

Wide-temperature-range tribological behavior and control mechanism of SnAg/ZrW₂O₈-incorporated Ni-based adaptive composite coatings

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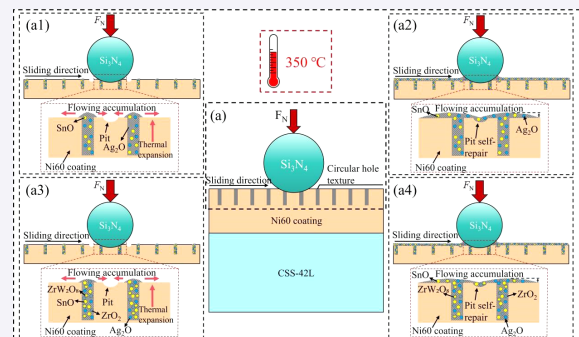
ABSTRACT: To realize the adaptive regulation of friction performance for core mechanical components over a wide temperature range, an integrated antifriction and wear-resistant composite structure combining coating, texture, and lubricant was proposed and prepared. Arrayed circular micropore textures were fabricated on CSS-42 L high-temperature bearing steel with a nickel-based hard coating, and SnAg soft metal lubricant doped with the negative thermal expansion agent ZrW₂O₈ was filled into the textures. Cellular automaton models were established to simulate the diffusion process of the lubricant, and combined with systematic tribological experiments, the frictional behavior and adaptive regulatory mechanism at different temperatures were systematically analyzed. Simulation results based on cellular automata models show that with increasing temperature, the proportion of medium- and high-concentration regions of SnAg lubricant increases gradually and reaches 75.28% at 350 °C, confirming the favorable diffusion behavior at elevated temperatures. Tribological tests reveal that the 95Sn5Ag-filled coating and the 95Sn5Ag–10 wt% ZrW₂O₈-filled coating exhibit significantly superior tribological properties compared with the pure Ni-based coating across a wide temperature range. At 350 °C, the average friction coefficients of the 95Sn5Ag-filled coating and the 95Sn5Ag–10 wt% ZrW₂O₈-filled coating are 0.42 and 0.44, respectively, reduced by 35.4% and 39.7% compared with room temperature, and the wear rates decrease to 1.3×10^{-7} and 2.0×10^{-7} mm³·N⁻¹·m⁻¹. The lubricating layer thicknesses reach 4.48 and 4.18 μm, increasing by 164% and 80%, respectively. The 95Sn5Ag–10 wt% ZrW₂O₈-filled coating presents a more stable adaptive lubrication performance. The unique “inhibition at high temperatures and promotion at low temperatures” regulatory mechanism of ZrW₂O₈ effectively enhances the wide-temperature adaptability. The synergistic effect of coating, texture, and lubricant enables excellent antifriction and self-lubrication, which provides an efficient and feasible strategy for the active design and performance optimization of wear-resistant and lubricating functions of mechanical components.

KEYWORDS: coating; friction and wear; SnAg; ZrW₂O₈; regulatory mechanism

1 Introduction

The friction and wear of key components in high-end equipment, such as deep-sea exploration equipment, high-precision machine tools, rail transit systems, and aerospace devices, have become critical factors restricting their working efficiency and service life [1–3]. As the operating conditions of high-end equipment become increasingly harsh, the relative motion between key components leads to a substantial increase in friction-induced volume loss [4, 5]. To address this issue, scholars at home and abroad have carried out a series of studies, mainly focusing on wear-resistant coatings [6], surface textures [7], and solid

lubricants [8]. Studies have found that the combination of different coatings and solid lubricants can meet the anti-friction and wear-resistant requirements of key components under severe working conditions [9]. Yuan et al. [10] prepared a WC–Co–Cu–BaF₂/CaF₂ composite coating on the surface of mild steel, and the results showed that the friction coefficient and wear rate of the composite coating samples were reduced by more than 40% and 80%, respectively, compared with the substrate. Ideris et al. [11] evaluated the effectiveness of different coatings (uncoated, diamond-like carbon (DLC), chromium nitride (CrN), and titanium aluminum nitride (TiAlN)) and lubricants (anti-friction graphene oxide additive oil and high-performance nanoengine oil



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additive) in reducing friction and wear through ring-block tests. The results indicated that the friction coefficient decreased with increasing load, while the lubricant temperature increased accordingly. Compared with uncoated blocks, coated blocks exhibited lower wear volume loss, and the combination of CrN-coated blocks and anti-friction graphene oxide additive oil presented the optimal tribological performance. Qin et al. [12] constructed a PEO/Ag/MoS₂ composite lubricating coating system on the surface of Ti6Al4V alloy and evaluated its tribological performance over a wide temperature range (RT–600 °C). The results showed that the PEO/Ag/MoS₂ multilayer coating exhibited a low friction coefficient (0.1–0.2) over a wide temperature range (RT–600 °C), with performance significantly superior to that of PEO, PEO/MoS₂, and PEO/Ag coatings. The above scholars mainly realized the improvement of anti-friction and wear-resistant performance through the synergy between the hard substrate/coating and soft lubricating phase. Among them, the doping of lubricants can improve the surface lubrication characteristics [13], and hard coatings provide excellent wear resistance [14]. The two work synergistically to overcome the tribological limitations of single coatings [15]. However, the bonding strength between lubricants and coatings in such structures and their stability during the friction process remain the current challenges and need further investigation to achieve a reliable improvement in performance [16, 17].

To overcome the insufficient lubricant retention and limited interfacial stability of conventional self-lubricating systems, surface texturing has been introduced as an effective structural regulation strategy. Microtextures can act as lubricant reservoirs and interfacial regulation units, reducing the real contact area while improving lubricant retention and promoting the controlled release and spreading of the lubricant during sliding [18]. Based on this concept, Qiu et al. [19] prepared a Zr coating on the surface of TC4 alloy and fabricated dimple textures on the coating before conducting a systematic study on its tribological properties. The results showed that the friction coefficient of this novel coating–texture composite material was close to that of the TC4 substrate, while its wear rate was significantly reduced, exhibiting excellent wear resistance. Taking YG8 cemented carbide as the substrate, Han et al. [20] prepared three types of AlCrN coating samples (microtextured coating, coating with microtextures, and nontextured coating) and systematically investigated the effects of microtextures and the preparation process of coating composite materials on the macro- and microproperties of the cemented carbide surface. The results indicated that the microtextured coating samples had significantly higher microhardness, resistance to plastic deformation and wear resistance than the other two types of samples. In addition, these samples featured better frictional stability, smaller fluctuation amplitude, a shorter initial wear stage, a longer steady wear stage, and a markedly reduced wear rate. Chen et al. [21] used H62 brass as the test sample to study the process quality and tribological properties of surface microtextures prepared by nanosecond laser ablation in air and with low-melting-point alloy coatings. The findings revealed that low-melting-point alloy coatings could improve the processing quality of surface microtextures, and the friction coefficients of the various prepared microtextures were significantly reduced.

In addition, the anti-friction and wear-resistant structure designed by the coupling of texture and lubricant can effectively overcome the limitations of boundary lubrication on metal surfaces. Liu et al. [22] prepared a self-lubricating material by filling the SnAgCu lubricant into the surface textures of M50 steel, and the research showed that the content of SnAgCu lubricant

distributed on the worn surface varied in different wear stages. Compared with the samples with a single texture or filled with pure lubricants (Ag, Sn), the synergy between the lubricant and texture was the main reason for the reduction in the friction coefficient and wear rate of the composite samples. Long et al. [23] investigated the tribological behavior of thrust roller bearings with dimple textures under starved lubrication conditions, and the results indicated that appropriate dimple parameters and a suitable graphene mass fraction could synergistically exert a positive effect on the tribological performance of the bearings. Compared with the smooth bearings lubricated with base oil, their average coefficient of friction (COF) was reduced by 31%, and the wear loss was reduced by 35%.

The above studies demonstrate that a rational composite design of coating, texture, and lubricant can effectively exert a synergistic enhancement effect and significantly improve the anti-friction and wear resistance of metallic materials under severe working conditions [24].

In recent years, our research group has proposed a coating–texture–lubricant composite structure, which realizes the organic synergy of the three functions by integrating the surface protection performance of the coating [25], the regulation ability of the texture on frictional contact states [26], and the continuous lubrication ability of solid lubricants [6]. This structure not only gives full play to the unique advantages of each component but also significantly improves the anti-friction and wear resistance of materials under complex working conditions through the coupling effect. For example, our research group [27] explored the tribological performance of a composite structure with a Ni60 coating–surface texture–50Sn40Ag10Cu lubricant system constructed on the surface of 42CrMo steel at different temperatures. The results showed that the textures on the coating surface not only significantly reduced the actual area of frictional contact but also enhanced the mechanical interlocking effect between the lubricating film and the coating, thus effectively improving the frictional adaptability and wear resistance of the composite material.

The above combinations of different coatings, textures, and solid lubricants can effectively improve the overall tribological performance of metal surfaces [28]. However, domestic and foreign studies on the tribological behavior of such composite structures have mostly focused on passive control, and active control of the lubricant diffusion and film formation–precipitation process under complex working conditions has not yet been achieved. Especially under a wide temperature range, the diffusion behavior of lubricants remains unclear, and systematic quantitative descriptions and regulation methods are lacking.

To address the above problems, this paper proposes a coating–texture–lubricant composite structure and further introduces a negative thermal expansion agent to realize the active control of the lubricant diffusion and film formation–precipitation process, thereby achieving the active regulation of frictional behavior. Taking CSS-42 L bearing steel as the substrate material and Ni60 as the hard wear-resistant coating material, this paper fills composite solid lubricants (95Sn5Ag and 95Sn5Ag–10 wt% ZrW₂O₈) into the surface textures of the coating. A quantitative prediction method for micropore precipitation is established based on cellular automaton models to explore the tribological performance under a wide temperature range and the adaptive regulatory mechanism of solid lubricants during the friction process. This research provides theoretical support for the design and development of friction components under complex working conditions.

2 Theoretical section

2.1 Cellular automata model theory

As discrete mathematical models, cellular automata models have gradually become important tools for simulating the evolution process of complex systems in recent years. Different from traditional continuous models, cellular automata models use discrete time, space and state variables to effectively characterize many dynamic systems that are difficult to describe accurately by continuous methods, and they provide new ideas and operable research approaches for investigating the behavioral mechanisms of complex systems [29, 30].

Cellular automata models [31] consist of four basic components: cells, cellular space, neighbors, and rules. A cell is the basic unit of the model, which is distributed in a discrete form in space, and the state of each cell is taken from a finite set. The cellular space is a grid structure composed of cells, which can be one-dimensional [32], two-dimensional, or even higher-dimensional; square, triangular, and hexagonal grids are mostly adopted for two-dimensional cellular space [33, 34]. Neighbors are defined as the set of surrounding cells that exert an influence on the central cell during the state update process—for example, the von Neumann neighborhood and Moore neighborhood are commonly used for two-dimensional square grids [35, 36]. A rule [37] is a function that determines the next state of a cell based on the current states of the cell and its neighbors. Figure 1 illustrates the relationships among cells, cellular space, neighbors, and rules.

During the friction and lubrication process, there exists a complex coupling relationship among numerous factors, such as surface dynamic wear, surface lubrication behavior, and contact mechanics. These factors are intertwined and interact with each other, making the study of friction and lubrication phenomena quite challenging. As a powerful simulation tool, cellular automata models [38], by virtue of their discrete modeling characteristics, decompose this complex system into simple cells and local rules and further simulate the overall tribological behavior through the local interactions between cells. At the microscale, cellular automata models can elaborate on the behaviors of various components in the friction and lubrication system, such as the diffusion of lubricant molecules and the interaction of surface

asperities. Meanwhile, they can reflect the overall performance of the system macroscopically, thus enabling the numerical simulation of the friction and lubrication process.

The diffusion of lubricant from a single pore and its smearing precipitation onto the worn surface constitute a dynamic process involving multiphysical field coupling, mainly including the lubricant expansion process [39] and the tangential-shear-driven spreading process driven by tangential shear action [40]. Current domestic and international studies on the formation mechanism of lubricating films usually focus on only one of these processes, and no systematic coupled simulation of the synergistic effect of expansion and tangential-shear-assisted spreading has been carried out yet. Friction-induced lubricating film formation is the key to reducing friction and wear under boundary and mixed lubrication conditions [41]. The formation mechanism of friction films is complex and usually involves physical adsorption and chemical reactions between lubricant additives and friction surfaces, as well as the deposition of wear debris [42, 43]. To deeply reveal the dynamic mechanism of the process where lubricant expands and spreads onto the worn surface, this theoretical section adopts cellular automata models to simulate the morphological evolution of lubricating films formed on the worn surface by 95Sn5Ag lubricant filled in a single circular pore under different temperatures and tangential shear action, which provides a simulation method and theoretical basis for an in-depth understanding of the dynamic behavior of lubricants.

2.2 Developing a single-pore lubricant model

The modeling and simulation approach of cellular automaton models for the lubricant precipitation process from a single pore is illustrated in Fig. 2. As shown in Fig. 2, the cellular automata models for single-pore lubricant precipitation simulate and analyze the process by altering cell states in accordance with the actual material parameters. A model of the frictional interface for lubricant precipitation from a single pore is constructed, and the key influencing factors during the wear process are systematically considered and classified, thus establishing a relatively complete set of evolution rules for cellular automata models.

With the increase in simulation time, surface cells generate pit cells and barrier cells under the action of tangential shear action, accompanied by concentration conversion. Driven by the

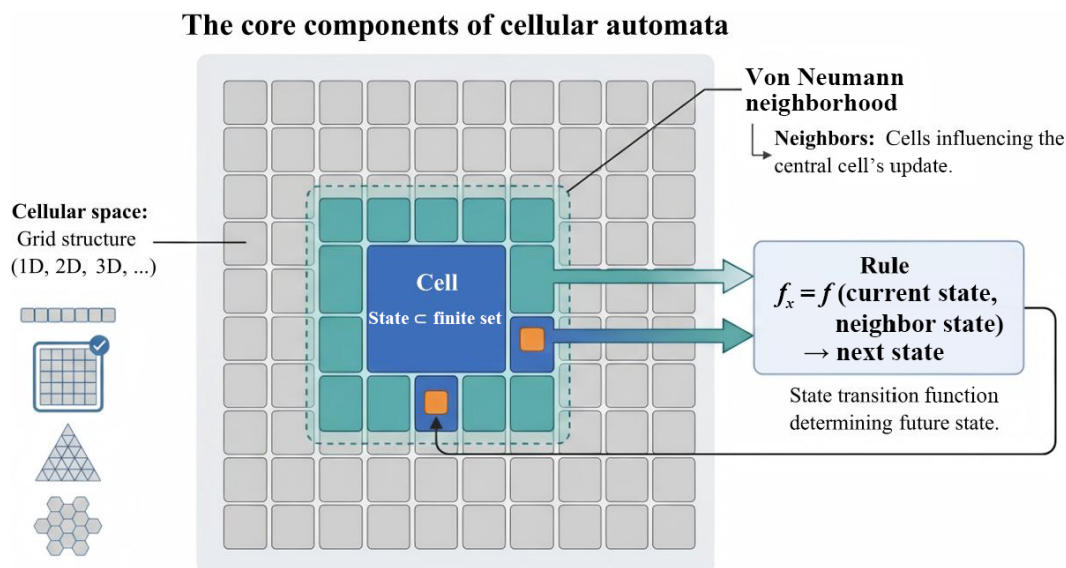


Fig. 1 Principles of cellular automata models.

temperature-induced self-diffusion rule, the system identifies concentration cells, pit cells, and barrier cells based on the current cell concentration: concentration cells undergo direct state conversion, barrier cells inhibit the conversion process, and pit cells execute the absorption rule depending on the properties of their neighboring cells. The concentration conversion process causes partial lubricant loss, which in turn affects the concentration update and state conversion of surface cells, thus completing an entire cycle of iteration. After 1,000 time steps are completed, the number of cells in each concentration region on the surface is output as the simulation result.

The model design framework for simulating the diffusion and surface spreading of lubricant from a single pore based on cellular automata models is shown in Fig. 3(a). Combining the irregular and random flow characteristics of lubricant on the worn surface,

this model constructs a static lubricant precipitation model subjected to temperature and tangential shear action on a two-dimensional plane. The flow and migration of lubricant between cells are realized by defining evolution rules for the changes in cell concentration. For the issue of lubricant distribution, the following assumptions are made for the constructed evolution model: (1) The splashing loss of lubricant caused by the movement of the friction pair or the nonuniform tangential shear action is neglected. (2) The influence of uneven temperature distribution in the cellular internal temperature field on the lubricant flow behavior is neglected.

Cells are specifically classified into pit cells, barrier cells, and concentration cells. Concentration cells are further divided by concentration intervals into plane cells, low-concentration regions ($0 < \text{cell concentration} < 0.3$), medium-concentration regions ($0.3 \leq$

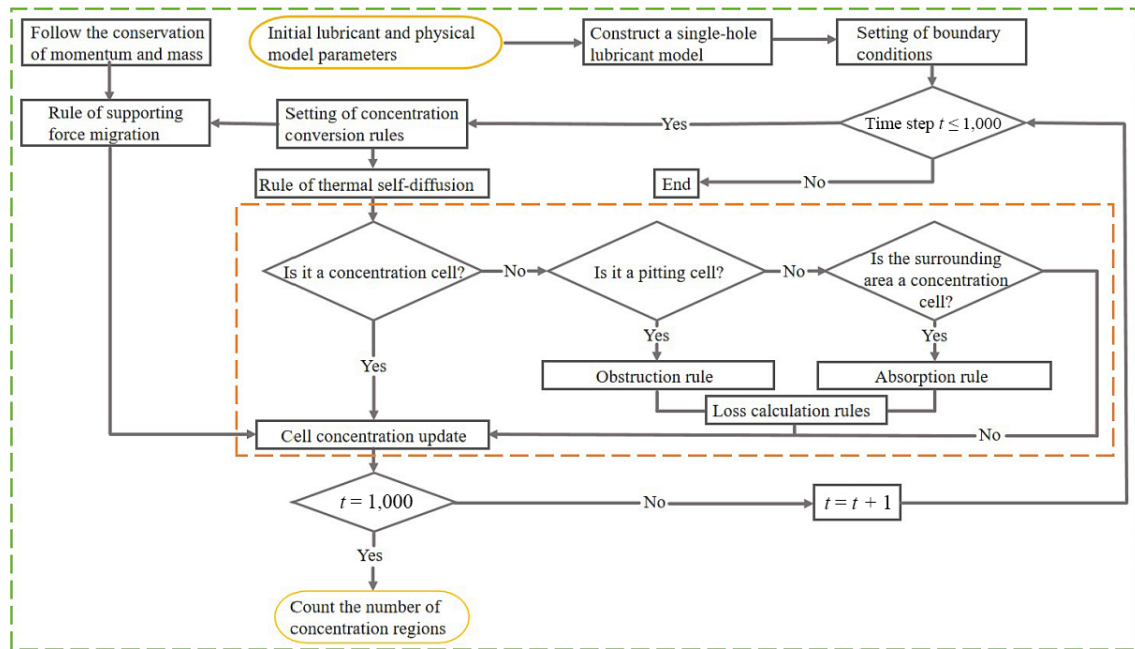


Fig. 2 Design approach for simulating single-micropore lubricant separation.

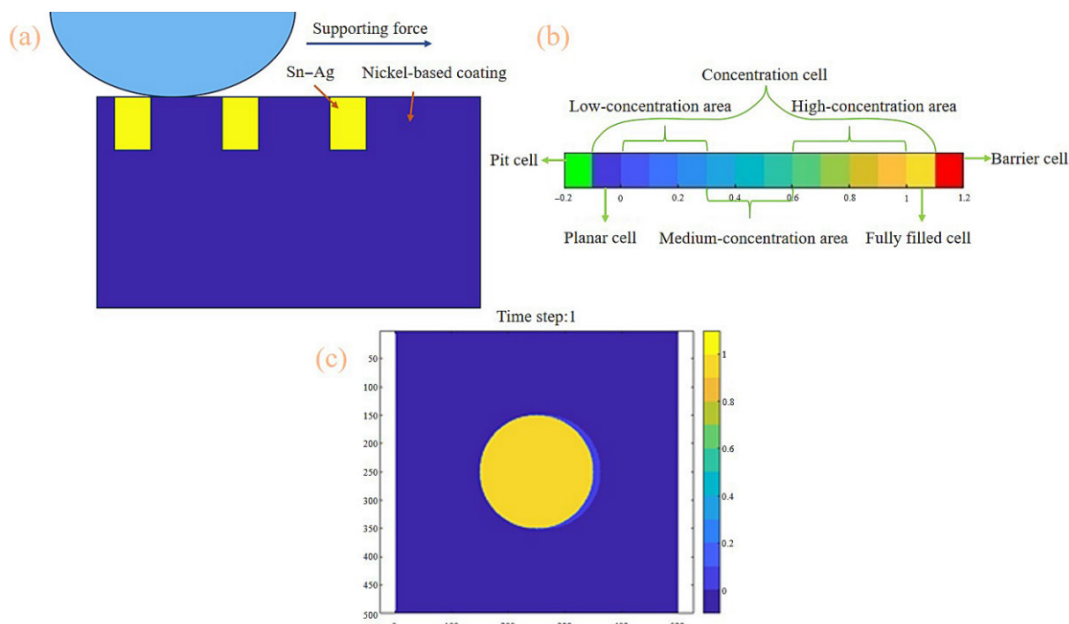


Fig. 3 (a) Surface contact motion model; (b) cell division; (c) initial cell state.

cell concentration < 0.6), high-concentration regions ($0.6 \leq \text{cell concentration} < 1$), and fully filled cells, as shown in Fig. 3(b).

Calculation method: Under a 5 N normal load and sliding-induced tangential shear action, the dynamic update of the surface concentration of a single-pore lubricant is simulated to predict the lubricant concentration evolution process over 1,000 time steps. The size of the cellular region is set to $500 \mu\text{m} \times 500 \mu\text{m}$, with the initial state shown in Fig. 3(c). A circular region with a diameter of $200 \mu\text{m}$ is defined as fully filled cells, and all other cells are plane cells.

2.3 Evolutionary rules for single-pore lubricant crystallization

Based on the simulation framework of the lubricant exudation process using cellular automata models, the evolution rules of the single-pore lubricant exudation model can be divided into two categories: temperature-induced self-diffusion rules and tangential shear-driven migration rules. The modeling and simulation of the dynamic exudation behavior of lubricant inside a circular pore are realized through the concentration conversion between cells and the generation mechanism of different types of cells. Inside the pore, the lubricant flows and diffuses between cells under the influence of temperature, with a higher temperature leading to a greater probability of self-diffusion. Meanwhile, tangential shear action drives the migration of the lubricant on the surface. In this study, the Moore neighborhood is adopted to define the connection relationship between cells, where the interaction and coordination mechanism among cells is the core of the lubricant exudation model based on cellular automata models. The specific rule settings are as follows.

2.3.1 Self-diffusion rule for temperature

The 95Sn5Ag lubricant undergoes volume expansion under the influence of temperature, and spontaneous diffusion to the surrounding areas occurs when the expansion reaches a certain degree. The expansion and diffusion behavior of the lubricant is mainly affected by the distribution of the temperature field. In actual working conditions, the temperature in the temperature field exhibits characteristics such as uneven heating due to external factors. In the simulation process, a constant temperature boundary condition is applied around the cellular model to better realize the conversion of lubricant concentration.

The self-diffusion process of the single-pore lubricant on the cell surface under temperature influence follows the Arrhenius equation:

$$D = D_0 \left(-\frac{E_a}{k_B T} \right) \quad (1)$$

where D is the equivalent diffusion coefficient used in the cellular automata models, D_0 is the initial equivalent diffusion coefficient, E_a is the equivalent activation energy, k_B is the Boltzmann constant, and T is the temperature.

From a microscopic perspective, the temperature-induced self-diffusion rules are closely related to temperature changes. Variations in temperature significantly affect the thermal motion

of molecules, thereby altering the mass transfer characteristics between cells. In this model, cells are distinguished by their current concentration because a diffusion driving force is generated between cells due to concentration differences, which promotes the migration of lubricant from high-concentration cells to low-concentration cells. This process proceeds continuously until the concentration gradient in the system tends to balance, ultimately achieving a uniform distribution of the temperature field.

It should be explicitly noted that the values of D_0 and E_a listed in Table 1 are not fundamental thermodynamic constants for atomic diffusion of SnAg. Instead, they serve as mesoscopic phenomenological equivalent parameters specifically calibrated for the cellular automata (CA) transition rules [44, 45]. In this CA framework, D_0 characterizes the macroscopic mobility and effective spreading capability of the softened lubricant on the friction interface, which phenomenologically increases with ambient temperature. The activation energy E_a is fixed at an equivalent value of 100 J/mol to mathematically scale the Arrhenius-type probability functions. This phenomenological setup ensures continuous computational stability across different temperatures while successfully reproducing the experimentally observed macroscopic dynamics of high-temperature lubricant exudation and tribofilm formation.

2.3.2 Tangential shear-driven migration rule

The single-pore lubricant migrates under tangential shear action, and its flow behavior satisfies the conservation of momentum and mass conservation equations. Under tangential shear action, part of the surface lubricant is prone to loss, which induces the generation of pit cells and barrier cells. The specific evolution rules are as follows: during sliding-induced tangential shear action, the movement of the lubricant follows the conservation of momentum and mass conservation equations. Pit cells are formed by local surface damage under tangential shear action and possess the ability to absorb the surrounding lubricant (the pit cell absorption rule). This rule requires first judging the surrounding cells, identifying the lubricant distribution state and concentration differences of adjacent cells, and then realizing the absorption of lubricant from the surrounding cells. Barrier cells are generated by the accumulation of surface debris produced when the tangential shear action acts on the material surface. The barrier rule means that the formation of barrier cells significantly hinders the flow of lubricant and even interrupts its microscopic movement. Once formed, such cells remain stable and interfere with the concentration distribution of the surrounding cells. The loss rule refers to the specific rules for lubricant loss and consumption under the action of tangential shear action. Under actual working conditions, the tangential shear action causes the lubricant to rub, mix, and migrate with the surrounding medium during flow, all of which lead to lubricant loss.

2.4 Simulation results

The flow process of the entire single-pore lubricant on the surface was simulated in accordance with the aforementioned evolution

Table 1 Material parameter settings

Temperature (°C)	Initial diffusion coefficient D_0 (cm ² /s)	Activation energy E_a (J/mol)	Boltzmann constant k_B (J/K)
Room temperature	0.1	100	1.38×10^{-23}
150	0.3	100	1.38×10^{-23}
250	0.5	100	1.38×10^{-23}
350	0.7	100	1.38×10^{-23}

rules. To intuitively display the distribution state of lubricant concentration in surface cells, a single-pore lubricant exudation model with a grid resolution of $1\ \mu\text{m}$ was adopted for analysis in this simulation. Figures 4(a)–4(d) illustrate the distribution of the surface lubricant concentration under different temperature conditions. At low temperatures, the flow behavior of the lubricant is dominated by the tangential shear action; in this case, the absorption effect of pit cells on the lubricant is relatively weak, while the hindering effect of barrier cells on lubricant flow is more

pronounced. With increasing temperature, the fluidity and diffusion rate of the lubricant are enhanced. This change enables the lubricant to more effectively overcome the adverse effects caused by pit and barrier cells, thus forming a more uniform distribution on the worn surface.

It can be observed from Fig. 4(a) that the surface lubricant distribution is relatively sparse. This is because tangential shear action leads to the generation of a large number of pit cells, which continuously absorb the surrounding lubricant and result in a

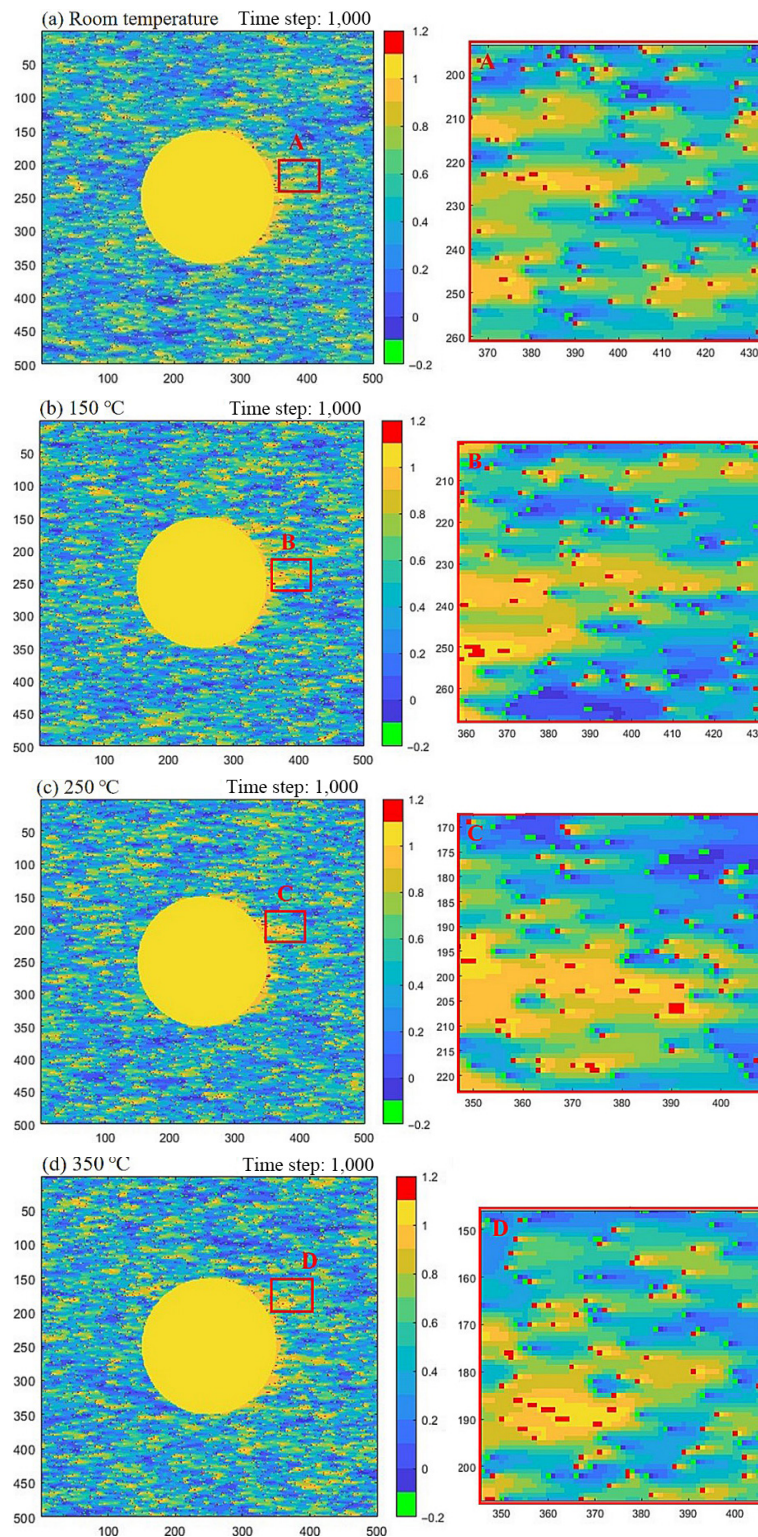


Fig. 4 Surface lubricant concentration distribution at different temperatures: (a) room temperature; (b) 150 °C; (c) 250 °C; (d) 350 °C.

significant decrease in the concentration in their vicinity; in contrast, the lubricant concentration is relatively high in areas with fewer pit cells. From Fig. 4(b), it can be found that under the combined effects of temperature and tangential shear action, the lubricant concentration distribution tends to be balanced. This is because the uniform distribution of surface barrier cells and pit cells alters the flow path of the lubricant and, together with the cell absorption mechanism, jointly drives the concentration distribution toward equilibrium, although local regions of relatively high or low concentration still exist. Figure 4(c) shows a more uniform lubricant concentration distribution. Under the combined effects of this temperature and tangential shear action, the barrier cells generated on the surface affect the flow direction of the lubricant but do not change its cell concentration; therefore, a relatively continuous lubricating film can form around them, while the concentration in the vicinity of areas with dense pit cells is absorbed to the minimum level. An ideal lubricant distribution state can be observed in Fig. 4(d). This is because temperature and tangential shear action significantly improve the fluidity and spreading behavior of the lubricant, thereby effectively weakening the interference effects caused by barrier cells and pit cells, making the surface lubricant coverage denser with a majority of high-concentration cells.

As shown in Fig. 5, the proportions of high-concentration regions in the surface lubricant at 150, 250, and 350 °C are approximately 68.41%, 71.12%, and 75.28%, respectively, which are significantly higher than the 65.55% observed at room temperature. With the increase in temperature, the concentration distribution of the surface lubricant tends to an ideal state of more uniform distribution. In actual frictional working conditions, the surface lubricant is subjected to a more complex environment than that in the simulation model. In addition to temperature and tangential shear action, it may also be affected by the coupling effects of multiple factors, such as surface roughness, contact pressure, and environmental media.

3 Experimental section

3.1 Sample preparation

The substrate material used in this study was CSS-42 L bearing steel (abbreviated as S1), Ni60 was adopted as the hard wear-resistant coating material, ZrW₂O₈ was selected as the negative thermal expansion agent, and the solid lubricants were 95Sn5Ag

(abbreviated as SA) and 95Sn5Ag-10 wt% ZrW₂O₈ (abbreviated as SZ). Previous studies have shown that the content of solid lubricating phases has an important influence on the balance between lubrication performance, mechanical integrity, and tribofilm stability [17]. Based on this consideration, preliminary thermophysical property calculations were carried out for SnAg-ZrW₂O₈ composite lubricants with different ZrW₂O₈ contents. The density, elastic modulus, coefficient of thermal expansion, specific heat capacity, and thermal conductivity were estimated using the rule of mixtures, Voigt-Reuss-Hill average, Kerner model, mass-weighted averaging, and Maxwell model, respectively. The calculated results showed that increasing the ZrW₂O₈ content reduced the effective coefficient of thermal expansion and thermal conductivity of the composite lubricant, indicating an enhanced thermal-regulation effect. However, excessive ZrW₂O₈ addition may weaken the continuity and spreading ability of the soft SnAg lubricant and increase the possibility of ceramic-particle accumulation at the friction interface. Therefore, 10 wt% ZrW₂O₈ was selected as a representative intermediate addition level to balance the thermal-regulation capability and lubricant continuity. Laser cladding technology was employed to prepare a nickel-based coating (abbreviated as S2) and a textured nickel-based coating (abbreviated as S3) on the surface of CSS-42 L bearing steel. Finally, the 95Sn5Ag and 95Sn5Ag-10 wt% ZrW₂O₈ solid lubricants were filled into the arrayed circular micropores on the surface of the textured nickel-based coating via the high-temperature melting infiltration method.

The internal morphology of the CSS-42 L bearing steel is shown in Fig. 6(a). The cladding powder was Ni60 alloy powder with a purity of over 99% and a uniform particle size of 15 μm. The micromorphology of the spherical Ni60 powder is presented in Fig. 6(b), and its local micromorphology is shown in Fig. 6(c). The spherical particles are round and plump, meeting the experimental requirements.

The specific preparation process of the Ni-based hard coating is as follows: First, the surface of the bearing steel was polished smooth with sandpaper and cleaned with absolute ethanol to remove surface defects such as impurity particles, ensuring sufficient energy absorption during the cladding process. Second, Ni-based hard coatings were prepared from the powder via laser cladding technology (using an RFL-C6000 X high-power high-speed laser cladding machine). A coaxial powder feeding method was adopted in the cladding process, with the laser cladding parameters set as follows: output power of 3,500 W, linear velocity of 2 m/min, hatch spacing of 0.7 mm, powder feeding rate of 21 g/min, distance of 15 mm between the cladding head and the substrate, shielding gas pressure of 0.2 MPa, and ambient temperature as the processing temperature (see Fig. 7(a)). After the coating was cooled to room temperature, the macroscopic surface morphology of the Ni-based coating is shown in Fig. 7(b), which demonstrates a smooth surface without undesirable defects such as cracks and pores (the roughness value is 0.1 μm). Furthermore, the hardness of the Ni-based coating is increased by 20% compared with that of the substrate, reaching 360 HV_{0.2}. The material was cut into small discs with a diameter of 25 mm and a substrate thickness of 5 mm by wire electrical discharge machining (WEDM), and the coating surface was subsequently ground and polished (see Fig. 7(c)).

On the basis of the prepared Ni-based hard coating, SnAg/ZrW₂O₈ Ni-based composite coatings were fabricated. First, micropores with uniform pore size and smooth micropore walls were prepared by electrical discharge drilling (EDD). The main process parameters and procedures for drilling on the surface of

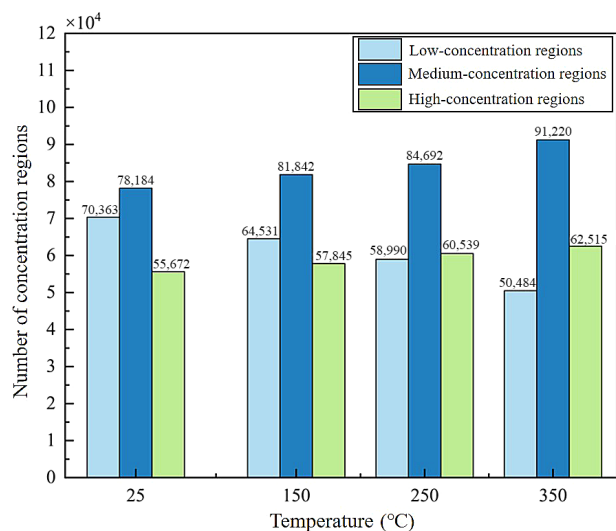


Fig. 5 Number of concentration zones at different temperatures.

the Ni-based hard coating are as follows: First, the coating surface was ground and polished to ensure a flat, clean surface free of obvious protrusions, impurities, and other defects, thus guaranteeing the normal operation of the machine tool. Second, a numerical control (NC) electrical discharge machine (see Fig. 7(d)) was configured, with the guide and electrode wire installed; after the workpiece was clamped, the machining center was calibrated to the coordinate (0, 0). The core machining parameters were set as follows: voltage of 380 V, current of 0.1–1 A, pulse width and pulse interval of 0.2–1.5 μ s, and vibration frequency of 300–800 Hz. ISO codes for circular micropore positioning were generated through graphic programming with Z-axis lifting commands added; after machining, debris was completely removed to keep the working environment clean. The morphological characterization results confirmed that Figs. 7(e) and 7(f) show the morphologies of the circular micropore textures on the coating surface, with uniformly distributed micropores on

the coating; Fig. 7(g) reveals that the circular micropores are arranged in a highly regular array; Fig. 7(h) further indicates that the single-micropore walls are smooth without melting and erosion defects. These results demonstrate that the process successfully realized the synergistic control of uniform pore size and smooth micropore walls. The above technical route ensured the geometric accuracy and interface integrity of the micropores, laying a structural foundation for the subsequent filling of 95Sn5Ag and 95Sn5Ag–10 wt% ZrW_2O_8 lubricants via high-temperature melting infiltration.

Finally, 95Sn5Ag and 95Sn5Ag–10 wt% ZrW_2O_8 solid lubricants were uniformly filled into the arrayed circular micropores on the surface of the textured Ni-based coating by the high-temperature melting infiltration method. Figures 8(a)–8(c) show that the circular micropores on the SA coating surface are neatly arranged and fully filled, with tight interfacial bonding between SnAg and the Ni-based coating without cracks. The

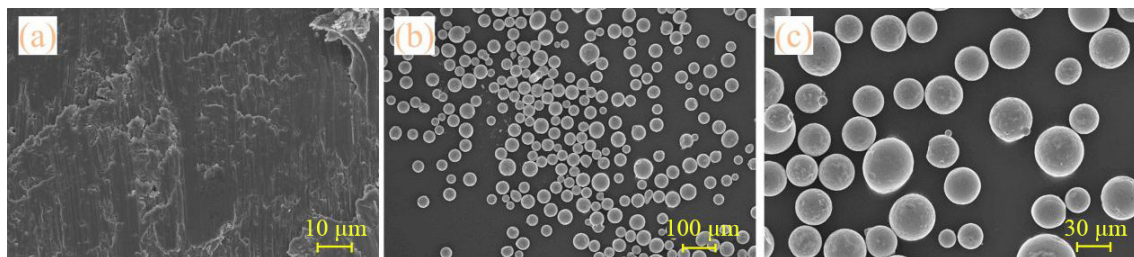


Fig. 6 (a) Micromorphology of CSS-42 L bearing steel; (b) micromorphology of Ni60 powder; (c) micromorphology of Ni60 powder.

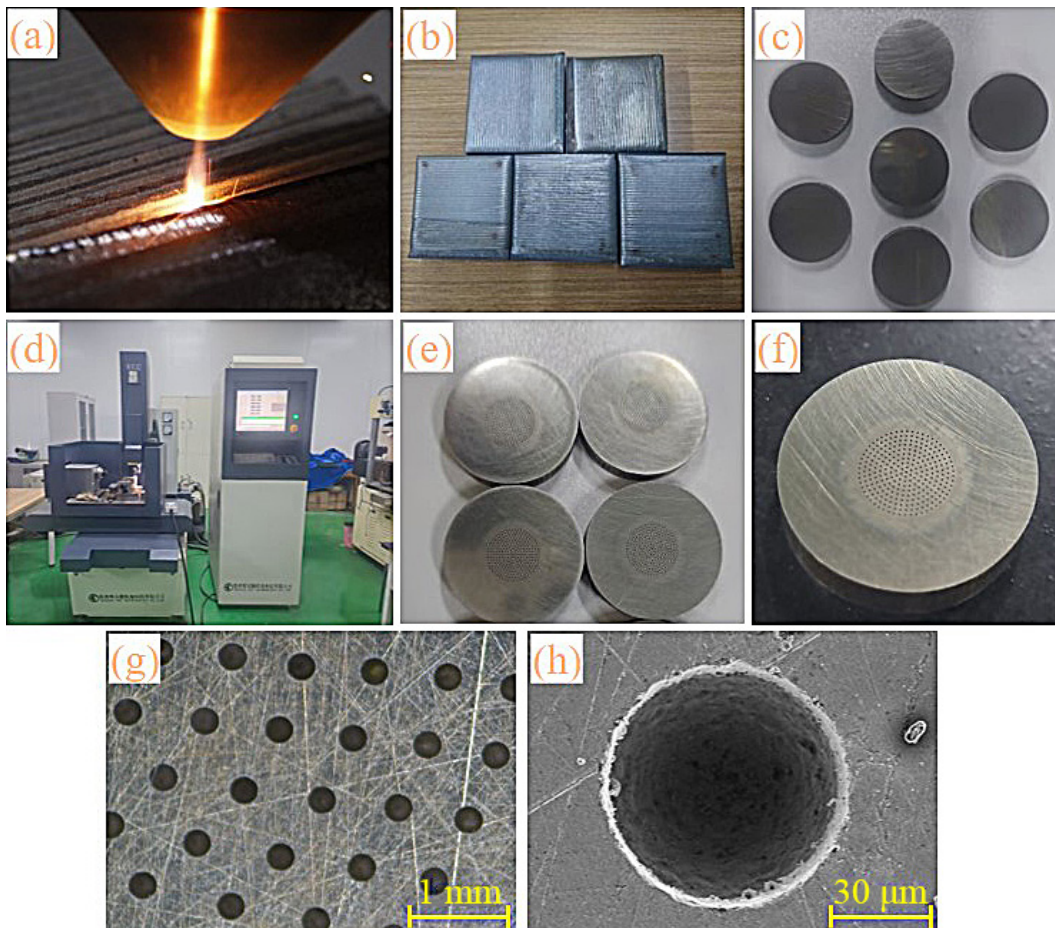


Fig. 7 (a) Laser cladding equipment; (b) macroscopic morphology of the nickel-based coating surface; (c) sample after polishing; (d) electrodischarge drilling machine; (e, f) macroscopic surface array of circular micropores; (g) micromorphology of arrayed circular micropores; (h) micromorphology of individual circular micropores.

elemental surface distribution maps (Figs. 8(c1)–8(c3)) confirm the presence of Ag/Sn lubricating phases inside the micropores and Ni as the main element on the surface. The cross-sectional morphology in Fig. 8(d) indicates that the circular micropores have a regular shape with dense and defect-free SnAg filling inside; the corresponding elemental surface distribution maps in Figs. 8(d1)–8(d5) show the enrichment of Sn/Ag at the micropore centers and Ni/Fe/Cr (components of the Ni-based coating) on both sides. Figures 8(e) and 8(f) show that the filling rate of the SZ coating micropores is more than 65%, with ZrW₂O₈ particles uniformly attached to the surface of spherical SnAg and forming a good bond with the Ni-based coating. The above results verify the structural integrity of the SA/SZ composite coatings and the

effective filling of lubricants, which meet the requirements of friction and wear tests.

3.2 Friction and wear test

This study focuses on SA and SZ samples to investigate their wear rates, friction coefficient evolution characteristics, and wear mechanisms at different temperatures (room temperature, 150, 250, and 350 °C). The friction experiments employed ball-on-plane contact. Based on Hertzian contact theory, contact stresses were calculated using Eqs. (2) and (3).

$$q = \left(\frac{6F}{\pi^3 R^2 E^*} \right)^{\frac{1}{3}} \quad (2)$$

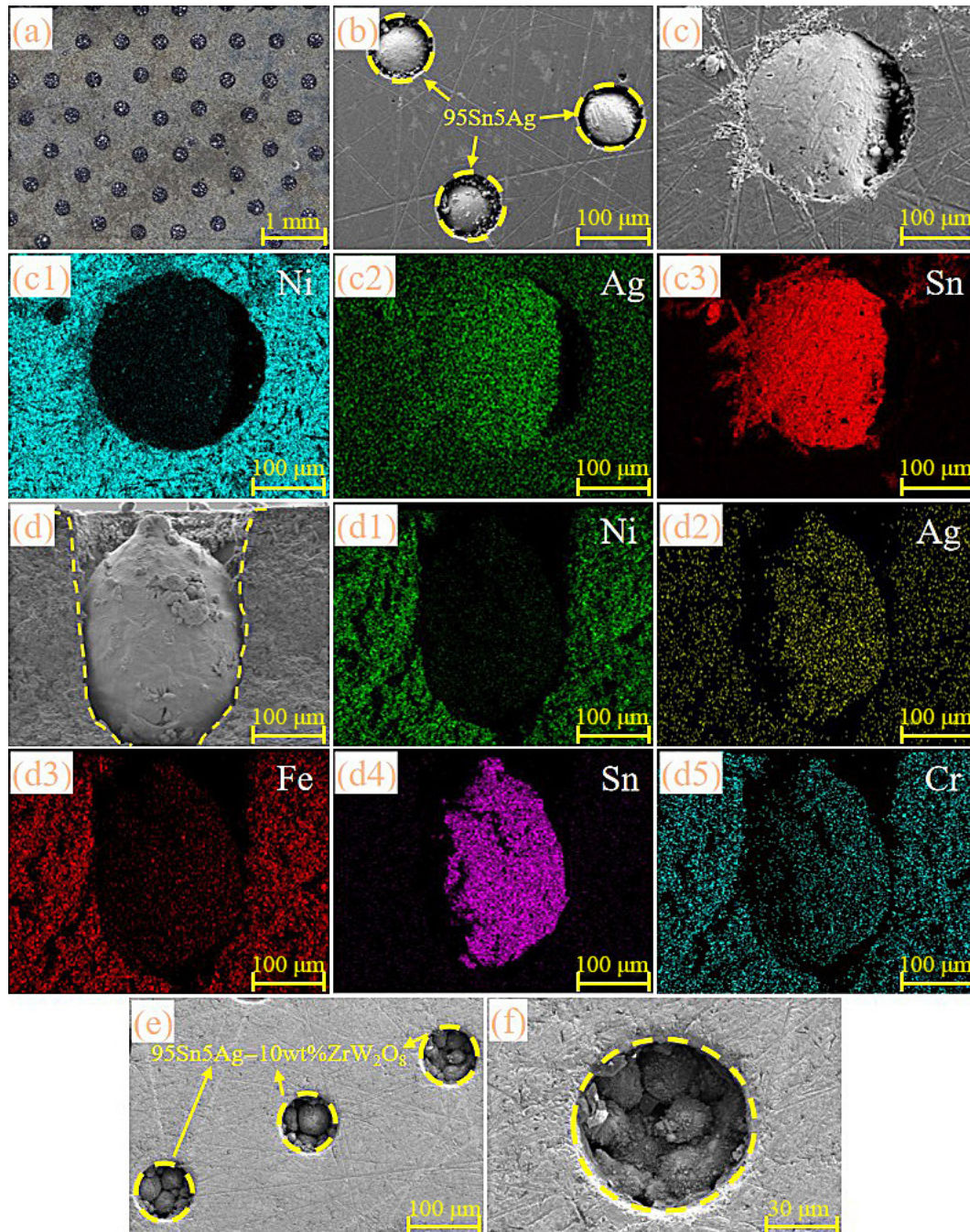


Fig. 8 (a) Surface micromorphology of arrayed micropores filled with 95Sn5Ag; (b) surface micromorphology of multimicropore filling; (c) micromorphology of a single micropore and (c1–c3) elemental distribution of each component; (d) cross-sectional micromorphology of micropores and (d1–d5) elemental distribution; (e) surface micromorphology of micropores filled with 95Sn5Ag–10 wt% ZrW₂O₈; (f) surface micromorphology of a single micropore.

$$E^* = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \quad (3)$$

In the formula, F represents the applied load (N), q denotes the applied stress (MPa), R indicates the radius of the grinding ball specimen (mm), E_1 and E_2 denote the elastic moduli of the material (MPa), and μ_1 and μ_2 denote the Poisson's ratios of the material.

Tests were conducted using an HT-1000 high-temperature friction and wear tester with a load setting of 5 N. The mating pair consisted of a 4 mm diameter Si3N4 ball operating at a sliding speed of 0.25 m/s for 30 min. The above test temperatures and tribological parameters were selected according to representative contact conditions of bearing-type sliding components under wide-temperature service environments. Room temperature was used to simulate the start-up or ambient-service stage, 150 and 250 °C were selected to represent intermediate-temperature sliding conditions, and 350 °C was used to evaluate lubricant release and tribofilm formation under medium-to-high-temperature continuous sliding. A load of 5 N, sliding speed of 0.25 m/s, and test duration of 30 min were set with reference to reported ball-on-plane friction tests of microtextures filled with low-melting-point alloys/solid lubricants and high-temperature self-lubricating coatings [22, 27, 28]. These conditions were used to establish stable sliding contact and ensure the comparability of the friction coefficient, wear rate, and worn-surface morphology under different temperatures. The 95Sn5Ag and 95Sn5Ag–10 wt% ZrW₂O₈ lubricant systems were also designed for such wide-temperature sliding conditions, in which SnAg provides soft-metal lubrication and surface spreading ability, while ZrW₂O₈ regulates lubricant release and tribofilm stability under temperature variation. The coefficient of friction was acquired in real time by a force sensor. The wear rate was determined by measuring the wear scar profile (depth and width) using a three-dimensional white light interferometer. Based on this, the cross-sectional area A of the wear scar was calculated. The wear rate of the friction pair was expressed as the volumetric wear rate. Subsequently, the wear volume and wear rate were obtained using Eqs. (4) and (5).

$$V = AB \quad (4)$$

$$K = V/FL \quad (5)$$

In the formula, V represents volumetric wear (mm³), B denotes scratch length (mm), F indicates applied load (N), L signifies sliding distance (m), and K denotes volumetric wear rate (mm³·N⁻¹·m⁻¹).

3.3 Characterization methods

To clarify the coating structure, lubricant filling state, and worn-surface evolution characteristics, scanning electron microscopy (SEM, ZEISS Sigma 360, Germany) and energy-dispersive spectroscopy (EDS, ZEISS Sigma 300, Germany) were used to analyze the morphology and elemental distribution of the raw powders, Ni-based coating, circular micropores, lubricant-filled regions, worn surfaces, and wear-track cross-sections. The phase compositions of the Ni-based coating and composite coating surfaces were characterized by X-ray diffraction (XRD, Rigaku SmartLab SE, Japan). A three-dimensional optical interferometer (Zygo ZeGage Plus PROFILER STITCHING, USA) was used to measure the three-dimensional wear-track morphology, wear-track depth, and wear-track width, from which the wear volume and wear rate were calculated. X-ray photoelectron spectroscopy

(XPS, Thermo Scientific K-Alpha, USA) was performed to analyze the chemical states of Ni, Ag, Sn, W, Zr, and O in the composite lubricating layer formed on the worn surface of the SZ coating. All XPS binding energies were calibrated using the C 1s peak at 284.8 eV. High-resolution spectra of C 1s, O 1s, Ni 2p, Ag 3d, Sn 3d, W 4f, and Zr 3d were further fitted to identify the chemical states of the main elements in the tribofilm.

4 Results and discussion

4.1 Microstructure and phase analysis of nickel-based hard coatings

To investigate the friction and wear properties of the prepared coatings, it is essential to ensure that their microstructure and structure possess the tribological characteristics required for the service environment. The surface morphology of the Ni-based hard coating (Fig. 9(a)) reflects the forming quality of laser cladding. Figure 9(b) shows the local microstructure of the Ni60 coating, with a uniform distribution of its constituent elements (Ni, Fe, Cr, and Si) and no obvious defects, such as cracks or pores, observed inside the coating (see Figs. 9(b1)–9(b4)).

XRD diffraction analysis was performed on the Ni-based coating, and the results in Fig. 10(a) indicate that its main phases are γ -Ni and FeNi₃. Intense molten pool convection significantly promoted the uniform distribution and interdiffusion of elements, creating favorable conditions for the formation of Ni-Fe phases. Combined with the aforementioned element distribution characteristics, the XRD results further confirm that complex chemical reactions occurred between the Ni60 alloy powder and the substrate at the interface during the cladding process, generating compounds such as FeNi₃ and iron chromium carbide (Cr,Fe)₇C₃. These reaction products effectively enhanced the microstructural stability of the coating. Figures 10(b) and 10(c) present the EDS line scan results of the coating/substrate interface, where Fig. 10(b) is the interface morphology and Fig. 10(c) shows the distribution law of Fe, Ni, Cr, and Si elements from the CSS-42 L bearing steel substrate to the interior of the coating. Integrating the aforementioned microstructural observation and phase analysis, this spectrum further reveals that with the exception of Fe, the contents of Ni, Cr, and Si all exhibit a gradient increase from the substrate to the interior of the coating. Fe is mainly enriched on the substrate side, and this distribution characteristic indicates a low dilution rate of the molten pool, meaning that a limited amount of the substrate material was melted into the coating during preparation, which effectively guaranteed the compositional independence and stability of the coating. Correspondingly, Ni is highly enriched inside the coating, with a content significantly higher than that in the substrate, which directly confirms the Ni-dominated compositional characteristic of the Ni-based coating. In addition, the distribution curves of Si and Cr in the interfacial transition zone also show significant variations. The moderate distribution of Si in the coating can generally improve its key properties, such as hardness and oxidation resistance, while Cr tends to form hard phases, such as chromium carbides, which is one of the main mechanisms for enhancing the wear resistance and corrosion resistance of the coating.

4.2 Variation rules of friction coefficient and wear loss

To evaluate the differences in the tribological properties of S1, S2, and S3, a friction and wear testing machine was used in this study to investigate the friction coefficients and wear losses of the three

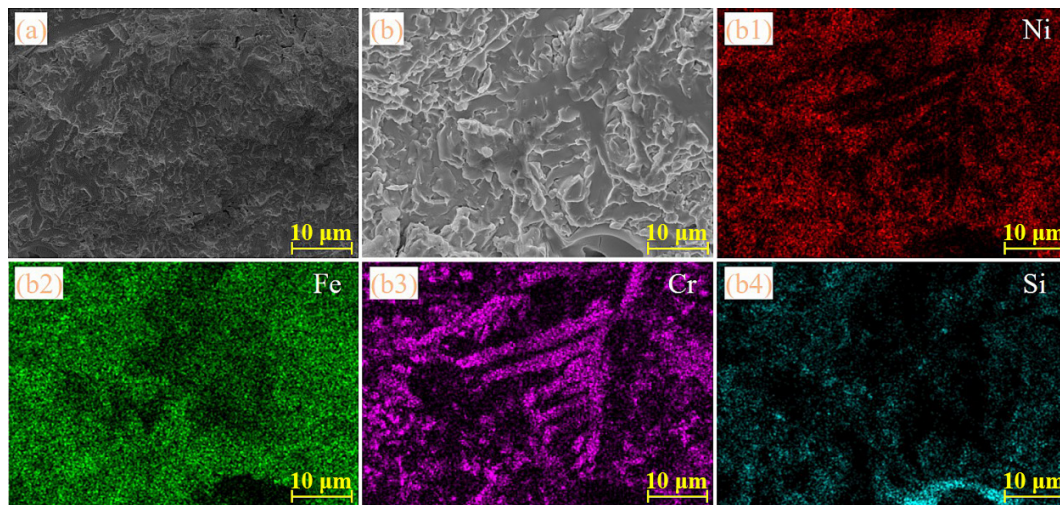


Fig. 9 Nickel-based coating: (a) microstructure; (b) local microstructure; (b1–b4) elemental distribution.

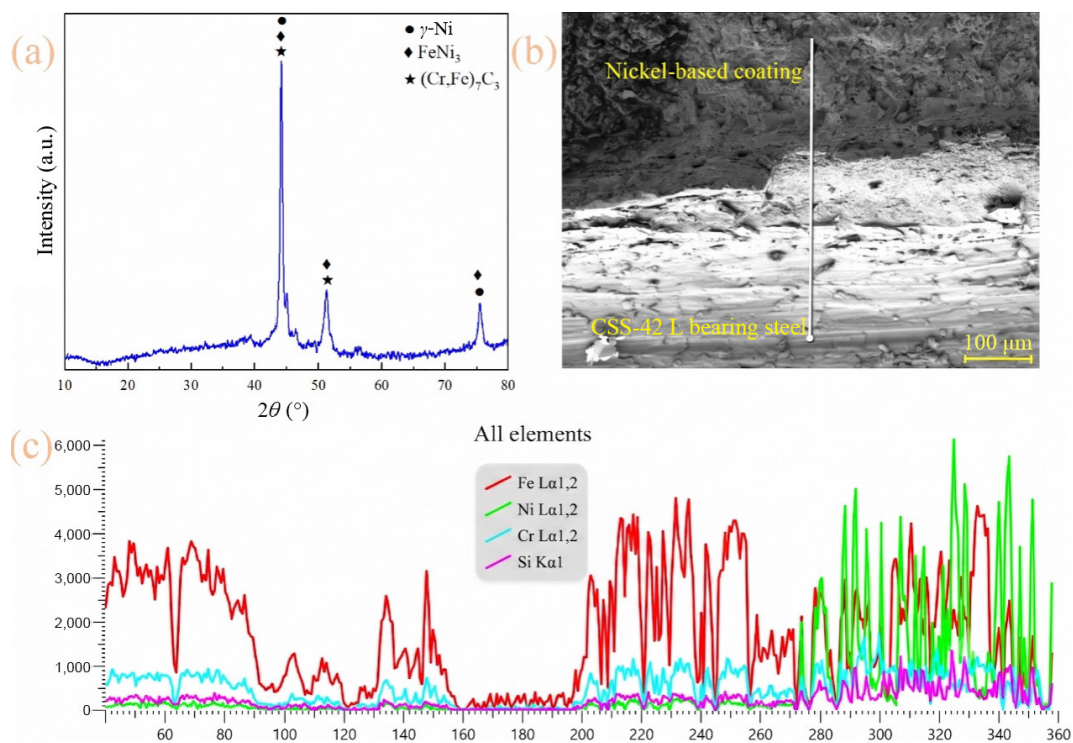


Fig. 10 (a) XRD pattern of the nickel-based coating surface; (b) microstructure at the interface; (c) elemental distribution maps.

samples. Figure 11 shows the average friction coefficients and wear rates of S1, S2, and S3 at room temperature. The test results indicated that the average friction coefficients of S1, S2, and S3 were 0.78, 0.72, and 0.69, respectively, and their wear rates were 8.0×10^{-7} , 6.0×10^{-7} , and $6.6 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, respectively. In comparison, both the friction coefficient and wear rate of S1 were higher than those of S2 and S3. This was mainly attributed to the fact that the hardness of S2 and S3 was significantly higher than that of S1, endowing them with excellent wear resistance. Meanwhile, the arrayed circular micropore texture on the surface of S3 effectively reduced the friction coefficient by decreasing the effective contact area. It is worth noting that although texturing (S3) further reduced the friction coefficient of the coating, its introduction might weaken the local hardness of the coating, resulting in a slightly higher wear rate of S3 than that of S2.

On this basis, 95Sn5Ag and 95Sn5Ag–10 wt% ZrW₂O₈ lubricants were filled into the S3 samples to reveal the temperature

dependence of the tribological properties of the SnAg Ni-based composite coating (SA) and SnAg/ZrW₂O₈ Ni-based composite coating (SZ), with the results presented in Fig. 12. As the temperature increased from 25 to 350 °C, the friction coefficient of the SA material exhibited the following variation: room temperature (0.65) → 150 °C (0.47, a decrease of 27%) → 250 °C (0.54) → a minimum value at 350 °C (0.42). In contrast, the friction coefficient of the SZ material showed a continuous decreasing trend: room temperature (0.73) → 150 °C (0.51, a decrease of 30.1%) → 250 °C (0.47, a decrease of 35.6%) → 350 °C (0.44). Both materials reached their minimum friction coefficients in the high-temperature region (350 °C) (SA: 0.42; SZ: 0.44), which is mainly attributed to the significant enhancement of the lubricating effect of Ag at this temperature. The above results indicate that both SA and SZ can exhibit optimal frictional properties at 350 °C.

The wear rate data show that the wear rates of SA and SZ at

room temperature (3.2×10^{-7} and $4.3 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, respectively) were significantly higher (more than twice) than those at 350 °C. With the increase in temperature, the wear rate of SA showed a nonmonotonic variation: decreasing to $2.8 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at 150 °C $\rightarrow$ rising to $3.0 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at 250 °C $\rightarrow$ dropping sharply to $1.3 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at 350 °C. For the SA coating, the wear rate at 250 °C shows a slight increase compared with that at 150 °C. This phenomenon may be attributed to the transitional state of the SnAg lubricating phase from shear-driven exudation at lower temperatures to thermally assisted spreading at higher temperatures. At this temperature, SnAg possesses a certain degree of mobility; however, its exudation and spreading may not yet be sufficient to form a continuous and stable lubricating layer. In the absence of ZrW_2O_8 regulation, the spatial distribution of the lubricant is more likely to be uneven, resulting in the coexistence of local lubricant accumulation and insufficiently lubricated regions. This may lead to a temporary deterioration in friction and wear behavior. When the temperature further increases to 350 °C, the spreading of the lubricant becomes more sufficient, and the continuity of the lubricating layer is improved, leading to a decrease in the wear rate. The wear rate of the SZ decreased continuously: $3.1 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at 150 °C $\rightarrow$ $2.4 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at 250 °C $\rightarrow$ $2.0 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at 350 °C. Combined with the aforementioned friction coefficient performance, the excellent wide-temperature-range tribological properties of SA and SZ can be attributed to the synergistic effect

of the surface texture and the filled solid lubricants (95Sn5Ag and 95Sn5Ag–10 wt% ZrW_2O_8).

In summary, compared with the bearing steel substrate, the coatings significantly reduced the wear rate by virtue of their excellent wear resistance, while the surface texturing design effectively lowered the friction coefficient. In the wide-temperature-range tests (from room temperature to 350 °C), both SA and SZ materials exhibited optimal tribological properties at 350 °C, where the average friction coefficients dropped to the minimum values (SA: 0.42; SZ: 0.44) and the wear rates reached the minimum values simultaneously (SA: $1.3 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$; SZ: $2.0 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$), which fully demonstrates their applicability at high temperatures.

Compared with the reported self-lubricating coating and composite systems, the present coating–texture–lubricant structure exhibits moderate friction coefficients but relatively low wear rates at 350 °C. Although the COF values of the present SA and SZ coatings are higher than those of the reported Ag/BaF₂/CaF₂-containing systems, their wear rates are markedly lower. This indicates that the present structure is more effective in suppressing material removal under the selected sliding conditions. The improved wear resistance may be attributed to micropore-assisted lubricant storage and SnAg lubricating film formation, while the SZ coating further introduces ZrW_2O_8 -regulated lubricant release and composite tribofilm formation.

4.3 Friction and wear mechanisms of SnAg/ZrW₂O₈ nickel-based composite coatings under different temperature conditions

4.3.1 Micromorphology of worn surfaces of SA and SZ at room temperature

To further investigate the friction and wear mechanisms of SA and SZ materials under different temperature conditions, our research group analyzed their surface micromorphology to reveal the effect of lubricants on each wear stage and conducted microarea elemental distribution analysis to further verify the distribution and function of lubricants during the wear process.

At room temperature, the lubricant in the micropores of the SA and SZ materials is gradually exuded mainly under the sliding-induced tangential shear action of the mating pair. Compared with SA, SZ exhibits a higher friction coefficient due to the

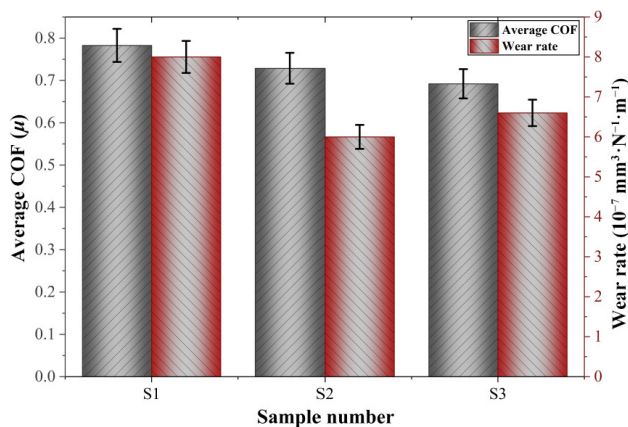


Fig. 11 Average friction coefficient and wear rate of S.

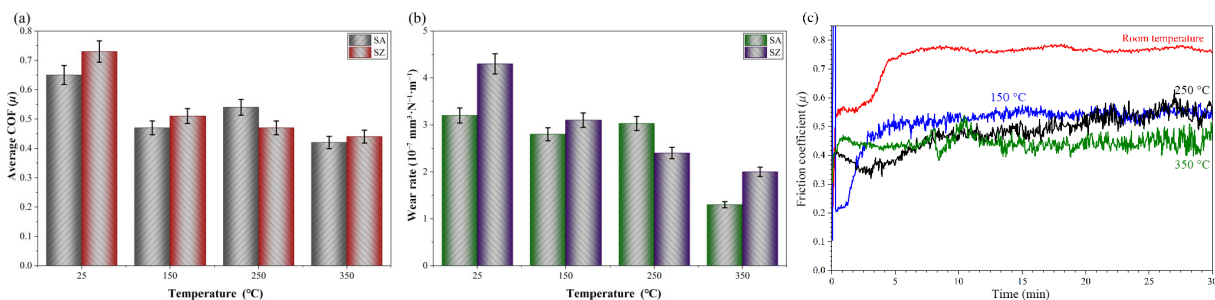


Fig. 12 Tribological properties of the SA and SZ at different temperatures: (a) average friction coefficient; (b) wear rate; (c) friction coefficient curves of the SZ.

Table 2 Comparison of the tribological performance of different self-lubricating systems

Lubricant/texture design	Test condition	COF	Wear rate ($\text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$)
Ni-based coating + circular micropore texture + 95Sn5Ag	350 °C, 5 N, Si_3N_4 ball, 0.25 m/s, 30 min	0.42	1.3×10^{-7}
Ni-based coating + circular micropore texture + 95Sn5Ag–10 wt% ZrW_2O_8	350 °C, 5 N, Si_3N_4 ball, 0.25 m/s, 30 min	0.44	2.0×10^{-7}
Thermally sprayed NiMoAl–Cr ₂ O ₃ –Ag–BaF ₂ /CaF ₂ coating [18]	350 °C, 5 N, alumina ball, reciprocating sliding	0.29	2.02×10^{-4}
CuNi matrix + 12.5 wt% BaF ₂ /CaF ₂ + 5 wt% Ag [16]	500 °C, 5 N, Si_3N_4 ball, 0.1 m/s, 30 min	0.32	1.49×10^{-5}

ZrW₂O₈ hard particles introduced during the wear process. Figures 13(a)–13(c) show the surface morphologies of the SA material at different stages of room-temperature wear. For instance, the initial stage (Fig. 13(a)) presents groove characteristics accompanied by particle accumulation. The elemental analysis at the corresponding test points 1 and 2 (Figs. 13(g) and 13(h)) shows enrichment of Sn and O elements and a reduction in Ni at the accumulated particle sites, indicating that these particles are oxidation products of tin and confirming the oxidation characteristics of the lubricant. When the SA material enters the rapid wear stage, as shown in Fig. 13(b), spalling layers and clearly visible lubricating particles appear on the SA surface, which indicates that it is difficult to achieve a rapid and uniform distribution of lubricating particles merely under the tangential shear action of the mating pair. In the subsequent steady wear stage (Fig. 13(c)), although the surface is relatively flat, long-term friction leads to the formation of spalling pits accompanied by particle accumulation. Comprehensive observation of Figs. 13(a)–13(c) shows that under the continuous shear and squeezing action of the counterpart ball, the lubricating particles and wear debris on the worn surface mainly exhibit extrusion migration, compressive fragmentation, and local agglomeration. It should be noted that a small amount of wear debris may provide transient local support or undergo local particle rotation in the contact region. However, these particles are discontinuous in size, morphology, and distribution on the worn surface and therefore cannot form a stable and continuous rolling contact layer. Accordingly, the friction process in this study did not transform from sliding friction into rolling friction. The dominant wear mechanisms remain abrasive wear, fatigue wear, and local oxidative wear under sliding friction conditions. In addition, the analysis of the wear mechanism of the SA material at room temperature shows that it is mainly fatigue wear, abrasive wear, and local oxidation wear.

Figure 13(d) specifically presents the surface

microcharacteristics of the SZ at the initial stage of room-temperature wear. Obvious microcracks and spalling pits can be observed on the worn surface at this stage, which is mainly due to the significant microcutting effect on the surface by the ZrW₂O₈ hard particles contained in the material as abrasive grains during the friction process. Figure 13(i) shows the results of elemental distribution analysis at the corresponding test point 3, where the content of oxygen (O) is as high as 54.75 wt%, the contents of nickel (Ni) and tin (Sn) are 21.1 wt% and 23.67 wt%, respectively, and a small amount of silver (Ag), zirconium (Zr), tungsten (W), and other elements are also present. It can be inferred that oxidation reactions occur on the Ni-based surface during friction, generating corresponding oxidation products; meanwhile, the elemental composition further confirms that ZrW₂O₈ participates in the friction process and effectively inhibits the further development of friction. As the wear process progresses to the rapid stage (Fig. 13(e)), the continuous friction of the mating pair leads to a significant expansion of spalling pits on the worn surface. In this process, the Ni-based coating exhibits excellent wear resistance, and the SnAg lubricant in the micropores begins to fill and repair the formed spalling pits. After entering the steady wear stage (Fig. 13(f)), the long-term friction makes the characteristics of spalling pits more obvious, and SnAg lubricant can be observed filling and repairing around the pits, which is mainly due to its good flow characteristics that enable it to effectively wet and repair the damaged areas on the surface. The comprehensive analysis of Figs. 13(d)–13(f) indicates that the filling and repair behavior of the SnAg lubricant in the micropores under tangential shear action is the key factor reducing the surface wear degree of the SZ. In addition, the research reveals that the main wear mechanisms of SZ at room temperature are fatigue wear and adhesive wear, accompanied by slight oxidation wear.

4.3.2 Micromorphology of worn surfaces of SA and SZ at 150 °C

Compared with the room temperature condition, the friction

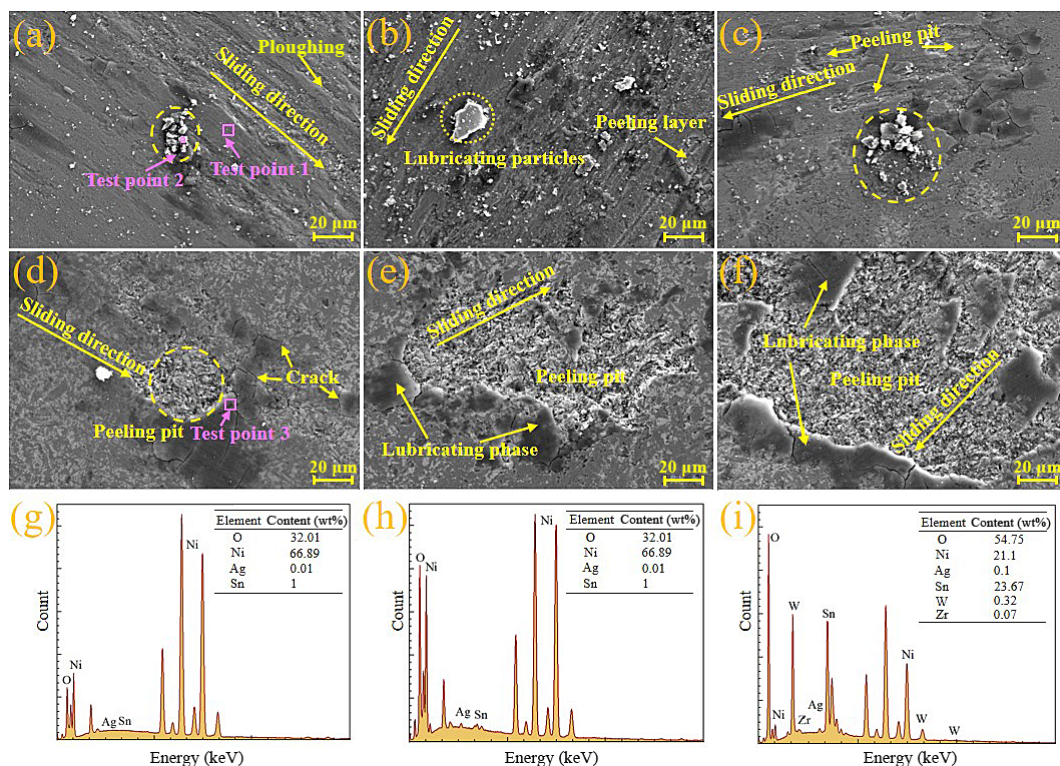


Fig. 13 (a–c) Microstructure of the worn surface of SA at room temperature; (d–f) microstructure of the worn surface of SZ at room temperature; (g–i) EDS point maps.

coefficients and wear rates of SA and SZ decrease significantly at 150 °C, which can be mainly attributed to two reasons: on the one hand, driven jointly by the temperature rise and the sliding-induced tangential shear action of the mating pair, the SnAg lubricant in the micropores continuously exudes onto the worn surface; on the other hand, the ZrW_2O_8 particles doped in the micropores undergo negative thermal expansion (volume shrinkage) with the increase in temperature, a characteristic that effectively regulates the supply of the SnAg lubricating film on the surface. Figures 14(a)–14(c) specifically illustrate the evolution of the surface micromorphology of the SA material at different wear stages at 150 °C. At the initial stage (Fig. 14(a)), the lubricating particles in the circular micropores on the surface are in a nonuniform agglomeration state, and the tangential shear action of the mating pair is the key driving force for the migration of SnAg to the worn surface at this time. When entering the rapid wear stage (Fig. 14(b)), a large number of ploughing grooves form on the worn surface accompanied by exuded lubricating particles; under the continuous action of the mating pair, these particles are distributed relatively uniformly on the surface, meeting the lubrication requirements of the friction process. At the steady wear stage (Fig. 14(c)), the surface exhibits obvious plastic deformation and ploughing groove characteristics, and long-term friction causes the lubricating particles to aggregate, migrate, and accumulate on one side under the tangential shear action of the mating pair. This phenomenon is highly consistent with the simulation results of cellular automata models in Section 2—the simulation shows that the migration path of the lubricant deflects after encountering barrier cells, leading to a local increase in concentration. A comprehensive analysis of Figs. 14(a)–14(c) reveals that under the synergistic effect of temperature and tangential shear action, the SnAg in the micropores undergoes three states in sequence: exudation, uniform distribution, and segregated distribution, and this distribution characteristic is

mainly controlled by the tangential shear action of the mating ball. The research further confirms that the main wear mechanisms of SA material at 150 °C are abrasive wear and fatigue wear, accompanied by local adhesive wear.

Under the same temperature conditions (150 °C), the evolution of the worn surface of the SZ is shown in Figs. 14(d)–14(f). At the initial stage of wear (see Fig. 14(d)), the overall surface is flat and smooth with only fine ploughing grooves and a small amount of lubricating particles present. This phenomenon stems from the intelligent regulation effect of ZrW_2O_8 : its negative thermal expansion characteristic effectively restricts the exudation amount of the SnAg lubricant, leading to its moderate distribution on the surface and the maintenance of a good initial state. When entering the rapid wear stage (Fig. 14(e)), obvious spalling pits appear on the surface; at this time, the exuded lubricating particles can be observed filling these surface depressions and actively repairing the damaged parts, indicating that SnAg plays a positive role in alleviating the aggravation of wear and providing protection and repair. At the steady wear stage (Fig. 14(f)), the surface presents prominent ploughing groove characteristics, and the SnAg lubricant is concentrated in the severely worn areas to preferentially reduce the wear degree of these key parts. This targeted distribution strategy reflects the self-regulatory mechanism of the material in response to differential wear requirements. The elemental distribution data in Fig. 14(g) (Ni: 80.02 wt%, O: 9.49 wt%, trace amounts of other elements) further corroborate the surface state. A comprehensive analysis of Figs. 14(d)–14(f) indicates that under the precise regulation of ZrW_2O_8 , the SnAg lubricant in the micropores undergoes a dynamic process of exudation from the micropores, surface distribution, and filling repair in sequence. The research also confirms that the main wear mechanisms of the SZ at 150 °C are abrasive wear and adhesive wear.

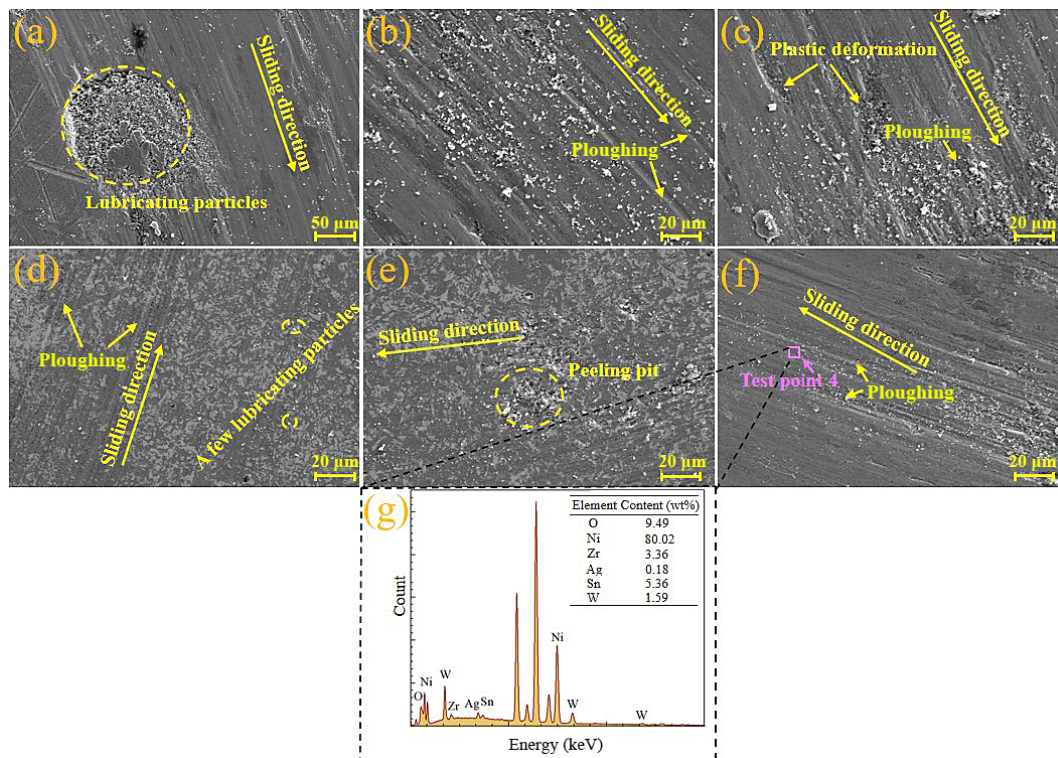


Fig. 14 (a–c) Micrographs of the worn surface morphology of SA material at 150 °C; (d–f) micrographs of the worn surface morphology of SZ material at 150 °C; (g) EDS point map.

4.3.3 Micromorphology of worn surfaces of SA and SZ at 250 °C

At a high temperature of 250 °C, the friction coefficient and wear rate of the SZ are significantly lower than those of the SA. The core of this advantage lies in the ZrW₂O₈ material doped in its micropores: driven synergistically by temperature and sliding-induced tangential shear action of the mating pair, ZrW₂O₈ plays a pivotal role in lubrication regulation. Figures 15(a)–15(c) illustrate the evolution process of the worn surface of SA at the same temperature (250 °C). At the initial stage (see Fig. 15(a)), obvious ploughing grooves have formed on the surface, and the lubricant in the micropores migrates along the friction sliding direction. When entering the rapid wear stage (see Fig. 15(b)), the continuous sliding of the mating pair intensifies the formation of ploughing grooves and drives the migration of lubricating particles on the surface; although lubrication effects are observed in local areas, the overall coverage is insufficient. At the steady wear stage (see Fig. 15(c)), the distribution of the surface lubricant tends to be relatively balanced, and the accumulated particles attempt to form a relatively complete covering layer to reduce wear loss, which is consistent with the simulation results of the lubricant surface concentration distribution in Section 2. However, compared with the lower-temperature condition, the SA coating at 250 °C still shows obvious ploughing grooves and local particle accumulation, indicating that the SnAg lubricant has not yet formed a sufficiently continuous and stable protective layer. Therefore, 250 °C can be regarded as a transitional temperature stage for SA, where lubricant exudation and spreading are enhanced but the lubricating film remains insufficiently stabilized. A comprehensive analysis of Figs. 15(a)–15(c) indicates that under the action of temperature and tangential shear action, the SnAg exuded from the micropores of SA can only meet the local lubrication demand and fail to form a sufficient and effective surface protective film, which directly results in its relatively high friction coefficient and wear rate at this temperature. The lubricant behavior of SA follows a sequential process: exudation from the micropores, migration to the surface

for uniform distribution, and final formation of particle accumulation. The research also points out that the main wear mechanisms of SA at 250 °C are abrasive wear and fatigue wear, accompanied by slight oxidation wear.

Figures 15(d)–15(f) show the evolution of the worn surface of the SZ at the same temperature (250 °C). At the initial stage of wear (see Fig. 15(d)), the exudation of SnAg lubricant from the micropores is driven synergistically by temperature and tangential shear action: the temperature rise promotes the thermal expansion and exudation of SnAg, among which the part above the friction interface is actively carried away by the tangential shear action of the mating pair and spread to the worn interface. Figures 15(d1)–15(d4) present the elemental surface distribution maps (O, Ni, Ag, and Sn) of SZ at the initial wear stage at 250 °C, which further reveal the main distribution characteristics of SnAg on the worn surface. Meanwhile, ZrW₂O₈ effectively restricts the excessive exudation of the lubricant. This synergistic mechanism ensures the precise delivery of the lubricant to the interface to meet the local lubrication demand. When entering the rapid wear stage (see Fig. 15(e)), the overall surface remains relatively flat; despite the presence of obvious ploughing grooves, the SnAg distribution exhibits macroscopic uniformity with local accumulation. This indicates that the lubricant has the ability to dynamically adapt to wear demands and continuously provides lubrication protection by maintaining effective coverage. At the steady wear stage (see Fig. 15(f)), a fully lubricated covering layer forms on the worn surface, which significantly slows down the wear process; although obvious ploughing grooves still exist, the SnAg distribution tends to be in dynamic equilibrium, effectively ensuring a sustained lubrication effect. A comprehensive analysis of Figs. 15(d)–15(f) reveals that under thermomechanical synergistic driving, the lubricating particles undergo an evolution process of exudation from the micropores, local accumulation, and final realization of uniform distribution. The research further confirms that the main wear mechanisms of SZ at 250 °C are oxidation wear, abrasive wear, and fatigue wear, accompanied by slight adhesive wear.

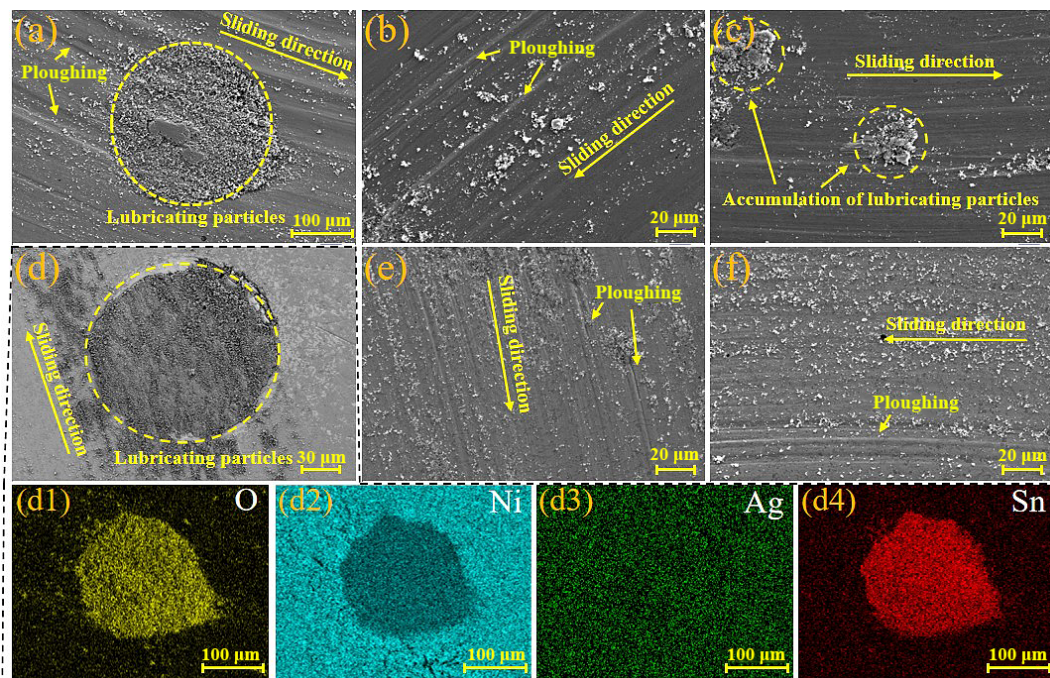


Fig. 15 (a–c) Microstructural morphology of the worn surface of SA at 250 °C; (d–f) microstructural morphology of the worn surface of SZ at 250 °C; (d1–d4) elemental distribution patterns on the surface shown in Fig. 15(d).

4.3.4 Micromorphology of worn surfaces of SA and SZ at 350 °C

At the extremely high temperature of 350 °C, both SA and SZ exhibit low average friction coefficients and wear rates. The core mechanism lies in the following: the intense temperature rise drives a large amount of SnAg lubricant in the micropores to exude onto the worn surface via thermal expansion; meanwhile, the doped ZrW_2O_8 effectively inhibits the excessive loss of lubricant at this temperature, maintaining lubrication stability. Figures 16(a)–16(c) detail the evolution of the surface morphology of SA under this condition. At the initial stage (see Fig. 16(a)), the high temperature prompts SnAg to expand rapidly and exude in large quantities, which spreads on the surface in a short time to form a relatively thick initial lubricating layer. This layer significantly isolates the direct contact between the mating pair and the substrate, mitigating early-stage damage. When entering the rapid wear stage (see Fig. 16(b)), the combined effect of sustained high temperature and friction causes the uniform lubricating layer to differentiate: local areas thicken due to lubricant accumulation, while high-shear regions thin out owing to excessive consumption, leading to spatial inhomogeneity in lubrication performance. At the steady wear stage (see Fig. 16(c)), surface damage intensifies, with ploughing grooves and spalling pits interweaving to form a complex microstructure. Although a distinct lubricating layer still covers the surface (this morphology is consistent with the high-temperature spreading and film-

forming tendency of lubricant simulated in Section 2), surface oxidation induced by high temperature has exerted a negative impact on the wear resistance of the material. A comprehensive analysis of Figs. 16(a)–16(c) reveals that the wear process of SA at 350 °C is the result of a complex coupling of the temperature field, the dynamic behavior of SnAg (expansion and exudation—spreading and film-forming—local failure), and the mechanical action of the mating pair, among which the rapid exudation of SnAg is crucial for surface protection. The research ultimately confirms that the main wear mechanisms of SA at this temperature are abrasive wear, fatigue wear, and significant high-temperature oxidation wear.

Figures 16(d)–16(f) show the surface micromorphology characteristics of SZ at different wear stages at a high temperature of 350 °C. Figure 16(d) corresponds to the initial stage, where little lubricant is observed on the worn surface, and a small amount of ploughing grooves still remain around the circular micropores. For the initial wear stage of SZ at 350 °C, the elemental distribution maps (Figs. 16(d1)–16(d6)) show that the SnAg lubricant in the micropores is prone to oxidation at high temperatures, while the regulatory component ZrW_2O_8 uniformly covers the surface and effectively inhibits the excessive exudation of SnAg, resulting in its uniformly dispersed state. When entering the rapid wear stage (Fig. 16(e)), the worn surface becomes smooth overall, although some ploughing grooves still exist; at this

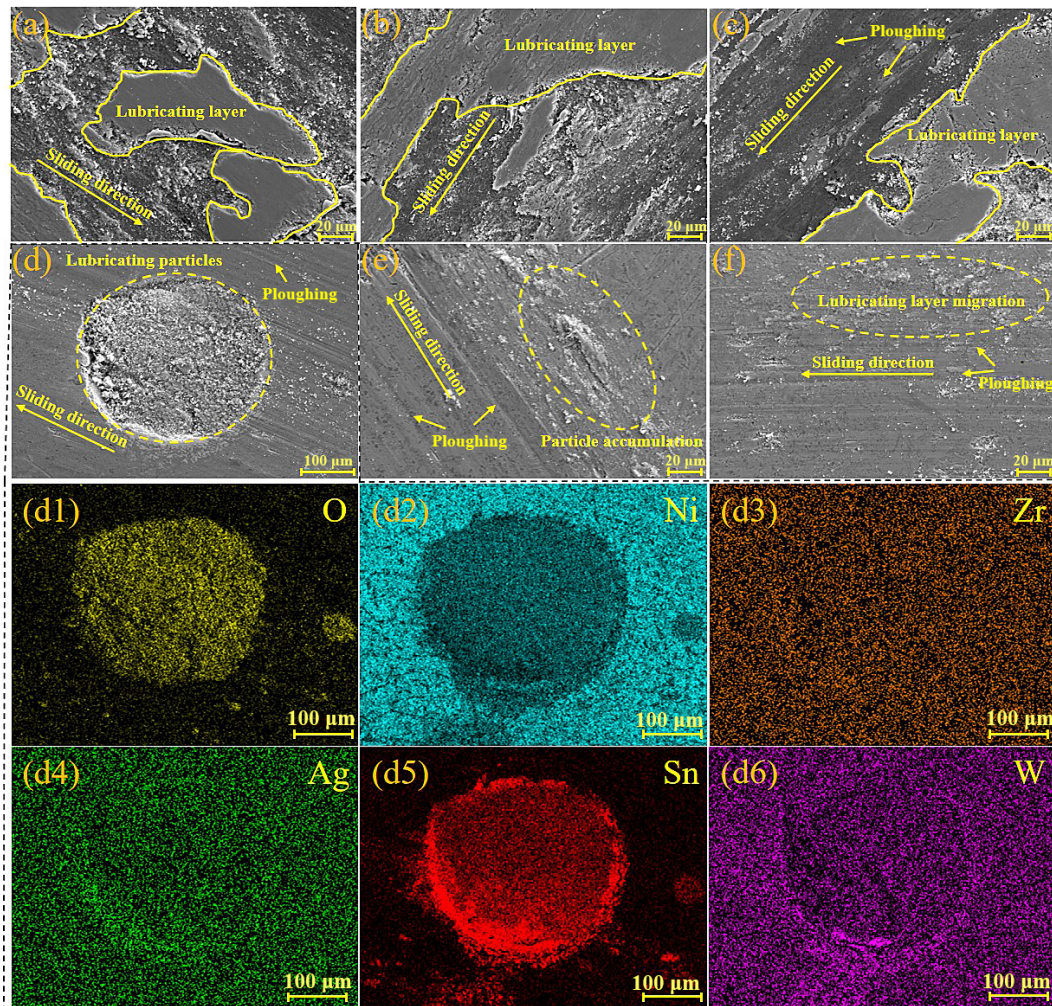


Fig. 16 (a–c) Microstructural morphology of the worn surface of SA at 350 °C; (d–f) microstructural morphology of the worn surface of SZ at 350 °C; (d1–d6) elemental distribution patterns on the surface shown in Fig. 16(d).

time, the SnAg lubricant accumulates on the surface, which significantly alleviates the damage caused by friction. When wear progresses to the steady stage (Fig. 16(f)), an obvious migration phenomenon of the surface lubricant occurs. This migration drives the lubricating particles to form a more complete and continuous lubricating layer during friction, thus meeting the lubrication requirements more effectively. This indicates that the distribution and action mechanism of SnAg are optimized at this stage, which can maintain a good lubrication effect through self-migration. A comprehensive analysis of Figs. 16(d)–16(f) shows that the SnAg lubricant in the micropores undergoes a transformation process of exudation from the micropores, accumulation formation, and subsequent migration and spreading during the wear process. The research further confirms that the main wear mechanisms of SZ at 350 °C include oxidation wear, abrasive wear, fatigue wear, and adhesive wear.

4.4 Phase analysis of the surface lubricating layer in SnAg/ZrW₂O₈ nickel-based composite coatings

To further analyze the chemical composition of the lubricating layer formed on the worn surface of the SZ coating, high-resolution XPS spectra were fitted, as shown in Fig. 17. All binding energies were calibrated using the C 1s peak at 284.8 eV. In the C 1s spectrum, the fitted peaks at 284.8, 286.5, and 288.4 eV correspond to C–C, C–O, and C=O related species, respectively.

The O 1s spectrum can be fitted into peaks at 530.0, 531.1, 532.3, and 533.7 eV, which are associated with metal–oxygen bonds and oxygen-containing surface species. The Ni 2p spectrum shows metallic Ni and nickel oxide-related components together with satellite peaks, indicating local oxidation of the Ni-based coating surface during high-temperature sliding.

For the lubricating elements, the Ag 3d spectrum shows two peaks at 367.6 and 373.6 eV, corresponding to Ag 3d_{5/2} and Ag 3d_{3/2}, respectively, indicating the presence of Ag-related lubricating species in the tribofilm. The Sn 3d spectrum contains Sn²⁺- and Sn⁴⁺-related components, which can be assigned to SnO/SnO₂-related species. In addition, the W 4f spectrum exhibits W⁶⁺ 4f_{7/2} and W⁶⁺ 4f_{5/2} peaks at 36.2 and 38.9 eV, respectively, while the Zr 3d spectrum shows Zr⁴⁺ 3d_{5/2} and Zr⁴⁺ 3d_{3/2} peaks at 182.5 and 184.9 eV, respectively. These W–O- and Zr–O-related species are associated with the ZrW₂O₈-containing composite lubricant.

The XPS results indicate that the lubricating layer formed on the worn surface of the SZ coating is not composed of a single lubricating phase but consists of Ag-related lubricating species, SnO/SnO₂-related species, W–O/Zr–O related species, and nickel oxide-related species. The Ag-related species and SnO/SnO₂-related species are associated with the lubrication and oxidation behavior of the SnAg lubricant during high-temperature sliding, while the W–O and Zr–O related species indicate the

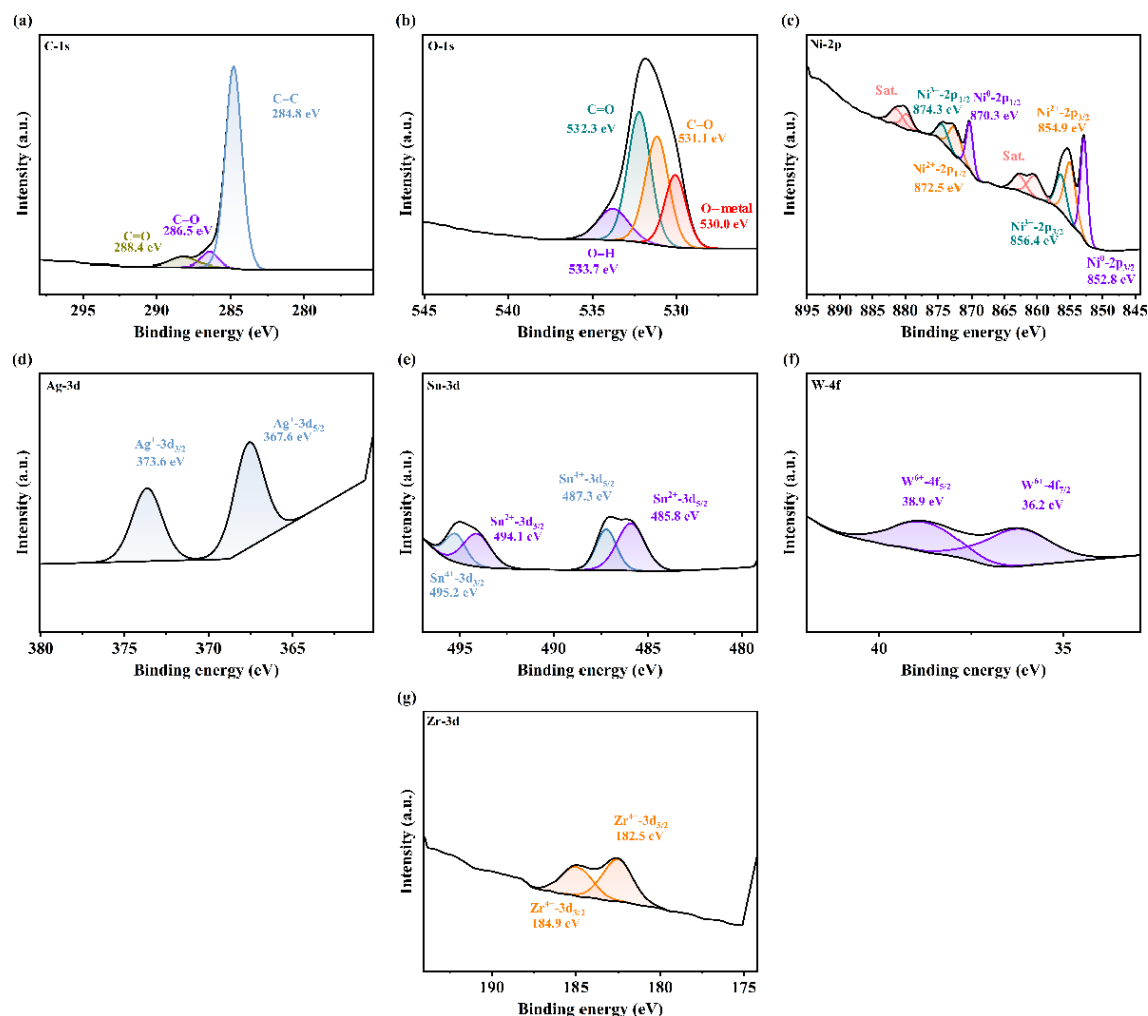


Fig. 17 High-resolution XPS spectra and fitted peaks of the composite lubricating layer formed on the worn surface of the SZ coating: (a) C 1s; (b) O 1s; (c) Ni 2p; (d) Ag 3d; (e) Sn 3d; (f) W 4f; (g) Zr 3d.

participation of the ZrW_2O_8 -containing phase in the composite tribofilm. Previous studies have shown that ZrO_2 -containing ceramic phases can improve the hardness, wear resistance, or scratch resistance of coatings and composites [46, 47]. Therefore, the Zr–O related species detected in the present tribofilm may contribute to the stability and load-bearing capacity of the composite lubricating layer. These results provide chemical evidence for the synergistic lubrication behavior of SnAg and ZrW_2O_8 during high-temperature sliding.

4.5 Evolution of the friction subsurface microstructure of the SnAg/ ZrW_2O_8 Ni-based composite coating under temperature action

By observing the evolution of the microstructure of frictional cross-sections, combining the morphology of each layer, the state of the lubricating film, and grain evolution at different temperatures, and comparing with the variation rules of friction coefficients and wear rates of SA and SZ, this paper analyzes the adaptive behavior of the composite material at high temperatures. Figure 18 presents the microstructure of the wear scar cross-sections of SA at different temperatures, which can be divided into three main regions: the surface layer, the load-bearing layer, and the Ni-based coating layer. As the part in direct contact with the external environment, the state of the surface layer exerts a crucial influence on frictional behavior; the load-bearing layer is located beneath it, undertaking mechanical loads and resisting deformation. Figure 18 shows that as the temperature rises from room temperature to 350 °C, the thickness of the surface layer of SA changes as follows: room temperature (1.70 μm) $\rightarrow$ 150 °C (2.32 μm) $\rightarrow$ 250 °C (4.04 μm) $\rightarrow$ 350 °C (4.48 μm). At room temperature (see Fig. 18(a)), the wear scar cross-section maintains a relatively intact structure, with only a small amount of fine lubricating particles in the surface layer, and an obvious grain refinement zone appears beneath it. This zone features a dense structure, fine grains, and high strength, which is significantly different from the internal Ni-based coating layer below. When the temperature rises to 150 °C (see Fig. 18(b)), a continuous lubricating film forms on the surface, leading to a simultaneous decrease in the friction coefficient and wear rate; although refined grains also exist in the load-bearing layer at this stage, their size is larger than that at room temperature, which is attributed to the surface lubricating film sharing part of the load. At 250 °C (see Fig. 18(c)), the surface lubricating film thickens further, and the

grain refinement zone in the load-bearing layer expands significantly because the material is more prone to plastic deformation at high temperatures. Figure 18(d) shows the cross-sectional morphology at 350 °C, where a lubricating film with sufficient thickness is formed on the surface, and a distinct lubricating film structure also appears in the load-bearing layer. This microstructural characteristic is consistent with the low friction coefficient and wear rate of the material at this temperature—the surface lubricating film effectively reduces frictional damage, and grain refinement improves the mechanical properties of the load-bearing layer simultaneously. The synergistic effect of the two enables the SA to exhibit excellent tribological properties at high temperatures.

Figure 19 shows the microstructure evolution of the wear scar cross-sections of the SZ at different temperatures. As the temperature rises from room temperature to 350 °C, the thickness of the surface layer of the SZ changes as follows: room temperature (2.32 μm) $\rightarrow$ 150 °C (3.0 μm) $\rightarrow$ 250 °C (2.4 μm) $\rightarrow$ 350 °C (4.18 μm). At room temperature (see Fig. 19(a)), the cross-sectional structure is relatively intact, and the surface layer is thin, which facilitates the rapid response to frictional force; a grain refinement zone appears in the load-bearing layer, indicating that the material undergoes microstructural adjustment and that its wear resistance is improved. At 150 °C (see Fig. 19(b)), fine lubricating particles are distributed in the surface layer, which effectively reduces the direct contact between friction pairs, thereby decreasing wear; meanwhile, the range of grain refinement in the load-bearing layer expands, further enhancing structural integrity and mechanical properties. When the temperature rises to 250 °C (see Fig. 19(c)), the surface layer undergoes phase transformation or chemical reactions due to direct contact friction and high temperature, resulting in changes in its properties; the load-bearing layer experiences microstructural refinement or deformation under thermomechanical coupling, which affects its load-bearing and wear-resistant capabilities. At 350 °C (see Fig. 19(d)), the structural changes of each layer become more significant: the surface layer undergoes oxidation or physical transformation, with its composition and structure readjusted, which affects the lubrication effect; the load-bearing layer experiences the evolution of grain size and phase distribution under the combined action of thermal stress and mechanical load, thereby regulating its mechanical properties and wear behavior.

In summary, the regulation of the lubricating behavior of the

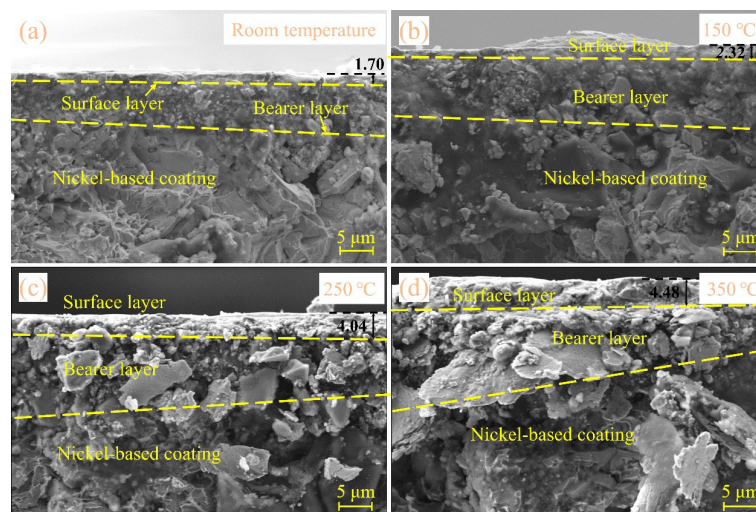


Fig. 18 Micromorphology of the cross-section of SA at different temperatures: (a) room temperature; (b) 150 °C; (c) 250 °C; (d) 350 °C.

material by ZrW₂O₈ exhibits a significant temperature dependence. At medium and low temperatures, the presence of ZrW₂O₈ promotes the exudation and spreading of the SnAg lubricant, effectively thickening the lubricating layer and improving the surface lubrication performance. At high temperatures (350 °C), however, it instead inhibits the excessive exudation of SnAg, leading to a significant reduction in the thickness of the surface lubricating layer and avoiding early failure caused by insufficient strength due to an overly thick lubricating film. This “intelligent” regulatory mechanism of “inhibition at high temperatures and promotion at low temperatures” fully demonstrates the negative thermal expansion characteristic of ZrW₂O₈, realizing adaptive lubrication management of the material.

4.6 Analysis of the adaptive regulatory mechanism of frictional properties over a wide temperature range

Figure 20(a) shows the cross-sectional micromorphology of the SnAg lubricant exuding from the material pores to the worn surface under the high-temperature environment of 350 °C. The

distribution of SnAg in the pores is nonuniform: the density in some areas is high due to mixing with ZrW₂O₈. For example, at test points 5 and 6 (see Figs. 20(b) and 20(c)), the contents of W, O, and Zr are prominent, with small amounts of Sn, Ag, and Ni present simultaneously. This indicates that under the combined action of high temperature and pressure, ZrW₂O₈ closely coats the surface of SnAg, forming a dense composite structure. In contrast, the lubricant distribution on the other side is sparse with good fluidity, which facilitates the faster migration of SnAg to the surface for lubrication. A transition zone exists between the pore walls and the lubricant, and the exudation process exhibits obvious hierarchical characteristics: Ni and Sn elements are enriched near the pore orifices (e.g., test point 7, see Fig. 20(d)), which is attributed to the thermal expansion and good fluidity of Sn; near the worn surface (e.g., test point 8, see Fig. 20(e)), SnAg comes into contact with the mating pair preferentially and spreads to form a lubricating layer under the action of friction and tangential shear action. The element distribution in this area tends to be uniform, with a significant proportion of Ni and O, reflecting the compositional changes under the interactive influence of high-temperature exposure and friction.

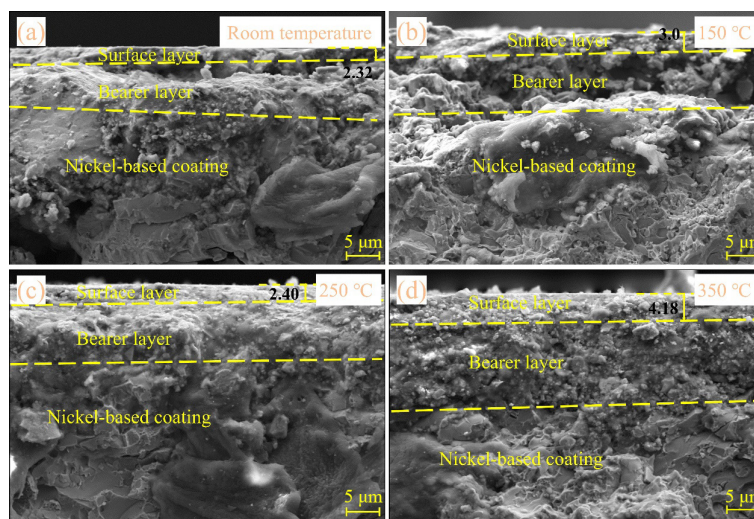


Fig. 19 Micromorphology of the cross-section of SZ at different temperatures: (a) room temperature; (b) 150 °C; (c) 250 °C; (d) 350 °C.

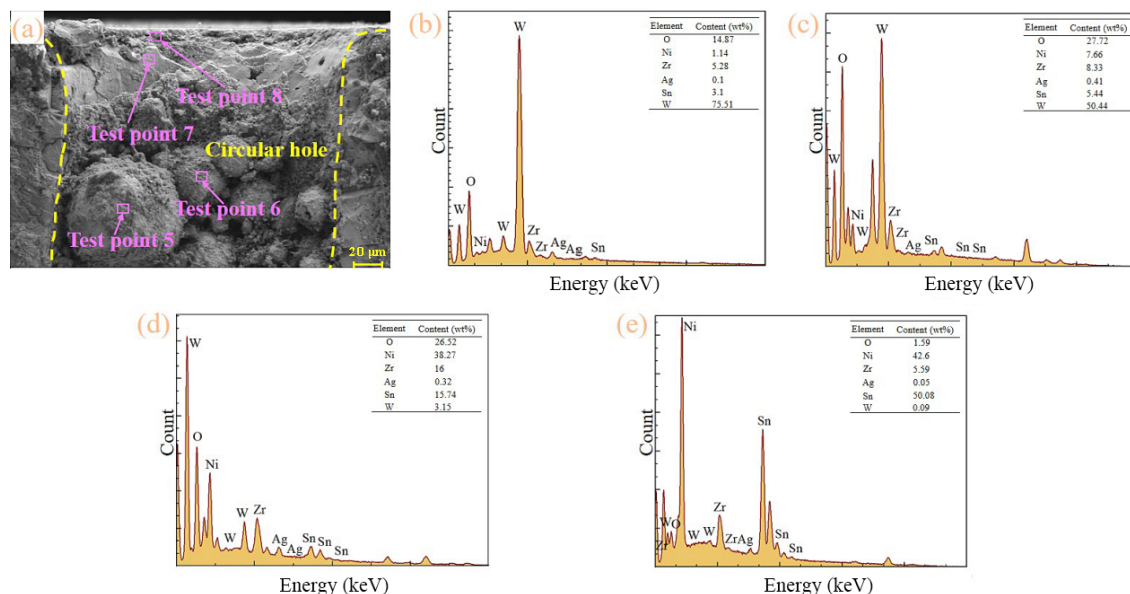


Fig. 20 (a) Cross-sectional micromorphology of lubricant exuding from micropores to the worn surface; (b–e) EDS point scan maps.

From a microstructural perspective, the aforementioned characteristics of the nonuniform distribution and dynamic migration of SnAg lubricant in the pores reflect the interaction and evolution of various components inside the SZ during the high-temperature wear process. The introduction of ZrW_2O_8 can effectively regulate the exudation process and composition distribution of SnAg, thereby optimizing the formation and stability of the lubricating film and significantly improving the tribological properties of the material under harsh conditions such as high temperatures.

Through the composite design of coating–texture–lubricant, SA has become an integrated functional material with friction reduction, wear resistance, and self-lubrication properties, which can effectively cope with frictional behaviors under complex working conditions. Under the adaptive regulation effect of ZrW_2O_8 , the SZ coating can form a relatively stable lubricating layer on the friction surface, showing potential application value for medium- and high-temperature sliding components. Figure 21(a) shows the mechanism diagram of SA/SZ self-lubrication integration, among which Figs. 21(a1) and 21(a2) illustrate the self-lubrication mechanism of the SnAg Ni-based composite coating. Figure 21(a1) reveals the dynamic response process of SA at 350 °C, where high temperature promotes the oxidation of the 95Sn5Ag lubricant in the pores to form SnO/SnO₂-related species and Ag-related oxidation species. Driven by thermal expansion, the lubricant overflows from the pores to form an initial lubricating layer in the initial wear stage, and microcracks and pits are generated on the friction interface due to the action of the mating pair at the same time. Figure 21(a2) shows the strengthening mechanism in the steady wear stage: the lubricant fills the pits to achieve “self-repair” under tangential shear action and its own fluidity; the oxidation products spread to form a continuous lubricating layer; further analysis of the frictional subsurface shows that a thick lubricating layer forms in the surface layer region, which significantly prolongs the lubrication life.

Compared with SA, the adaptive regulatory mechanism of SZ is

shown in Figs. 21(a3) and 21(a4). Figure 21(a3) reveals its response process at 350 °C: high temperature triggers the reaction of substances in the pores to generate SnO/SnO₂-related species, Ag-related species, and W–O/Zr–O related species; meanwhile, the doped ZrW_2O_8 material undergoes volume shrinkage upon heating, which effectively inhibits the excessive exudation of 95Sn5Ag lubricant due to thermal expansion and forms an appropriate lubricating layer around the pores to meet the initial friction demand. Figure 21(a4) shows the regulatory mechanism in the steady wear stage: 95Sn5Ag achieves pit “self-repair” under the synergistic effect of temperature and tangential shear action; ZrW_2O_8 precisely regulates its exudation amount to ensure continuous lubrication; further analysis of the frictional subsurface shows that at 350 °C, the surface layer thickness of SA increases from 1.7 to 4.48 μm, with an increase of 164%, while the thickness variation range of SZ is relatively concentrated (2.32 to 4.18 μm), with an increase of 80%. This indicates that the doping of ZrW_2O_8 effectively improves the thermal stability of the material and promotes the formation of a more uniform-thickness lubricating layer, thus significantly reducing the loss and excessive accumulation of lubricant.

The XPS fitting results further support the proposed adaptive regulatory mechanism. The Ag-related species and SnO/SnO₂-related species indicate that the SnAg lubricant participates in surface lubrication and tribofilm formation during high-temperature sliding. Meanwhile, the W–O- and Zr–O-related species suggest that the ZrW_2O_8 -containing phase is involved in the formation of the composite tribofilm. Therefore, the adaptive lubrication behavior of the SZ coating can be attributed to the coupled effects of micropore-assisted lubricant storage, temperature-assisted SnAg migration, and ZrW_2O_8 -regulated composite tribofilm formation.

It should be noted that the adaptive lubrication mechanism is sensitive to contact stress. A moderate contact stress is beneficial for promoting the release, spreading, and tribofilm formation of the SnAg lubricant from the micropores to the friction interface.

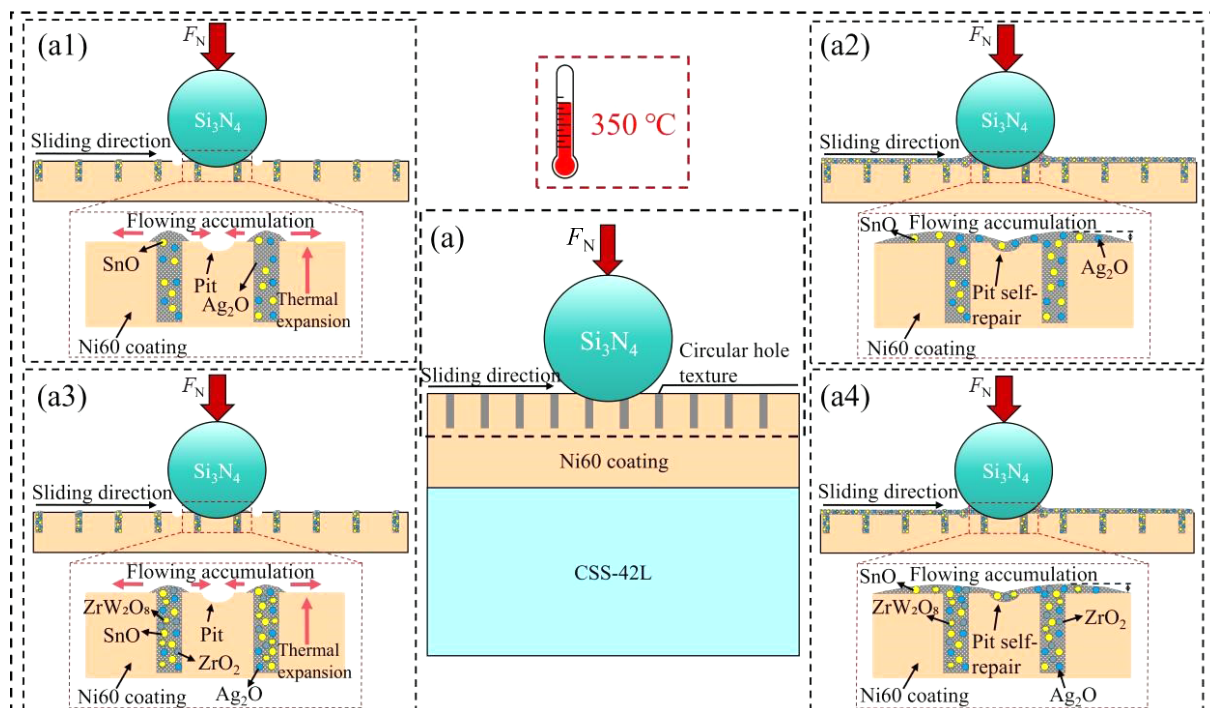


Fig. 21 (a) Integrated self-lubrication mechanism diagram for SA/SZ; (a1, a2) integrated synergistic friction reduction and wear resistance self-lubrication mechanism diagram for SA; (a3, a4) integrated synergistic friction reduction and wear resistance self-lubrication mechanism diagram for SZ.

However, under higher loads, impact loading, or complex environmental media, the lubricant may be squeezed out or consumed by shear more rapidly, which may affect the continuity and load-bearing stability of the lubricating film. Therefore, the present results demonstrate the adaptive lubrication potential of the coating–texture–lubricant system under medium- and high-temperature sliding contact, where temperature variation represents an important aspect of harsh service conditions. Nevertheless, its long-term reliability under more complex service environments, such as deep-sea equipment, high-precision machine tools, rail transit, and aerospace applications, still requires further verification under higher contact stress, cyclic thermal loading, and complex environmental conditions.

5 Conclusions

In this paper, a wide-temperature-range adaptive Ni-based composite coating system (SA/SZ) is proposed. With CSS-42 L bearing steel as the substrate, a Ni60 hard coating was deposited via laser cladding technology, and a three-dimensional “coating–texture–lubricant” composite system was constructed by coupling the design of a surface arrayed circular micropore texture with solid lubricant filling technology (95Sn5Ag and 95Sn5Ag–10 wt% ZrW₂O₈). The main conclusions drawn are as follows:

(1) Based on cellular automata models, a single-pore numerical model for simulating the exudation and flow behavior of lubricant was established in this paper, and pit cells and barrier cells were defined to describe the actual structure. A series of evolution rules, including self-diffusion, absorption, hindrance, and loss, were introduced into the model to systematically simulate the dynamic exudation process of the lubricant. The simulation results show that the proportion of medium- and high-concentration regions increases gradually with increasing temperature, rising from approximately 65.55% at room temperature to 68.41%, 71.12%, and 75.28% at 150, 250, and 350 °C, respectively. Under the coupling effect of temperature and tangential shear action, the migration path of the lubricant changes and the absorption rules also significantly affect the morphology of its surface concentration distribution. Cellular automata models simulate the diffusion and exudation process of the lubricant with temperature, laying a theoretical foundation for subsequent experiments.

(2) This study innovatively proposes a ternary synergistic design concept of coating–texture–lubricant. In this system, the Ni60 hard coating provides substrate wear-resistant support, effectively reducing the room-temperature wear rate compared with the substrate, while the arrayed circular micropore texture reduces the effective contact area and thus the friction coefficient. With increasing temperature, the 95Sn5Ag lubricant on the surface of the SA material exuded due to thermal expansion to form a self-lubricating film, with the exudation amount showing a gradual increasing trend. In contrast, the SZ material can achieve a lubricant supply matching the friction demand under the regulatory effect of ZrW₂O₈, exhibiting better lubrication response characteristics. Moreover, an adaptive regulatory mechanism of the friction interface is constructed under the synergistic effect of the doped ZrW₂O₈ and SnAg lubricant. The synergy of the three enables SA/SZ to exhibit a continuously stable friction coefficient and excellent wear resistance in the wide temperature range from room temperature to 350 °C.

(3) The lubricant in the texture can form a lubricating layer on the worn surface to provide a friction-reducing effect, thus cooperating with the regulatory effect of ZrW₂O₈ to construct a highly efficient adaptive lubrication system. 350 °C is the optimal

operating temperature in the wide temperature range, at which the friction coefficients of SA and SZ decrease to 0.42 and 0.44, respectively, and the wear rates drop to as low as 1.3×10^{-7} and $2.0 \times 10^{-7} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$. The friction coefficient of SA shows a nonmonotonic variation (a decrease of 27% at 150 °C), while that of SZ decreases continuously (a cumulative decrease of 39.7% at 350 °C). Wear rate analysis indicates that the introduction of ZrW₂O₈ enables the wear rate of the SZ to decrease stably with temperature, overcoming the abnormal increase in the SA wear rate at 250 °C.

(4) With increasing temperature, the frictional subsurface exhibits a significant thermomechanical coupling response: the rate of increase in the surface layer thickness of SZ doped with ZrW₂O₈ (80%) is significantly lower than that of SA (164%), which reflects the significant temperature dependence of ZrW₂O₈ (inhibition at high temperatures and promotion at low temperatures). This endows the material with wide-temperature adaptability and optimizes its tribological properties.

(5) XPS characterization indicates that the composite lubricating layer contains Ag-related lubricating species, SnO/SnO₂-related species, W–O/Zr–O related species, and nickel oxide-related species. These species provide chemical evidence for the formation of a composite tribofilm during high-temperature sliding. The Ag-related and SnO/SnO₂-related species are associated with the lubrication and oxidation behavior of the SnAg lubricant, while the W–O/Zr–O related species may contribute to the stability and load-bearing capacity of the composite lubricating layer. The synergistic formation of this composite tribofilm is beneficial for reducing material removal and improving the wear resistance of the SZ coating.

(6) The structural form proposed in this paper endows the material with adaptive lubrication characteristics under wide-temperature conditions. Such composite materials are expected to be applied to key moving components such as sliding bearings and pistons, providing a new solution to the lubrication problems of traditional moving components under complex working conditions.

CRediT authorship contribution statement

Xiyao Liu, Feng Qiao, and Jun Wang: Conceptualization, writing—original draft, and writing—review & editing. Lejia Qin, Bentian Luo, and Ji Li: Formal analysis, investigation, and methodology. Zhiwei Lu, Li Chen, and Jiliang Zhang: Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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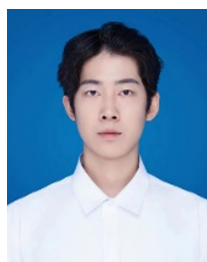
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