

Oil-containing microcapsule-triggered lubrication enables ultra-low friction and high wear resistance in phenolic epoxy coating

Xiaoyu Li^{1,3}, Yubo Liu^{1,2}, Zhengyuan Li^{1,2}, Chenggang Sun¹, Meirong Cai^{1,2},
Hongliang Liu,^{1,3} Yang Wu^{1,2,4*}, Feng Zhou²

¹ Shandong Laboratory of Advanced Materials and Green Manufacturing at Yantai Zhongke Research Institute of Advanced Materials and Green Chemical Engineering, Yantai, Shandong 264006, China.

² State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Science, Lanzhou, Gansu 730000, China.

³ School of Chemistry and Chemical Engineering, Yantai University, Yantai, Shandong 264005, China.

⁴ Qingdao Centre of Resource Chemistry and New Materials, Qingdao, Shandong 266100, China.

Corresponding authors: Yang Wu, yangwu@licp.cas.cn

Received: March 17, 2026; Revised: June 12, 2026; Accepted: July 6, 2026

© The Author(s) 2026.

Abstract: Oil-containing self-lubricating composite material is an effective approach to address the wear issues of polymer materials. In this work, the traditional lubricant 500SN was encapsulated within melamine-formaldehyde (MF) resin shells through *in-situ* polymerization to prepare 500SN@MF microcapsules. Comprehensive characterizations confirmed that the 500SN@MF microcapsules have a well-defined spherical morphology, improved thermal stability, and excellent compatibility with phenolic epoxy resin. The 500SN@MF microcapsules were mixed with phenolic epoxy and cured at room temperature to form a composite self-lubricating coating. Tribological performance tests demonstrated that the composite coating exhibited exceptional anti-wear and friction-reducing properties, with a friction coefficient (COF) of ~ 0.038 and a notably low wear rate of $0.077 \times 10^{-6} \text{ mm}^3/(\text{N} \cdot \text{m})$ under 5 N load and 20000 friction cycles. Significantly, the 500SN@MF microcapsules could be produced in small batches while maintaining an intact core-shell structure, which offers a scalable material solution for achieving efficient, long-term lubrication in mechanical components and significantly extending their service life.

Keywords: microcapsule; self-lubricating coating; anti-friction; anti-wear; large-scale preparation

1. Introduction

Friction, a universally existing physical phenomenon that occurs at contact surfaces where there is relative motion or a tendency for motion, impedes the relative motion and simultaneously induces wear, which causes an energy penalty and material wear-out failure[1, 2]. So, the development of effective lubrication techniques to reduce friction and wear is a central research objective in the field of tribology[3]. Polymeric composite coatings have drawn considerable interest owing to strong adaptability to the substrate, easy processing and low comprehensive usage cost[4-6]. However, the inherent softness of polymer coatings results in poor frictional properties, particularly wear resistance, which fails to meet operational requirements. To enhance its wear resistance, various technical approaches have been extensively explored, among which the incorporation of lubricating fillers is regarded as an effective strategy[7]. To date, solid particles with anti-wear property, such as alumina, carbon nanotubes, CaF_2 crystals, BN, WS_2 , PTFE, graphite and molybdenum disulfide, have been extensively investigated[8-14]. Generally, the friction-reduction and anti-wear capacities of the composites are enhanced simultaneously owing to the generation of a seamless, uniform transfer film derived from such solid lubricants within the frictional contact zone[15]. Although introducing solid lubricants into polymeric systems demonstrates

certain friction-reducing effects, a superior lubrication performance comparable to that of liquid lubricants cannot be achieved because liquid lubricants establish a stable "solid-liquid-solid" interface for hydrodynamic lubrication[16, 17]. However, liquid lubricants are still confronted with several challenges in polymeric systems, such as poor compatibility with the coating matrix, difficulties in being retained on the friction surface for extended periods, and a tendency to leak during operation, which collectively limit their application in some situations[18, 19].

Microencapsulation technology, enabling liquid lubricant stability and uniform dispersion in coating matrix by encapsulation with microcapsules, stands out as a promising approach for overcoming these aforementioned issues[20]. When surface wear occurs, the microcapsules rupture and release lubricant, achieving the "on-demand" supply[21]. This controllable release delivers a sustained supply of lubricant at the contact region, remarkably enhancing the lubrication performance of the composites[22, 23]. Recently, microencapsulation technology has gained extensive research interest with common microcapsule preparation methods including solvent evaporation, interfacial polymerization, in-situ polymerization and emulsion polymerization[24-27]. In terms of shell material selection, organic or inorganic shell materials are primarily categorized. Inorganic shell materials mainly include silica, titanium dioxide, calcium carbonate, etc.[28-30], while organic shell materials cover polystyrene, polyurethane, urea-formaldehyde resin, melamine-formaldehyde (MF) resin, and so on[30-33]. In contrast to inorganic shells, organic shells generally possess

superior sealing performance and thermal stability, which was more extensively studied in previous reports[34, 35]. And among organic shell materials, MF resin can not only afford excellent structural stability, but also feature low cost and simple preparation process, endowing it with broad application in microcapsule shell materials[36]. As for lubricant materials, 500SN, a typical mineral base oil, presents favorable lubricating properties and stable film-forming ability, which can generate a lubricating film on contact surfaces to lower sliding resistance and alleviate wear. Meanwhile, 500SN has excellent compatibility and rheological properties which make it an ideal carrier for lubrication systems and contribute to the development of a durable lubricious layer. These characteristics further justify the rational selection of 500SN as the core material in microcapsule[37, 38].

Although the microcapsule technique is widely reported for fabricating self-lubricating composite materials, controlling the morphology and uniformity of microcapsules remains a challenge, and meanwhile, the large-scale preparation of these microcapsules is still restricted. To address above issues, a reliable and scalable method was reported for fabricating 500SN@MF microcapsules in this work, which feature a 500SN lubricant core and a MF resin shell. The shape and size of 500SN@MF microcapsules was controlled by optimizing the core-shell ratio of the microcapsules during their preparation. The as-prepared microcapsules exhibit not only favorable thermal stability but also excellent compatibility with the phenolic epoxy resin matrix. Thus, the uniform composite self-lubricating coating was fabricated by incorporating

500SN@MF into the phenolic epoxy resin. As shown in Fig. 1, the composite coating facilitates the rapid release of 500SN lubricant to generate a liquid lubrication film when mechanically worn, thereby imparting a minimized coefficient of friction alongside a reduced wear rate to the matrix, and significantly enhances its wear resistance.

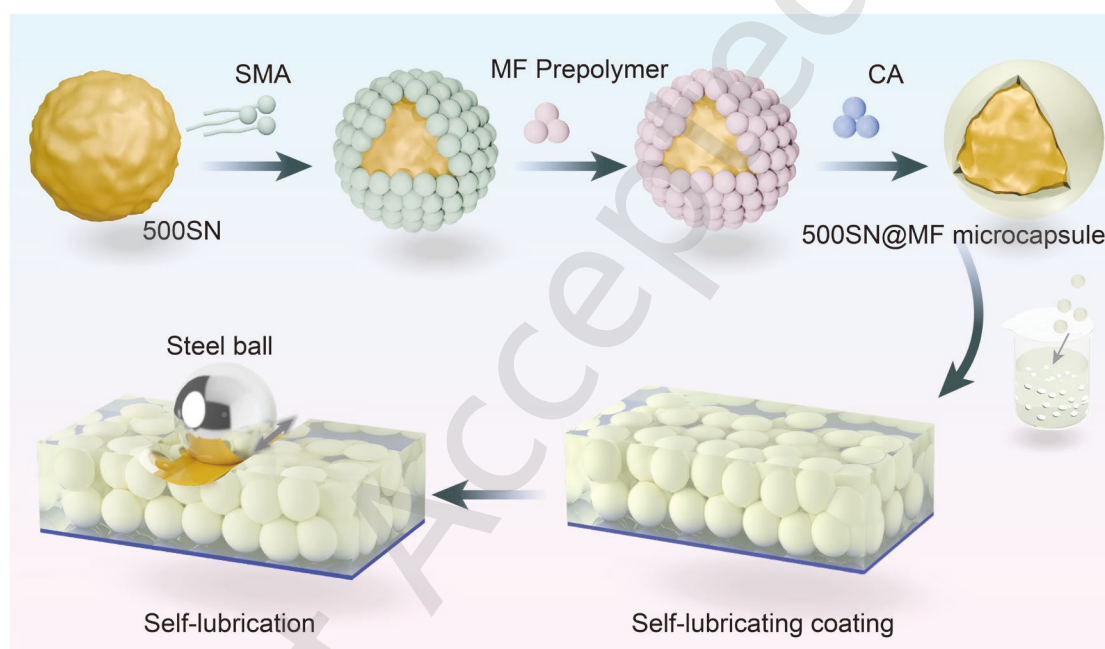


Fig. 1 Illustrative schematics for the preparation of 500SN@MF microcapsules and the self-lubricating behavior of the 500SN@MF composite coating.

2. Experiment

2.1 Materials and Reagents

Melamine (99%) and citric acid were supplied by Shanghai Macklin Biochemical Co., Ltd., while Chongqing Chuandong Chemical Group Co., Ltd. provided the

formaldehyde solution (37 wt.%). Triethanolamine (99%) was sourced from Aladdin Biochemical (Shanghai, China). Nanjing Yinxin Chemical Co., Ltd. (Nanjing, China) offered the styrene maleic anhydride (SMA) (95%). Lanzhou Institute of Chemical Physics (CAS) provided the lubricant oil 500SN. Xylene was acquired via Shanghai Denuo Chemical Co., Ltd., and the phenolic epoxy resin was procured from Shandong Jinhong New Materials Technology Co., Ltd.. Without undergoing additional purification, all analytical-grade chemicals were utilized directly as delivered.

2.2 Preparation of 500SN@MF microcapsules

Firstly, the MF prepolymer was synthesized through the following steps: melamine (80 g), formaldehyde solution (172 g), and deionized water (800 mL) were mixed in a single-neck round-bottom flask. After adjusting the pH of the mixture to 8-9 using triethanolamine solution, continuous stirring was maintained at 70 °C for 1 h, yielding the desired prepolymer solution. Then, 500SN was added to a 2 wt.% SMA solution, and a high-speed homogenizer running at 10,000 rpm was applied for 10 minutes to transform the mixture into an oil-in-water (O/W) emulsion. Finally, the aforementioned prepolymer and emulsion were combined in a flask, and mechanical agitation was applied at 300 rpm and 80 °C. The pH value was adjusted to approximately 6 by adding citric acid, followed by 2 h of continuous heating and stirring for the solidification of the MF shell. At last, the powdery 500SN@MF microcapsules were obtained by spray drying. During spray drying, the atomization pressure was maintained in the range of 0.2~0.6 MPa, and the feed rate was controlled

at 5~10 mL·min⁻¹. The inlet and outlet temperatures were maintained at 180~200 °C and 80~90 °C, respectively, ensuring efficient solvent evaporation and intact microcapsule formation.

2.3 Fabrication protocol for self-lubricating coatings

To fabricate self-lubricating coatings with a range of mass fractions (0, 10, 15, 20, 25, 30 wt.%), various amounts of 500SN@MF microcapsules were ultrasonically dispersed in 5 g of phenolic epoxy resin diluted with xylene. Thereafter, the incorporation of 1 g of curing agent was executed, followed by a homogenization treatment. A series of self-lubricating coatings with 500SN@MF microcapsules mass fraction of 0, 10, 15, 20, 25, and 30 wt.% were obtained after curing at room temperature.

2.4 Characterizations

The micromorphology of 500SN@MF microcapsules and the microstructural profiles of the coating surfaces as well as fractured cross-sections were analyzed via field emission scanning electron microscopy (CLARA GMH) at 10 kV. Fourier transform infrared spectroscopy (FTIR, Nicolet IS10) was employed to identify the chemical functional groups of 500SN, 500SN@MF microcapsules, and raw MF resin, aiming to verify the successful synthesis of microcapsules. Thermogravimetric analyzer (TGA, Mettler Toledo) was utilized for assessing the thermal decomposition of 500SN@MF microcapsules. During the test, the sample was heated at 10 °C/min within the temperature span of 20~900 °C under continuous nitrogen flow. Nanoindentation measurements were carried out on individual coatings with a KLA iMicro nanoindenter.

To evaluate the mechanical properties, tensile evaluations were carried out via a universal testing machine (Instron 5944, 2 kN). Samples were cut into a dumbbell shape with an active region of $10 \times 2 \times 0.5$ mm. A minimum of three replicates were tested for each group with the stretching velocity of 50 mm/min.

2.5 Tribological tests

To evaluate the coatings' friction and wear behaviors, a CSM TRB3 reciprocating tribometer was used to investigate the prepared coatings in a ball-on-flat contact mode. The sliding counterpart was a 3-mm-radius AISI 304 stainless steel ball. Under constant-load conditions, the load was maintained at 5 N. The reciprocating movement had an amplitude of 3 mm and a frequency of 2 Hz. A total of 20,000 cycles were completed, equivalent to a cumulative sliding distance of 120 m. To further elucidate the effects of external parameters on tribological behavior, load- and frequency-dependent tests were performed. For the load-dependent measurements, the frequency and amplitude length were fixed at 2 Hz and 3 mm, respectively, with a total of 500 cycles (sliding distance: 3 m), while the applied load was varied from 2 to 10 N (2, 4, 6, 8, and 10 N). For the frequency-dependent tests, the normal load (5 N) and stroke length (3 mm) were kept constant, and the tests were carried out for 500 cycles (sliding distance: 3 m) with frequencies ranging from 1 to 5 Hz. To evaluate the contact pressure during the friction tests, Hertzian contact theory was adopted to calculate the Hertzian contact stress under different loads. For a ball-on-flat contact configuration, the reduced

Young's modulus (E^*), contact radius (a), and mean contact pressure (P_m) were determined as follows[39]:

$$\frac{1}{E^*} = \frac{1}{2} \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right) \quad (1)$$

$$a = \left(\frac{3RF_n}{2E^*} \right)^{1/3} \quad (2)$$

$$P_m = \frac{F_n}{\pi a^2} \quad (3)$$

in which E^* represents the reduced Young's modulus; the Young's moduli for the AISI 304 stainless steel ball and the 25 wt.% microcapsules-loaded coating are denoted as E_1 (193 GPa) and E_2 (0.919 GPa), respectively; ν_1 (0.30) and ν_2 (0.35) correspond to the Poisson's ratios of the steel ball and the composite coating with 25 wt.% microcapsules, respectively; a is the contact radius; F_n signifies the applied normal load; the steel ball radius is given by R (3 mm); and P_m acts as the mean contact pressure. **Table S1** compiles the computed Hertzian contact stress values obtained across various loading conditions. All experiments were conducted under ambient conditions.

A confocal laser scanning microscope (CLSM) was employed to inspect the wear scar morphology, which yielded the 3D topographies of the worn area, from which the volume (V) of material loss was directly determined. Based on the data, the quantification of the wear rate (W , mm³/(N·m)) was achieved according to the mathematical expression itemized below[40]:

$$W = \frac{V}{F \times L} \quad (4)$$

where V is the wear volume loss (mm^3), F is the applied normal load (N), and L is the sliding distance (m). Through this approach, the wear resistance can be quantitatively analyzed, thereby guaranteeing highly precise and comparable data outputs.

3. Results and discussion

3.1 Preparation and characterization of 500SN@MF microcapsules

To prepare 500SN@MF microcapsules, the *in-situ* polymerization mechanism involving MF prepolymers was triggered along the phase boundary of an O/W emulsion to achieve highly efficient encapsulation, as illustrated in **Fig. 1**. The anionic surfactant SMA tends to accumulate at the phase boundary to stabilize the O/W emulsion. Meanwhile, hydrophilic carboxyl side chains stretch outward toward the surrounding aqueous continuous medium, while the hydrophobic aryl moieties are tightly embedded in the 500SN oil phase, forming stable polymeric micelles. Subsequently, the MF prepolymers are adsorbed onto the surface of oil colloidal particles. Under acidic conditions, these adsorbed MF prepolymers undergo *in-situ* polycondensation and gradual crosslinking (**Fig. S1**), ultimately forming a dense and robust shell on the oil droplet surface[32]. To achieve the optimal synthesis method of microcapsules, the mass ratio of MF prepolymer solution to 500SN was systematically adjusted. As depicted in **Fig. 2a**, with the mass proportion between shell and core fixed at 4/1, only a small quantity of 500SN is successfully encapsulated into spherical microcapsules, and the majority of 500SN lubricant remains unencapsulated because of the insufficient

dosage of prepolymer. When the mass ratio is increased to 8/1, excess prepolymer causes excessive crosslinking reaction, which results in the fusion and adhesion of the shell of adjacent microcapsules (**Fig. 2b**). Under the optimal mass ratio of 6/1, the prepared 500SN@MF microcapsules exhibit a smooth surface and regular morphology. Specifically, the micrographs (**Fig. 2c**) reveal that these fractured microcapsules possess an average shell thickness of approximately 301 nm, while statistical analysis (**Fig. S2**) indicates a corresponding diameter distribution ranging from 3.66 to 31.17 μm .

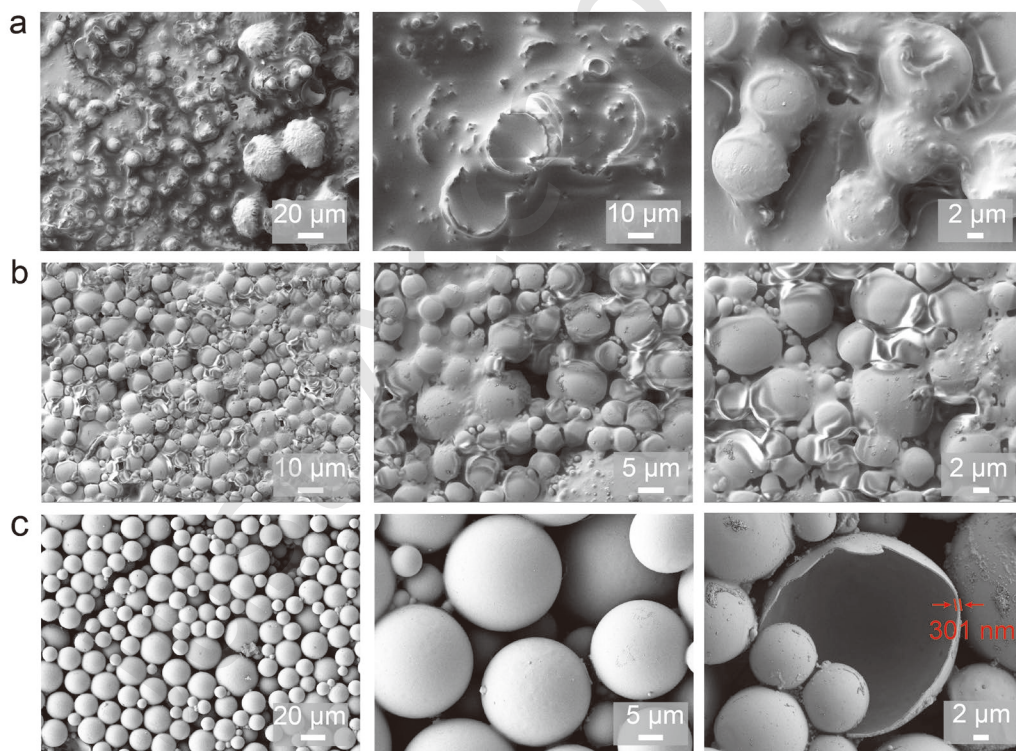


Fig. 2 SEM images of 500SN@MF microcapsules with different mass ratios of MF prepolymer solution to 500SN: 4/1 (a), 8/1 (b), 6/1 (c).

After determining the optimal core-to-shell ratio, large-scale preparation of 500SN@MF microcapsules was further attempted. As shown in **Fig. 3**, approximately

4.5 L of microcapsule emulsion was obtained by increasing the ratio of reactants, followed by spray drying to yield 426.57 g of 500SN@MF microcapsules powder (**Figs. 3a-c**). The morphology of the 500SN@MF microcapsule surfaces is shown in **Fig. 3d**. The 500SN@MF microcapsules exhibit a consistent spherical morphology, and the distinct core-shell structure is evident in fractured specimens with a shell thickness of 320 nm. The statistical results indicated the microcapsule diameter under this condition ranged from 11.51 to 51.51 μm , with an overall slightly increased size (**Fig. S3**). To verify the functional structures, Fourier transform infrared spectroscopy evaluation was carried out (**Fig. 3e**). The MF resin spectrum displays a prominent band centered near 3339 cm^{-1} , reflecting the stretching vibrations of N-H and O-H groups. The signal at 1491 cm^{-1} is attributed to the bending mode of the $-\text{CH}_2-$ linkage. The bending modes of the triazine ring correspond to the two absorption bands at 1554 and 811 cm^{-1} . Meanwhile, the distinct peak at 1007 cm^{-1} is assigned to overlapping C-O stretching vibrations[41-43]. In the case of 500SN lubricant, distinct symmetric and asymmetric C-H stretching vibrations appear at 2850 and 2924 cm^{-1} . These typical absorption signals can be clearly observed in the FTIR spectra of 500SN@MF microcapsules, which strongly prove that the MF polymer shell fully covers the inner 500SN core. To further investigate the thermal decomposition behavior of the 500SN@MF microcapsules, thermogravimetric tests were performed, with the corresponding curves compiled in **Fig. 3f**. The thermal decomposition temperature of pure 500SN was approximately $288\text{ }^{\circ}\text{C}$ under a nitrogen atmosphere, while that of the MF resin was

around 400 °C. Notably, the heat resistance of the fabricated 500SN@MF microcapsules was significantly enhanced after microencapsulation, with the main thermal weight loss process occurring at approximately 400 °C. This result indicates that the encapsulation effect of the MF resin effectively improves the thermal stability of 500SN, enabling it to adapt to a wider temperature range in practical applications, especially to withstand higher service temperatures. The encapsulation efficiency of 500SN in 500SN@MF microcapsules was measured via solvent extraction, which allowed quantification of the core mass percentage in the microcapsules. After the microcapsules were thoroughly ground, the core material was repeatedly extracted using n-hexane, and the remaining shell residues were washed and dried to a constant weight. Based on these results, the actual mass fraction of 500SN was calculated to be 53.89%, indicating that a relatively high core loading capacity was achieved in the microcapsule. As shown in **Fig. S4**, the original microcapsules were observed to exhibit intact spherical morphologies, whereas the spherical structures completely disappeared after grinding, and no intact microcapsules were detected. These observations indicate that the shell structures were effectively destroyed, thereby ensuring that the encapsulated core material could be fully released and efficiently extracted. This result further confirms the validity and reliability of the determined core content. The most significant advantage of microcapsules is that the encapsulation transforms the liquid lubricant into a solid powder (**Fig. 3g**), which greatly avoids the leakage of liquid

lubricant, while improving the interfacial dispersion within the resin matrix and eliminating phase segregation during the curing procedure[44].

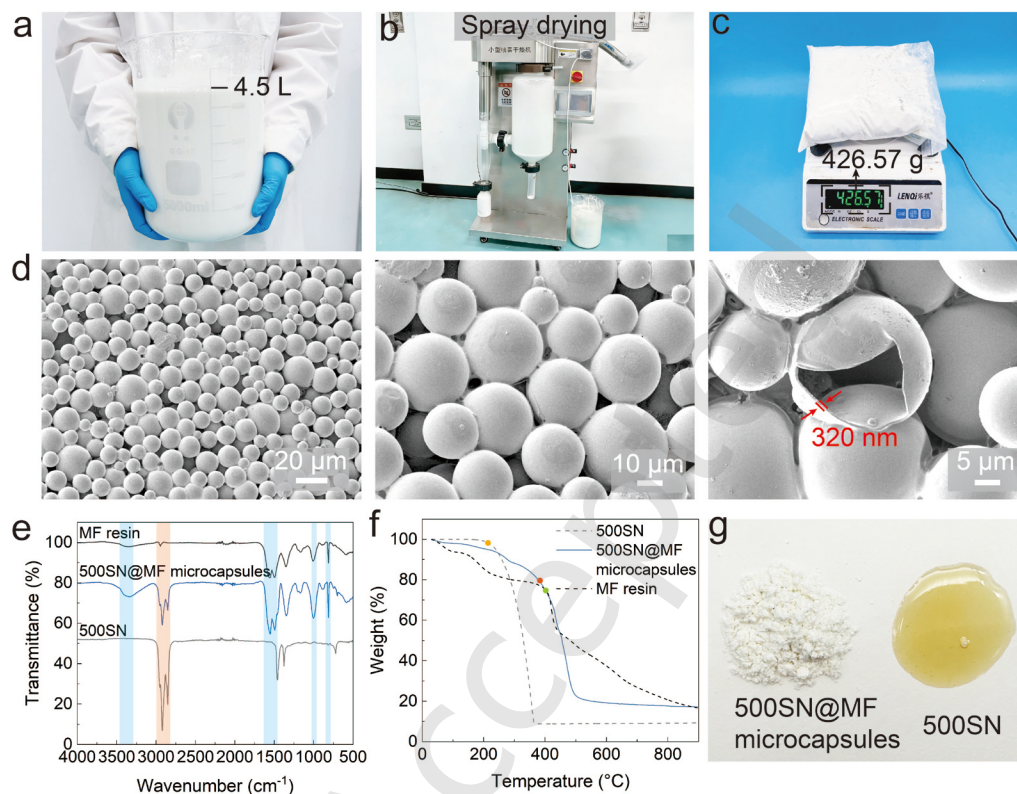


Fig. 3 Optical photograph of (a) the as-prepared 500SN@MF microcapsule emulsion; (b) the spray-drying process; (c) the spray-dried 500SN@MF microcapsule powder with large production. (d) SEM images of the large-scale preparation of 500SN@MF microcapsules with the mass ratio of MF prepolymer solution to 500SN: 6/1. Fourier transform infrared (FTIR) spectra (e) and TGA curves (f) of MF resin, 500SN, and 500SN@MF microcapsules. (g) Optical photographs of 500SN and 500SN@MF microcapsules.

3.2 Preparation and characterization of self-lubricating coatings

To achieve the self-lubricating coating, the 500SN@MF microcapsules were doped as additives into a phenolic epoxy resin by rapid dispersion with various mass fractions, after which an appropriate amount of solvent as well as a curing agent were incorporated. Then uniform liquid film was coated on a glass substrate and thermally cured at room temperature (**Fig. 4a**). SEM was adopted to analyze the surface and cross-section morphological structures, as shown in **Figs. 4b** and **S5**. A smooth surface was observed for the pure phenolic epoxy coating (0 wt.% 500SN@MF microcapsules addition). And as the microcapsule content increased, intact spherical microcapsules were uniformly distributed inside the coating without any agglomeration, which illustrates a good compatibility between 500SN@MF microcapsules and the resin matrix.

Mechanical characteristics are key factors that dominate the tribological behaviors of coatings, as these properties directly influence the bearing capacity, deformation coordination, and wear resistance mechanisms inherent during frictional contact. Therefore, the mechanical properties of coatings with different microcapsule contents were further systematically characterized and analyzed. The tensile strength and elongation at break of the neat phenolic epoxy coating were measured to be 55.3 MPa and 9.02%, respectively. Whereas, as the dosage of 500SN@MF microcapsules rose stepwise, both tensile strength and breaking elongation of the composite coatings declined steadily (**Fig. 4c**). This tendency arises mainly from the two factors. Firstly, 500SN@MF microcapsules fail to form strong interfacial bonds with the surrounding

resin matrix. Although the microcapsules were well dispersed in the coating, as evidenced by cross-sectional electron microscopy in **Fig. S5**, a significant majority of the microcapsules delaminated from the coating matrix rather than fractured themselves. The weak interaction between microcapsules and resin matrix induces the generation and expansion of microcracks, which eventually weakens the overall load resistance of the coatings. Moreover, the premature initiation and rapid propagation of microcracks lead to earlier failure under tensile loading, thereby reducing the elongation at break and limiting the deformation capacity of the coatings. In addition, microcapsules, as dispersed phases within the matrix, disrupt the original continuous structure of the resin matrix. This disruption impedes uniform stress transfer under loading, thereby reducing the toughness of the coatings and further contributing to the decrease in the coatings' breaking elongation[45-47].

The introduction of microcapsules has also exerted a significant influence on the elastic modulus and hardness of the coatings (**Figs. 4d and 4e**). To investigate the effect of microcapsule content on the mechanical properties of the coatings, nanoindentation tests were performed, where the hardness is expressed as nanoindentation hardness (H , GPa). As 500SN@MF microcapsule loading increases, both the coatings' elastic modulus and hardness show a gradual decreasing trend from 7.18 to 4.82 GPa and from 0.55 to 0.38 GPa, respectively. This result is inherently consistent with the variation trend of tensile strength properties, and it is speculated that the main reason lies in the fact that the core material of 500SN@MF microcapsules (500SN) is a liquid oily

substance with inherently low hardness and elastic modulus. Meanwhile, as microcapsule dosage rises, the share of the low-modulus component in the coatings increases accordingly, further impairing the bulk mechanical properties to a greater extent[48, 49].

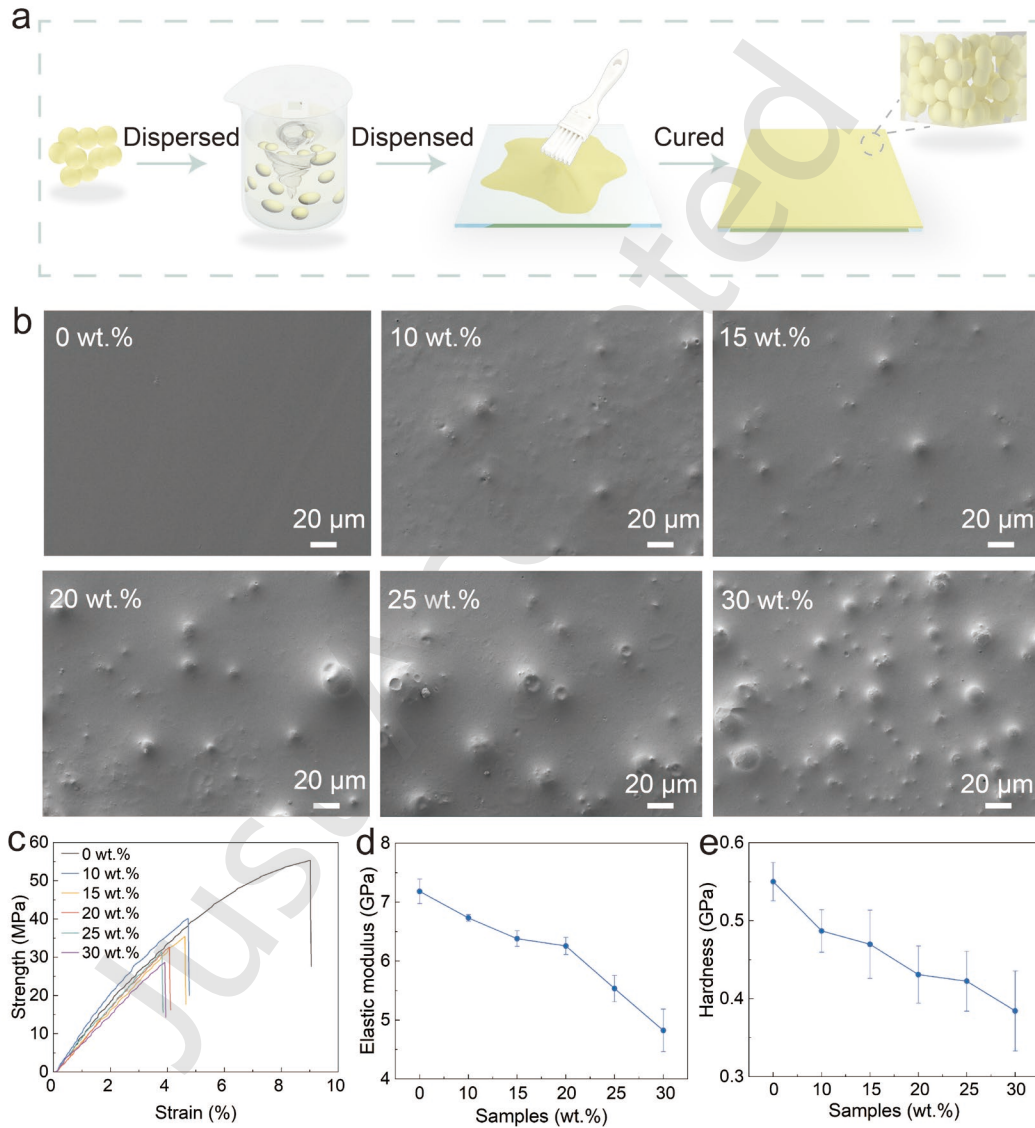


Fig. 4 (a) Schematic representation of the preparation route for self-lubricating coatings. (b) Surface micrographs of coatings at different microcapsule loadings.

Stress-strain curves (c), elastic modulus (d), and hardness (e) of coatings with varied 500SN@MF microcapsule fractions.

3.3 Tribological Properties of Self-Lubricating Coatings

To systematically elucidate the evolution of friction and wear characteristics across different 500SN@MF microcapsule loading, the reciprocating tribological measurements were carried out (**Fig. 5a**). **Figs. 5b** and **5c** are the friction curves and mean friction values for composite coatings filled with varying microcapsule dosages during 20000 reciprocating friction cycles under a 5 N load at a frequency of 2 Hz. From the above results, the pure phenolic epoxy coating exhibited a high friction coefficient and reached ~ 0.78 . In contrast, the friction coefficients of coatings incorporated with 500SN@MF microcapsules were significantly reduced, exhibiting a distinct content-dependent behavior. Specifically, for coatings with 10 wt.% as well as 15 wt.% microcapsule contents, the COF initially decreased to 0.03 and 0.01, respectively, then gradually increased to about 0.28 and 0.23. Their mean friction coefficients were remained at 0.18 and 0.11. This unstable trend, with an early reduction and a later rebound, is primarily caused by the imbalance between lubricant supply and consumption. For coatings with low microcapsule contents, a small amount of 500SN lubricant can be released during the early stage of the sliding process, with the friction coefficient decreasing briefly. However, the limited core material reserve is inadequate to compensate for lubricant loss across the contact interface, so a stable oil film cannot be established. As a result, the friction coefficient subsequently rebounds. At a

microcapsule loading of 25 wt.%, the coating exhibited the lowest COF and remained relatively stable at approximately 0.038, approximately 4.87% of that measured for neat phenolic epoxy coating. Variations in the friction coefficient are ascribed to transformation of the friction state from traditional solid-solid dry friction to solid-liquid interface lubrication because a sufficient number of microcapsules ruptured under frictional stress, continuously releasing 500SN lubricant to form an oil lubrication film (**Fig. 5d**). However, when the microcapsule content was further increased to 30 wt.%, the average friction coefficient of the coating increased to 0.084. This phenomenon may be mainly dictated by the deterioration of the coating's mechanical performance. Specifically, a sharp decline in both hardness and elastic modulus occurred under excessively high microcapsule loading, which caused the coating to fail under contact stress during friction cycles and consequently deteriorated its tribological behavior.

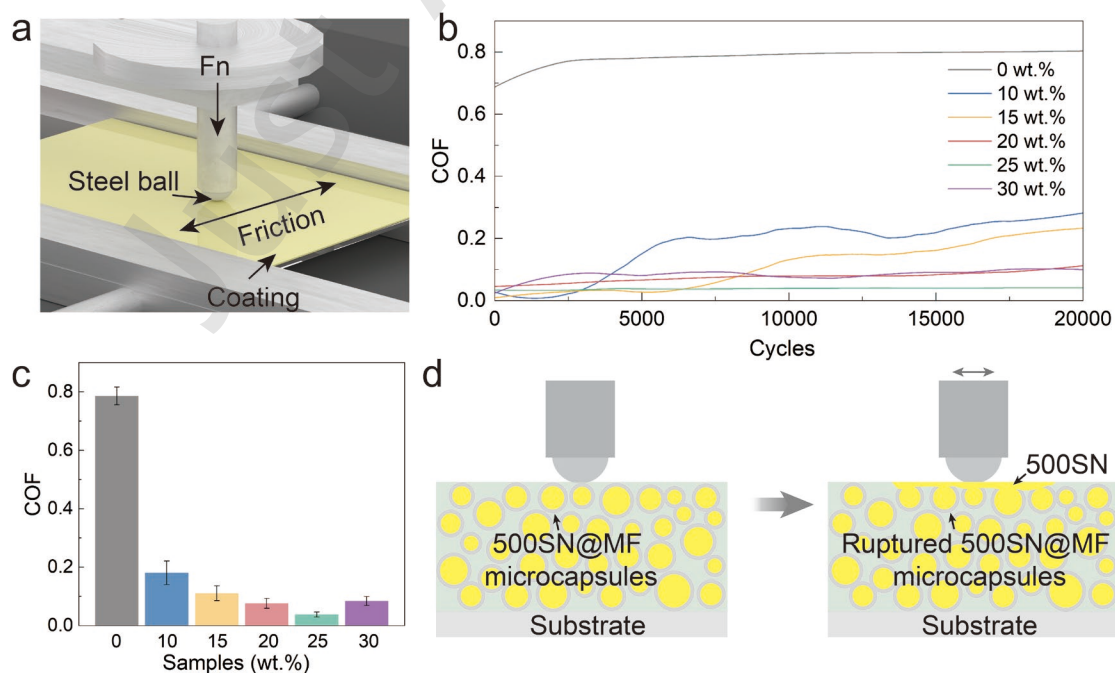


Fig. 5 (a) Scheme of the friction testing machine. (b) Curves of the COF of coatings in 20000 cycles under a 5 N load at a frequency of 2 Hz. (c) Average COF of coatings in 20000 cycles under a 5 N load at a frequency of 2 Hz. (d) Schematic depiction of the lubricant release and friction-reduction mechanism in the self-lubricating coating.

To explore the wear mechanism in depth, the morphologies of worn surfaces were analyzed using SEM images (**Fig. 6**). For the pure phenolic epoxy coating, the wear scar was wide and deep, and obvious crack propagation traces and a large number of agglomerated wear debris were clearly observed in the high-magnification images (**Fig. 6a**), which indicated that the phenolic epoxy coating predominantly suffered from combined fatigue and abrasive wear. Under dry friction conditions, repeated frictional stress induced the generation of fatigue cracks on the coating surface. After crack propagation, spallation occurred, and the spalled particles acted as abrasives to aggravate the surface plowing damage, ultimately resulting in severe surface failure[50-53]. In contrast, the composite coating with microcapsules suffered less severe surface deterioration during friction (**Figs. 6b-f**). Broken microcapsule shells could be observed in the high-magnification images (**Fig. S6**), which confirms that the "rupture-release-lubrication" mechanism of microcapsules under frictional stress is effective in reducing wear.

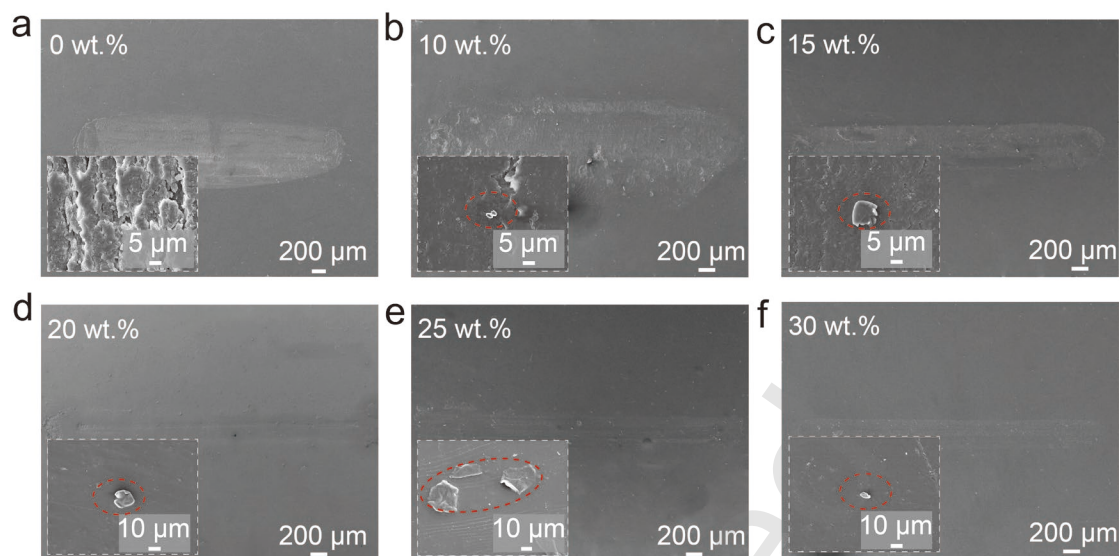


Fig. 6 SEM images of wear scars on coatings with different 500SN@MF

microcapsule contents after 20000 reciprocating friction cycles at 2 Hz under a 5 N load.

CLSM measurements were performed to quantify the wear volumes of the coatings, while simultaneously revealing their microscale features and frictional damage states (**Fig. 7**). As shown in **Figs. 7a-f**, a clear wear mark can be observed for the pure phenolic epoxy coating. But for the microcapsule composite coatings, the wear marks became increasingly shallow with increasing microcapsule content and were difficult to discern on the composite coatings containing 20 wt.%, 25 wt.%, and 30 wt.% microcapsules. The change trend of wear mark depth and wear rate is similar (**Figs. 7g and 7h**). The wear mark depth and wear rate of pure phenolic epoxy coating reached 62 μm and $1.23 \times 10^{-4} \text{ mm}^3/(\text{N} \cdot \text{m})$, respectively. Raising the microcapsule fraction led to a progressive drop in wear depth and wear rate, with the best tribological performance achieved at 25 wt.% microcapsule content. The wear depth as well as wear rate was

only $3.4\ \mu\text{m}$ and $0.077 \times 10^{-6}\ \text{mm}^3/(\text{N}\cdot\text{m})$, respectively, which demonstrated excellent wear resistance. Further raising the microcapsule dosage to 30 wt.% triggered a marginal expansion across the wear depth alongside wear rate, reaching $5.6\ \mu\text{m}$ and $1.67 \times 10^{-6}\ \text{mm}^3/(\text{N}\cdot\text{m})$, which is fully consistent with the variation trend of the friction coefficient. This result further confirms the synergistic regulation mechanism of "mechanical properties-lubricative effect"[54, 55]. The lubricative effect and mechanical properties synergistically result in superior wear resistance with an appropriate microcapsule content. Insufficient or excessive microcapsule content leads to deficient lubrication or poor mechanical performance issues, which reduces its wear resistance[54].

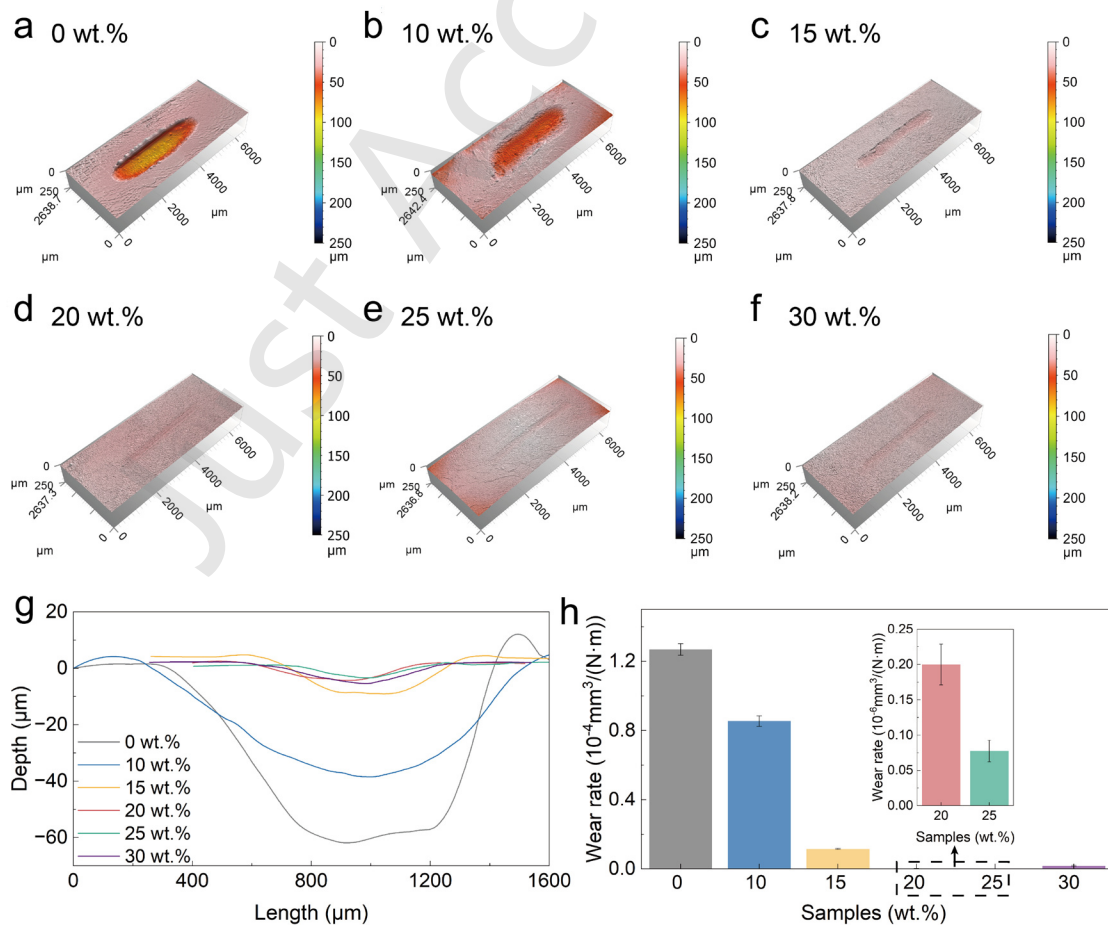


Fig. 7 (a~f) Three-dimensional characterization of wear scar morphology on coatings with different 500SN@MF microcapsule contents. The wear mark depth (g) and wear rate (h) of coatings with different 500SN@MF microcapsule contents after 20000 reciprocating friction cycles at 2 Hz under a 5 N load.

Then, the tribological behaviors of the optimal constitution (25 wt.%) under different friction conditions were evaluated in detail. As shown in **Figs. 8a and b**, with friction frequency kept at 2 Hz, raising the normal load beginning at 2 N and reaching 10 N induces a substantial reduction in the mean COF from an initial value of 0.06 to ultimately 0.015. The core reason for this phenomenon lies in the load-dependent lubrication release. At a low load, the frictional stress is insufficient to trigger the rupture of microcapsules rapidly and sufficiently, leading to a limited total amount of 500SN lubricant released. Consequently, a continuous lubricating film can scarcely form across the friction interface, and local solid-solid contact still exists between the friction pairs, which results in high frictional resistance. In contrast, at a high load, the higher contact pressure enables microcapsules to be ruptured more easily, allowing 500SN to be sufficiently released in the contact area and form an effective boundary lubricating layer. This layer can effectively isolate the surfaces of the tribopairs, thus endowing the composite with excellent friction reduction performance[56, 57]. In contrast, a higher applied load greatly increases the coating's volumetric loss and wear rate (**Figs. 8c and S7**). Specifically, the wear rate stands at $0.18 \times 10^{-7} \text{ mm}^3/(\text{N} \cdot \text{m})$ at a low load of 2 N, whereas it rises sharply to $1.32 \times 10^{-7} \text{ mm}^3/(\text{N} \cdot \text{m})$ at 10 N. The inverse

variation is attributed to the fact that the Hertzian contact stress between the friction pairs is significantly enhanced under high-load conditions, far exceeding the interfacial force observed at low loads (**Table S1**). Prolonged friction under high contact pressure easily triggers plastic deformation, microcrack initiation, as well as delamination on polymer-based composite coatings, which cannot counteract the friction coefficient-reducing effect of lubricating film formation under high load conditions. After long-term friction cycles, the damage accumulation effect on the coating surface becomes prominent, which in turn raises the wear rate drastically[58-60]. Subsequently, the frequency-related friction and wear traits of the composite coating were examined at 5 N. As shown in **Figs. 8d** and **8e**, the friction coefficient stands at 0.064 at a low frequency of 1 Hz, whereas it drops sharply to 0.008 at 5 Hz. The above trend further results from the more effective formation of the lubricating film. High sliding frequency triggers microcapsule breakdown and lubricant outflow, while boosting fluidity and spreadability of the lubricant at the contact interface, thereby significantly reducing the friction coefficient. Similarly, the coating's wear volume and wear rate showed a continuous rising trend with the increase of friction frequency (**Figs. 8f** and **S8**), evidenced by a wear rate of $0.14 \times 10^{-7} \text{ mm}^3/(\text{N} \cdot \text{m})$ at 1 Hz that sharply jumped to $2.61 \times 10^{-7} \text{ mm}^3/(\text{N} \cdot \text{m})$ when the frequency was 5 Hz, which can be attributed to the rapid heat accumulation under high friction frequency. The friction heat reduces the coating's hardness, and the softened surface is more prone to damage under frictional action, thereby further raising the wear rate markedly[58, 61, 62].

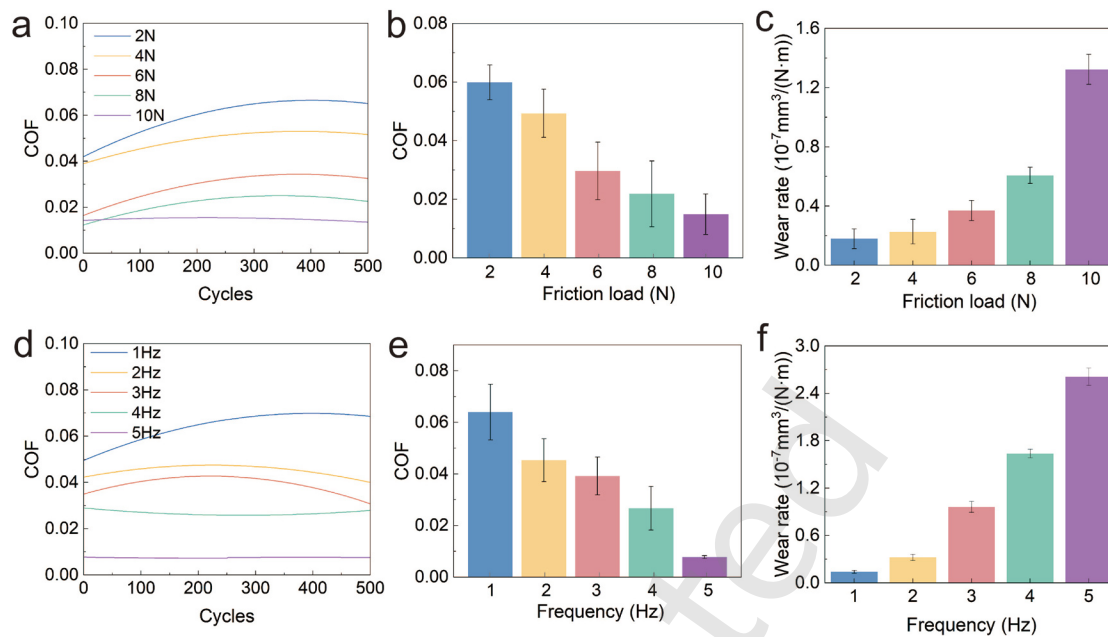


Fig. 8 Tribological properties of the composite coating with 25 wt.% microcapsule content. (a) dynamic COF curves, (b) average COF, and (c) wear rate under varying loads; (d~f) corresponding results under different sliding frequencies.

4. Conclusion

In summary, a large-scale preparation of 500SN@MF microcapsules was successfully achieved in this study via *in-situ* polymerization encapsulation with MF resin shells. The microencapsulation significantly enhanced the thermal stability of the lubricant, with the decomposition temperature increasing from 288 to 400 °C. More importantly, these microcapsules demonstrated excellent dispersibility within the phenolic epoxy resin matrix, effectively preventing oil leakage and the phase separation between the liquid lubricant and the polymer matrix. Tribological tests confirmed that the composite phenolic epoxy coatings containing 500SN@MF microcapsules were able to rapidly release the lubricant upon mechanical wear to form a continuous

lubricating film at the friction interface for anti-wear and friction-reduction. Specifically, with an ideal content of 25 wt.% 500SN@MF microcapsules, the coating demonstrated remarkable tribological properties under 5 N over 20000 cycles, acquiring a mean COF of 0.038 and a wear rate of $0.077 \times 10^{-6} \text{ mm}^3/(\text{N} \cdot \text{m})$. Significantly, these outstanding friction and wear resistance characteristics can greatly extend the service life of self-lubricating materials, which presents a productive design for high-performance materials and provides a feasible coating solution to safeguard mechanical components functioning under stringent lubrication conditions.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

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

Acknowledgements

We gratefully acknowledge support from the Key Project of Shandong Province (SYS202203), the National Natural Science Foundation of China (52475229), and the Gansu Provincial Science Fund for Distinguished Young Scholars (23JRRA651).

References

- [1] J. Luo, X. Zhou, Superlubricative engineering—Future industry nearly getting rid of wear and frictional energy consumption, *Friction* 8(4) (2020) 643-665.
- [2] K. Holmberg, A. Erdemir, Influence of tribology on global energy consumption, costs and emissions, *Friction* 5(3) (2017) 263-284.
- [3] V.W. Wong, S.C. Tung, Overview of automotive engine friction and reduction trends—Effects of surface, material, and lubricant-additive technologies, *Friction* 4(1) (2016) 1-28.
- [4] W. Pei, X. Pei, Z. Xie, J. Wang, Research progress of marine anti-corrosion and wear-resistant coating, *Tribology International* 198 (2024) 109864.
- [5] R.J. Wood, P. Lu, Coatings and surface modification of alloys for tribo-corrosion applications, *Coatings* 14(1) (2024) 99.
- [6] J. Liu, Y. Fang, Y. Ou, X. Shi, Y. Zhang, Q. Chen, L. Li, F. Zhou, W. Liu, Synergistic anti-corrosion and anti-wear of epoxy coating functionalized with inhibitor-loaded graphene oxide nanoribbons, *Journal of Materials Science & Technology* 220 (2025) 140-149.
- [7] M. Shao, H. Ruan, F. Song, Y. Zhang, C. Wang, T. Wang, Q. Wang, Solid–Liquid Synergistic Smart-Lubrication System for Long-Lasting Low Friction and Extreme Wear Resistance, *Langmuir* 41(43) (2025) 29426-29433.
- [8] Q. Huang, X. Shi, Y. Xue, K. Zhang, C. Wu, Recent progress on surface texturing and solid lubricants in tribology: Designs, properties, and mechanisms, *Materials Today Communications* 35 (2023) 105854.
- [9] A. Fouly, M.G. Alkalla, Effect of low nanosized alumina loading fraction on the physicomechanical and tribological behavior of epoxy, *Tribology International* 152 (2020) 106550.
- [10] C. Jiguo, Tribological properties of polytetrafluoroethylene as additive in titanium complex grease, *Industrial Lubrication and Tribology* 64(2) (2012) 98-103.
- [11] L. Wang, B. Wang, X. Wang, W. Liu, Tribological investigation of CaF₂ nanocrystals as grease additives, *Tribology international* 40(7) (2007) 1179-1185.

- [12] N. Kumar, V. Saini, J. Bijwe, Tribological investigations of nano and micro-sized graphite particles as an additive in lithium-based grease, *Tribology Letters* 68(4) (2020) 124.
- [13] P.G. Grützmacher, A.A. Voevodin, A. Korényi-Both, M.C. Righi, C. DellaCorte, N. Bagcivan, A. Erdemir, C. Gachot, The Promise of Solid Lubricants for a Sustainable Future, *Advanced Materials* 38(8) (2026) e00867.
- [14] S. Huang, D. Jia, W. Hu, S. Zhan, T. Yang, W. Zhang, B. Lu, H. Duan, Morphology-regulated molybdenum disulfide/multi-walled carbon nanotubes hybrids for enhanced tribological and mechanical performance of polyether ether ketone composites, *Chemical Engineering Journal* (2025) 166758.
- [15] X. Li, Z. Li, H. Luo, N. Shi, C. Fu, B. Huang, C. Yu, H. Li, Preparation of inorganic oil-containing carbon nanocapsules and tribological properties of PA6 composites, *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 698 (2024) 134590.
- [16] S.-c. Kang, D.-w. Chung, Improvement of frictional properties and abrasive wear resistance of nylon/graphite composite by oil impregnation, *Wear* 254(1-2) (2003) 103-110.
- [17] Z.Z. Zhang, W.M. Liu, Q.J. Xue, Effects of various kinds of fillers on the tribological behavior of polytetrafluoroethylene composites under dry and oil-lubricated conditions, *Journal of Applied Polymer Science* 80(11) (2001) 1891-1897.
- [18] Y. Wan, H. Luo, Y. Wang, Y. Huang, Q. Li, F. Zhou, G. Chen, Friction and wear behavior of three-dimensional braided carbon fiber/epoxy composites under lubricated sliding conditions, *Journal of materials science* 40(17) (2005) 4475-4481.
- [19] H. Li, Q. Wang, M. Li, Y. Cui, Y. Zhu, B. Wang, H. Wang, Preparation of high thermal stability polysulfone microcapsules containing lubricant oil and its tribological properties of epoxy composites, *Journal of microencapsulation* 33(3) (2016) 286-291.
- [20] Y. Zhang, H. Chen, K. Gao, Y. Li, J. Jiao, Y. Ren, C. Yu, G. Zhou, L. Zhang, J. Luo, Superlubricity microcapsules, *ACS Applied Materials & Interfaces* 17(9) (2025) 14634-14644.

- [21] C. Yang, K. Hu, G. Xie, G. Yang, L. Zhang, J. Kang, 3D Printing Composite with Microcapsules for On-Demand Lubrication, *Tribology Letters* 72(1) (2024) 31.
- [22] N. Khun, H. Zhang, J. Yang, E. Liu, Tribological performance of silicone composite coatings filled with wax-containing microcapsules, *Wear* 296(1-2) (2012) 575-582.
- [23] H. Li, Q. Wang, H. Wang, Y. Cui, Y. Zhu, B. Wang, Fabrication of thermally stable polysulfone microcapsules containing [EMIm][NTf₂] ionic liquid for enhancement of in situ self-lubrication effect of epoxy, *Macromolecular Materials and Engineering* 301(12) (2016) 1473-1481.
- [24] Y. Liu, Y. Wu, Y. Ma, P. Wang, B. Yu, X. Pei, S. Liu, F. Zhou, Reversible thermochromic and heat storage coating for adaptive de/anti-icing and thermal regulation, *Chemical Engineering Journal* 482 (2024) 148837.
- [25] H. Zhang, X. Wang, Synthesis and properties of microencapsulated n-octadecane with polyurea shells containing different soft segments for heat energy storage and thermal regulation, *Solar Energy Materials and Solar Cells* 93(8) (2009) 1366-1376.
- [26] X. Yan, Y. Wang, H. Liu, R. Li, C. Qian, Synthesis and characterization of melamine-formaldehyde microcapsules containing pyraclostrobin by in situ polymerization, *Polymer Science, Series B* 60(6) (2018) 798-805.
- [27] D. Xu, R. Yang, Efficient preparation and characterization of paraffin-based microcapsules by emulsion polymerization, *Journal of Applied Polymer Science* 136(21) (2019) 47552.
- [28] L. Chai, X. Wang, D. Wu, Development of bifunctional microencapsulated phase change materials with crystalline titanium dioxide shell for latent-heat storage and photocatalytic effectiveness, *Applied Energy* 138 (2015) 661-674.
- [29] F. Tang, L. Liu, G. Alva, Y. Jia, G. Fang, Synthesis and properties of microencapsulated octadecane with silica shell as shape-stabilized thermal energy storage materials, *Solar Energy Materials and Solar Cells* 160 (2017) 1-6.
- [30] S. Yu, X. Wang, D. Wu, Microencapsulation of n-octadecane phase change material with calcium carbonate shell for enhancement of thermal conductivity and

serving durability: synthesis, microstructure, and performance evaluation, *Applied energy* 114 (2014) 632-643.

[31] X. Bai, J. Li, C. Wang, Q. Ren, Thermo-expandable microcapsules with polyurethane as the shell, *Journal of Polymer Research* 27(7) (2020) 185.

[32] X. Li, Y. Liu, Y. Ma, H. Liu, Y. Wu, F. Zhou, Biomimetic Laminated Photothermal Superhydrophobic Energy-Storage Coatings with Synergistic Temperature-Matched Phase Change for Enhanced Anti-Icing and Deicing, *ACS Applied Materials & Interfaces* 17(38) (2025) 54115-54124.

[33] S. Sarkar, B. Kim, Synthesis of graphene oxide–epoxy resin encapsulated urea–formaldehyde microcapsule by in situ polymerization process, *Polymer composites* 39(3) (2018) 636-644.

[34] T.K. Maiti, P. Dixit, A. Suhag, S. Bhushan, A. Yadav, N. Talapatra, S. Chattopadhyay, Advancements in organic and inorganic shell materials for the preparation of microencapsulated phase change materials for thermal energy storage applications, *Rsc Sustainability* 1(4) (2023) 665-697.

[35] B.T. Lobel, D. Baiocco, M. Al-Sharabi, A.F. Routh, Z. Zhang, O.J. Cayre, Current challenges in microcapsule designs and microencapsulation processes: A review, *ACS applied materials & interfaces* 16(31) (2024) 40326-40355.

[36] G. Dou, Z. Lu, Y. Hu, Y. Sun, H. Jiang, G. Peng, Improvement of the rupture strength of MF shell microcapsule by incorporating TiO₂ nanoparticles with an optimal content, *Journal of Applied Polymer Science* 140(42) (2023) e54549.

[37] H.A. Hussein, H.H. Mahdi, A.K. Ghazi, Tribological behavior and lubrication mechanism of fine particles in the base oil SN500, *Journal of Engineering and Sustainable Development* 23(5) (2019) 108-116.

[38] Y. Wang, Q. Chen, J. Qin, X. Liu, P. Guo, Y. Wang, M. Cai, F. Guo, F. Zhou, Novel Polymer Gel Lubricant Functionalized with a Phosphate Anion for Friction Reduction and Film Thickness Enhancement in Multiple Lubrication Conditions, *ACS Applied Materials & Interfaces* 17(7) (2025) 11164-11175.

- [39] Y. Liu, C. Qin, R. Xu, Y. Liu, Y. Wu, B. Yu, X. Pei, F. Zhou, Organic–inorganic hybrid polysiloxane brushes with improved lubrication and load-bearing capacity, *Langmuir* 38(9) (2022) 2832-2839.
- [40] J. Yan, C. Wu, J. Hou, X. Zhang, Y. Liu, Y. Zhang, P. Li, H. Che, Z. Xing, Y. Wang, Tribological properties of polyimide coatings filled with graphene oxide and MXene composite nanofillers, *Tribology International* 189 (2023) 109000.
- [41] L. Jia, W. Liu, W. Wang, R. Fan, P. Liu, Synthesis and characterization of cellulose nanofibers improved melamine formaldehyde resin shell microcapsules for phase change thermal storage materials, *Journal of Applied Polymer Science* 141(31) (2024) e55742.
- [42] R. Naresh, R. Parameshwaran, V.V. Ram, Microcapsules of n-dodecanoic acid/melamine-formaldehyde with enhanced thermal energy storage capability for solar applications, *Journal of Science: Advanced Materials and Devices* 7(3) (2022) 100462.
- [43] C. Wang, L. Bao, L. Tao, R. Yang, T. Wang, Q. Wang, Achieving superior wear resistance in epoxy resin with novel graphitic carbon nitride/polysulfone microcapsules, *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 716 (2025) 136740.
- [44] X. Wang, J. Huang, Z. Guo, Overview of the development of slippery surfaces: Lubricants from presence to absence, *Advances in Colloid and Interface Science* 301 (2022) 102602.
- [45] T. Liu, W. Qian, Y. Deng, R. Chen, Y. Zhao, H. Ge, Seamlessly embedded microcapsules in self-repairing coatings: Improved compatibility and enhanced corrosion resistance recovery, *Surface and Coatings Technology* 484 (2024) 130830.
- [46] W. Wu, L. Chu, S.J. Garcia, S. van der Zwaag, M. Li, L. Shen, N. Bao, Fabrication of graphene oxide-modified self-healing microcapsules for Cardanol-based epoxy anti-corrosion coatings, *Progress in Organic Coatings* 183 (2023) 107777.
- [47] Y. Ma, Y. Zhang, J. Liu, Y. Ge, X. Yan, Y. Sun, J. Wu, P. Zhang, GO-modified double-walled polyurea microcapsules/epoxy composites for marine anticorrosive self-healing coating, *Materials & Design* 189 (2020) 108547.

- [48] F. Ahangaran, M. Hayaty, A.H. Navarchian, F. Picchioni, Micromechanical assessment of PMMA microcapsules containing epoxy and mercaptan as self-healing agents, *Polymer testing* 64 (2017) 330-336.
- [49] Y. Chang, X. Yan, Preparation and self-repairing properties of MF-coated shellac water-based microcapsules, *Coatings* 10(8) (2020) 778.
- [50] J. Hua, T. Peng, X. Zhu, R. Ren, Z. Huang, G. Zhang, Effect of rail surface hard defects on the wear damage and properties of high-speed wheel steel, *Wear* (2025) 206302.
- [51] G.Y. Lee, C. Dharan, R.O. Ritchie, A physically-based abrasive wear model for composite materials, *Wear* 252(3-4) (2002) 322-331.
- [52] R. Ohana, R. Klein, R. Shneck, J. Bortman, Experimental investigation of the spall propagation mechanism in bearing raceways, *Materials* 16(1) (2022) 68.
- [53] V. Bonache, M. Salvador, J. García, E. Sánchez, E. Bannier, Influence of plasma intensity on wear and erosion resistance of conventional and nanometric WC-Co coatings deposited by APS, *Journal of Thermal Spray Technology* 20(3) (2011) 549-559.
- [54] Y. Shen, Y. Wang, C. Zhao, X. Wang, Q. Yu, M. Cai, B. Yu, F. Zhou, Ultra-low friction, ultra-fast response and low-VOC self-lubricating coating based on oil-filled silica microcapsules, *Tribology International* 209 (2025) 110701.
- [55] H. Li, Y. Cui, Z. Li, Y. Zhu, H. Wang, Fabrication of microcapsules containing dual-functional tung oil and properties suitable for self-healing and self-lubricating coatings, *Progress in organic coatings* 115 (2018) 164-171.
- [56] P. Bandeira, J. Monteiro, A.M. Baptista, F.D. Magalhães, Tribological performance of PTFE-based coating modified with microencapsulated [HMIM][NTf₂] ionic liquid, *Tribology letters* 59(1) (2015) 13.
- [57] L. Zhang, G. Xie, S. Wu, S. Peng, X. Zhang, D. Guo, S. Wen, J. Luo, Ultralow friction polymer composites incorporated with monodispersed oil microcapsules, *Friction* 9(1) (2021) 29-40.

- [58] H. Li, J. Wang, X. Li, S. Dong, N. Shi, Z. Li, Improve the thermal properties of oil-loaded polysulfone microcapsules by optimizing copper layer for self-lubricating polyamide, *Polymer Composites* 45(11) (2024) 10443-10456.
- [59] W. Yan, E.P. Bus so, N.P. O'Dowd, A micromechanics investigation of sliding wear in coated components, *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 456(2002) (2000) 2387-2407.
- [60] P. Mandal, A.P. Ehiasarian, P.E. Hovsepian, Tribological behaviour of Mo–W doped carbon-based coating at ambient condition, *Tribology International* 90 (2015) 135-147.
- [61] J. Liu, M. Wang, H. Yin, A study of the friction characteristics of rubber thermo-mechanical coupling, *Polymers* 16(5) (2024) 596.
- [62] M. Molewyk, V. Wong, C. James, In Situ Control of Lubricant Properties for Reduction of Power Cylinder Friction through Thermal Barrier Coating: SAE Technical Paper No, 2014-01, 2014.



Xiaoyu Li is currently pursuing a master's degree at Shandong Laboratory of Advanced Materials and Green Manufacturing (Yantai) and Yantai University. Her research mainly focuses on the preparation of microcapsules and the study of functional coatings.



Yubo Liu is an assistant professor at the Lanzhou Institute of Chemical Physics (LICP), Chinese Academy of Sciences (CAS). He received his bachelor's degree at Ocean University of China in 2018, and his Ph. D. degree at Northwest Polytechnical University in 2023. Now, his research interests mainly focus on functional coatings and anti-icing materials.



Zhengyuan Li is currently pursuing a Ph.D. degree under the supervision of Prof. Yang Wu at the State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences (LICP, CAS). He received his bachelor's degree from Shandong University of Technology in 2022. His research interests focus on functional coatings, particularly antifogging and anti-/de-icing materials.



Chenggang Sun is currently working as an Intermediate Engineer at the Shandong Laboratory of Advanced Materials and Green Manufacturing (Yantai). He graduated from Jilin Agricultural University. His current research interests focus on the

development and application of industrial protective coatings, specialty low surface energy protective coatings.



Meirong Cai obtained her Ph.D. degree in 2012 at Lanzhou Institute of Chemical Physics (LICP), Chinese Academy of Sciences (CAS). She is a full professor at the State Key Lab of Solid Lubrication in LICP. Her research interests are tribochemistry, solid-liquid composite lubrication, ionic liquid lubricants, and supramolecular gel lubricants.



Hongliang Liu is currently a professor at Yantai University. He received his Ph.D. degree from Lanzhou University in 2010. Between 2010 and 2014, he pursued postdoctoral research at the Institute of Chemistry, Chinese Academy of Sciences (ICCAS). Subsequently, he was employed at the Technical Institute of Physics and Chemistry of the Chinese Academy of Sciences (ITPC-CAS) from 2014 to 2020. During this period (October 2018 to July 2019), he served as a visiting scholar at

Carnegie Mellon University in the United States. His primary research interests include bionic interface materials, flexible conductive materials, and super-wettable membrane materials.



Yang Wu is a professor at the Lanzhou Institute of Chemical Physics (LICP), Chinese Academy of Sciences (CAS). He received his bachelor's degree at Qufu Normal University in 2010 and his Ph.D. degree at LICP in 2015. His current research interests focus mainly on the interface friction control, aqueous lubrication, and underwater adhesion of soft materials (basic research) and the R&D of functional coatings (application technology).



Feng Zhou is a full professor at the Lanzhou Institute of Chemical Physics (LICP), Chinese Academy of Sciences (CAS), and head of the State Key Laboratory of Solid Lubrication. He gained his PhD in 2004 and spent three years (2005–2008) in the Department of Chemistry, University of Cambridge as a research associate. His

research interests include bioinspired tribology, biomimic surfaces/interfaces of soft matter, lubricant additives, and drag-reduction, anti-biofouling functional coatings.

Just Accepted