, corrosive wear and adhesive wear are the main mechanisms in

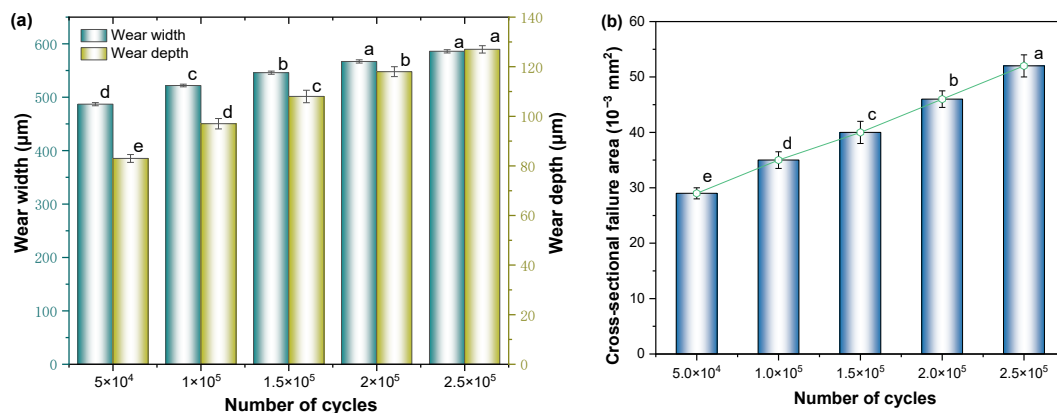


Fig. 10 Wear scar profile parameters: (a) wear width and wear depth and (b) cross-sectional failure area. Error bars represent standard deviations from three independent repeated tests. Different lowercase letters indicate statistically significant differences among groups according to one-way ANOVA followed by Tukey's post hoc test ($p < 0.05$).

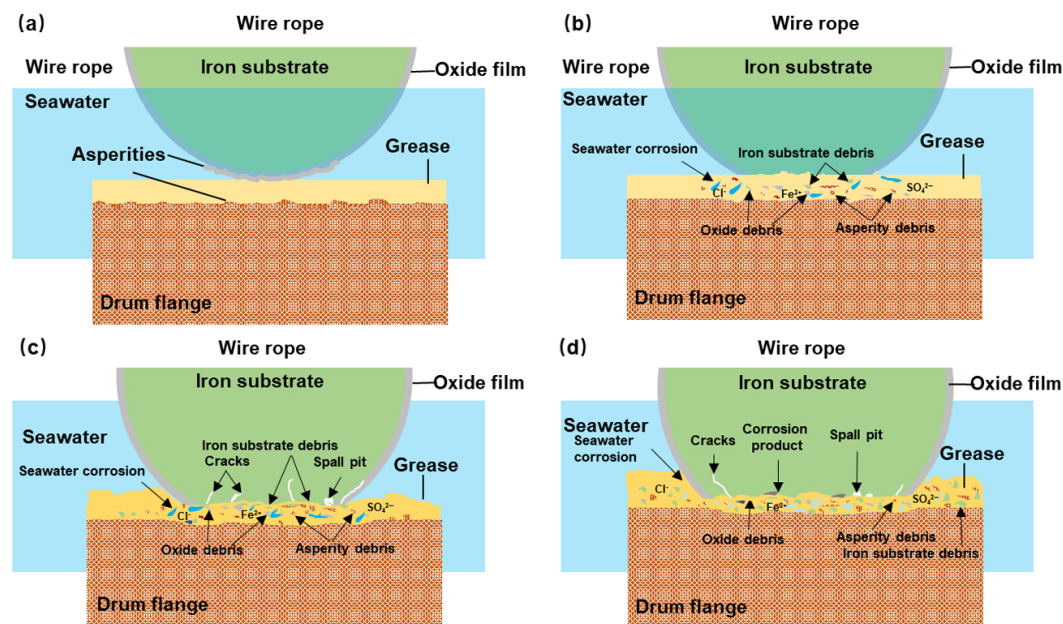


Fig. 11 Schematic illustration of corrosion-assisted wear damage of the steel wire rope under the grease + seawater condition.

this stage. At $N = 1 \times 10^5$ cycles, parallel wear tracks and scattered debris are observed along the sliding direction at low magnification, while ploughing grooves, localized spalling pits, and flocculent corrosion products appear at high magnification (Fig. 12(b)). These features indicate that abrasive wear begins to interact with corrosion-assisted degradation, and the dominant mechanism changes to abrasive wear combined with corrosive wear. At $N = 1.5 \times 10^5$ cycles, the wear zone exhibits severe ploughing deformation and accumulated corrosion products (Fig. 12(c)). Furrows, adhered materials, wear particles, corrosion grooves, plastic deformation, and microcracks further demonstrate that the interaction between seawater corrosion and mechanical wear has become more intense. At this stage, abrasive wear, adhesive wear, and corrosive wear act simultaneously. In the steady-state wear stage, Figs. 12(d) and 12(e) reveal parallel ploughing grooves, localized debris accumulation, and clustered corrosion products at low magnification, together with severe plastic deformation, microcracks, and agglomerated corrosion products at high magnification. These observations indicate that

the corrosion–wear coupling effect is further strengthened, and the wear mechanism finally evolves into a complex combination of corrosive wear, adhesive wear, and abrasive wear.

3.5 Volume loss and wear coefficient

The results in Fig. 13(a) indicate that wear loss accumulates continuously with increasing cycle number. Specifically, the wear volume increases from approximately 0.79 mm^3 at 5.0×10^4 cycles to 3.08 mm^3 at 2.5×10^5 cycles, corresponding to a 288.75% increase. This continuous increase reflects the progressive degradation of the contact interface during reciprocating sliding. The protective layer at the interface is repeatedly removed, and the fresh steel substrate is continuously exposed to the artificial seawater environment. Chloride ions then accelerate localized corrosion in the exposed regions, whereas mechanical sliding removes corrosion products and oxide films. The repeated coupling of protective film damage, substrate exposure, localized corrosion, and material removal is therefore responsible for the increasing wear volume. Unlike the monotonic increase in wear

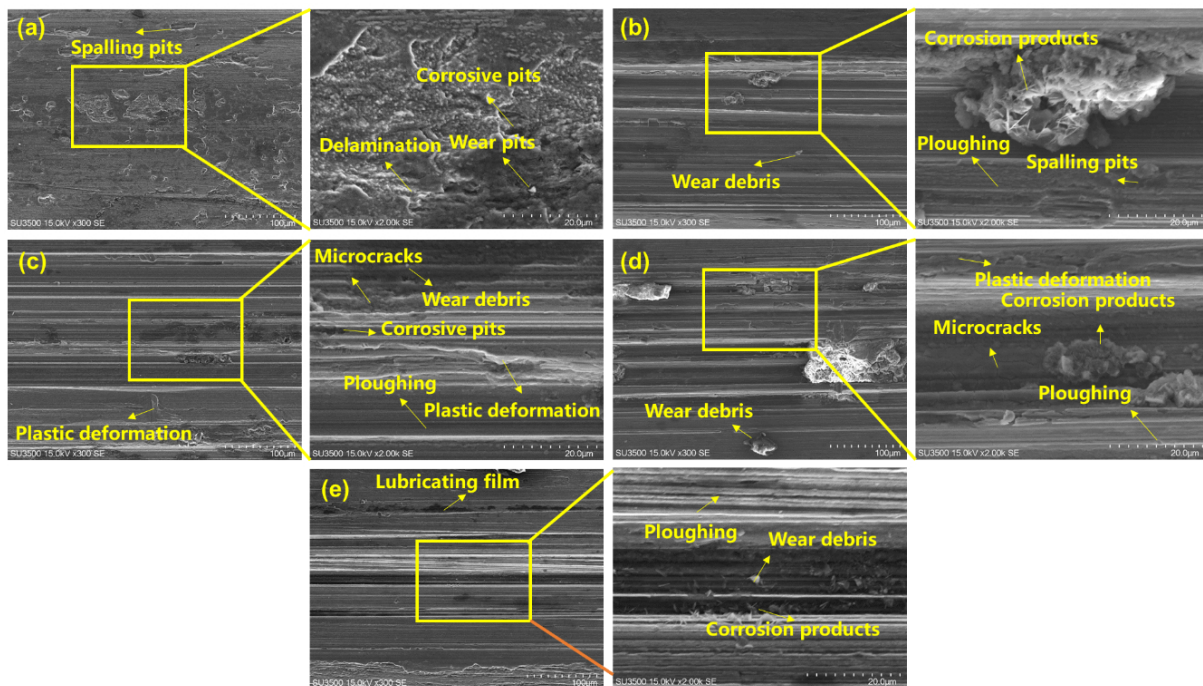


Fig. 12 SEM morphologies of worn wire surfaces: (a) $N = 5.0 \times 10^4$, (b) $N = 1.0 \times 10^5$, (c) $N = 1.5 \times 10^5$, (d) $N = 2.0 \times 10^5$, (e) $N = 2.5 \times 10^5$.

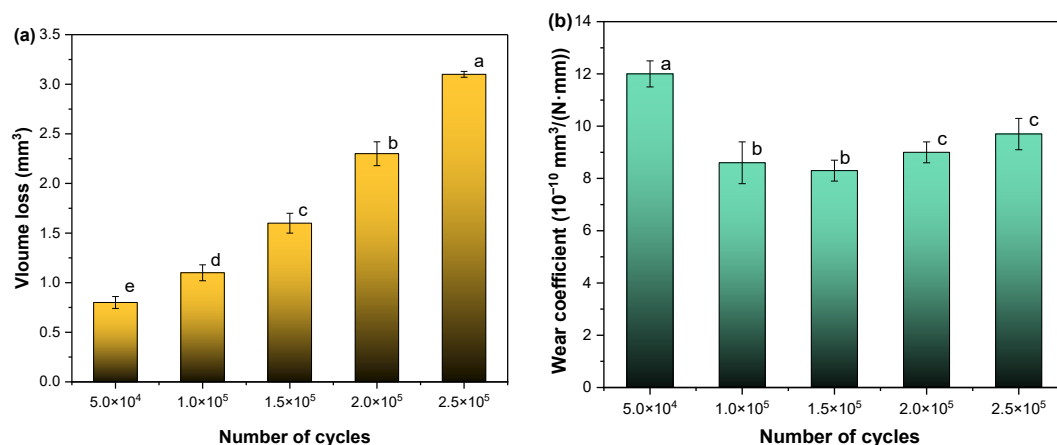


Fig. 13 (a) Volume loss and (b) wear coefficient. Error bars represent standard deviations from three independent repeated tests. Different lowercase letters indicate statistically significant differences among groups according to one-way ANOVA followed by Tukey's post hoc test ($p < 0.05$).

volume, the specific wear coefficient follows a three-stage evolution: initial decrease, relative stabilization, and slight increase, as shown in Fig. 13(b). The relatively high wear coefficient in the early stage is mainly associated with rapid rupture of the native oxide film under frictional shear. Once local defects are formed, chloride ions can penetrate the interface and attack the exposed steel substrate, thereby strengthening localized corrosion and corrosion-assisted wear. When the cycle number reaches 1.5×10^5 , the wear coefficient decreases to $8.2 \times 10^{-10} \text{ mm}^3/(\text{N} \cdot \text{mm})$, which is 31.1% lower than the initial value. This minimum value suggests that a protective interfacial structure has gradually developed. Under continuous shear, metallic wear debris, oxide corrosion products, and entrapped grease are mixed and compacted to form a composite lubricating protective film. This film improves the interfacial load-bearing capacity, blocks the corrosive medium, reduces direct chloride attack on the steel substrate, and suppresses abrasive-particle-induced ploughing. At 2.5×10^5 cycles, the wear coefficient increases slightly to $9.6 \times 10^{-10} \text{ mm}^3/(\text{N} \cdot \text{mm})$, but it remains clearly below the initial level. This slight rebound indicates that long-term cyclic stress and corrosive exposure cause local fatigue failure of the lubricating protective film, thereby enhancing the corrosion–wear coupling to a limited extent. Nevertheless, the persistence of a relatively stable, large-area lubricating film prevents severe wear acceleration and maintains the specific wear coefficient at a low level. Therefore, the evolution of the wear coefficient is governed by the competition between protective film formation and localized film degradation under coupled mechanical and corrosive actions.

4 Effect of frictional parameters on friction and wear behaviors

4.1 Friction coefficient

Figure 14 shows that both increasing contact load and increasing friction frequency contribute to a reduction in the steady-state friction coefficient of the steel wire rope. When the contact load rises from 1,400 to 1,800 N, the steady-state friction coefficient decreases from 0.40 to approximately 0.36, as shown in Figs. 14(a) and 14(b). This load-dependent reduction suggests that a more stable lubricating interface is formed under higher normal loading. Specifically, the increased load enlarges the real contact area of the line-contact pair, which facilitates grease spreading and enhances its film-forming capacity. The seawater medium also produces a stronger hydrodynamic lubrication effect, thereby separating the metallic surfaces more effectively and reducing the interfacial shear strength [38]. Meanwhile, higher loading promotes the crushing and flattening of surface asperities at the beginning of sliding, which shortens the running-in stage and accelerates the transition toward a stable friction state [39]. A similar decreasing tendency is observed with increasing friction frequency. As the frequency increases from 2 to 4 Hz, the steady-state friction coefficient drops from approximately 0.42 to 0.37. This behavior is associated with the higher interfacial shear rate induced by faster reciprocating motion. On the one hand, the increased shear rate promotes the orientational alignment of grease molecules, enabling the formation of a more uniform and

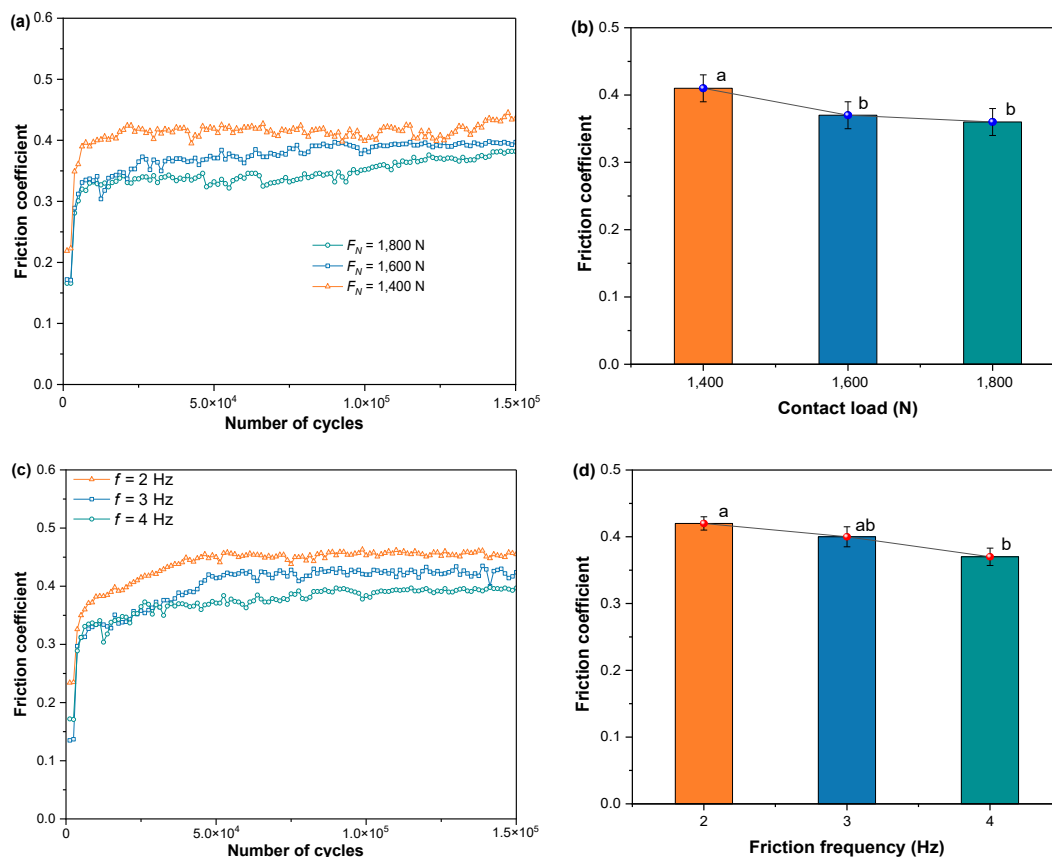


Fig. 14 Evolution curves of the friction coefficient under different frictional parameters: (a) friction coefficient under different contact loads, (b) friction coefficient in stable period under different contact loads, (c) friction coefficient under different friction frequencies, (d) friction coefficient in stable period under different friction frequencies. Error bars represent standard deviations from three independent repeated tests. Different lowercase letters indicate statistically significant differences among groups according to one-way ANOVA followed by Tukey's post hoc test ($p < 0.05$).

continuous protective film [40]. On the other hand, the higher frequency improves the renewal and replenishment of the seawater–grease mixture at the contact interface. This flow-assisted renewal removes wear debris more efficiently and reduces the abrasive contribution to friction. Therefore, the decrease in the friction coefficient under higher loads and frequencies can be attributed to the combined effects of enhanced grease film formation, strengthened seawater-assisted hydrodynamic lubrication, accelerated asperity smoothing, and improved debris removal.

4.2 Wear profile and cross-sectional failure area

Figure 15 demonstrates that both the contact load and friction frequency significantly affect the wear profile and cross-sectional failure area of the most severely worn wires. Under increasing contact load, the wear scar expands in both width and depth. Specifically, as the contact load increases from 1,400 to 1,600 N, the wear width increases from 522 to 546 μm , while the wear depth increases from 97 to 108 μm , corresponding to increases of 5% and 11%, respectively. When the contact load further rises to 1,800 N, the wear width and wear depth reach 584 and 129 μm , with increases of 7% and 19%, respectively. These results indicate a positive correlation between contact load and wear damage, and the accelerating increase suggests that higher normal loading intensifies local contact stress and promotes deeper material removal. Consistently, the cross-sectional failure area also increases with contact load and follows an approximately parabolic growth relationship, as shown in Fig. 15(b). The friction frequency produces a similar aggravating effect on the wear

damage. As shown in Fig. 15(c), increasing the frequency from 2 to 4 Hz enlarges the wear width from 504 to 546 μm , corresponding to an 8% increase, and increases the wear depth from 89 to 108 μm , corresponding to a 21% increase. The higher increase in wear depth compared with wear width indicates that material removal is more severe along the depth direction under high-frequency sliding. This behavior is mainly related to the intensified microcutting and ploughing effects of wear debris trapped at the contact interface. With increasing friction frequency, these abrasive particles interact with the worn surface more frequently, resulting in expanded wear scars and enhanced subsurface material loss. As presented in Fig. 15(d), the cross-sectional failure area increases from 0.03 mm^2 at 2 Hz to 0.033 mm^2 at 3 Hz and 0.04 mm^2 at 4 Hz, with an overall increment of 0.01 mm^2 . These results confirm that a higher friction frequency accelerates the accumulation of wear damage in the steel wire rope.

4.3 Wear mechanisms

Figures 16(a), 16(b), and 12(c) reveal that increasing the contact load significantly changes the surface damage mode of the worn steel wire. At 1,400 N, the worn surface is relatively smooth, and the damage is mainly reflected by parallel ploughing furrows along the sliding direction. Only localized debris accumulation, corrosion grooves, and clustered corrosion products are observed, indicating relatively mild corrosion-assisted abrasive damage. When the load increases to 1,600 N, the worn surface exhibits obvious plastic deformation, enlarged furrows, sliding-direction microcracks, and more widely distributed corrosion grooves and

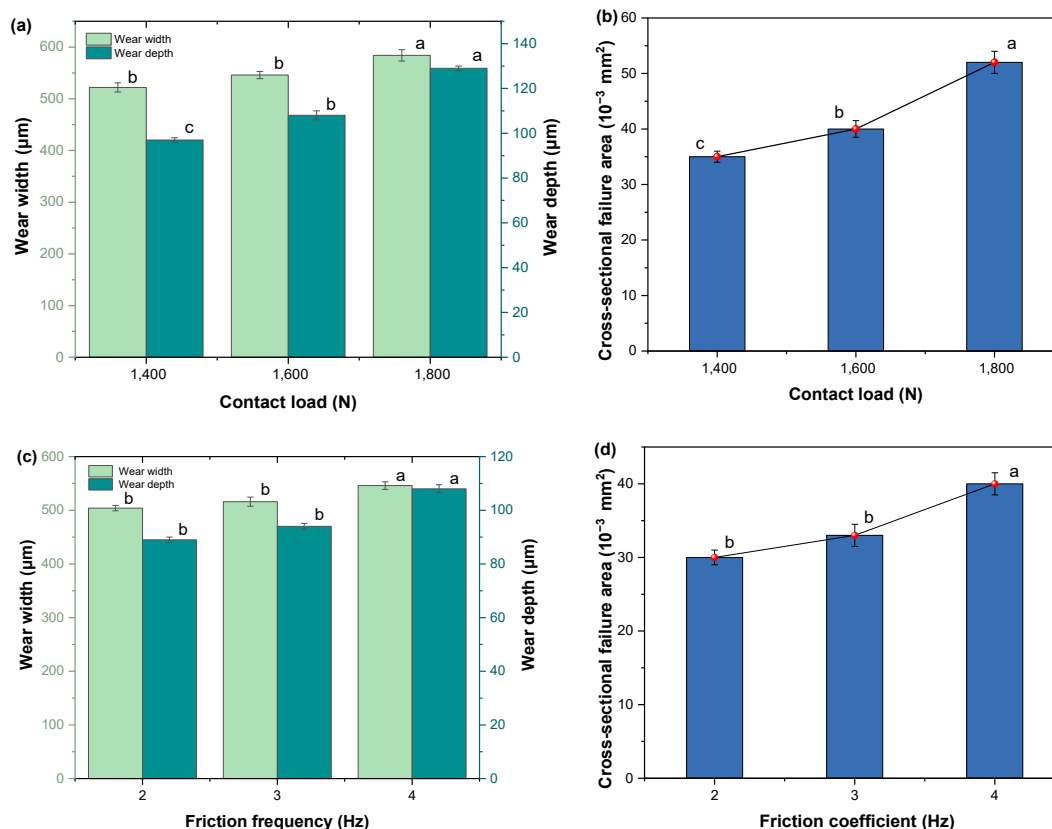


Fig. 15 Wear width, wear depth, and cross-sectional failure area of worn wires: (a) wear width and depth under different contact loads, (b) cross-sectional failure area under different contact loads, (c) wear width and depth under different friction frequencies, and (d) cross-sectional failure area under different friction frequencies. Error bars represent standard deviations from three independent repeated tests. Different lowercase letters indicate statistically significant differences among groups according to one-way ANOVA followed by Tukey's post hoc test ($p < 0.05$).

debris. This indicates that the higher contact stress promotes plastic strain accumulation and microcrack initiation. Meanwhile, entrained third-body particles produce stronger microcutting and ploughing effects, which intensify abrasive wear. The higher pressure also weakens the lubricating film locally, allowing seawater to penetrate the interface and interact with the exposed steel substrate. Consequently, the coupling between abrasive wear and seawater-induced localized corrosion becomes stronger. At 1,800 N, the damage mechanism changes from furrow-dominated abrasion to severe corrosion-fatigue-assisted delamination. The typical ploughing morphology is largely replaced by network cracks, lamellar corrosion delamination, abundant corrosion products, and numerous microcracks with cross-scale propagation. This transition is attributed to the combined action of high contact stress, tribo-thermal elevation, and Cl⁻-induced matrix corrosion. Under these conditions, the corrosive medium can penetrate rapidly along crack paths, promoting crack extension and lamellar spalling. The exfoliated corrosion products and metallic debris then act as additional third-body particles, further aggravating interfacial damage. The effect of friction frequency shows a similar transition from mild wear to severe coupled degradation. As shown in Figs. 16(c), 16(d), and 12(c), at 2 Hz, the surface damage is mainly characterized by parallel furrows, localized plastic deformation, slight debris accumulation, and local corrosion pits, suggesting that abrasive wear and corrosive wear dominate. At 3 Hz, the expansion of plastic deformation zones, enlargement of furrows, initiation of sliding-direction microcracks, continuous corrosion grooves, and debris

clusters indicate the development of a mixed mechanism involving abrasive wear, adhesive wear, and corrosive wear. When the frequency reaches 4 Hz, the contact surface displays extensive plastic deformation, dense microcracks, and corrosion grooves. The increased cyclic shear frequency promotes severe plastic strain accumulation, rapid crack initiation and propagation, and lamellar delamination. At the same time, frictional heat accumulation accelerates Cl⁻-induced localized corrosion, while the corrosive medium continuously invades the matrix through cracks. Thus, a positive feedback loop is formed: mechanical wear exposes fresh surfaces and promotes corrosion, whereas corrosion weakens the matrix and accelerates wear. This coupled wear-corrosion feedback is responsible for the severe degradation of the steel wire rope–drum flange contact surface.

4.4 Volume loss and wear coefficient

Figure 17(a) indicates that increasing the contact load intensifies material loss from the steel wire rope. When the contact load rises from 1,400 to 1,600 N, the volume loss increases from 1.30 to 2.31 mm³, representing a 78% increase. The wear coefficient also increases from 7.70×10^{-10} to 10.60×10^{-10} mm³/(N·mm), corresponding to a 38% increase. The enhanced volume loss is primarily caused by the higher pressure per unit contact area, which accelerates interfacial material detachment. However, the smaller increase in the wear coefficient compared with volume loss suggests that the material's intrinsic wear resistance is not seriously weakened within this contact-load range. The effect of friction frequency is shown in Fig. 17(b). As the frequency

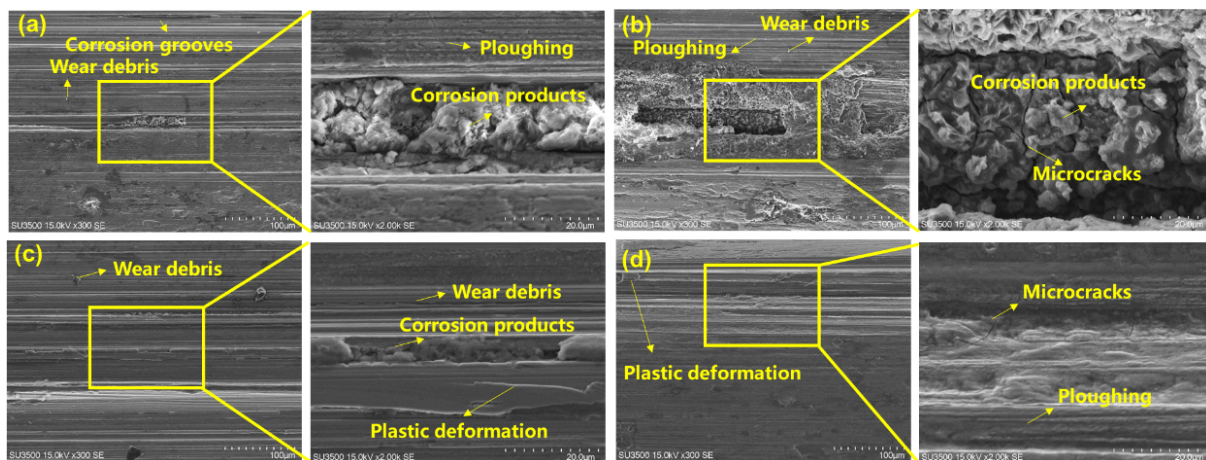


Fig. 16 SEM images of worn wire wear scars: (a) $F_N = 1,400$ N, $f = 4$ Hz, (b) $F_N = 1,800$ N, $f = 4$ Hz, (c) $F_N = 1,600$ N, $f = 2$ Hz, (d) $F_N = 1,600$ N, $f = 3$ Hz.

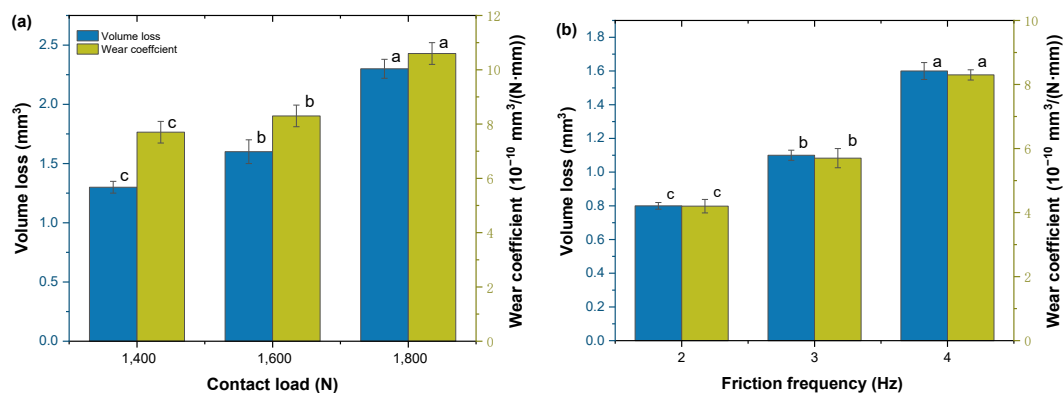


Fig. 17 Volume loss and wear coefficient under different friction parameters: (a) under different contact loads and (b) under different friction frequencies. Error bars represent standard deviations from three independent repeated tests. Different lowercase letters indicate statistically significant differences among groups according to one-way ANOVA followed by Tukey's post hoc test ($p < 0.05$).

increases from 2 to 4 Hz, the volume loss increases from 0.81 to 1.60 mm³, with a net increment of 0.79 mm³, while the wear coefficient increases from 4.20×10^{-10} to 8.30×10^{-10} mm³/(N·mm). This simultaneous increase is mainly governed by the higher number of friction cycles per unit time. Higher-frequency sliding promotes frictional heat accumulation and a local temperature rise at the interface, which may cause thermal softening of the surface layer. The resulting reduction in surface hardness promotes severe plastic deformation and facilitates material removal, thereby increasing both the volume loss and wear coefficient.

The opposite tendencies of the wear coefficient under increasing cycle number and increasing mechanical severity reflect two competing interfacial processes. Under constant contact load and frequency, increasing the cycle number favors interfacial running-in. Grease residues, metallic debris, corrosion products, and oxide debris are gradually compacted into a third-body/composite interfacial layer, which lowers the material removal efficiency per unit load and sliding distance [41, 42]. Therefore, the wear coefficient initially decreases with increasing cycle number. In contrast, when the cycle number is fixed, a higher contact load or friction frequency directly strengthens the contact stress, cyclic shear, debris-induced microcutting, and frictional heat accumulation [42]. These factors destroy the protective interfacial layer locally and accelerate material detachment. Consequently, the wear coefficient increases monotonically with contact load and friction frequency. Thus, the wear coefficient evolution is controlled by the balance between protective third-body layer formation and mechanically induced destruction of the interfacial layer.

5 Effect of environmental conditions on friction and wear behaviors

5.1 Friction coefficient

Figure 18 demonstrates that the service environment strongly affects the friction response of the steel wire rope–drum flange contact pair. Regardless of the environmental medium, the friction coefficient undergoes two characteristic stages: a rapid rise in the initial running-in stage and a subsequent steady-state wear stage with slight fluctuations. The steady-state average friction coefficient follows the sequence of air (0.71) > seawater (0.39) > grease + seawater (0.36) > grease (0.32), indicating that grease

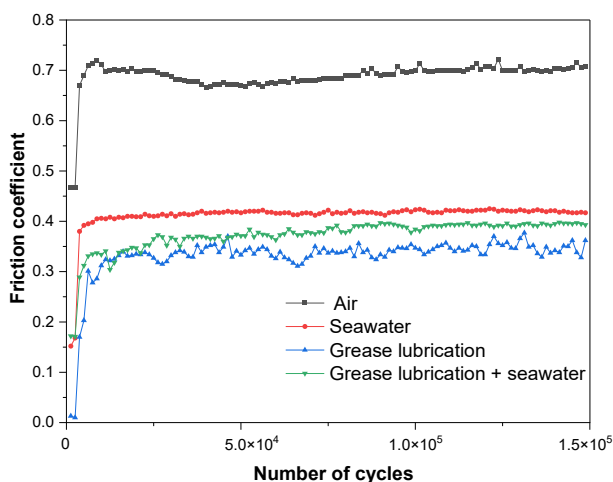


Fig. 18 Evolution curves of the friction coefficient of steel wire rope under different environmental service conditions.

lubrication provides the most effective friction reduction, whereas air produces the most severe frictional resistance. The highest friction coefficient in air is caused by typical dry friction behavior. Without an effective lubricating medium, surface asperities directly interlock and adhere to each other, leading to high interfacial shear resistance. In seawater, the friction coefficient decreases because polar water molecules can form a temporary liquid film between the wire rope and drum flange, which provides limited physical lubrication [43]. In addition, seawater cooling and the formation of oxide or corrosion product films help reduce direct metal-to-metal seizure [44]. However, the seawater film cannot maintain strong lubrication because of its low viscosity and limited load-carrying capacity. The lowest friction coefficient under grease lubrication is attributed to the formation of a stable and continuous grease film with good adhesion and a relatively high load-bearing ability. This film separates the friction pair surfaces, suppresses direct asperity contact, and reduces interfacial shear. The fluctuation in the grease-lubricated friction curve is mainly related to the unsteady interfacial flow of the grease. In the coupled grease + seawater environment, seawater ingress partially dilutes or emulsifies the grease, weakening film continuity and load-bearing capacity compared with pure grease. Local film rupture therefore slightly increases the friction coefficient. Nevertheless, residual grease still adheres to the steel surface and provides partial separation of the contact pair. Consequently, the grease + seawater condition exhibits a lower friction coefficient and reduced wear damage compared with seawater alone.

5.2 Wear profile and cross-sectional failure area

Figure 19 reveals that the service environment has a significant influence on the wear damage of the steel wire rope. In air, the absence of an effective lubricating medium leads to the most severe wear, with the wear width, wear depth, and cross-sectional wear area reaching 711 μm, 217 μm, and 0.040 mm², respectively. After seawater is introduced, these values decrease to 83%, 60%, and 48% of the air-condition values. This improvement is mainly associated with seawater-induced cooling and the formation of a transient interfacial liquid film, which partially suppresses frictional heat accumulation and sliding-induced surface damage. The strongest wear reduction is obtained under grease lubrication. The continuous grease film separates the contact pair surfaces and provides a stable physical barrier, thereby reducing the direct asperity interaction and material removal. Accordingly, the wear width, wear depth, and cross-sectional wear area are reduced to approximately 70%, 40%, and 27% of the values measured in air, respectively. In the grease + seawater coupled environment, however, seawater ingress partially damages the protective function of the grease film through localized dilution or emulsification. The resulting decrease in film continuity and load-bearing capacity causes the wear width, wear depth, and cross-sectional wear area to rise to 77%, 50%, and 36% of the air-condition values, respectively. Therefore, the environmental effect on wear damage follows the order of air > seawater > grease + seawater > grease. This trend indicates that wear reduction is governed by the competition between seawater-assisted cooling/transient lubrication and grease-film protection, while seawater-induced degradation of the grease film makes the coupled condition less protective than pure grease lubrication.

5.3 Wear mechanisms

Figures 20 and 21 reveal that the damage mode of the steel wire rope–drum flange contact pair strongly depends on the service

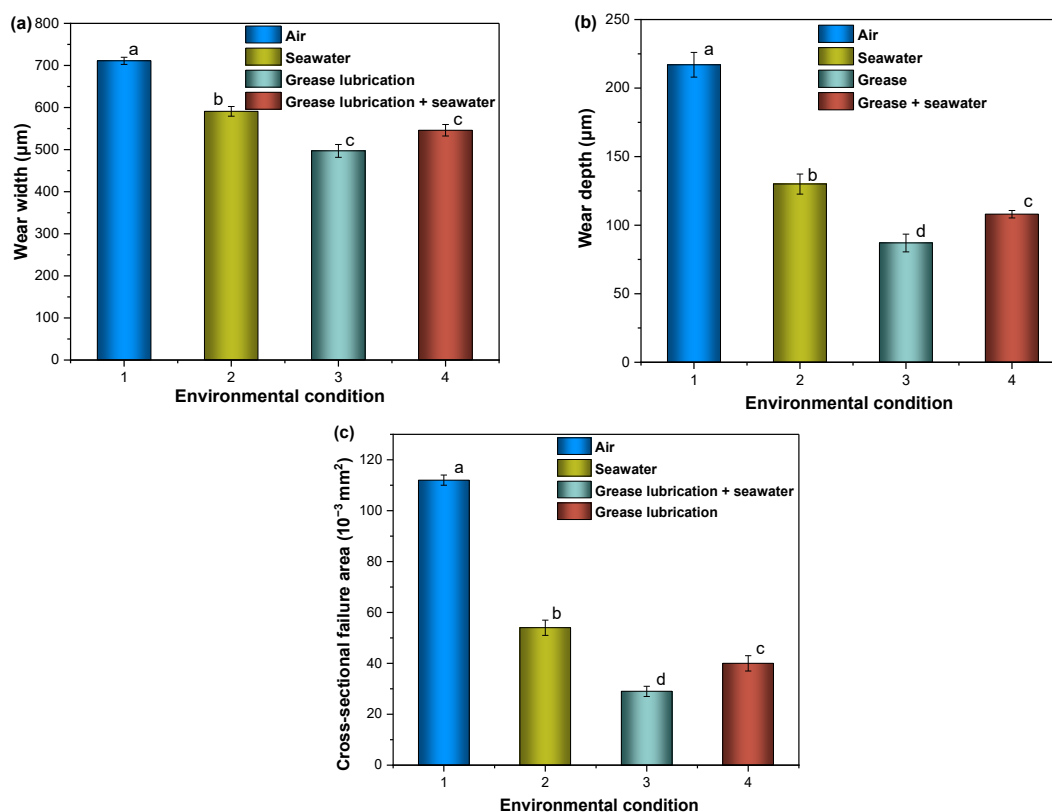


Fig. 19 Wear profile and cross-sectional failure area of worn wires under different environmental service conditions: (a) wear width, (b) wear depth, and (c) cross-sectional failure area. Error bars represent standard deviations from three independent repeated tests. Different lowercase letters indicate statistically significant differences among groups according to one-way ANOVA followed by Tukey's post hoc test ($p < 0.05$).

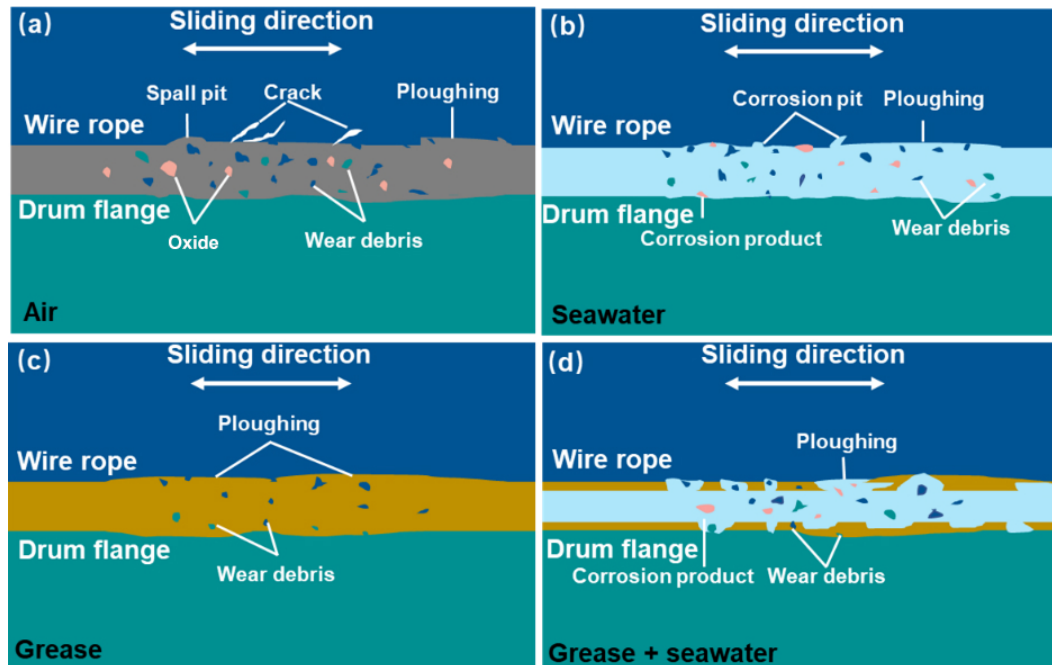


Fig. 20 Schematic illustration of the wear damage mechanisms of steel wire rope under different environmental conditions.

environment. The dominant degradation process evolves from mechanical wear in air to corrosion-assisted coupled wear in seawater-containing environments. In air, the absence of a lubricating medium leads to typical dry friction. Severe asperity interlocking and adhesion increase the interfacial shear resistance, so reciprocating sliding readily induces microcrack initiation, material delamination, and spalling. Frictional heat also promotes

surface oxidation and facilitates the detachment of oxidized wear debris. Accordingly, the worn surface in Fig. 21(a) exhibits large delaminated regions, spalling pits, and cracks, indicating that adhesive wear and oxidative wear dominate. In seawater, the damage mechanism changes from purely mechanical wear to corrosion-assisted wear. Although water molecules provide limited physical lubrication and cooling, Cl^- ions in seawater

penetrate the contact interface and induce localized pitting corrosion on the exposed steel surface. These corrosion pits create stress concentration sites, which accelerate microcrack initiation and propagation during reciprocating sliding. The dense corrosion grooves and deep ploughing marks observed in Fig. 21(b) indicate that corrosive wear and abrasive wear jointly control material removal [45, 46]. Under grease lubrication, the damage is greatly reduced because the grease forms a continuous physical barrier between the wire rope and the drum flange. This lubricating film suppresses direct asperity contact and lowers interfacial shear, resulting in a relatively smooth surface with only slight plastic deformation and fine microploughing marks (Fig. 21(c)). Therefore, the wear mechanism under pure grease lubrication is mainly mild abrasive wear [38]. The grease + seawater coupled environment shows an intermediate but more complex damage behavior. Residual grease still provides partial surface coverage and reduces direct contact between seawater and the steel substrate. However, seawater ingress locally emulsifies or dilutes the grease, reducing film continuity and load-bearing capacity. Once the protective film is damaged by mechanical ploughing, fresh metal is exposed and undergoes Cl⁻-induced electrochemical dissolution [46]. Reciprocating sliding then removes oxide debris and corrosion products, while newly formed corrosion products accumulate and further weaken the material's wear resistance [45]. The coexistence of spalling pits, microcracks, and clustered corrosion products in Fig. 21(d) demonstrates a

synergistic mechanism involving corrosive wear, abrasive wear, and adhesive wear. Therefore, the damage severity under the grease + seawater condition is higher than that under pure grease lubrication but lower than that under seawater exposure alone. Overall, the environmental effect can be interpreted as a competition between grease-film protection and seawater-induced corrosion, which results in an intermediate damage level between pure grease lubrication and seawater exposure.

5.4 Volume loss and wear coefficient

Figure 22(a) shows that the service environment has a substantial influence on the wear volume of the steel wire rope. Among the tested conditions, the air environment produces the largest wear volume, reaching 4.10 mm³. This value is approximately 1.5 and 4.5 times higher than those measured under seawater and grease lubrication, respectively. For the single-environment cases, the wear volume therefore decreases in the order of air > seawater > grease. The pronounced material loss in air is mainly attributed to dry sliding contact between the steel wire rope and the drum flange. Under this condition, direct asperity contact, adhesive junction formation, and repeated plastic deformation facilitate material delamination and spalling, thereby accelerating wear loss. Compared with air, the wear volume is reduced in seawater. This reduction can be explained by the transient cooling and lubricating effects of seawater, which partially alleviate direct dry contact and frictional heat accumulation during sliding [47].

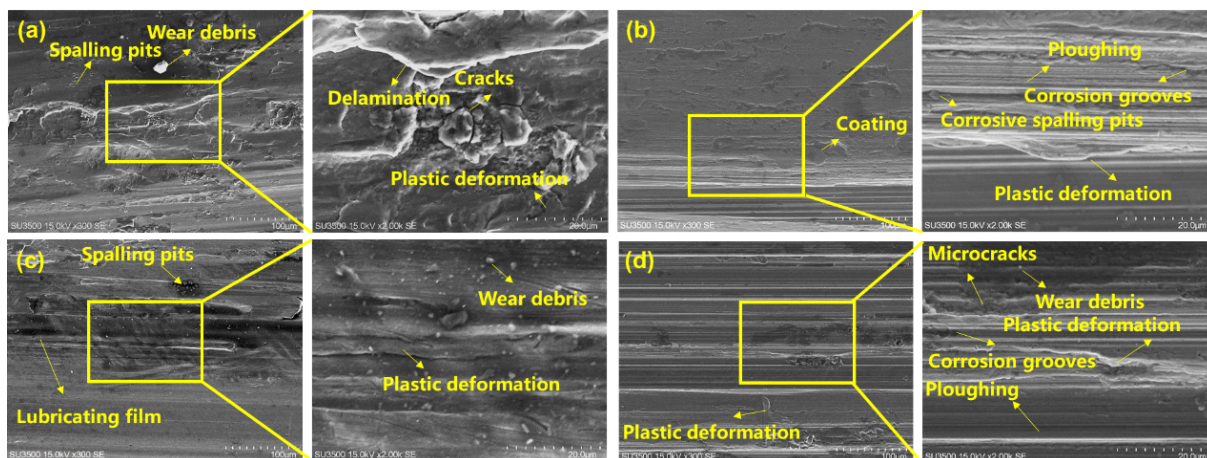


Fig. 21 Microscopic morphologies of the most severely worn wires under different environmental conditions: (a) air, (b) seawater, (c) grease, and (d) grease + seawater.

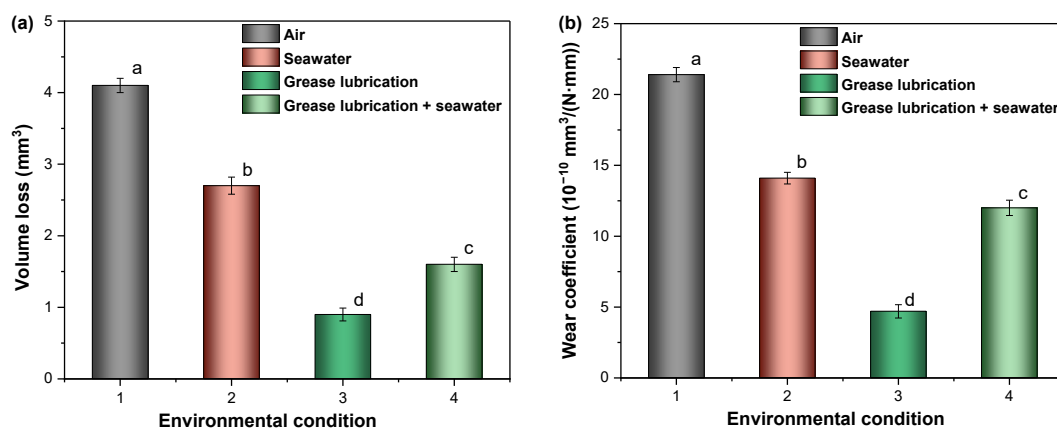


Fig. 22 Volume loss and wear coefficient under different environmental service conditions: (a) volume loss and (b) wear coefficient. Error bars represent standard deviations from three independent repeated tests. Different lowercase letters indicate statistically significant differences among groups according to one-way ANOVA followed by Tukey's post hoc test ($p < 0.05$).

Nevertheless, seawater has low viscosity and cannot form a stable lubricating film with sufficient load-bearing capacity. In addition, chloride ions promote localized corrosion on the exposed steel surface, while corrosion products and oxide debris may enter the contact interface and act as third-body abrasives during sliding [48]. Thus, although the wear volume in seawater is lower than that in air, corrosion-assisted wear and abrasive damage are still significant. The lowest wear volume is obtained under pure grease lubrication. This is because grease adheres to the steel wire surface and forms a relatively continuous lubricating film at the rope–flange contact interface. The grease film effectively reduces metal-to-metal contact, suppresses asperity shearing, and limits the penetration of corrosive media, thereby mitigating both mechanical wear and corrosion-assisted damage. In the grease + seawater coupled environment, the wear volume is lower than that in seawater but remains approximately 2.5 times higher than that under pure grease lubrication. This intermediate level of damage indicates that the grease film is partially deteriorated by seawater ingress but still maintains a certain degree of protection. Seawater may dilute or emulsify grease, reducing the film continuity, adhesion, and load-bearing capacity. Local rupture of the degraded film allows seawater to reach the exposed steel substrate, where localized corrosion and material removal are promoted during reciprocating sliding. However, compared with seawater alone, the residual grease layer still serves as a partial physical barrier and lubricant, reducing direct seawater exposure and corrosion-assisted wear.

Figure 22(b) further shows that the wear coefficient follows a variation trend similar to that of the wear volume. Under pure grease lubrication, the wear coefficient is $4.7 \times 10^{-10} \text{ mm}^3/(\text{N} \cdot \text{mm})$, corresponding to the strongest wear resistance among the tested environments. By comparison, the wear coefficients in seawater and grease + seawater are approximately 4.6 and 3.0 times higher than that under pure grease lubrication, respectively. In particular, the wear coefficient in the grease + seawater environment is approximately 15% lower than that in seawater alone, further verifying that the residual grease film still provides partial protection even after seawater-induced degradation. However, because seawater ingress weakens the lubricating film and promotes localized corrosion at film defects, the wear coefficient under grease + seawater remains considerably higher than that under pure grease lubrication. Taken together, the wear volume and wear coefficient results confirm that the wear severity follows the order of air > seawater > grease + seawater > grease. Therefore, the grease film under the grease + seawater condition should be regarded as a partially degraded but still functional protective layer: it is less efficient than pure grease lubrication but still reduces wear damage compared with seawater exposure alone [38].

6 Conclusions

Based on a custom-built wire rope test rig, this study systematically evaluated the friction and wear behavior of offshore drilling hoisting steel wire ropes under typical operating conditions, multiple service environments, and different frictional parameters. The coupled effects of cycle number, environmental condition, contact load, and friction frequency on wear evolution and damage mechanisms were clarified. The following conclusions can be drawn:

(1) The friction coefficient of the steel wire rope–drum flange contact pair exhibits a typical three-stage evolution with increasing cycle number, including rapid growth, gradual increase, and steady-state fluctuation. Higher contact loads and friction

frequencies reduce the steady-state friction coefficient. Among the tested environments, the steady-state friction coefficient increases in the sequence of grease, grease + seawater, seawater, and air, indicating that grease lubrication provides the most effective friction reduction.

(2) In the typical grease + seawater environment, the maximum wear depth of the wire rope increases as the number of cycles increases. The corresponding wear mechanism gradually shifts from mild adhesive/abrasive wear to a multimechanism damage mode involving abrasive wear, adhesive wear, and corrosion-assisted wear. The wear severity is positively related to the cycle number, contact load, and friction frequency, demonstrating that both prolonged cyclic sliding and increased mechanical severity accelerate rope degradation.

(3) The environmental medium strongly affects the wear resistance of the steel wire rope. The wear depth, volume loss, and wear coefficient of the wire rope, together with the wear width, wear depth, and cross-sectional failure area of the most severely worn wire, follow the decreasing order of air, seawater, grease + seawater, and grease. In air, dry contact promotes adhesive wear and oxidative wear. In seawater, abrasive wear and corrosion-assisted wear dominate due to the combined action of mechanical sliding and seawater corrosion. Grease lubrication substantially suppresses wear by forming a protective lubricant film. In the grease + seawater condition, seawater ingress partially deteriorates the grease film, but the remaining lubricant layer still reduces wear compared with seawater exposure alone.

(4) These findings indicate that controlling the lubrication and marine-medium exposure at the rope–drum flange interface is essential for improving the service reliability of offshore drilling hoisting systems. In practical applications, maintaining a continuous grease film, reducing seawater intrusion, enhancing sealing and drainage near the drum flange, using surface strengthening or corrosion-resistant treatments on the flange, and regularly inspecting the rope–flange contact region are recommended to reduce wear damage and improve the operational safety of the hoisting system.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Electronic Supplementary Material

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