

Study on the Tribological and Anti-icing Properties of GN/PUA-PTFE Coating on Railway Turnouts under Multiple Temperature Conditions

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Study on the Tribological and Anti-icing Properties of GN/PUA-PTFE Coating on Railway Turnouts under Multiple Temperature Conditions

Abstract: Three fast drying composite coatings were prepared from waterborne polyurethane acrylate (PUA) with graphene/PTFE as lubricants to improve the wear resistance and anti icing performance of railway turnout slide plates over a wide temperature range ($-25\text{ }^{\circ}\text{C}$ to $75\text{ }^{\circ}\text{C}$). The coatings were evaluated by friction and wear tests, low temperature icing experiments, and microstructural characterization. An optimal hardness to modulus ratio ($H/E = 0.0316$) and a water contact angle of 146° were obtained for the T3 coating with 15 wt% graphene. At $-25\text{ }^{\circ}\text{C}$, a 90.6% reduction in ice accretion relative to the steel substrate was achieved, and after thermal aging at $70\text{ }^{\circ}\text{C}$, the ice accretion remained 0.023 g. The lowest wear rate ($1.62 \times 10^{-4}\text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at $75\text{ }^{\circ}\text{C}$) and a friction coefficient as low as 0.16 were recorded for T3. A lubricating transfer film was formed by graphene/PTFE, superhydrophobicity and anti icing were imparted by the micro /nano structure, and wide temperature durability was ensured by the dense, chemically inactive structure. A design basis for fast drying coatings applied to turnout slide plates is thus provided.

Keywords: Railway turnout slide plate; fast-drying coating; graphene; wide-temperature-range tribology; anti-icing performance

1. Introduction

As the core component of a railway turnout system, the slide plate experiences multiple severe challenges—such as dry sliding friction and ice accretion—during the switching movement of the switch rail, as illustrated in Fig. 1. In high-altitude regions like the Qinghai–Tibet Plateau, winter temperatures can drop below $-20\text{ }^{\circ}\text{C}$, readily causing ice formation, whereas summer temperatures may exceed $30\text{ }^{\circ}\text{C}$, and the frictional heating generated during sliding further accelerates wear. Therefore, the slide plate must possess excellent wear resistance, anti-icing capability, and high-temperature stability to ensure long-term, reliable operation of the turnout system.

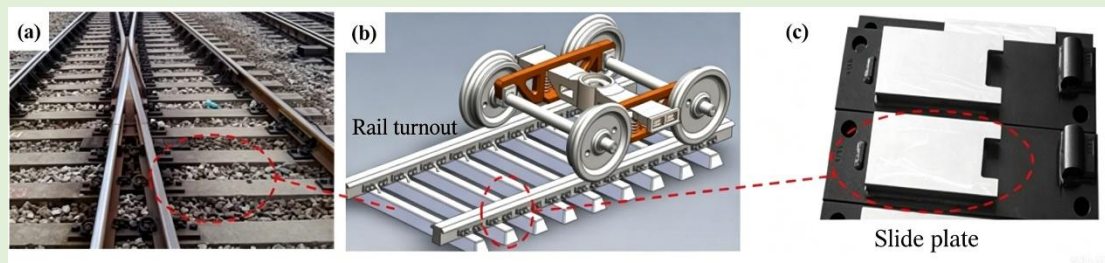


Fig. 1. Schematic illustration of a railway turnout: (a) the turnout, (b) the slide plate.

Steel alloys are commonly employed as materials for railway turnout slide plates. Liu [1] found that during dry sliding wear under a load of 50 N, the average friction coefficient of 304 stainless steel was 0.35, whereas the wear resistance of TiNi alloy was two orders of magnitude higher than that of stainless steel. It was reported by Godse [2]

that under loads of 8 kg, 12 kg and 16 kg, the friction coefficients of 304 stainless steel were 0.433, 0.491 and 0.537, respectively. Astudillo [3] compared the mechanical and tribological properties of Hadfield steel and Fermanal steel and found that under a load of 3 N, their average friction coefficients were 0.461 and 0.399, respectively. By Yazıcı [4], it was observed that the dominant wear mechanism of AISI 316L stainless steel was adhesive wear, and that the friction coefficient was approximately 0.4 at the onset of sliding and was observed to increase to 0.55 after 2000 s of testing. It can thus be concluded that steel alloys lack self-lubricating properties and exhibit high friction coefficients. A high friction coefficient is one of the primary factors responsible for the rapid failure of steel alloy components [5].

Surface technologies can be employed to enhance the performance of steel alloy slide plates under special environments, as the wear resistance of these materials is governed by their surface characteristics. Currently, the mainstream surface treatment methods include electrospark deposition, magnetron sputtering, thermal spraying, chemical vapor deposition, and others. To prepare a coating with high wear resistance and hardness, an electrode composed of a 92 wt% WC + 8 wt% Co mixture was deposited on a cast steel roll substrate by Wang [6] using electrospark deposition. The coating was found to exhibit a nano-scale granular and dendritic structure, a low friction coefficient of 0.13, and an average wear resistance 3.3 times that of the cast steel roll substrate. A duplex coating was produced on steel by Durdu [7] through electrospark deposition and micro-arc oxidation. It was found that the average friction coefficients of St35 steel, the ESD coating, and the duplex coating over a sliding distance of 0 to 100 m were 0.237, 0.273, and 0.281, respectively, with the latter exhibiting high tribological performance and wear resistance. By Komarov [8], it was discovered that the pre-hardening of a steel substrate exerts a significant influence on the tribological properties of magnetron-sputtered TiN coatings. The wear rate ratio between the TiN coating deposited on pre-hardened AISI 304 steel and that on non-hardened AISI 304 steel was reported to be 1.53, representing a 52.8% improvement in wear resistance. A WC-Co coating was thermally sprayed onto carbon steel by Wood [9]. It was found that the friction coefficient of the HVOF coating at room temperature was merely 0.30, and its tribological performance was demonstrated to be superior to that of the LENS-deposited coating. Multilayer graphene films were synthesized on GCr15 bearing steel substrates by Singh [10] in a low-pressure chemical vapor deposition (LPCVD) apparatus using a gas mixture of acetylene and hydrogen. A minimum friction coefficient of 0.13 was obtained at a normal applied load of 1 N. However, these methods are gradually being replaced by other technologies due to such drawbacks as low deposition rates, high cost of magnetron sputtering, relatively high coating surface roughness, the dependence of CVD techniques on high-temperature environments, and the complexity and high cost of the required equipment. At present, polymer coating technology has been widely applied

to railway turnout slide plates under various temperature conditions, demonstrating significant application advantages owing to its rapid curing characteristics, highly efficient production processes, light weight, and outstanding corrosion resistance and wear resistance. It was found by Friedrich [11] that nano-modified PEEK polymer coatings prepared on a bronze steel substrate exhibited excellent tribological performance under higher loads and at elevated temperatures. The average friction coefficient was maintained in the vicinity of 0.06 over the temperature range from 100 °C to 225 °C. Various polymers were selected as matrices by Zhang [12], and the 20-hour sliding processes of two PA 66 composites, with and without nanoparticles, were tested at 2 MPa and 2 m/s. Through comparison, it was found that the average friction coefficient of the SCF-reinforced composite at 100 °C was 0.8, whereas that of the nano-TiO₂-reinforced composite at 35 °C was only 0.33. The tribological properties of polymers at different temperatures were investigated by Huimin [13]. An epoxy/polyurethane polymer system with molecular ratios of 2:1 and 1:2 was designed, and a friction coefficient as low as 0.112 was recorded at 223 K. To improve the tribological properties of polymer coatings at room temperature, an epoxy coating was reinforced with nano-graphene by Zhang [14]. The results indicated that, at room temperature, the average friction coefficient of the coating containing 4.0 wt% graphene was only 0.74, which was 80% lower than that of the pure epoxy coating. The use of polyetheretherketone (PEEK) and polytetrafluoroethylene (PTFE) coatings was investigated by Stead [15] with an emphasis on their tribological performance between -20 °C and 120 °C. It was found that the friction coefficient of PEEK fluctuated in the range 0.75–0.1, whereas that of PTFE remained at approximately 0.05.

At extremely low temperatures, moisture or condensed water in the air may freeze on the surface of the slide plate. The normal fit between the slide plate and the switch rail and stock rail can be obstructed by this ice layer, resulting in difficult or inaccurate turnout switching. Moreover, when the ice layer is non-uniformly attached to the slide plate surface, uneven wear may be inflicted on the slide plate during the switching process, thereby accelerating its deterioration. Hence, excellent anti-icing performance is indispensable. A waterborne coating was prepared by Huang [16], which consisted of a copolymer network of methacrylic acid, acrylamide, N-2-hydroxyethyl acrylamide, and methoxypolyethylene glycol, with free polyethylene glycol dispersed therein. After 50 icing-deicing cycles, the time for complete ice accretion was 10 min, compared with 3 min for bare aluminum. A Fe₃O₄ nanoparticle/fluororesin composite superhydrophobic coating was proposed and fabricated by Wu [17] through a facile reverse permeation process. The robust nano/micro hierarchical structure ensured that the coating possessed outstanding superhydrophobic properties. At an ambient temperature of -20 ± 1 °C, the icing time was substantially prolonged from approximately 0.8 min to about 35.8 min. A mixed coating composed of a silicon-based compound and a PTFE compound was prepared by Wang [18], and a water contact angle of 108.5° was obtained. The freezing

time of water droplets on its surface could be significantly delayed; at an ambient temperature of -10°C , the time required for a water droplet to freeze was found to be approximately 29.5 s.

The above studies demonstrate that polymer coatings possess excellent anti-wear characteristics. However, under the complex operating conditions to which railway turnout slide plates—as a critical component—are subjected, research specifically addressing their performance under low-temperature dry sliding wear and icing-prone environments in vital regions is extremely scarce. In light of this, a novel polymer coating is conceived and designed in this study by incorporating three different contents of graphene into a PUA–PTFE/SiC–SiO₂ polymer system. Subsequently, such coatings are prepared on steel alloy surfaces, and tribological analyses and anti-icing tests are conducted under different temperature environments, together with the analysis of the friction, wear, and anti-icing mechanisms.

2. Experimental Sections

2.1 Coating Preparation

In this study, three graphene-reinforced PUA/PTFE fast-drying composite coatings (T1, T2, T3) with different filler ratios were designed; their specific compositions are presented in Table 1, and detailed information on each raw material together with its suppliers is provided in Appendix A, and the detailed methodology are provided in Appendix B.

Table 1. Composition and content of the three composite coatings.

Sample	Solvent	Epoxy resin	Lubricating filler			Wear-resistant filler		Additive
\	Alcohol	PUA	PTFE	GN	SiO ₂	SiC	PFOTES	
T1	14	16	2	2	4	1	1	
T2	14	16	2	3	3	1	1	
T3	14	16	2	6	0	1	1	

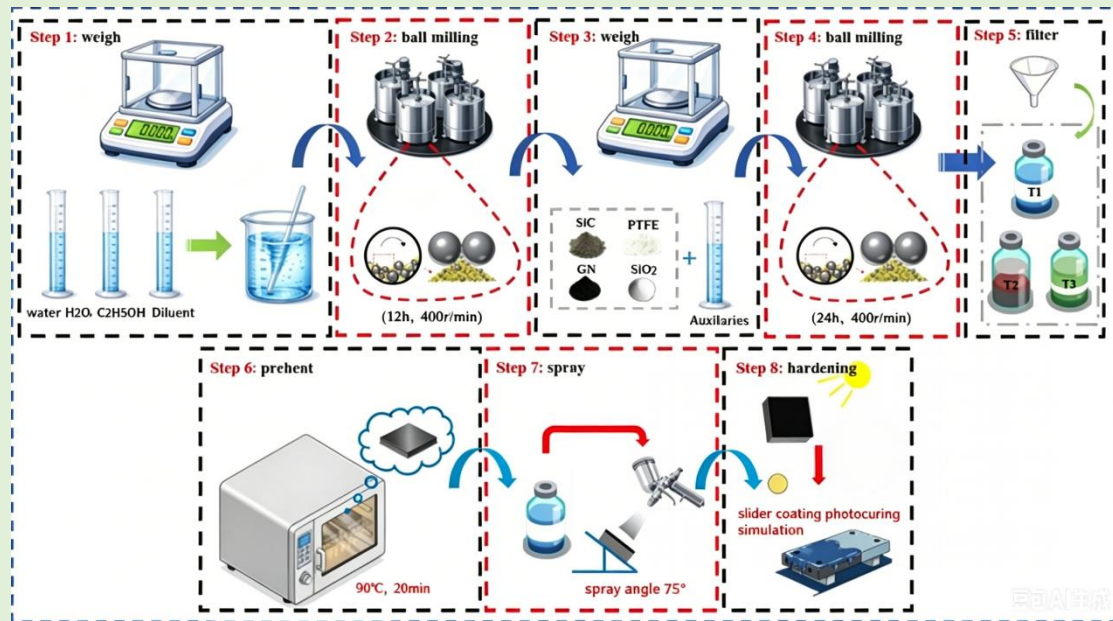


Fig. 2. Preparation of the composite coatings.

2.2 Characterization of coating micromorphology and mechanical properties

Comprehensive characterizations of the prepared coatings, including surface drying time (ASTM D1640, finger touch method), phase composition (XRD, D8 Advance, Bruker), surface and cross-sectional morphology (SEM/EDS, SU500, Hitachi), surface chemical states (XPS, PHI VersaProbe 4, ULVAC-PHI), Raman spectroscopy (DXR3, Thermo Fisher), wettability (water contact angle, SL250, Shanghai Solon), mechanical stability (sandpaper abrasion test, 200 g load, 500# sandpaper, 20 cycles), anti-icing performance (-25°C , 60% RH, ice accretion weight measurement), as well as hardness and elastic modulus (nanoindentation, TI Premier, Hysitron), are documented in Appendix C.

2.3 Friction and Wear Tests under Multiple Temperature Conditions

Under dry sliding wear conditions, the tribological performance of these composite coatings over a wide temperature range was evaluated using a high-temperature friction and wear tester (MMQ-02GL, Jinan Yihua Tribology Testing Technology Co., Ltd., China). Low temperature was achieved by liquid nitrogen cooling and an electric low-temperature control valve, and high temperature was controlled by a high-temperature furnace. To more accurately simulate the actual wide-temperature-range service environment, tribological experiments were conducted at -25°C , 25°C , and 75°C . The high-temperature condition was provided by the furnace, whereas the low-temperature condition was generated by liquid nitrogen cooling and precisely regulated by an electric cryogenic control valve. To simulate the working conditions of a railway turnout slide plate, a 304 stainless steel pin, which is commonly employed in turnout slide plates, was selected as the counterpart material. A normal load of 2 N was applied, and the contact stress state determined by the Hertzian contact theory was close to that encountered in

practice. The sliding radius was set to 5 mm, and the tribological test was conducted for a duration of 30 min. The experimental conditions were designed to simulate the dry sliding wear state of railway turnout slide plates at different temperatures. The lower specimen was the as-prepared coating sample, and rotational sliding friction was performed at a rotation radius of 5 mm. The chemical composition and content of the counterpart material are presented in Table 2.

Table 2. Chemical composition and content of the friction pair.

Friction pair	Chemical composition (wt%)									
	Cr	Fe	Ni	Mn	Cu	Al	GN	P	S	Si
304 stainless steel pin	8	Remainder	11	2	-	-	0.08	0.045	0.030	1

The wear tracks were measured using a laser scanning microscope (LSM 900, Carl Zeiss, Germany). The wear rate was calculated according to the wear rate formula [20].

3 Results and Discussion

3.1 Phase Analysis

The XRD patterns of the three polymer coatings with different GN/SiO₂ contents are presented in Fig. 3. The characteristic diffraction peaks of GN and SiO₂ can be clearly identified in the patterns. The characteristic peaks of GN are located at 26.6° and 54.7°, corresponding to its (004) and (008) crystal planes, respectively, which are consistent with the standard card PDF#26-1080. The strongest peak appears at 26.6°, and based on Bragg's law (Cu K α radiation, $\lambda \approx 1.54 \text{ \AA}$), the interlayer spacing is calculated to be approximately 0.335 nm, indicating that the typical graphitic layered structure of GN is retained [21]. The characteristic diffraction peaks of SiO₂ are located at 35.9° and 39.1°, corresponding to the (110) and (102) crystal planes, respectively. For the T3 coating, in which no SiO₂ was incorporated in this study, no obvious diffraction peaks are observed at the corresponding positions, which is consistent with the design. In addition, the characteristic diffraction peaks of SiC are detected in all coatings, located at 34.1°, 45.2°, and 65.6°, corresponding to the (101), (105), and (109) crystal planes, respectively. It can be observed from the patterns that the diffraction peak intensity of GN is correspondingly enhanced as the GN content increases, whereas the diffraction peak intensity of SiO₂ is weakened as its content decreases. After sunlight curing, no shift is observed in the diffraction peak positions in the XRD patterns of any coating, indicating that GN exhibits

good chemical stability during the curing process and does not react with the other components of the coating.

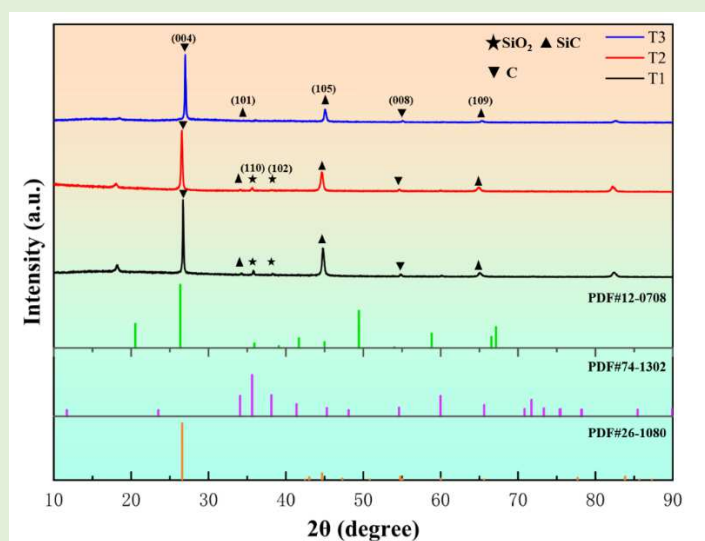


Fig. 3. XRD patterns of the three composite coatings.

3.2 Water Contact Angle

In cold environments, the slide plate is susceptible to cold air attack, causing ice to form on its surface, which can prevent the timely completion of rail-switching operations at the turnout. Therefore, ensuring good anti-icing performance is indispensable. According to the literature [22], hydrophobic materials with excellent anti-icing properties have been reported, and on this basis, the water contact angle was measured in this study. The corresponding results are presented in Fig. 4; the water contact angles of the T1 coating, T2 coating, T3 coating, and the steel substrate were 116°, 140°, 146°, and 74°, respectively. The steel substrate surface was found to exhibit a hydrophilic state, whereas the T3 coating demonstrated the best hydrophobic performance. In the literature [23–24], it has been reported that hydrophobic nanoparticles are mixed with polymers to improve the hydrophobicity of coatings, and rough, polymer-wrinkled particle morphologies have been exhibited. The surfaces of the three composite coatings were therefore characterized by SEM, and the results were found to resemble those described in the above literature. The surface of the T1 coating was smoother than those of the other two coatings, and distinct pores were observed on the surface, through which water molecules could readily penetrate into the interior of the coating, causing the surface wettability to be greatly enhanced; this observation was corroborated by the water contact angle shown in Fig. 4(a). In contrast, the surface of the T3 coating was uniformly covered with a micro-/nano-porous structure, as shown in Fig. 5(c). A large amount of air could be trapped by this regular porous structure, reflecting the good hydrophobic performance of the T3 coating.

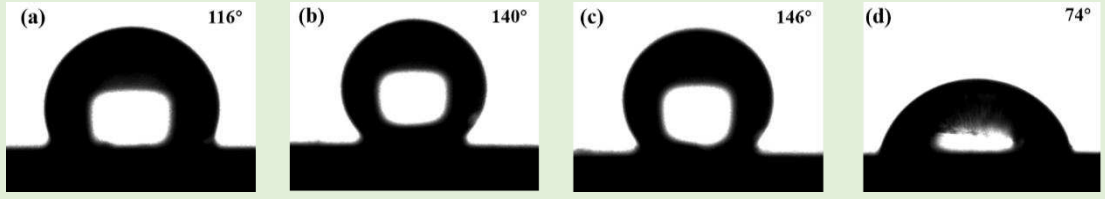


Fig. 4. Water contact angles of the three coatings and the substrate: (a) T1 coating, (b) T2 coating, (c) T3 coating, and (d) steel substrate.

Furthermore, to better investigate the hydrophobic properties of the polymer coating surfaces, SEM characterization of the three polymer coatings was conducted, as presented in Fig. 5. It was observed that the T1 coating surface was smoother than those of the other two coatings and exhibited numerous pores and cracks. Such a microstructure allows water molecules to readily penetrate into the interior of the coating, greatly enhancing its wettability; this phenomenon is corroborated by the minimum water contact angle shown in Fig. 4(a). As shown in Fig. 5(c), the surface of the T3 coating was evidently covered with a micro-/nano-porous structure. This highly ordered, hierarchically rough structure can effectively trap and stably retain a large amount of air at the solid–liquid interface, thereby forming a stable air cushion layer on the coating surface.

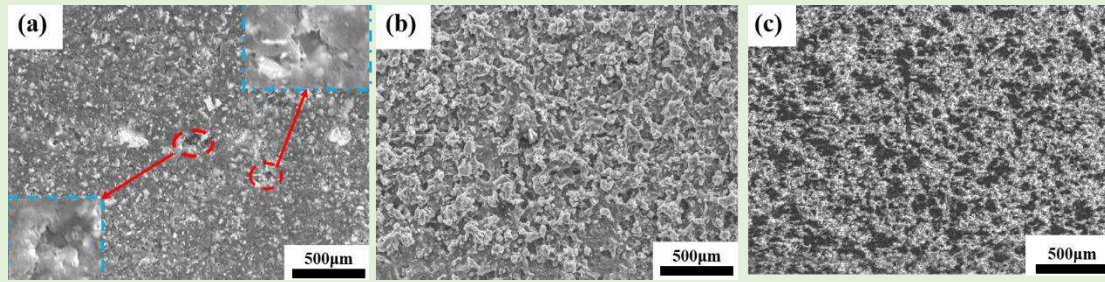


Fig. 5. Surface SEM images of the three coatings: (a) T1 coating, (b) T2 coating, and (c) T3 coating.

For a more comprehensive characterization of the wetting behavior of the coating surfaces, contact angle hysteresis tests were further performed on the basis of the static water contact angle measurements, and the corresponding data are presented in Table 3. The advancing contact angle (θ_A) and receding contact angle (θ_R) were measured, and the water contact angle hysteresis (θ_{CAH}) was derived as their difference ($\theta_A - \theta_R$). The smallest contact angle hysteresis was exhibited by the T3 coating. The experimental results were combined with theoretical models. According to the general hysteresis angle model proposed by Makkonen [25] and Li [26], the extra friction tension ($F/W = \gamma_{SL}$) generated at the continuously moving advancing contact line must be balanced by a corresponding variation in the contact angle, namely:

$$\gamma_{SL,A} = \gamma_{LV}(\cos\theta - \cos\theta_A) \quad (3-1)$$

$$\gamma_{SL,R} = \gamma_{LV}(\cos\theta_R - \cos\theta) \quad (3-2)$$

$$\Delta E = \gamma_{SL,A} - \gamma_{SL,R} = \gamma_{LV}(\cos\theta_R - \cos\theta_A) \quad (3-3)$$

In Eqs. (3-1) and (3-2), γ_{LV} denotes the surface tension of water, which is typically 72.8 mJ/m². The advancing and receding contact angles of the three polymer coatings were substituted into Eq. (3-3), and the contact angle hysteresis energy differences (ΔE) between the advancing and receding states for the T1, T2, and T3 coatings were calculated to be 35.25 mJ/m², 21.76 mJ/m², and 10.85 mJ/m², respectively. For the T3 coating in this study, the ΔE was found to be 10.85 mJ/m², which is very close to the low hysteresis energy difference typically exhibited by superhydrophobic coatings (generally < 10 mJ/m²), indicating surface wetting characteristics that approach an ideal superhydrophobic state. The hysteresis energy difference can faithfully reflect the “adhesion” of a surface [27–28]. The T1 coating was shown to possess the lowest static contact angle but the largest hysteresis energy difference, suggesting the strongest “pinning” effect on water droplets and making droplet motion difficult on the surface. In contrast, the T3 coating not only exhibited the highest static water contact angle but also the smallest hysteresis energy difference; its surface was highly uniform and featured a micro-/nano-rough structure (Fig. 4(c)), allowing water droplets to slide off extremely easily with minimal energy dissipation.

Table 3. Contact angle hysteresis data of the polymer coatings and the steel substrate.

Sample	WCA/(°)	Theta A/(°)	Theta R/(°)	Contact angle hysteresis/(°)	f1/%
T1	116	131.6	100.4	31.2 ± 2.0	44.0
T2	140	153.4	126.5	26.9 ± 1.8	18.3
T3	146	153.6	138.3	15.3 ± 1.3	13.4
Steel	74	76.9	79.1	/	/

Furthermore, all three polymer coatings were demonstrated by their water contact angles to be in a hydrophobic state. This phenomenon can be explained by the Cassie–Baxter theory: when a water droplet is brought into contact with the hydrophobic coating surface, a large amount of air is trapped in the voids on the surface owing to its unique micro/nano-structure, and the contact between the water droplet and the solid surface is consequently reduced. Under this condition, the coating surface is actually a composite interface composed of air and the protruding solid surface, which can be expressed by the Cassie–Baxter equation [29]:

$$\cos \theta_y = f_1 \cos \theta_1 + f_2 \cos \theta_2 \quad (3-4)$$

In Eq. (3-4), the apparent contact angle of the coating surface is denoted by θ_y ; the area fractions of the solid surface and air per unit apparent area are represented by f_1 and f_2 , respectively ($f_1 + f_2 = 1$); and the intrinsic contact

angles of a water droplet on the solid surface and in air are denoted by θ_1 and θ_2 , respectively. Since the contact angle of a water droplet in air, θ_2 , is equal to 180° , Eq. (3-4) can be simplified to Eq. (3-5):

$$\cos \theta_y = f_1(\cos \theta_1 + 1) - 1 \quad (3-5)$$

Based on the contact angle of the aluminum surface in Fig. 3(d) and the contact angles of the hydrophobic coatings T1, T2, and T3 presented in Table 3, the area fractions of the solid surface in the composite interfaces of the three hydrophobic coatings were calculated to be 44%, 18.3%, and 13.4%, respectively. That is, the area fractions of water droplets in contact with air were 56%, 81.7%, and 88.1%, respectively. This result indicates that for the T3 coating, which exhibits the strongest hydrophobicity, the real contact area between its surface structure and water droplets is the smallest—only approximately 11.9%—while up to 88.1% of the area is in contact with air. This is a characteristic feature of the Cassie–Baxter state: water droplets primarily “sit” on a trapped air cushion, which greatly reduces solid–liquid contact and adhesion, thereby giving rise to a high contact angle and a low contact angle hysteresis. This finding also provides strong data support for the subsequent icing experiments.

3.3 Microstructural Characterization

The cross-sectional micro-morphologies of the three polymer coatings are presented in Fig. 6. As shown, all three coatings are tightly bonded to the substrate, and no distinct defects are observed at the interfaces. From the cross-sectional morphologies, it can be further seen that the best compactness is exhibited by the T3 coating, followed by the T2 coating. This result is primarily attributed to the structural regulation effect exerted by the addition of graphene (GN) and its surface modification. On the one hand, GN is characterized by a typical layered structure with weak interlayer van der Waals forces; slip can readily occur during its deposition, thereby reducing the frictional resistance between particles and facilitating particle rearrangement and dense packing. On the other hand, the surface energy of GN can be reduced by the modifier PDMS/PFOTES, particle agglomeration can be mitigated, and its dispersion and flowability in the system can be further improved. Consequently, with the increase in GN content, the compactness of the coating is enhanced, while the uniform deposition and arrangement of other filler particles are also promoted. Combined with the surface SEM morphologies of the three coatings shown in Fig. 6, it can be observed that the T3 coating exhibits an interwoven and densely packed structure with the best denseness, which effectively reduces voids and defects within the coating. In contrast, the compactness of the T1 and T2 coatings is relatively poor: obvious pores and defects are visible on the surface of the T1 coating, which is mainly caused by the difficulty in dispersing the high content of SiO_2 nanoparticles in the polymer matrix and their severe agglomeration. The interfacial bonding between the agglomerates and the matrix is weak, so that they readily become pore nucleation sites and stress concentration sources. Meanwhile, the GN content in this coating is low, and the

graphene nanosheets fail to form a continuous network structure, thereby being unable to effectively suppress SiO₂ agglomeration or fill the gaps between particles. The maximum pore size in the T1 coating is approximately 7.32 μm , and agglomeration and stacking of GN and SiO₂ are still observed in the T2 coating. These results are consistent with the descriptions reported in the literature [30–33] that SiO₂ exhibits poor dispersion in the PTFE matrix and tends to cause internal aggregation of the material.

To further investigate the influence of GN and SiO₂ content on the coating microstructure, the distribution and content of C, Si, and O elements in the three coatings were characterized by EDS. The elemental distributions are presented in Fig. 7, and the corresponding contents are listed in Table 4. From the EDS results, localized aggregation of SiC and C elements can be observed in the T1 coating, together with a small amount of SiO₂ agglomeration; in the T2 coating, a certain degree of aggregation is exhibited by all three elements, C, Si, and O. These distribution characteristics corroborate the morphological results observed by SEM. The elemental contents of the three coatings listed in Table 4 are basically consistent with the material compositions adopted in the experimental design, which further confirms the reliability of the preparation process and the controllability of the coating composition.

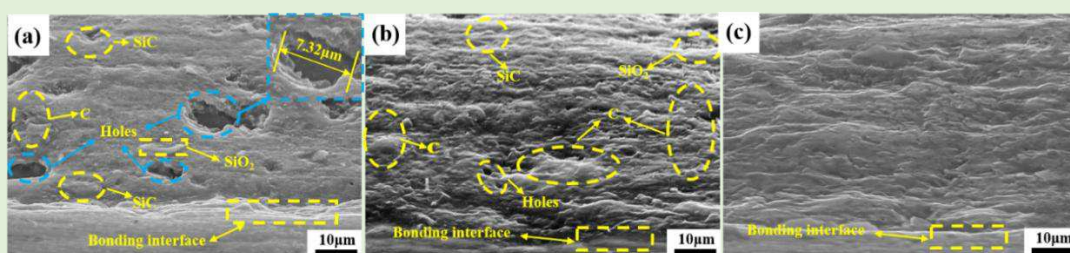


Fig. 6. Cross-sectional micro-morphologies of the polymer coatings: (a) T1 coating, (b) T2 coating, and (c) T3 coating.

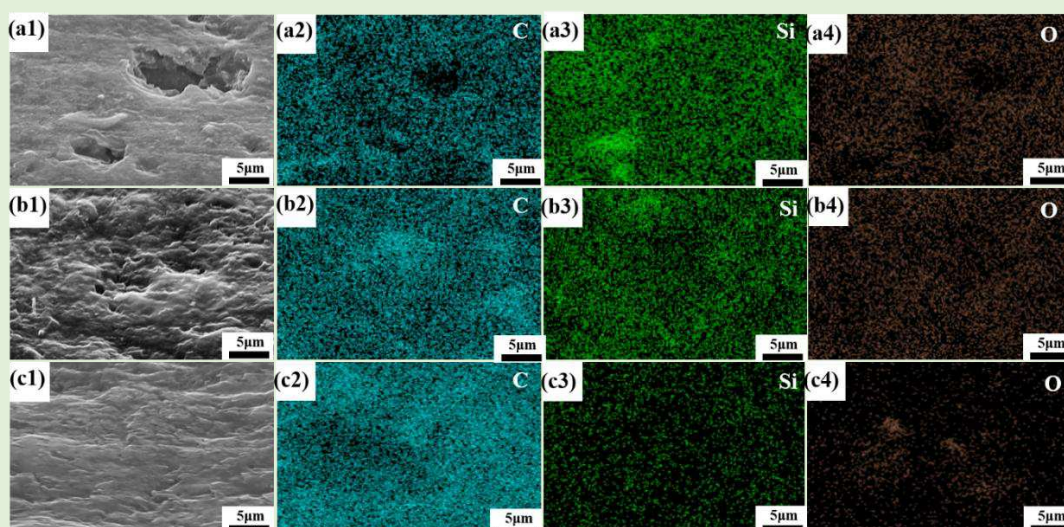


Fig. 7. EDS scanning results of the coatings: (a) Z1 coating, (b) Z2 coating, and (c) Z3 coating.

Table 4. EDS analysis of the different coatings.

Sample	Elemental content (wt%)		
	C	O	Si
T1	62.67	25.64	11.48
T2	66.48	24.60	8.66
T3	82.08	15.74	1.84

To further investigate the differences in chemical composition and microstructure of the synthesized polymer coatings, the XPS spectra are presented in Fig. 8. The survey spectrum of GN-SiO₂ is shown in Fig. 8(a), in which strong signals of three elements are observed, including O 1s, F 1s, C 1s, and Si 2p. In Fig. 8(b), three distinct intensity peaks are identified in the C 1s spectrum, corresponding to C-C bonds (284.8 eV), C-O-C bonds (286.4 eV), and O-C=O bonds (288.5 eV). The C-C bond constitutes the predominant peak in the entire C 1s spectrum with the highest intensity, and it is mainly derived from the sp²-hybridized carbon of graphene (GN) and the aliphatic carbon backbone of the waterborne polyurethane acrylate (PUA). The O-C=O bond corresponds to carbonyl carbon, which is a distinctive characteristic of ester functional groups, and its main source is the ester linkages in the PUA molecular chains. Furthermore, as revealed by Figs. 8(c-d), the intensities of both C=O and C-O bonds in the T1 coating are higher than those in the T3 coating. Two primary reasons can be identified for this observation. On the one hand, graphene is a carbon material with a sp²-hybridized carbon six-membered ring structure, its intrinsic C-C bond corresponding to a C 1s peak at 284.8 eV, and it is characterized by low, or even negligible, oxygen content [34]. In the T3 coating, the high GN content acts as an “inert filler”, by which the relative concentration of the PUA resin (the main source of oxygen-containing functional groups) within the detected region is reduced. On the other hand, SiO₂ filler is present in both the T1 and T2 coatings. In its normal state, SiO₂ is hydrophilic, and its surface is typically rich in hydroxyl (-OH) and silanol (Si-OH) groups; moisture can be readily adsorbed via hydrogen bonding, or local oxidation can occur in air to form oxygen-containing functional groups (C=O, C-O). No SiO₂ is contained in the T3 coating, and thus any possible contribution of oxygen-containing functional groups introduced by SiO₂ is avoided, by which the overall C-O and C=O signals are further reduced.

An anomalous result is observed in Figs. 8(e-f). Although the total SiO₂ content is zero in the T3 coating, the intensity of its surface Si 2p signal is found to be higher than that of the SiO₂-rich T1 coating. This strongly indicates that surface enrichment of the SiC wear-resistant filler has occurred during the curing process of the T3 coating. Such a surface enrichment effect is mutually corroborated by the highest nanohardness and the optimal compactness

of the T3 coating (Fig. 6(c)). It implies that a “hard layer” reinforced by SiC is formed on the outermost surface of the T3 coating, which plays a crucial role in its outstanding wear resistance under a wide range of operating conditions.

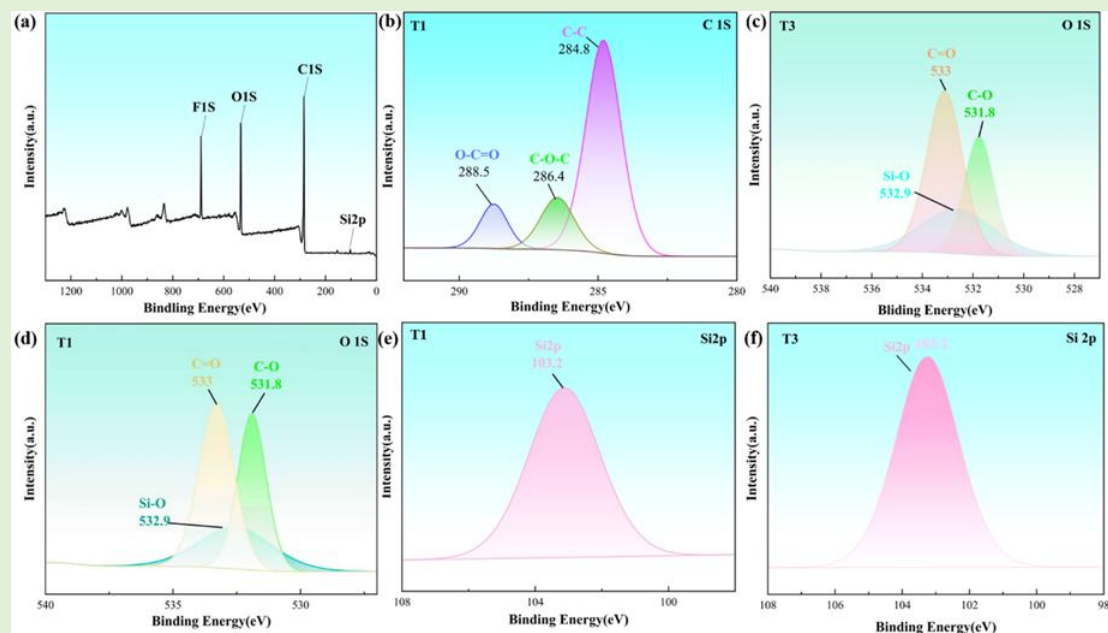


Fig. 8. (a) XPS survey spectrum of the composite coating; (b) C 1s spectrum of the T1 coating; (c) O 1s spectrum of the T3 coating; (d) O 1s spectrum of the T1 coating; (e–f) Si 2p spectra of the T1 and T3 coatings.

The Raman spectra are presented in Fig. 9 A broad envelope in the range of 400–800 cm^{-1} is observed for the T1 coating, which is characteristic of amorphous SiO_2 and is consistent with the formulated composition of T1; in contrast, no obvious SiO_2 signal is detected in the same region for the T3 coating, confirming the absence of SiO_2 in its composition. Distinct characteristic peaks at 1350 cm^{-1} and 1580 cm^{-1} are observed for all three coatings, corresponding to the D band and G band of graphene, respectively. According to the literature [35], the D band and G band are indicative of the disorder and the graphitic order of carbon, respectively, and the intensity ratio of the D band to the G band ($I_{\text{D}}/I_{\text{G}}$) is regarded as an important indicator for evaluating the internal structure of coating materials. A smaller $I_{\text{D}}/I_{\text{G}}$ ratio is associated with a higher degree of order and fewer defects. The $I_{\text{D}}/I_{\text{G}}$ values of the T1, T2, and T3 coatings were determined to be 1.32, 0.62, and 0.46, respectively, and a gradual decrease in $I_{\text{D}}/I_{\text{G}}$ was observed with increasing graphene content. These results are corroborated by the SEM morphologies of the three composite coatings presented in Fig. 5, where loose structures and pores were found for the T1 and T2 coatings, whereas fewer defects and higher compactness were exhibited by the T3 coating.

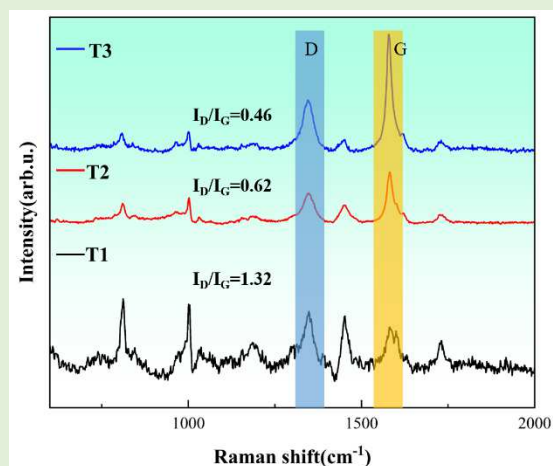


Fig. 9. Raman spectra of the composite coatings.

3.4 Coating Durability

Presented in Fig. 10 are the variations in water contact angle of the three composite coatings and the substrate after 200 cycles of abrasion on 500# sandpaper, together with the corresponding surface SEM images. The water contact angle of the 45# steel substrate was reduced from 74° to 32° after the cyclic sandpaper abrasion, indicating a greatly enhanced hydrophilicity. The water contact angle of the T1 coating was decreased from 116° to 100°, that of the T2 coating from 140° to 117°, and that of the T3 coating from 146° to 134°. A decreasing trend in water contact angle was thus observed for both the polymer coatings and the steel substrate. However, compared with the other two polymer coatings, the water contact angle of the T3 coating was reduced by only 8.22%, while those of the T1 and T2 coatings were decreased by 13.79% and 16.43%, respectively. Good hydrophobicity was still maintained by the T3 coating after sandpaper abrasion, whereas the water contact angles of the T1 and T2 coatings were decreased substantially, gradually approaching a hydrophilic state. When these test results are referenced and compared with the relevant data reported in recent literature [36–37], it is found that the wear resistance of the T3 coating is comparable to, or even superior to, the hydrophobic wear resistance described therein. Therefore, the best mechanical stability is exhibited by the T3 coating, followed by the T2 coating, and the poorest is shown by the T1 coating. From the SEM morphologies in Figs. 10(b–d), a large number of pores and structural defects are observed on the surface and in the interior of the T1 and T2 coatings. These pores, acting as stress concentration sources, significantly weaken the mechanical integrity of the coatings and reduce their resistance to shear and plowing actions. Under the cyclic loading of the sandpaper abrasion test, these initial defects serve as initiation and propagation sites for cracks, thereby accelerating fatigue spalling and material loss of the coatings and leading to a rapid deterioration of their protective performance. As has also been pointed out in studies on the evolution of worn surface morphology, porous structures can intensify local stress concentration during the wear process and are regarded as one of the key factors

responsible for the premature failure of coatings [38]. Moreover, the superhydrophobic properties of a coating are essentially governed by its specific micro-/nano-scale composite rough structure, which constitutes the physical basis for the formation and stabilization of an air cushion layer at the solid–liquid interface. During the continuous mechanical abrasion process, irreversible degradation is imposed on the coating surface microstructure, which is mainly manifested as the connection and enlargement of pores and the spalling of functional fillers. Such structural degradation directly leads to a decrease in surface roughness and a loss of air-trapping capability, causing a transition of the wetting state from the Cassie–Baxter regime to the Wenzel state or even to complete wetting. Macroscopically, this is reflected by a continuous decline in the water contact angle and the loss of the hydrophobic function. This, by contrast, highlights the significant advantages of the T3 coating (Fig. 10(d)), whose dense, uniform, and defect-free structure, achieved through its high graphene content and SiO₂-free formulation, not only effectively resists wear but also maintains a stable superhydrophobic surface over a long period, thereby ensuring the long-term service of the coating under severe operating conditions.

In summary, the inherent porous defective structure of the T1 and T2 coatings is identified as the intrinsic cause of their inferior wear resistance and hydrophobic durability. This finding further underscores the pronounced advantages of the T3 coating, which, by virtue of its high graphene content and SiO₂-free formulation, attains a dense, uniform, and defect-free structure—a structure that can not only effectively withstand wear but also sustain a stable superhydrophobic surface for extended periods, thus guaranteeing the long-term service reliability of the coating under harsh operating conditions.

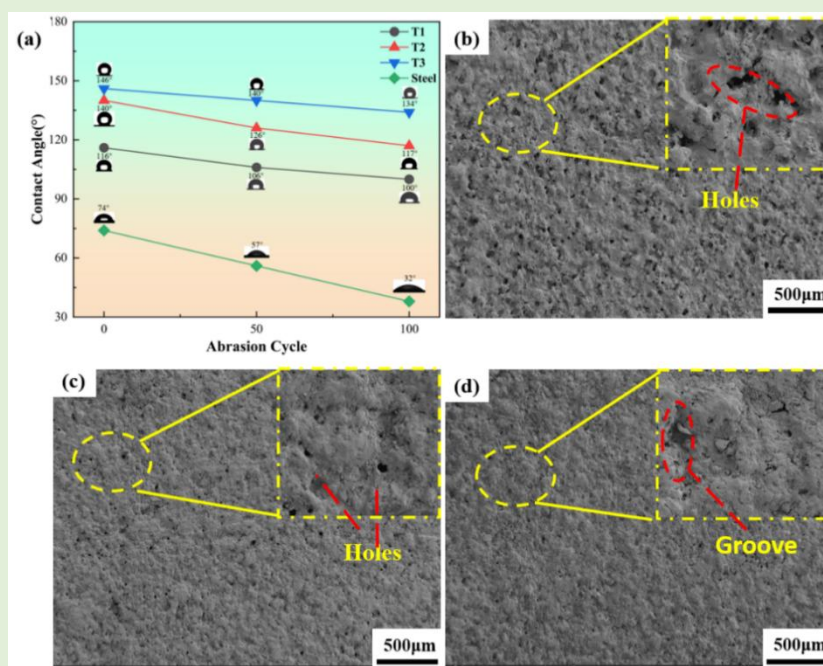


Fig. 10. (a) Water contact angle variation; (b–d) surface SEM images of the T1, T2, and T3 coatings.

3.5 Anti-icing Performance of the Coatings

In cold-region weather conditions, the friction experienced by the switch rail on the slide plate is significantly increased by the ice layer, which may subsequently prevent the turnout from switching correctly. Therefore, equipping the slide plate with excellent active anti-icing capability is considered crucial. In this study, the anti-icing performance was quantitatively evaluated by measuring the ice accretion weight of the coatings under a steady-state low-temperature environment [39-41]. The specimens were placed in a constant temperature and humidity chamber at $-25\text{ }^{\circ}\text{C}$ and $60 \pm 1\%$ RH for 60 min, and the results are presented in Fig. 11. After the test, the weight of the 45# steel substrate was found to increase from 3.505 g to 3.644 g, giving an ice accretion increment of 0.139 g. Under the same experimental conditions, the ice accretion increments of the T1, T2, and T3 polymer coatings were determined to be 0.022 g, 0.020 g, and 0.013 g, respectively. The lowest ice accretion was clearly exhibited by the T3 coating, whose increment was far smaller than that of the 45# steel substrate and also significantly lower than those of the T1 and T2 polymer coatings. Furthermore, it was calculated that the relative increase in ice accretion of the T3 coating within 60 min was reduced by 90.6% compared with the 45# steel substrate, and by 40.35% and 30.50% compared with the T1 and T2 coatings, respectively.

The above differences were mainly attributed to the combined effect of surface wettability and microstructure. When the 45# steel substrate is exposed to the air, a thin film of chromium oxide (Cr_2O_3) rich in hydrophilic carboxyl ($-\text{OH}$) and carbonyl ($=\text{O}$) groups is formed. Through hydrogen bonding, water molecules from the environment can be strongly adsorbed by these polar groups, and because of the inherently high surface energy of steel, a continuous water film is promoted to spread over the surface (Fig. 4). At the low temperature of $-25\text{ }^{\circ}\text{C}$, this water film is rapidly and uniformly frozen into ice, resulting in the largest amount of ice accretion. In addition, as revealed by the XPS chemical functional group analysis in Figs. 8(c) and 8(e), SiO_2 is contained in both the T1 and T2 coatings, and the abundant hydroxyl ($-\text{OH}$) and silanol ($\text{Si}-\text{OH}$) groups on the surface can also adsorb water molecules, leading to the formation of a small amount of ice on the surfaces of the T1 and T2 polymer coatings. The resulting microscopic pores and defects become weak sites for capillary condensation of moisture, by which the continuity and stability of the air layer are disrupted and the anti-icing performance of the coating is consequently weakened.

The anti-icing performance was further found to be governed by the integrity of the microstructure. The best anti-icing performance was demonstrated by the T3 coating, which is directly attributable to its highest water contact angle (146° , Fig. 4(c)) and its dense, uniform micro-/nano-porous structure (Figs. 6(c) and 4(c)). A large amount of air can be stably trapped by such a structure, forming a robust composite air–solid interface that greatly retards the growth and adhesion of ice crystals. Although the T1 and T2 coatings also possess hydrophobicity, a considerable

number of pores and structural defects are observed on their surfaces (Figs. 6(a) and 6(b)). These pores readily serve as sites for capillary condensation of moisture, in which some liquid droplets become retained, disrupting the perfect continuity of the air layer and thus impairing the overall ice resistance. In summary, by virtue of its optimal hydrophobicity and the most refined surface microstructure, the lowest ice accretion and the most durable anti-icing effect were achieved by the T3 coating through a triple synergistic mechanism of “high hydrophobicity + dense micro-/nano-structure + low surface chemical activity”. This fully validates its engineering application potential for effectively suppressing surface icing and ensuring reliable switching of the turnout system in severe cold environments.

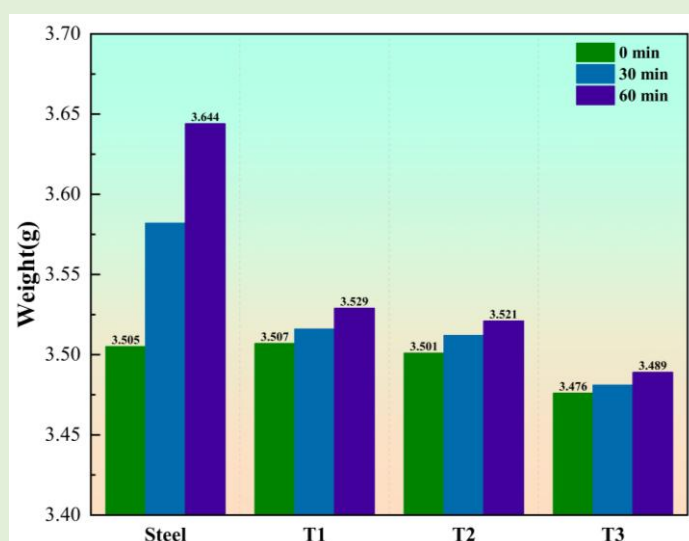


Fig. 11. Ice accretion weight of the three composite coatings under a low-temperature environment.

Railway turnouts are outdoor facilities that operate year-round without interruption. In temperate and alpine regions, the slide plates of railway turnouts are subjected to repeated alternation between high temperatures in summer and severe cold in winter. A single low-temperature test can only evaluate the “initial performance” of a coating, but cannot predict its performance retention under long-term thermal fatigue. Therefore, after the low-temperature environment test, the samples were further placed in a drying oven (1400BS) and preheated at 75 °C for two hours before being transferred into a constant temperature and humidity chamber (temperature −25 °C, humidity $60 \pm 1\%$ RH) for an anti-icing test. The results are presented in Fig. 12. After two hours of thermal aging at 70 °C, an increase in the amount of accreted ice was observed for all samples in the second low-temperature icing test. Nevertheless, the most outstanding anti-icing performance was still exhibited by the T3 coating: the ice accretion increment of the steel substrate was 0.207 g, that of the T1 coating was 0.067 g, that of the T2 coating was 0.051 g, and that of the T3 coating was merely 0.023 g. This result indicates that the T3 coating not only possesses excellent

initial anti-icing capability but also exhibits thermal stability that is significantly superior to those of the other coatings and the substrate, and it can effectively resist performance degradation induced by short-term thermal aging.

The observed phenomenon is primarily attributed to the unique chemical and structural characteristics of the T3 coating. In terms of chemical inertness and surface energy stability, it was revealed by the C 1s spectra (Figs. 8(c–d)) that the signal intensities of oxygen-containing functional groups such as C=O and C–O on the T3 coating surface were the weakest, indicating the highest chemical inertness of its surface. During the thermal treatment at 70 °C, further oxidation reactions can be effectively suppressed by such a low-reactivity surface, thereby maintaining its intrinsic low-surface-energy state. This is consistent with the discussion in the literature [42–43] on the relationship between oxygen-containing functional groups and surface chemical activity, i.e., that a lower content of oxygen-containing functional groups generally corresponds to higher chemical stability and more durable hydrophobicity. In terms of structural characteristics, as revealed by the SEM image in Fig. 6(c), a dense, continuous, and interwoven three-dimensional network structure was formed in the T3 coating owing to its high graphene content. Under high-temperature environments, this structure exerts a dual stabilizing effect: on the one hand, vigorous thermal motion and surface migration of the molecular chain segments of the polymer matrix (PUA) can be effectively suppressed, and adverse changes in surface chemical properties caused by chain segment rearrangement can thus be avoided; on the other hand, the graphene network itself can serve as a physical barrier, retarding the permeation of media such as oxygen and moisture and thereby delaying the thermo-oxidative aging of the matrix. As pointed out in the literature [44–46], graphene nanomaterials, by virtue of their unique lamellar structure and barrier properties, can be used to significantly enhance the flame retardancy and thermal stability of polymer-based composites, which provides supporting evidence for the above mechanism.

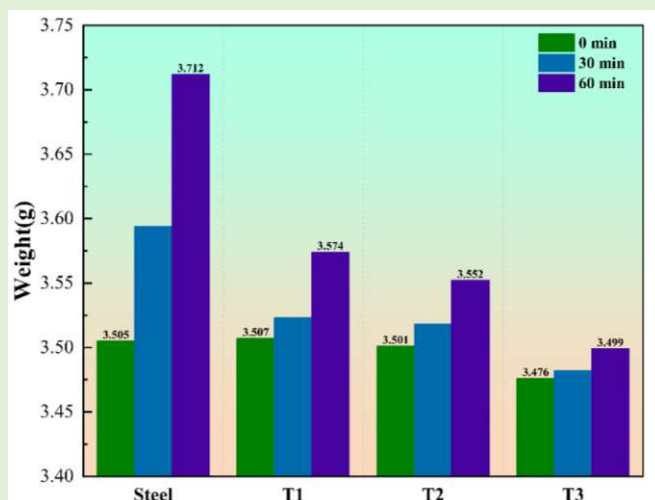


Fig. 12. Ice accretion weight of the three composite coatings under a low-temperature environment after high-temperature aging.

3.6 Hardness and Elastic Modulus

The variation in hardness and elastic modulus of the three polymer coatings is presented in Fig. 13. It can be readily observed that the hardness and elastic modulus of the polymer coatings exhibit a trend of first decreasing and then increasing with increasing GN content. The T3 composite coating with a GN content of 15 wt% was found to possess the highest elastic modulus and hardness, which were 2.91 GPa and 0.10 GPa, respectively. Compared with the T2 composite coating (7.5 wt% GN), the elastic modulus and hardness of the T3 coating were increased by 11.54% and 12.36%, respectively; compared with the T1 composite coating (5 wt% GN), the elastic modulus and hardness were increased by 31.82% and 33.33%, respectively. As reported in the literature [44], the hardness of nanopolymers can be enhanced by the addition of graphite, which corroborates the finding that the T3 coating exhibits the optimal elastic modulus and hardness. Combined with the SEM images of the three composite coatings in Fig.6, it can be seen that the best compactness and an absence of obvious pores are exhibited by the T3 coating, whereas a large number of pores and agglomerates are observed in the T1 coating, leading to a greater indentation depth and size and consequently a reduction in hardness.

It is noteworthy that the elastic modulus and hardness of the T2 coating were slightly lower than those of the T1 coating, exhibiting a “mid-component trap” phenomenon. The rigid agglomerates of SiO₂ and the two-dimensional graphene sheets mutually obstruct each other, whereby the potential for forming a continuous reinforcing network for each component is destroyed, and this is manifested as severe non-uniformity in elemental distribution in the SEM/EDS results (Fig. 7(b), Table 5). As a result, a large number of weak multiphase interfaces are generated, and a more unfavorable microporous network is likely to have been formed during the curing process. Macroscopically, the lowest stiffness and indentation resistance are exhibited by the T2 coating owing to such a structure.

The indentation depth results obtained from the nanoindentation test are shown in Fig. 13(b). At the maximum load of 1000 μ N, the largest indentation depth of 553.41 nm was recorded for the T1 coating, whereas the smallest indentation depth of 342.06 nm was recorded for the T3 coating, which indirectly confirms that the T3 coating with 15 wt% GN possesses the highest hardness. The ratio of hardness to elastic modulus (H/E) is a key parameter for evaluating the wear resistance and resistance to plastic deformation of a material and can be used to predict its tribological behavior. In general, a higher H/E value implies a greater capacity to withstand interfacial stresses and smaller flexural deformation, which contributes to mitigating surface spallation and improving wear resistance [45]. The highest H/E value, approximately 0.0316, was obtained for the T3 coating, representing an increase of 2.22%

and 4.41% compared with the T1 and T2 coatings, respectively. This indicates that the incorporation of graphene (GN) particles effectively improves the load-bearing capacity and anti-wear characteristics of the coating.

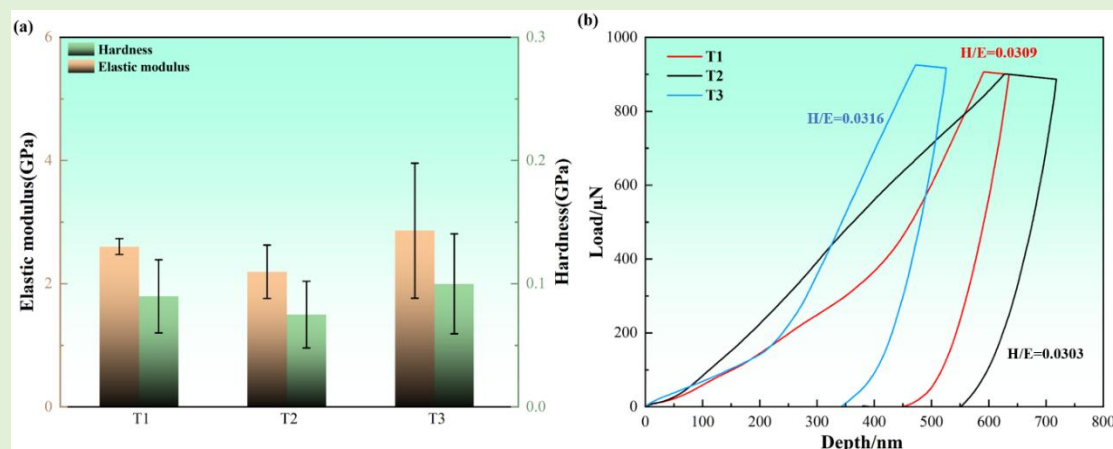


Fig. 13. (a) Elastic modulus and hardness of the three composite coatings; (b) nanoindentation test.

3.7 Multi-Temperature Tribological Analysis

Friction and wear tests were conducted under a high-temperature environment of 75 °C, and the variations in friction coefficient and wear rate of the 45# steel substrate and the three polymer coatings with the addition levels of GN/SiO₂ are presented in Fig. 14. The friction coefficient curves are shown in Fig. 14(a), from which it can be readily observed that the highest average friction coefficient (0.41) was exhibited by the 45# steel substrate. Among the prepared polymer coatings, the lowest average friction coefficient, merely 0.16, was obtained for the T3 coating, followed by the T2 coating with an average friction coefficient of 0.19, and the highest value (0.23) was recorded for the T1 coating. Compared with the conventional 45# steel substrate, the average friction coefficient of the T3 coating was reduced by 61%; compared with the T1 and T2 coatings, reductions of 30.4% and 15.8%, respectively, were achieved. An analysis of the friction coefficient curve profiles in Fig. 14(a) revealed that no distinct running-in period was observed for the T1 coating, whereas the T2 and T3 coatings passed through the running-in period and entered the steady-state wear stage only after 300 s and 600 s, respectively, with the COF gradually decreasing and then stabilizing. This difference is closely related to the coating composition and the lubrication mechanism. For the T1 coating, the high SiO₂ content acts as a hard wear-resistant filler that can enhance the load-bearing capacity of the coating, but the filler itself does not possess self-lubricating characteristics. Meanwhile, the relatively low graphene content is insufficient to rapidly form an effective lubricating film at the initial stage of friction. Consequently, the test entered the steady-state wear stage dominated by abrasive wear from the very beginning, and the friction coefficient was maintained at a relatively high level with small fluctuations. For the T2 and T3 coatings, both are rich in solid lubricants such as graphene and PTFE. At the initial stage of friction, the lubricating components

were gradually spread and compacted on the counterpart surface, and a certain period of time was required for a continuous and stable solid lubricating transfer film to be formed (the morphology of the transfer film is shown in Fig. 15); this process is referred to as the “running-in period.” This is consistent with the conclusion reported in the literature [46–47] that graphene/PTFE lubrication systems require the formation of a transfer film to achieve efficient friction reduction. In particular, the T3 coating, with the highest graphene content, formed the most complete and densest transfer film and thus exhibited the lowest and most stable friction coefficient after the running-in process, reflecting the most outstanding lubrication performance and high-temperature adaptability.

The wear rates of the polymer coatings and the substrate are presented in Fig. 14(b). The wear rates of the T1, T2, and T3 coatings were $5.17 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, $2.53 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, and $1.62 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, respectively, while that of the steel substrate was $7.32 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$. Among the three polymer coatings, the lowest wear rate was obtained for the T3 coating, and its wear resistance was improved by 68.7% and 36.1% compared with the T1 and T2 coatings, respectively. This can be attributed to the fact, as shown in Fig. 14(a), that the T3 coating with a high graphene content possessed the lowest friction coefficient under the high-temperature environment, by which the adhesive wear and thermal fatigue damage of the coating were significantly mitigated—a key reason for the low wear rate of the T3 coating. As pointed out in the literature [48–49], graphene nanoplatelets (GNPs) can synergistically enhance the interfacial heat conduction efficiency and form a stable solid lubricating transfer film, thereby jointly maintaining a low and stable friction coefficient. The onset of adhesive wear was thus directly suppressed, and the thermal fatigue damage was effectively alleviated by reducing the local interfacial temperature and the cyclic thermal stress, which in turn significantly improved the wear resistance of the composite coatings.

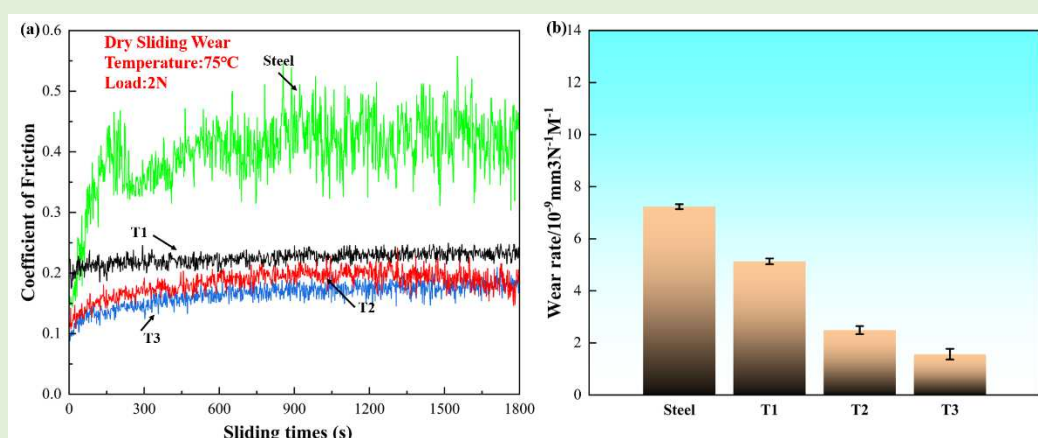


Fig. 14 Friction coefficient curves and wear rate of the composite coatings under dry sliding wear at 75 °C:

(a) friction coefficient, (b) wear rate.

The wear surface morphologies of the three polymer coatings and the 45# steel substrate after dry sliding

friction at 75 °C are presented in Fig. 15. As shown in Fig. 15(a), numerous continuous furrows were observed on the surface of the 45# steel, and this result is consistent with the highest wear rate of the substrate presented in Fig. 14(b). Among the polymer coatings, deep arc-shaped furrows and extensive irregular material detachment were observed on the T1 coating surface, by which the dominant wear mechanism was indicated to be abrasive wear. On the T2 coating surface, shallower arc-shaped furrows accompanied by localized depression and spallation were observed, and the lubricating transfer film formed on its surface was found to exhibit a discontinuous, fragment-like distribution, suggesting that a mixed mechanism of adhesive wear and abrasive wear was present. In contrast, the most outstanding surface integrity was exhibited by the T3 coating, where no distinct furrows or spallation pits were observed and a continuous, stable surface lubricating film was formed. Its wear mechanism was mainly determined to be adhesive wear, i.e., wear debris generated under cyclic shear was mechanically bonded with the resin matrix under the synergistic influence of instantaneous temperature rise and normal load, by which adhesive junctions were formed. From the locally magnified morphologies in Figs. 15(b–d), it can be learned that the most severe wear was experienced by the T1 coating, whereas the mildest wear was sustained by the T3 coating under dry friction at 75 °C. The above results indicate that, at this temperature, the incorporation of 15 wt% GN not only effectively enhanced the mechanical strength of the polymer matrix but also preserved the toughness and interfacial adhesion of the material, by which the overall wear resistance of the coating was significantly improved.

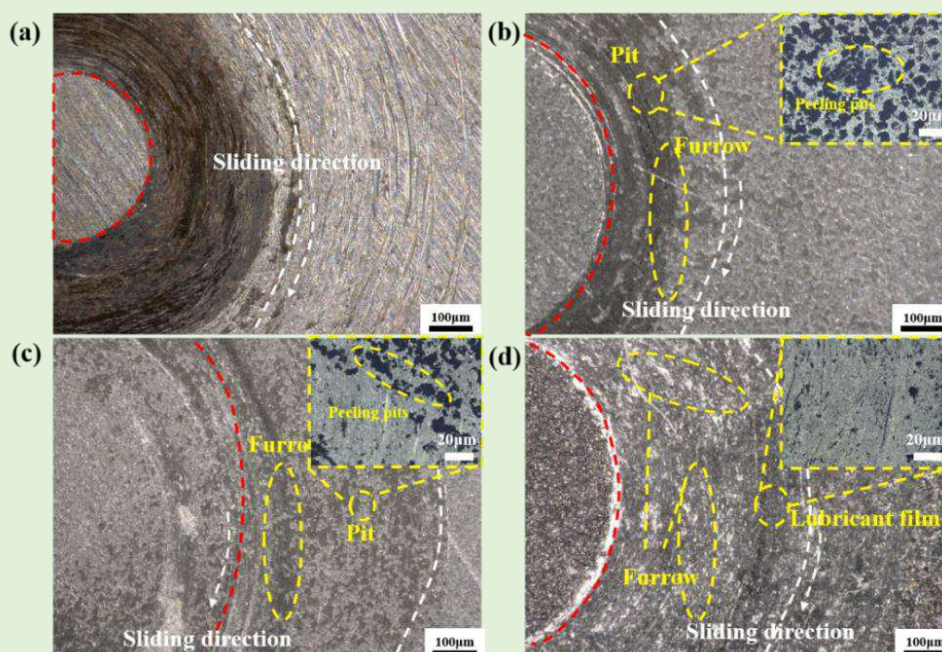


Fig. 15 Wear morphologies under dry friction at 75 °C: (a) 45# steel substrate, (b) T1 coating, (c) T2 coating, (d) T3 coating.

Surface morphologies of the pins after sliding against different specimens under dry friction at 75 °C: (a) 45#

steel substrate, (b) T1 coating, (c) T2 coating, (d) T3 coating. The dark regions correspond to transferred or adhered coating material debris, while the bright regions represent the exposed metallic substrate. It can be observed that the most severe damage was sustained by the pin surface slid against the 45# steel substrate (Fig. 16(a)), where a large continuous dark transferred layer was formed on the right side, the substrate was substantially covered, and severe spallation pits and deep furrows were observed, indicating that severe adhesive wear and abrasive wear had occurred. In contrast, the damage to the pin surfaces slid against the T1, T2, and T3 coatings (Figs. 16(b)–(d)) was significantly mitigated. With the increase in graphene (GN) content in the coatings, the area fraction of the dark transferred region on the pin surface was gradually reduced from approximately 20% (T1) to approximately 10% (T3), which directly reflects a progressive decrease in the degree of wear. It is particularly noteworthy that more continuous, uniform, and stably adhered solid lubricating transfer films were formed on the pin surfaces by the T2 and T3 coatings with higher GN contents; direct metal-to-metal contact between the friction pair was effectively isolated by these films, whereby the occurrence of adhesion and severe plowing was significantly suppressed. The above morphological characteristics are in excellent agreement with the wear rate data presented in Fig. 14(b) (where the lowest wear rate was recorded for the T3 coating) and with the wear morphologies of the coatings themselves shown in Fig. 15 (where the shallowest and smoothest wear track was exhibited by the T3 coating). Taken together, these three aspects demonstrate that, under high-temperature dry friction conditions, the most outstanding lubricating protective film on the counterpart surface can be formed by the T3 coating with the highest GN content. Not only is an extremely low wear rate exhibited by the coating itself, but the damage to the counterpart is also significantly alleviated by it, thereby systematically verifying its excellent high-temperature lubricity, wear resistance, and interfacial stability.

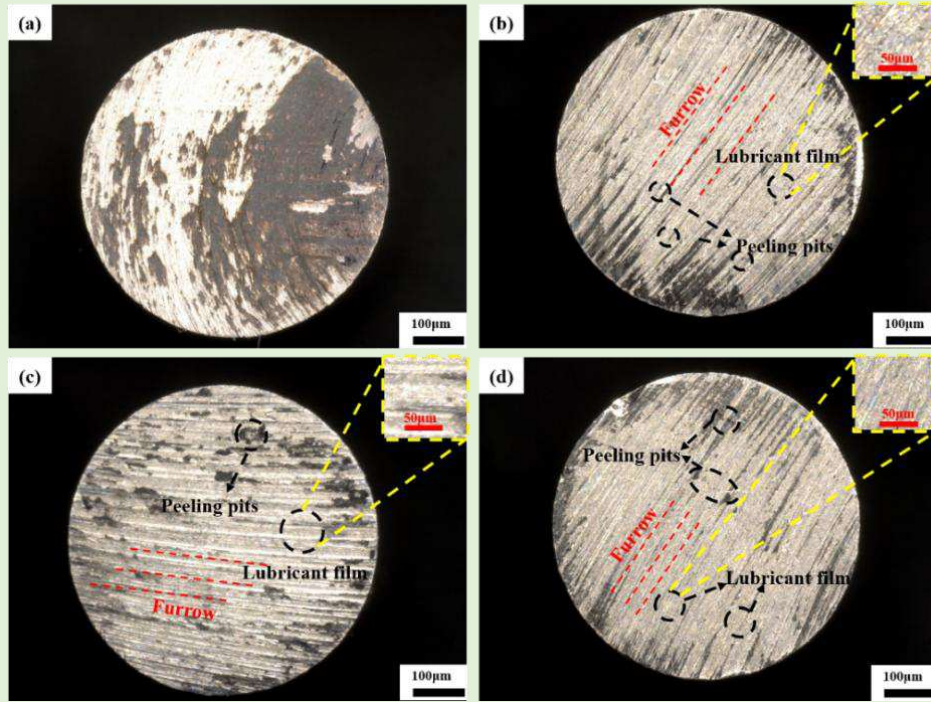


Fig. 16. Morphologies of the counterpart surface after dry friction at 75 °C: (a) 45# steel substrate, (b) T1 coating, (c) T2 coating, (d) T3 coating.

The wear performance of the polymer coatings was further investigated at room temperature of 25 °C. As shown in Fig. 17(a), the average coefficients of friction (COF) of the T1, T2, and T3 coatings were 0.13, 0.09, and 0.10, respectively, all of which were significantly lower than that of the uncoated steel substrate (0.29). Among them, the lowest average COF (0.09) was exhibited by the T2 coating, which was approximately 69 % lower than that of the steel substrate and also approximately 30 % and 10 % lower than those of the T1 and T3 coatings, respectively, indicating that the optimal interfacial lubrication effect at room temperature was achieved by T2. This difference is primarily attributed to the varying abilities of the coatings to form a lubricating transfer film and their interfacial adaptability at room temperature. In the T2 coating, a moderate proportion of graphene to SiO₂ was employed, and the synergistic effect of the two fillers was found to be more favorable for the formation of a uniform, stable transfer film with low shear strength at the friction interface at room temperature, by which the lowest frictional resistance was realized [50]. Although the highest graphene content was contained in the T3 coating, the formation of its transfer film may have been influenced by its more compact structure, resulting in a slightly slower optimization of the friction interface at room temperature compared with T2; hence, a marginally higher average COF was recorded, yet it was still maintained at an extremely low level (0.10) and was far superior to those of the T1 coating and the 45# steel substrate.

The wear rate results are presented in Fig. 17(b). The wear rates of the steel substrate and the T1, T2, and T3

coatings were $19.05 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, $4.05 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, $10.12 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, and $2.26 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, respectively. Compared with the other two as-prepared polymer coatings, the wear rate of the T3 coating was reduced by 44.2 % and 77.7 %, respectively. The difference in wear rate is closely related to the hardness characteristics of the coatings. As shown in Fig. 13(a), the highest hardness of 0.10 GPa was obtained for the T3 coating, which is consistent with its optimal wear resistance. Hardness is regarded as a key indicator of a material's resistance to plastic deformation and wear; a higher hardness enables the coating to exhibit a greater resistance to plastic deformation and micro-cutting under normal and shear loads, whereby abrasive wear and surface fatigue spallation are effectively suppressed [51]. Consequently, the lowest wear rate was exhibited by the T3 coating in the wear test. Although the lowest COF at room temperature was obtained for the T2 coating, indicating that its lubricating transfer film was highly effective in reducing friction, its hardness was lower than that of the T3 coating, and micro-defects induced by the introduction of SiO_2 still existed in its structure (Fig. 6(b)). These factors impaired its overall resistance to plastic deformation and wear, and as a result, a higher wear rate than that of the T3 coating was recorded for T2. Taken together, in terms of the two evaluation indicators of wear rate and average COF, the T3 coating achieved the lowest wear rate and exhibited the most outstanding comprehensive wear resistance, although its friction reduction performance was marginally lower than that of the T2 coating (by approximately 10 %).

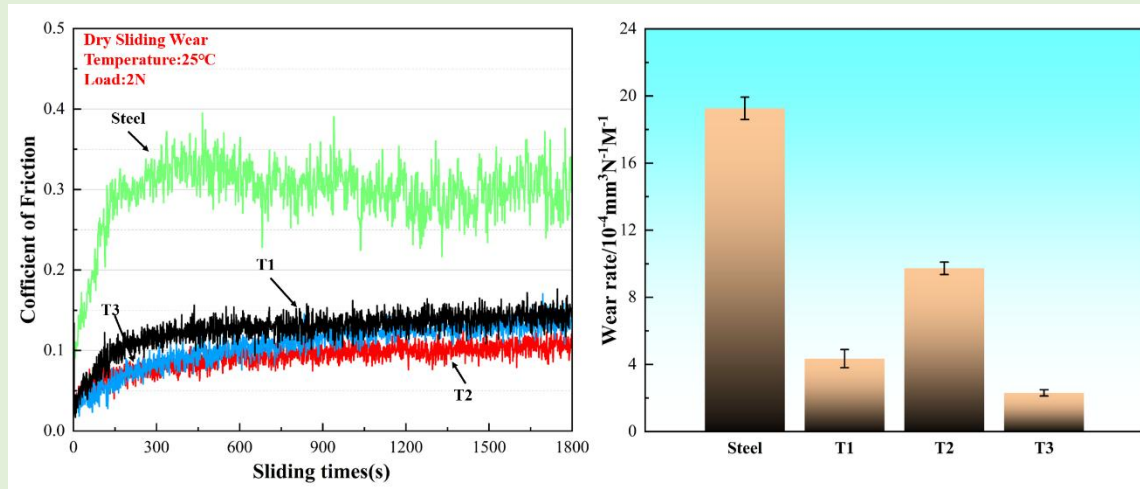


Fig. 17. (a) Friction coefficient and (b) wear rate of 45# steel and the polymer coatings under dry sliding at 25 °C.

The wear surface morphologies of the three polymer coatings and the 45# steel substrate at room temperature are presented in Fig. 18. As shown in Fig. 18(a), the surface of the uncoated 45# steel substrate was severely worn; dense and deep furrows and extensive material fracture and spallation were observed, and the surface material was almost completely removed by the counterpart. This morphological feature is fully consistent with the highest wear rate of the steel substrate presented in Fig. 17(b).

Among the three polymer coatings, relatively deep arc-shaped furrows accompanied by localized material depressions and spallation pits were observed on the worn surface of the T2 coating (Fig. 18(c)), indicating that its wear mechanism was dominated by abrasive wear and adhesive wear. In contrast, the smoothest surface was exhibited by the T3 coating (Fig. 18(d)), with no distinct furrows or large-area spallation being observed, and only a small amount of wear debris and tiny pores were visible in the high-magnification image, indicating the mildest wear. This morphological difference is in excellent agreement with the wear rate data in Fig. 17(b): the highest wear rate among the polymer coatings was recorded for T2, whereas the lowest was recorded for T3. The wear condition of the T1 coating was intermediate between the two (Fig. 18(b)); although no distinct deep furrows were observed on its surface, a considerable amount of wear debris was still present locally, suggesting that the material failure was mainly in the form of mild abrasive wear and fatigue spallation.

In summary, the reliability of the wear rate data is further confirmed by the microscopic observation of the wear morphologies at the micro-mechanism level. Owing to its highest graphene content, optimal hardness (0.10 GPa), and the densest microstructure (Fig. 6(c)), the strongest resistance to plowing, spallation, and plastic deformation was exhibited by the T3 coating during the friction process, and accordingly the mildest wear was sustained. In contrast, although the lowest friction coefficient at room temperature was obtained for the T2 coating, interfacial adhesion and micro-cutting were more prone to occur under sustained load owing to the defects introduced by SiO_2 in its structure (Fig. 13(b)) and its relatively lower hardness, resulting in relatively severe wear. This result further demonstrates that under dry friction conditions, the mechanical properties (such as hardness) and structural integrity of the coating are the key factors determining its wear life, and it further supports the pronounced superiority of the T3 coating in comprehensive tribological performance.

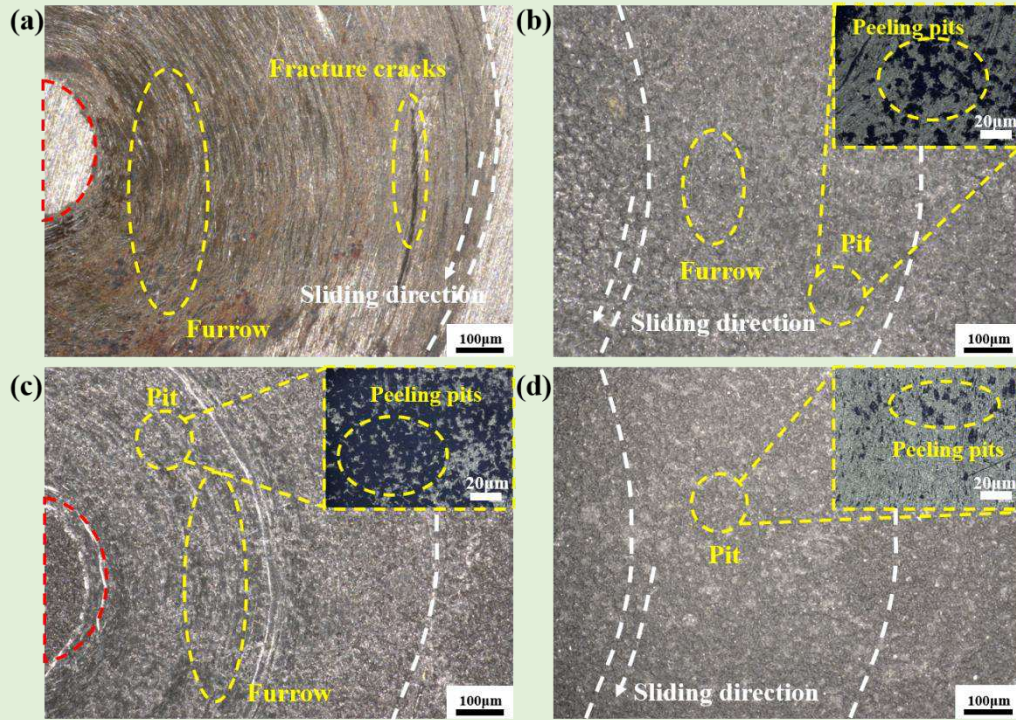


Fig. 18. Wear morphologies under dry friction at 25 °C: (a) 45# steel substrate, (b) T1 coating, (c) T2 coating, (d) T3 coating.

The wear micromorphologies of the counterpart surfaces after sliding against the 45# steel substrate and the three polymer coatings are presented in Fig. 19. It can be observed that, after sliding against the 45# steel substrate and the T2 coating, large areas of dark adhered regions were present on the counterpart surfaces, indicating that a considerable amount of coating material was scraped off and transferred to the counterpart during the friction process, which reflects a relatively strong adhesion effect and material loss. In contrast, less adhered material was observed on the surface slid against the T1 coating, where only a small number of abrasive particle spallation pits and debris were visible, and a lubricating transfer film with a certain protective function was formed on the surface. Most notably, almost no distinct coating adhesion or spallation pits were observed on the counterpart surface slid against the T3 coating (Fig. 19(d)), and the overall morphology was relatively smooth. The high-magnification image further revealed that the surface was covered with a continuous and dense lubricating transfer film, by which the direct contact between the counterpart and the coating was effectively prevented, thereby significantly suppressing the occurrence of adhesive wear and plowing effects and reducing interfacial wear.

The above observations of the counterpart morphologies are in excellent agreement with the wear rate data presented in Fig. 17(b) and with the wear morphologies of the coatings themselves shown in Fig. 18. Not only was the mildest wear sustained by the T3 coating itself (Fig. 18(d)), but the least surface damage was also inflicted on its corresponding counterpart, accompanied by the formation of a complete transfer film. Together with its lowest wear

rate (Fig. 17(b)), these results corroborate that, under room-temperature dry friction conditions, the most outstanding lubrication retention capability and wear resistance were possessed by the T3 coating. The counterpart morphologies of the T1 and T2 coatings further reveal the contribution of adhesion and material transfer to their wear mechanisms, and from the interfacial perspective, they provide a supplementary explanation for the relatively higher wear rates of these two coatings.

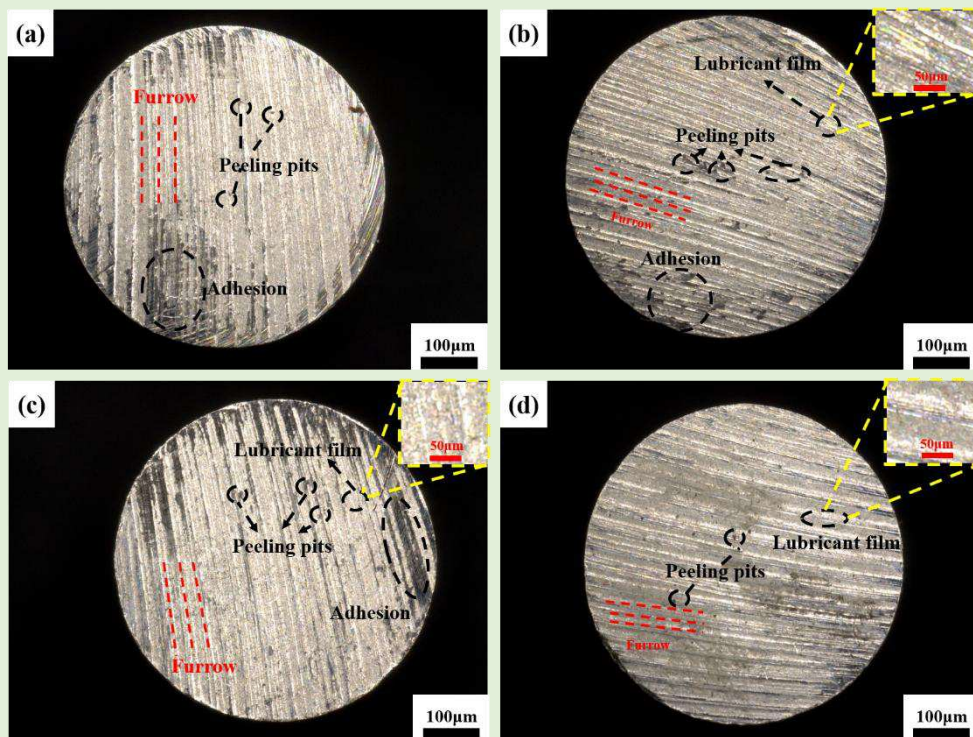


Fig. 19. Wear morphologies of the counterpart after dry friction at 25 °C: (a) 45# steel substrate, (b) T1 coating, (c) T2 coating, (d) T3 coating.

Fig. 20. Dry sliding wear performance of the three composite coatings and the steel substrate at -25°C is presented. The average coefficients of friction (COF) of the T1, T2, and T3 coatings were determined to be 0.22, 0.13, and 0.19, respectively, all of which were significantly lower than that of the steel substrate (0.39). Among them, the lowest COF (0.13) was exhibited by the T2 coating, which was over 66% lower than that of the steel substrate and approximately 46% lower than that of the T3 coating, indicating an excellent friction-reducing capability in the low-temperature environment. In an environment at -20°C , water vapor in the air can condense into ice on the contact surfaces. The frictional heat generated during sliding can induce premelting of this thin ice, forming a liquid water film. This phenomenon may be related to the “ice premelting–water film lubrication” mechanism unique to low-temperature interfaces. In an environment at -20°C , water vapor in the air readily condenses into ice on the contact surfaces; during low-speed sliding friction, frictional heat can cause the surface thin ice to premelt, forming an extremely thin liquid water film. It has been demonstrated that such a water film can significantly reduce the

shear resistance of the sliding interface [52]. It is possible that a transition from hydrophobic to hydrophilic is more readily undergone by the T2 coating during the friction process, by which the formation of a uniform and stable water film is promoted and a lower friction coefficient is achieved. Although the lowest friction coefficient at low temperature was exhibited by the T2 coating, its wear rate ($1.72 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$) was higher than that of the T3 coating ($1.02 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$). The wear rates of the steel substrate, T1, T2, and T3 were 2.22×10^{-4} , 1.57×10^{-4} , 1.72×10^{-4} , and $1.02 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, respectively. The lowest wear rate was demonstrated by the T3 coating, and its wear resistance was approximately 40% superior to that of T2.

This seemingly contradictory phenomenon—that the lowest friction coefficient did not correspond to the lowest wear rate—precisely reveals the underlying mechanism that “lubrication” and “load-bearing/anti-wear” capability must act synergistically in low-temperature tribology [53,54]. The T3 coating was characterized by the most favorable hydrophobicity and anti-icing performance (Figs. 4, 10, 11), and its surface was able to maintain a Cassie–Baxter wetting state. The trapped air layer served not only to retard ice formation but also as a thermal barrier that suppressed the ice–water phase transition; consequently, the formation of a continuous water film was less favored, and the contribution of water film lubrication was partially weakened, resulting in a slightly higher friction coefficient than that of T2. However, by virtue of the densified structure constructed through its high graphene content (Fig. 6, Fig. 4) and the resulting higher hardness and toughness, the T3 coating exhibited a greater resistance to plastic deformation, brittle spallation, and three-body wear at low temperature, by which a lower material loss rate was achieved.

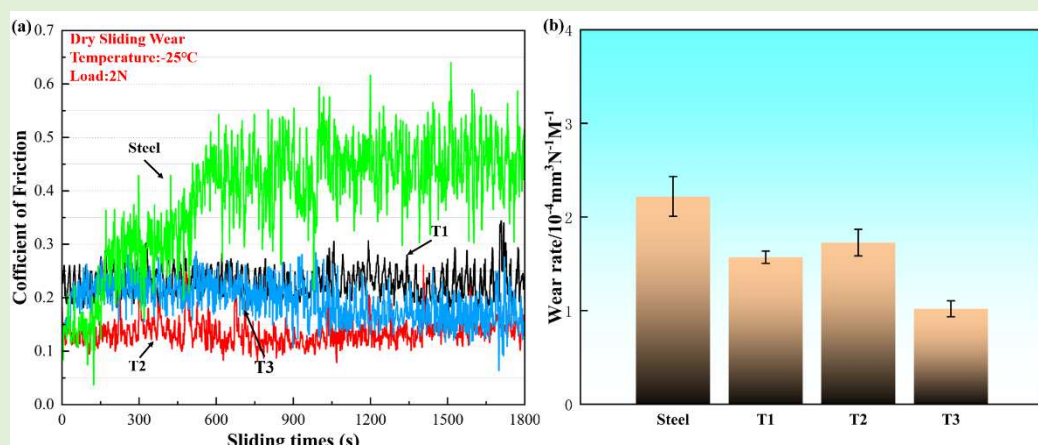


Fig. 20. Friction coefficient curves and wear rate of the composite coatings under dry sliding wear at $-25\text{ }^{\circ}\text{C}$:

(a) friction coefficient, (b) wear rate.

The wear surface morphologies of the three polymer coatings and the substrate (45# steel) at $-25\text{ }^{\circ}\text{C}$ are presented in Fig. 21. It can be observed that distinct arc-shaped deep furrows accompanied by numerous pits were

still present on the surface of the 45# steel, which is consistent with its highest wear rate (Fig. 20(b)). Among the three coatings, the most pronounced dark furrows were exhibited on the surface of the T2 coating, followed by the T1 coating, whereas almost no obvious furrow traces were observed on the T3 coating. This indicates that the wear mechanisms of the T1 and T2 coatings at low temperature were dominated by abrasive wear and adhesive wear, whereas the T3 coating was governed by mild adhesive wear. In addition, it can be found that the wear morphologies of all three polymer coatings in the low-temperature environment were far better than those under high-temperature and room-temperature conditions, and the wear rates were the lowest among the three operating conditions. The reason is that at $-20\text{ }^{\circ}\text{C}$, the segmental motion of the PUA polymer matrix is frozen, and low-temperature hardening occurs in the entire coating, leading to a general increase in both elastic modulus and hardness. This viewpoint was also mentioned by researchers [55] in their study of UV-cured PUA hard coatings. As a result, plastic deformation and viscous flow of the coating under normal load become less likely to occur; wear forms dominated by plastic ploughing and adhesive tearing in the low-temperature environment are suppressed. Compared with the softening, adhesion, and material transfer that readily occur under high temperature and with the certain plastic deformation capacity at room temperature, the brittle behavior of the coating is enhanced at low temperature. However, when the coating structure is intact (as in T3), its tendency for brittle fracture is relatively low, and a superior deformation resistance is instead exhibited. Graphene and PTFE still retain their lamellar slip characteristics at low temperature; in particular, the interlayer van der Waals interactions of graphene are not significantly altered at low temperature, and lubrication can still be provided through lamellar slip [56–57]. Meanwhile, because the interface temperature is relatively low under low-temperature friction, lubricant decomposition, oxidation, or rupture of the interfacial film caused by frictional heat is less likely to occur, and the lubricating transfer film is thus probably more stable. Owing to its high graphene content and dense structure, the transfer film formed by the T3 coating can still effectively isolate metal contact at low temperature, thereby reducing direct adhesion and ploughing.

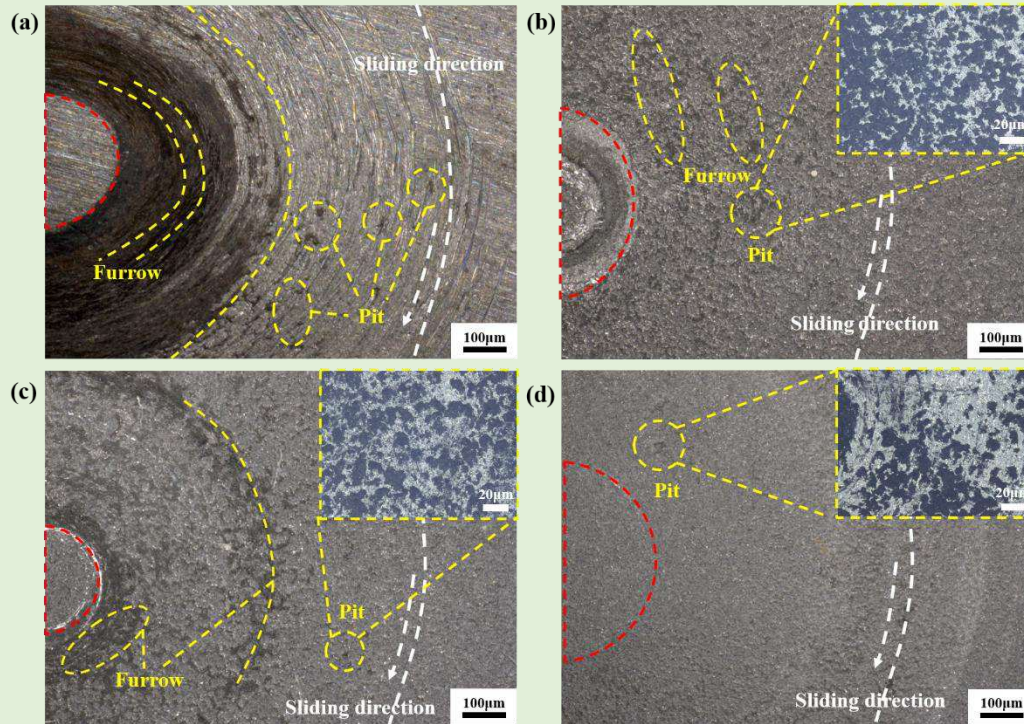


Fig. 21. Wear morphologies under dry friction at $-25\text{ }^{\circ}\text{C}$: (a) 45# steel substrate, (b) T1 coating, (c) T2 coating, (d) T3 coating.

Fig. 22. Surface morphologies of the pins after sliding against the substrate and the three polymer coatings under dry friction at $-25\text{ }^{\circ}\text{C}$ are presented. A large amount of coating adhesion was observed on the pin surface slid against the substrate. On the pin surface slid against the T2 coating, obvious black coating adhesion was also present, and dark furrows together with abrasive debris were observed. In contrast, a significantly improved surface condition was exhibited by the pin slid against the T3 coating, on which a continuous and stable lubricating film formed by the higher content of C/PTFE was observed. Direct interfacial contact was effectively reduced by this lubricating film, and material adhesion and abrasive damage were consequently decreased. It is indicated by this observation that, under low-temperature dry friction conditions, a continuous and stable solid lubricating transfer film can be more effectively formed on the counterpart surface by the T3 coating. This transfer film is mainly composed of graphene and PTFE, both of which are capable of retaining their lamellar slip characteristics at low temperature, and the shear stress at the friction interface is significantly reduced through relative slip between the lamellae. Direct metal-to-metal contact is isolated by the formed continuous lubricating film, by which adhesive wear and severe abrasive cutting are effectively suppressed. This is consistent with the lowest wear rate (Fig. 20(b)) and the most outstanding tribological performance exhibited by the T3 coating under this condition.

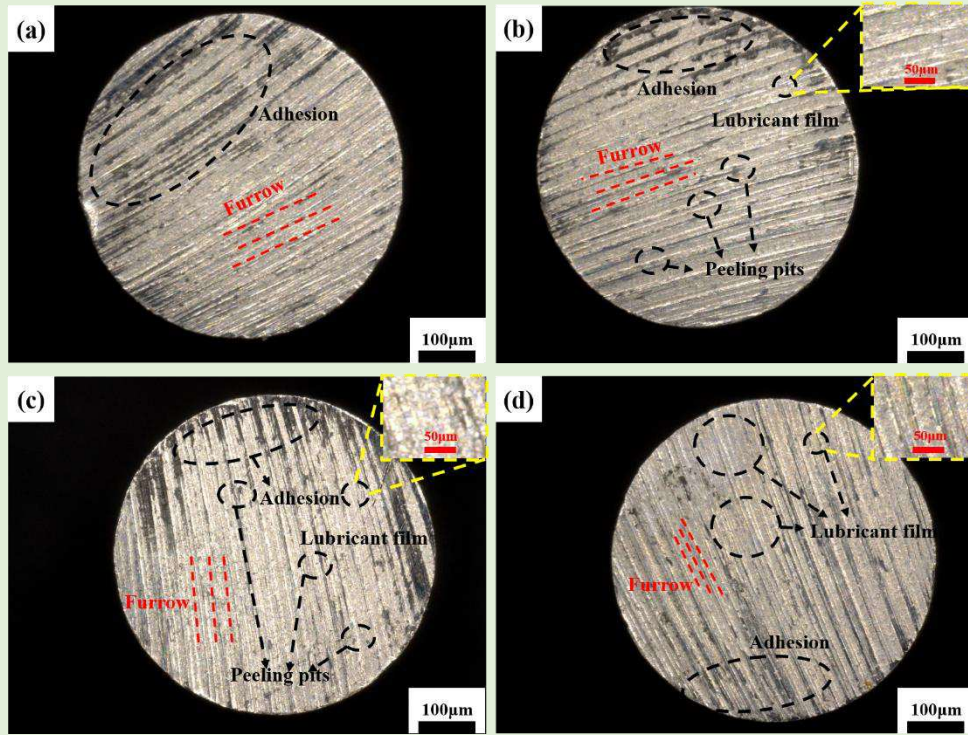


Fig. 22. Wear morphologies of the counterpart after dry friction at $-25\text{ }^{\circ}\text{C}$: (a) 45# steel substrate, (b) T1 coating, (c) T2 coating, (d) T3 coating.

A systematic comparison of the tribological behavior of the T1, T2, and T3 coatings and the 45# steel substrate under operating temperatures ranging from $-25\text{ }^{\circ}\text{C}$ to $75\text{ }^{\circ}\text{C}$ is presented in Fig. 23, covering the variation in two key indicators—friction coefficient and wear rate—with temperature. The test results indicate that the most excellent and stable comprehensive tribological performance over the entire temperature range was exhibited by the T3 coating. The average friction coefficient of this coating ranged from 0.10 to 0.19, and the wear rate was stably controlled within a low-value range of $(1.02\text{--}2.26) \times 10^{-4} \text{ mm}^3/(\text{N}\cdot\text{m})$. Compared with the bare 304 stainless steel substrate, the friction coefficient of the T3 coating at high temperature ($75\text{ }^{\circ}\text{C}$), room temperature ($25\text{ }^{\circ}\text{C}$), and low temperature ($-25\text{ }^{\circ}\text{C}$) was reduced by 61.0%, 65.5%, and 51.3%, respectively. The reduction in wear rate was even more pronounced, and the overall wear resistance was improved by more than 60%. Among the three prepared coatings, the lowest friction coefficients (0.09 and 0.13) were obtained for T2 at room and low temperatures; however, its wear rate was far higher than that of the T3 coating. Specifically, at room temperature, the wear rate of T2 ($10.12 \times 10^{-4} \text{ mm}^3/(\text{N}\cdot\text{m})$) was determined to be 4.5 times that of T3 ($2.26 \times 10^{-4} \text{ mm}^3/(\text{N}\cdot\text{m})$), and at low temperature, the wear rate of T2 ($1.72 \times 10^{-4} \text{ mm}^3/(\text{N}\cdot\text{m})$) was approximately 68.6% higher than that of T3 ($1.02 \times 10^{-4} \text{ mm}^3/(\text{N}\cdot\text{m})$). This comparison reveals that while the friction-reducing effect of the T2 coating is acceptable, its wear resistance is clearly insufficient. In contrast, the best match between friction and wear characteristics was achieved by the T3 coating. Not only was the lowest wear rate maintained over the entire temperature range by this coating, but the lowest

friction coefficient (0.16) and wear rate ($1.62 \times 10^{-4} \text{ mm}^3/(\text{N}\cdot\text{m})$) were simultaneously obtained under the high-temperature condition. From the perspective of the temperature response trend, the optimal performance of T3 was observed near room temperature, with only slight degradation upon heating, and its performance deterioration was far smaller than those of T1 and T2. The mechanism underlying the good temperature adaptability is attributed to the synergistic effect of the components: at moderate temperatures, the segmental mobility of the PUA chains is appropriate, which promotes the formation of a continuous lubricating transfer film by graphene and PTFE; at high temperatures, the dense three-dimensional network constructed by the high-content graphene sheets and SiC filler (see Fig. 6 and XPS analysis) effectively inhibits matrix softening and plastic flow, thereby preserving structural integrity and load-bearing capacity.

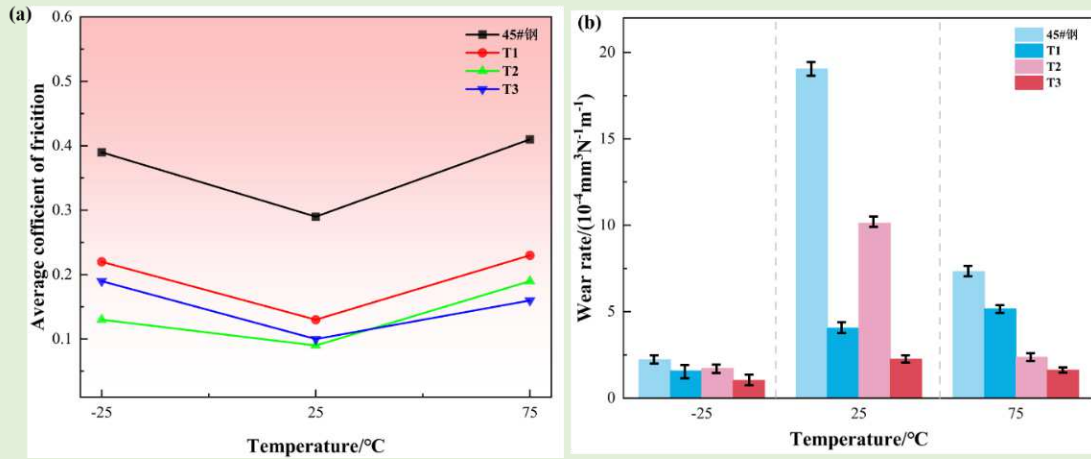


Fig. 23. Average friction coefficient (a) and wear rate (b) of the substrate and the polymer coatings under dry friction conditions at different temperatures.

In view of the stringent requirements of long service life and high reliability imposed on railway turnout slide plates, the coating evaluation system should go beyond the conventional single friction coefficient indicator, and greater emphasis should be placed on the wear rate parameter, which better reflects the long-term service capability of the material. This is because, under real service conditions, the slide plate must not only maintain a low friction resistance to ensure smooth turnout switching but also resist wear failure under prolonged, high-frequency sliding contact, so that the maintenance interval can be extended and the operating costs can be reduced. Owing to its lowest wear rate across the entire temperature range and its excellent operational stability, a successful balance between a low friction coefficient and high wear resistance was achieved by the T3 coating. A radar chart of the three coatings is presented in Fig. 24. In addition to the friction coefficient and wear rate, the H/E ratio, initial water contact angle, water contact angle after sandpaper abrasion, ice accretion increment during the first icing test, and ice accretion increment after thermal aging were compared with each other. By integrating the mechanical properties, static

hydrophobicity, mechanical durability, anti-icing performance, and thermal stability of the coatings into a unified evaluation framework, the optimal formulation could be identified in a more comprehensive and objective manner. It can be readily observed from the radar chart that the T3 coating is found to be in the leading position in all five dimensions. From the mechanical dimension, the highest H/E value and the best resistance to plastic deformation are exhibited by T3. From the hydrophobic dimension, the highest water contact angle and the strongest air-trapping capability are possessed by T3. Furthermore, from the durability dimension, a high contact angle of 138° is still maintained by T3 after sandpaper abrasion, and its mechanical robustness is significantly superior to those of T1 and T2. From the anti-icing and thermal stability dimensions, the best anti-icing performance and the smallest degradation are demonstrated by T3. In contrast, although a local advantage in the friction coefficient at room temperature is shown by T2, it is inferior to T3 in key engineering indicators such as hardness, hydrophobic durability, and anti-icing thermal stability, whereas T1 is at a disadvantage in all dimensions. With comprehensive consideration of the mechanical properties, hydrophobic characteristics, mechanical durability, anti-icing capability, thermal stability, and tribological analysis, the T3 coating is confirmed as the coating system with the optimal overall performance in this study.

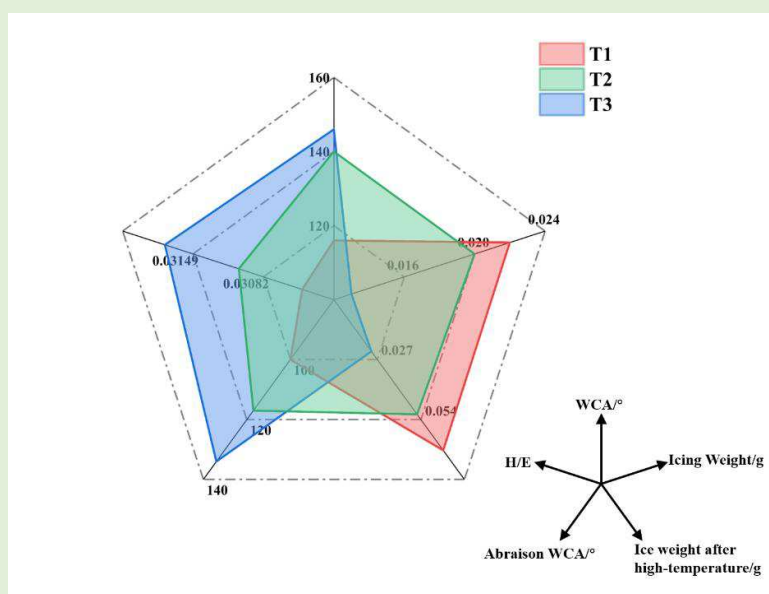


Fig. 24 Schematic diagram of radar performance of three coatings

Conclusions

In this study, the effects of graphene content on the tribological performance, anti-icing properties, and structural evolution mechanisms of PUA–PTFE/SiC–SiO₂ composite coatings over a wide temperature range were systematically investigated, and the main conclusions are drawn as follows:

(1) The highest mechanical properties were exhibited by the T3 coating (with a high graphene content), whose elastic modulus and hardness reached 2.91 GPa and 0.10 GPa, respectively, and whose H/E ratio was notably enhanced (being 2.22% and 4.41% higher than those of T1 and T2, respectively). The results indicate that the H/E ratio is a key factor influencing the wear resistance over a wide temperature range; by improving the resistance to plastic deformation, abrasive wear and surface spallation are effectively suppressed.

(2) Over the temperature range from $-25\text{ }^{\circ}\text{C}$ to $75\text{ }^{\circ}\text{C}$, the most outstanding tribological performance was shown by the T3 coating. Its average friction coefficient could be as low as 0.10 and reached 0.16 at elevated temperature, representing a maximum reduction of approximately 61% compared with the steel substrate. This performance enhancement is primarily attributed to the easy shear and slip characteristics of the layered graphene structure during friction, as well as the synergistic formation of a stable lubricating transfer film by PTFE and graphene, by which the interfacial shear resistance is significantly reduced and thermal fatigue wear is mitigated.

(3) The best anti-icing performance was achieved by the T3 coating. A water contact angle of 146° was attained, and the ice accretion amounted to only 0.013 g, which is approximately 90.6% lower than that of the steel substrate. Moreover, the lowest ice accretion was still maintained by the coating after thermal aging, reflecting excellent environmental stability. This is attributed to its dense and uniform micro-/nano-structure and low surface energy, which can effectively trap air to form a stable air cushion layer and thereby suppress moisture adsorption and ice crystal growth.

(4) Comprehensive microstructural and performance analysis reveals that a synergistic mechanism of “dense structure + lubricating transfer film + low surface energy” is constructed by the high graphene content. On the one hand, the compactness and mechanical properties of the coating are enhanced; on the other hand, interfacial lubrication and environmental stability are improved, thereby achieving an overall enhancement in low friction, low wear, and durable anti-icing performance under wide-temperature service conditions.

References

- [1] Liu R, Li D Y. Experimental studies on tribological properties of pseudoelastic TiNi alloy with comparison to stainless steel 304[J]. Metallurgical and Materials Transactions A, 2000, 31: 2773-2783. <https://doi.org/10.1007/bf02830337>.
- [2] Godse R S, Gawande S H, Keste A A. Tribological behavior of high fraction carbon steel alloys[J]. Journal of Bio-and Tribo-Corrosion, 2016, 2: 1-9. <https://doi.org/10.1007/s40735-016-0034-3>.
- [3] Astudillo A P C, Soriano G A F, Barona Osorio G M, et al. Comparative study of the mechanical and tribological properties of a Hadfield and a Fermanal steel[J]. Hyperfine Interactions, 2017, 238: 1-12. <https://doi.org/10.1007/s10751-017-1422-x>.
- [4] Yazıcı M, Kovacı H, Yetim A F, et al. Structural, mechanical and tribological properties of Ti and TiN coatings on 316L stainless steel[J]. Ceramics International, 2018, 44(12): 14195-14201. <https://doi.org/10.1016/j.ceramint.2018.05.022>
- [5] Xiao J, Cao J, Huang H, et al. Tribological and anti-corrosive performances of epoxy resin coatings filled with Ti₃AlC₂ at rise temperature[J]. Materials Chemistry and Physics, 2025: 131517. <https://doi.org/10.1016/j.matchemphys.2025.131517>.
- [6] Wang J, Meng H, Yu H, et al. Characterization and wear behavior of WC-0.8 Co coating on cast steel rolls by electro-spark deposition[J]. International Journal of Minerals, Metallurgy and Materials, 2009, 16(6): 707-713. <https://doi.org/10.4028/www.scientific.net/amr.160-162.176>.
- [7] Durdu S, Aktuğ S L, Korkmaz K. Characterization and mechanical properties of the duplex coatings produced on steel by electro-spark deposition and micro-arc oxidation[J]. Surface and Coatings Technology, 2013, 236: 303-308. <https://doi.org/10.1016/j.surfcoat.2013.10.004>.
- [8] Komarov F F, Konstantinov V M, Kovalchuk A V, et al. The effect of steel substrate pre-hardening on structural, mechanical, and tribological properties of magnetron sputtered TiN and TiAlN coatings[J]. Wear, 2016, 352: 92-101. <https://doi.org/10.1016/j.wear.2016.02.007>.
- [9] Wood R J K. Tribology of thermal sprayed WC-Co coatings[J]. International Journal of Refractory Metals and Hard Materials, 2010, 28(1): 82-94. <https://doi.org/10.1016/j.ijrmhm.2009.07.011>.
- [10] Singh S, Chen X, Zhang C, et al. Tribological performance of steel with multi-layer graphene grown by low-pressure chemical vapor deposition[J]. Journal of Tribology, 2020, 142(12): 122101. <https://doi.org/10.1115/1.4047458>.
- [11] Friedrich K. Polymer composites for tribological applications[J]. Advanced Industrial and Engineering Polymer

- Research, 2018, 1(1): 3-39. <https://doi.org/10.1016/j.aiepr.2018.05.001>.
- [12] Zhang Z, Hauptert F, Friedrich K. Enhancement of the wear resistance of polymer composites by nano-fillers[J]. German Patent Application, 2003 (10329228.4). <https://doi.org/10.1016/j.compositesa.2004.05.005>.
- [13] Huimin Q I, Yipo C U I, Jiaxin Y U, et al. Molecular Dynamics Simulations on the Tribological Properties of the Tunable Block Copolymers of Epoxy/Polyurethane in Different Temperatures[J]. TRIBOLOGY, 2022, 43(9): 1016-1025. <https://doi.org/10.1016/j.apsusc.2021.150051>.
- [14] Zhang Y, Zhang D, Wei X, et al. Enhanced tribological properties of polymer composite coating containing graphene at room and elevated temperatures[J]. Coatings, 2018, 8(3): 91. <https://doi.org/10.3390/coatings8030091>.
- [15] Stead I M N, Eckold D G, Clarke H, et al. Towards a plastic engine: Low—temperature tribology of polymers in reciprocating sliding[J]. Wear, 2019, 430: 25-36. <https://doi.org/10.1016/j.wear.2019.04.008>.
- [16] Huang Y, Zhang Z, Ma C, et al. Polymer coating for antiicing and deicing[J]. Polymer, 2024, 302: 127047. <https://doi.org/10.1016/j.polymer.2024.127047>.
- [17] Wu B, Cui X, Jiang H, et al. A superhydrophobic coating harvesting mechanical robustness, passive anti-icing and active de-icing performances[J]. Journal of Colloid and Interface Science, 2021, 590: 301-310. <https://doi.org/10.1016/j.jcis.2021.01.054>.
- [18] Wang H, Cao P, Xu S, et al. Anti-icing performance of hydrophobic coatings on stainless steel surfaces[J]. Heliyon, 2024. <https://doi.org/10.1016/j.heliyon.2024.e32319>.
- [19] Liu R, Sun Y, Gu H, et al. Synthesis and application of acrylate copolymer as high ink-absorption and fast drying coating agent for polyester fabric[J]. Progress in Organic Coatings, 2019, 136: 105298. <https://doi.org/10.1016/j.porgcoat.2019.105298>.
- [20] Bhushan B. Principles and applications of tribology[M]. John wiley & sons, 2013. <https://doi.org/10.1002/9781118403020>.
- [21] Putman K J, Rowles M R, Marks N A, et al. The role of the 2D-to-3D transition in x-ray diffraction analysis of crystallite size[J]. Journal of Physics: Condensed Matter, 2021, 33(29): 294002. <https://doi.org/10.1088/1361-648x/ac0083>.
- [22] Gao Y, Qu L, He B, et al. Study on effectiveness of anti-icing and deicing performance of super-hydrophobic asphalt concrete[J]. Construction and Building Materials, 2018, 191: 270-280. <https://doi.org/10.1016/j.conbuildmat.2018.10.009>.
- [23] Latthe S S, Sutar R S, Kodag V S, et al. Self-cleaning superhydrophobic coatings: Potential industrial

- applications[J]. *Progress in Organic Coatings*, 2019, 128: 52-58. <https://doi.org/10.1016/j.porgcoat.2018.12.008>.
- [24] Cao C, Yi B, Zhang J, et al. Sprayable superhydrophobic coating with high processibility and rapid damage-healing nature[J]. *Chemical Engineering Journal*, 2020, 392: 124834. <https://doi.org/10.1016/j.cej.2020.124834>.
- [25] Makkonen L. A thermodynamic model of contact angle hysteresis[J]. *The Journal of chemical physics*, 2017, 147(6):7-10. <https://doi.org/10.1063/1.4996912>.
- [26] Li Y. An analytical approach for determining contact angle hysteresis on smooth, micropillared, and micropored homogeneous surfaces[J]. *Journal of Colloid and Interface Science*, 2025, 679: 554-565. <https://doi.org/10.1016/j.jcis.2024.09.201>.
- [27] Luo H, Chen S, Zhu L, et al. Investigation of surface textures deterioration on pavement skid-resistance using hysteresis friction models and numerical simulation method[J]. *Friction*, 2024, 12(4): 745-779. <https://doi.org/10.1007/s40544-023-0811-1>.
- [28] Zhang D, Zhang Y, Li Q, et al. Origin of friction hysteresis on monolayer graphene[J]. *Friction*, 2022, 10(4): 573-582. <https://doi.org/10.1007/s40544-021-0517-1>.
- [29] Cassie A B D, Baxter S. Wettability of porous surfaces[J]. *Transactions of the Faraday society*, 1944, 40: 546-551. <https://doi.org/10.1039/tf9444000546>.
- [30] Zheng Q J, Yang R Y, Zeng Q H, et al. Interparticle forces and their effects in particulate systems[J]. *Powder Technology*, 2024, 436: 119445. <https://doi.org/10.1016/j.powtec.2024.119445>.
- [31] Wu Y, Wei Q, Cai M, et al. Interfacial friction control[J]. *Advanced materials interfaces*, 2015, 2(2): 1400392. <https://doi.org/10.1002/admi.201570013>.
- [32] Abe A, Goss J A, Zou M. Exploring the impact of spray process parameters on graphite coatings: morphology, thickness, and tribological properties[J]. *Coatings*, 2024, 14(6): 714. <https://doi.org/10.3390/coatings14060714>.
- [33] Matin E, Attar M M, Ramezanzadeh B. Investigation of corrosion protection properties of an epoxy nanocomposite loaded with polysiloxane surface modified nanosilica particles on the steel substrate[J]. *Progress in Organic Coatings*, 2015, 78: 395-403. <https://doi.org/10.1016/j.porgcoat.2014.07.004>.
- [34] Amontree J, Yan X, DiMarco C S, et al. Reproducible graphene synthesis by oxygen-free chemical vapour deposition[J]. *Nature*, 2024, 630(8017): 636-642. <https://doi.org/10.1038/s41586-024-07454-5>.
- [35] Shu B, Liu Z, Liu Z, et al. Preparation of SiO₂-decorated GO sheets and their influences on the properties of castor oil-based polyurethane coating film[J]. *Progress in Organic Coatings*, 2023, 175: 107382. <https://doi.org/10.1016/j.porgcoat.2022.107382>.

- [36] Yan H, Yuanhao W, Hongxing Y. TEOS/silane coupling agent composed double layers structure: A novel super-hydrophilic coating with controllable water contact angle value[J]. *Applied Energy*, 2017, 185: 2209-2216. <https://doi.org/10.1016/j.apenergy.2015.09.097>.
- [37] Lan L, Di Y, Wang H, et al. One-step modification method of a superhydrophobic surface for excellent antibacterial capability[J]. *Friction*, 2023, 11(4): 524-537. <https://doi.org/10.1007/s40544-022-0611-z>.
- [38] Abdullah M M, Rajab F M, Al-Abbas S M. Structural and optical characterization of Cr₂O₃ nanostructures: Evaluation of its dielectric properties[J]. *Aip Advances*, 2014, 4(2):6-7. <https://doi.org/10.1063/1.4867012>.
- [39] Szychta E, Szychta L. Comparative analysis of effectiveness of resistance and induction turnout heating[J]. *Energies*, 2020, 13(20): 5262. <https://doi.org/10.3390/en13205262>.
- [40] Ma L, Shi L B, Guo J, et al. On the wear and damage characteristics of rail material under low temperature environment condition[J]. *Wear*, 2018, 394: 149-158. <https://doi.org/10.1016/j.wear.2017.10.011>.
- [41] Xi Z, Li X, Xi K. Study on the reactivity of oxygen-containing functional groups in coal with and without adsorbed water in low-temperature oxidation[J]. *Fuel*, 2021, 304: 121454. <https://doi.org/10.1016/j.fuel.2021.121454>.
- [42] Li L, Yao X, Li H, et al. Thermal stability of oxygen-containing functional groups on activated carbon surfaces in a thermal oxidative environment[J]. *Journal of Chemical Engineering of Japan*, 2014, 47(1): 21-27. <https://doi.org/10.1252/jcej.13we193>.
- [43] Qi Y, Sun B, Zhang Y, et al. Study of Tribological properties and evolution of morphological characteristics of transfer films in PTFE composites synergistically reinforced with Nano-ZrO₂ and PEEK particles[J]. *Polymers*, 2023, 15(17): 3626. <https://doi.org/10.1063/1.4971912>.
- [44] Nasir A, Kausar A, Younus A. Polymer/graphite nanocomposites: Physical features, fabrication and current relevance[J]. *Polymer-Plastics Technology and Engineering*, 2015, 54(7): 750-770. <https://doi.org/10.1080/03602559.2014.979503>.
- [45] Ye H, Chen A, Liu S, et al. Effect of ultrasonic surface rolling process on the surface properties of Qal10-3-1.5 aluminum bronze alloy[J]. *Surface and Coatings Technology*, 2022, 433: 128126. <https://doi.org/10.1016/j.surfcoat.2022.128126>.
- [46] Lin P, You X, Song J, et al. Achieving synergistic enhancement of wear resistance and mechanical properties of ZrO₂ (Y₂O₃)-graphite composite inspired by dental crown architecture[J]. *Tribology International*, 2026: 111906. <https://doi.org/10.2139/ssrn.6100380>.
- [47] Zhuo X, Teng Y, Cao J, et al. The investigation of support effect from hard substrate to soft coating of PI/EP-

- PTFE under different coating thicknesses and frictional contacts[J]. *Materials Today Communications*, 2024, 41: 110690. <https://doi.org/10.2139/ssrn.4916783>.
- [48] Eyal Awwad K Y, Yousif B F, Fallahnezhad K, et al. Influence of graphene nanoplatelets on mechanical properties and adhesive wear performance of epoxy-based composites[J]. *Friction*, 2021, 9(4): 856-875. <https://doi.org/10.1007/s40544-020-0453-5>.
- [49] Liñeira del Río J M, Fernandes C M C G, Gonçalves D E P, et al. Synergistic effects of functionalized WS₂ and SiO₂ nanoparticles and a phosphonium ionic liquid as hybrid additives of low-viscosity lubricants[J]. *Lubricants*, 2024, 12(2): 58. <https://doi.org/10.3390/lubricants12020058>.
- [50] Kota A K, Li Y, Mabry J M, et al. Hierarchically structured superoleophobic surfaces with ultralow contact angle hysteresis[J]. *Advanced materials*, 2012, 24(43): 5838. <https://doi.org/10.1002/adma.201202554>.
- [51] Zhou L, Ding L, Yi X. A review of snow melting and de-icing technologies for trains[J]. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 2022, 236(8): 877-886. <https://doi.org/10.1177/09544097211059631>.
- [52] Tada T, Kawasaki S, Shimizu R, et al. Rubber-ice friction[J]. *Friction*, 2023, 11(8): 1534-1543. <https://doi.org/10.1007/s40544-022-0715-5>.
- [53] Li W, Zhan Y, Yu S. Applications of superhydrophobic coatings in anti-icing: Theory, mechanisms, impact factors, challenges and perspectives[J]. *Progress in Organic Coatings*, 2021, 152: 106117. <https://doi.org/10.1016/j.porgcoat.2020.106117>.
- [54] Xu W, Hu D, Yi M, et al. Mechanism of Ti₃SiC₂ on microstructure evolution and tribological enhancement of copper matrix composites[J]. *Tribology International*, 2025: 111002. <https://doi.org/10.1016/j.triboint.2025.111002>.
- [55] Fu J, Wang L, Yu H, et al. Research progress of UV-curable polyurethane acrylate-based hardening coatings[J]. *Progress in Organic Coatings*, 2019, 131: 82-99. <https://doi.org/10.1016/j.porgcoat.2019.01.061>.
- [56] Bandeira P, Monteiro J, Baptista A M, et al. Influence of oxidized graphene nanoplatelets and [DMIM][NTf₂] ionic liquid on the tribological performance of an epoxy-PTFE coating[J]. *Tribology International*, 2016, 97: 478-489. <https://doi.org/10.1016/j.triboint.2016.02.005>.
- [57] Zhang X, Liu Z, Li Y, et al. Robust superhydrophobic epoxy composite coating prepared by dual interfacial enhancement[J]. *Chemical Engineering Journal*, 2019, 371: 276-285. <https://doi.org/10.1016/j.cej.2019.04.040>.

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