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# Microstructure, Tribological Behavior and Corrosion Resistance of Electroless Ni–P Composite Coatings Reinforced with Hexagonal Boron Nitride Particles

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***Abstract***— *Electroless Ni–P and Ni–P/hexagonal boron nitride (h-BN) composite coatings were successfully deposited on steel substrates to investigate the influence of h-BN particles on the microstructure, mechanical properties, tribological performance, and corrosion resistance of the coatings. Micron-sized h-BN particles (0.5–0.7 μm) were incorporated into the electroless Ni–P matrix to produce a self-lubricating composite coating. The microstructure and surface morphology were characterized using scanning electron microscopy (SEM), X-ray diffraction (XRD), and atomic force microscopy (AFM). Mechanical properties were evaluated by nanoindentation, while tribological behavior and corrosion resistance were examined using ball-on-disk wear tests and electrochemical polarization measurements in 3.5 wt.% NaCl solution. The results demonstrated that h-BN particles were uniformly embedded within the Ni–P matrix without altering its amorphous structure. The incorporation of h-BN slightly increased the surface roughness but significantly improved the tribological performance owing to its intrinsic layered solid-lubricant structure. Compared with the conventional electroless Ni–P coating, the Ni–P/h-BN composite coating reduced the average coefficient of friction by approximately 45% and decreased wear loss by about 38%, while maintaining comparable corrosion resistance. Although a slight reduction in hardness was observed, the coating retained satisfactory mechanical integrity. These findings indicate that h-BN-reinforced electroless Ni–P composite coatings provide an effective approach for achieving excellent wear resistance, self-lubricating capability, and corrosion protection for engineering applications.*

***Keywords***— ***Electroless deposition, Ni–P composite coating, Hexagonal boron nitride (h-BN), Tribological behavior, Corrosion resistance, Self-lubrication.***

## I. INTRODUCTION

Electroless deposition is a surface treatment technique that utilizes chemical reduction reactions to form a uniform metallic coating on a substrate surface without the need for an external electric current. It offers advantages such as uniform coating thickness, the ability to coat complex geometries, excellent adhesion, and corrosion resistance, and is therefore widely used in the mechanical, aerospace, automotive, electronics, and precision manufacturing industries [1–4]. Among these, electroless Ni–P coatings have become one of the most representative nickel-based electroless coatings owing to their high hardness, excellent wear resistance, corrosion resistance, and good chemical stability, and are extensively applied for surface protection of various high-performance engineering components [2–5].

However, conventional Ni–P coatings still suffer from a relatively high coefficient of friction, insufficient self-lubricating capability, and performance degradation after prolonged wear under high-load dry sliding conditions. Consequently, recent research has progressively shifted toward the development of functional composite electroless coatings [6–8]. Through the co-deposition of various functional ceramic or solid lubricant

particles, such as $Al_2O_3$, SiC, $TiO_2$, $MoS_2$, graphene, and hexagonal boron nitride (h-BN), the wear resistance, corrosion resistance, and overall mechanical properties of the coatings can be effectively enhanced [7–11].

Hexagonal boron nitride (h-BN), possessing a layered hexagonal crystal structure similar to that of graphite and thus often referred to as "white graphite," exhibits a low coefficient of friction, high thermal conductivity, excellent chemical stability, high-temperature oxidation resistance, and good electrical insulation characteristics. Therefore, it is widely used in solid lubrication materials, high-temperature lubrication, and wear-resistant components [12,13]. Furthermore, since the interlayers of h-BN are primarily bonded by van der Waals forces, interlayer slip readily occurs during friction, forming a stable solid lubricating film that can effectively reduce the coefficient of friction and decrease wear loss. For this reason, h-BN has gradually become an important reinforcing material for nickel-based composite coatings in recent years [13–16].

Early studies have confirmed that h-BN can be successfully co-deposited into a Ni–P matrix, effectively reducing the coefficient of friction and improving wear resistance [17–20]. However, recent investigations indicate that the development of Ni–P composite coatings has progressively shifted from a single wear-resistant function toward a design that combines corrosion resistance, self-lubrication, and multifunctional capabilities [21–24]. At present, most research still focuses on reinforcing phases such as SiC, $Al_2O_3$, TiC, $MoS_2$, or graphene, while systematic studies addressing the interactive effects of h-BN reinforcement on the microstructure, tribological behavior, and corrosion performance of Ni–P composite coatings remain relatively limited [22–26].

Therefore, in this study, Ni–P/h-BN composite coatings were prepared by electroless deposition using micron-sized h-BN particles as a self-lubricating reinforcing phase. The effects of h-BN on the coating composition, crystal structure, surface morphology, roughness, mechanical properties, tribological behavior, and corrosion resistance were investigated and compared with those of a conventional Ni–P coating and the steel substrate. The aim is to establish the mechanism by which h-BN enhances the performance of Ni–P composite coatings, providing a reference for the design of engineering surfaces with high wear resistance and corrosion protection.

## II. EXPERIMENTAL PROCEDURE

Ni–P and Ni–P/h-BN composite coatings were deposited on steel substrates (50 mm × 25 mm × 2 mm). Prior to plating, the substrate surfaces were first degreased with acetone, then alkaline cleaned in a NaOH solution, and finally activated in a HCl solution. The substrates were rinsed with deionized water after each step. The detailed pretreatment steps are presented in Table 1. For the Ni–P/h-BN composite coating, h-BN particles with an average particle size of 0.5–0.7 μm were added to the plating bath to impart self-lubricating properties to the coating surface. In order to achieve effective affinity and uniform dispersion of the h-BN particles in the plating bath, the surfactant cetyltrimethylammonium bromide (CTAB) played a crucial role. Its role is important: it can not only increase the surface charge to improve the stability of the suspension, but also enhance the wettability of the suspended particles, thereby preventing particle agglomeration or aggregation. Furthermore, the presence of the surfactant enhanced the electrostatic adsorption of the suspended particles onto the substrate, facilitating their co-deposition. Additionally, magnetic stirring was employed to achieve optimal suspension uniformity of the h-BN particles in the bath. The deposition parameters for the electroless Ni–P/h-BN composite coating are listed in Table 2.

*Table 1. Pretreatment steps*

| Step | Procedure |
|---|---|
| 1 | Ultrasonic degreasing in acetone at room temperature for 10 min |
| 2 | Alkaline cleaning in 10% NaOH at 40 °C for 1.5 min |
| 3 | Acid activation in 50% HCl at 25 °C for 30 s |

*Table 2. Bath composition and operating conditions*

| Bath composition | | |
|---|---|---|
| 1 | Nickel sulfate | 30 g/L |
| 2 | Sodium lactate | 40 mL/L |
| 3 | Glycine | 10 g/L |
| 4 | Sodium hypophosphite | 30 g/L |
| 5 | $KIO_3$ | 2 mL/L |
| 6 | CO890 | 1 mL/L |
| 7 | h-BN particles | 0 and 10 g/L |
| | | |
| Operating Conditions | | |
| 1 | pH | 5.2 |
| 2 | Temperature | 90 °C |
| 3 | Stirring speed | 100 rpm |
| 4 | Plating time | 2 h |

The chemical composition of the coatings was determined using electron probe microanalysis (EPMA). The phase evolution and microstructure of the coatings were examined by X-ray diffraction (XRD). The surface morphology was characterized using scanning electron microscopy (SEM) and atomic force microscopy (AFM). The hardness of the coatings was measured using a Vickers microhardness tester under a load of 50 g. The tribological behavior of the coatings was evaluated using a reciprocating ball-on-disk wear tester under dry sliding conditions at room temperature and 50% relative humidity. A zirconia ball (diameter 6.25 mm, 1200 HV) was used as the counterface, with an amplitude of 1 mm, a frequency of 240 rpm, and a normal load of 10 N. The corrosion resistance of the Ni–P and Ni–P/h-BN composite coatings was evaluated using a potentiostat in a 3.5 wt.% NaCl aqueous solution at room temperature.

## III. RESULTS AND DISCUSSION

### 3.1 Coating composition

Insoluble hexagonal boron nitride (h-BN) particles were successfully co-deposited into the Ni–P matrix via electroless deposition, forming a Ni–P/h-BN composite coating. According to the EPMA analysis results (Table 3), the Ni–P coating was mainly composed of Ni and P, while after the addition of h-BN, B and N could be detected in the coating in addition to Ni and P, confirming that h-BN particles had been successfully incorporated into the Ni–P matrix. Compared with the pure Ni–P coating, the phosphorus content of the Ni–P/h-BN composite coating decreased slightly, while the h-BN content was approximately 2.66 wt.%. This phenomenon can be attributed to the fact that the presence of h-BN particles in the plating bath altered the adsorption and reduction behavior of nickel ions and hypophosphite ions on the substrate surface, causing some deposition sites to be replaced by h-BN particles, thereby leading to a slight decrease in phosphorus content. On the other hand, in this study, CTAB was employed as a surfactant, which could enhance the dispersibility and suspension stability of h-BN particles in the plating bath, reduce particle agglomeration, and enable the uniform co-deposition of h-BN into the Ni–P matrix. This result is consistent with the findings of recent composite electroless plating studies, which have indicated that an appropriate surfactant can effectively improve the co-deposition efficiency of second-phase particles and the uniformity of the coating.

*Table 3. EPMA analysis of Ni–P and Ni–P/h-BN composite coatings*

| Composition | Ni (wt%) | P (wt%) | BN(h) (wt%) |
|---|---|---|---|
| Ni-P | 88.18 | 11.82 | — |
| Ni-P/BN(h) | 89.67 | 7.67 | 2.66 |

### 3.2. Microstructure analysis

Fig. 1(a) compares the XRD patterns of the steel substrate, the Ni–P coating, and the Ni–P/h-BN composite coating. The XRD results show that both the Ni–P coating and the Ni–P/h-BN composite coating exhibit a broad diffraction peak at a 2θ of approximately 45°, indicating that the coatings still maintained the typical amorphous structure of high-phosphorus electroless Ni–P. After the addition of h-BN, neither the position nor the shape of the main peak changed significantly, implying that the h-BN particles did not alter the amorphous structure of the Ni–P matrix but were dispersed as second-phase particles within the coating. The characteristic diffraction peaks of h-BN can be observed in the magnified XRD pattern, confirming that h-BN had been successfully co-deposited into the coating. As the h-BN content in this study was only about 2.66 wt.% and the particle size ranged from 0.5 to 0.7 μm, its influence on the amorphous structure of Ni–P was limited. Recent related studies have also indicated that, at an appropriate addition level, h-BN mainly exists as a dispersed phase without inducing crystallization of the Ni–P matrix, thereby providing both self-lubricating capability and the corrosion resistance advantages of an amorphous coating.

### 3.3. Surface morphology

The scanning electron microscopy (SEM) images of the Ni–P and Ni–P/h-BN composite coatings are shown in Fig. 2. SEM observations revealed that the Ni–P coating surface exhibited a typical uniform nodular structure, while after the addition of h-BN, the coating surface remained well compact. However, some micron-sized h-BN particles could be observed uniformly distributed within the Ni–P matrix without evident large-scale agglomeration, indicating that CTAB and the stirring conditions effectively improved the dispersibility of h-BN in the plating bath.

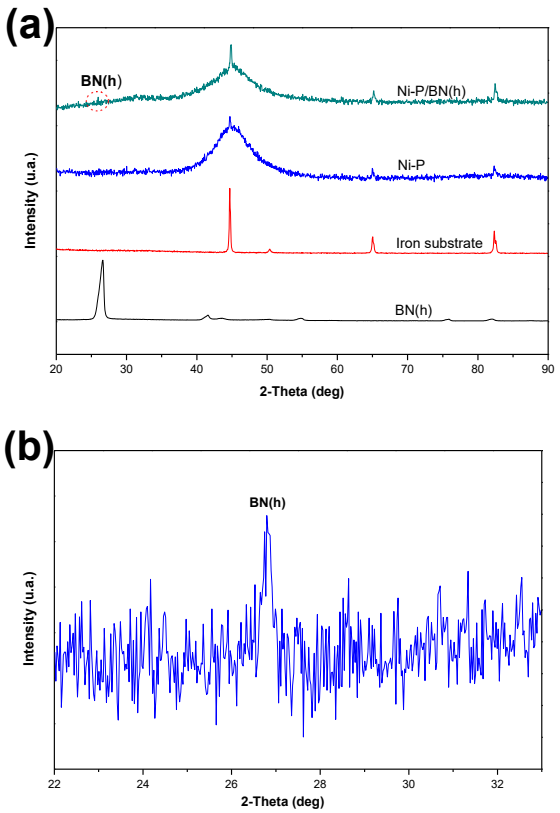


*Fig. 1. XRD patterns of (a) the Ni–P coating and (b) the Ni–P/h-BN composite coating.*

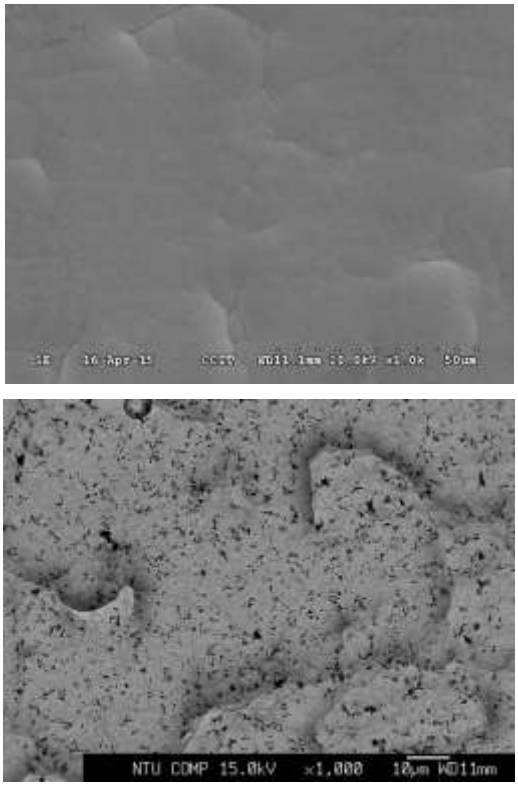


*Fig. 2. SEM surface morphology of (a) the Ni–P coating and (b) the Ni–P/h-BN composite coating.*

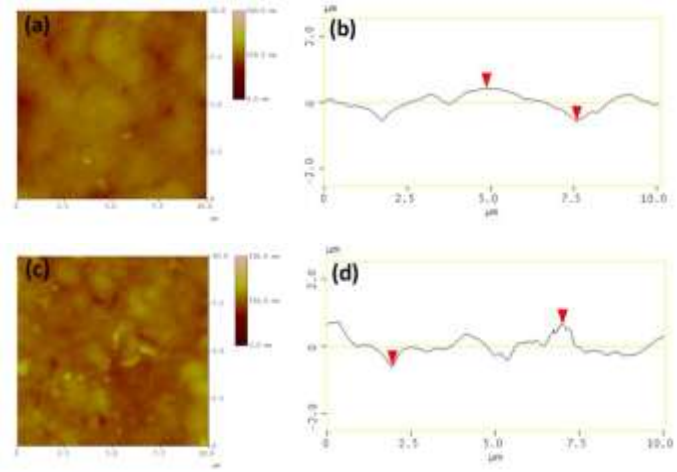


*Fig. 3. AFM surface morphology of (a) the Ni–P coating and (b) the Ni–P/h-BN composite coating; surface roughness of (c) the Ni–P coating and (d) the Ni–P/h-BN composite coating.*

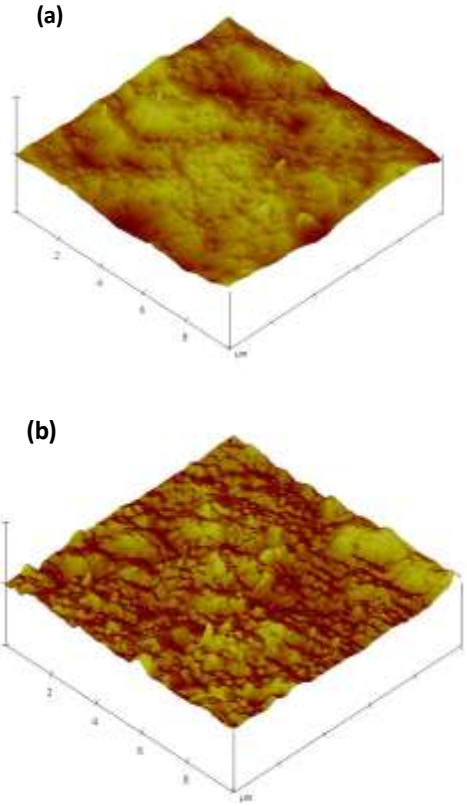


*Fig. 4. Three-dimensional AFM surface images of (a) the Ni–P coating and (b) the Ni–P/h-BN composite coating.*

Atomic force microscopy (AFM) was employed for observation. The surface roughness and AFM surface morphology images of the Ni–P and Ni–P/h-BN composite coatings are presented in Fig. 3(a–d). The three-dimensional AFM images of the Ni–P and Ni–P/h-BN

composite coatings are shown in Fig. 4(a,b). The AFM results showed that the surface roughness of the Ni–P/h-BN composite coating increased from 0.42 μm to 1.49 μm. The increase in roughness is mainly attributed to the partial protrusion of h-BN particles from the coating surface, which altered the growth mode of the Ni–P deposit. However, this increase in roughness did not cause an increase in coating defects; rather, it facilitated the formation of a stable lubricating film during the initial stage of wear, exerting a positive effect on the reduction of the coefficient of friction. Recent studies on composite coatings have also pointed out that a moderate degree of roughening can enhance the effectiveness of solid lubricant particles, whereas excessive addition may lead to particle aggregation and the formation of local porosity. Therefore, the content and dispersibility of the second-phase particles must be appropriately controlled.

### 3.4. Mechanical properties

The nanomechanical properties of the Ni–P and Ni–P/h-BN composite coatings were investigated, and it was demonstrated that the addition of h-BN particles to the Ni–P coating had a beneficial effect. Fig. 5 shows the indentation depth versus load curves. The nanoindentation results of the Ni–P and Ni–P/h-BN composite coatings were compared. Observations of the indentation depths formed during loading and unloading revealed that the Ni–P/h-BN composite coating exhibited a lower hardness. The addition of BN led to a decrease in hardness. The actual microhardness of the coating was obtained by calculation using the Oliver–Pharr method.

$$H = \frac{P_{max}}{A_c} \quad (1)$$

The microhardness H was measured using a Berkovich indenter, where the contact area $A_c=24.5\times h^2_c$ (2).

On the other hand, the elastic modulus was calculated using the following formula.

$$\frac{1}{E_r} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu_i^2)}{E_i} \quad (3)$$

Where “E” is the reduced modulus, “ν” is Poisson's ratio of the coating, “E” is Young's modulus of the coating, “ν” is Poisson's ratio of the indenter, and “E” is Young's modulus of the indenter.

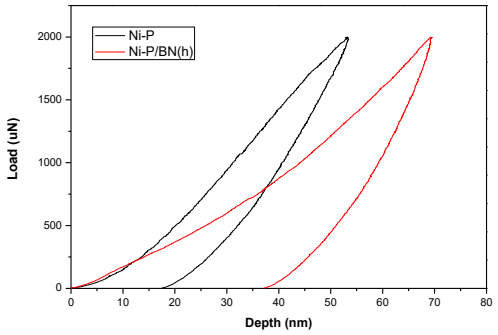


*Fig. 5. Nanoindentation load/unload curves of the Ni–P and Ni–P/h-BN composite coatings.*

Fig. 6(a,b) compares the microhardness and elastic modulus of the steel substrate, the Ni–P coating, and the Ni–P/h-BN composite coating. From Fig. 6(a), it can be observed that the Ni–P coating exhibited an average hardness of 4.92 GPa; however, after the incorporation of the self-lubricating h-BN particles, the overall hardness of the Ni–P coating decreased from 4.92 GPa to approximately 4.64 GPa. This is mainly attributed to the fact that the h-BN particles possess a hexagonal layered structure that can readily absorb external forces, thus resulting in a lower hardness of the Ni–P/h-BN composite coating. Studies on the co-deposition of soft particles in nickel-based coatings have also shown a similar decrease in hardness. Furthermore, the elastic modulus of the Ni–P/h-BN composite coating was likewise lower than that of the Ni–P coating after the incorporation of the h-BN particles, as shown in Fig. 6(b).

Fig. 6 presents a comparison of the nanohardness and elastic modulus of the steel substrate, the Ni–P coating, and the Ni–P/h-BN composite coating. As can be observed from Fig. 6(a), compared with the steel substrate, the Ni–P coating exhibited a higher hardness of up to 4.92 GPa owing to its high-phosphorus amorphous structure. However, after the co-deposition of h-BN particles into the Ni–P matrix, the coating hardness slightly decreased to 4.64 GPa, representing a reduction of approximately 5.7% (as shown in Fig. 6(b)). This result can be primarily attributed to the typical hexagonal layered crystal structure of h-BN, in which the interlayers are mainly bonded by Van der Waals forces. Therefore, interlayer slip readily occurs under external loading, increasing the capacity for local plastic deformation. In addition, the intrinsic hardness of h-BN is lower than that of the Ni–P matrix; consequently, the co-deposition of h-BN reduces the average load-bearing capacity of the overall coating, leading to a slightly greater indentation depth.

On the other hand, the decrease in hardness observed in this study was quite limited, indicating that the h-BN particles did not compromise the integrity of the amorphous Ni–P matrix but were uniformly dispersed as a second phase within the coating. The SEM and XRD analyses also confirmed that the addition of h-BN did not cause an increase in porosity or cracks in the coating, thus maintaining satisfactory mechanical integrity. Furthermore, the elastic modulus of the Ni–P/h-BN composite coating was also slightly lower than that of the Ni–P coating, indicating that h-BN can enhance the local elastic deformability of the coating. Recent related studies have likewise pointed out that although solid lubricant particles may cause a slight decrease in coating hardness, they can effectively reduce contact stress concentration, thereby improving the tribological performance. Hardness, therefore, is not the sole indicator for evaluating wear resistance.

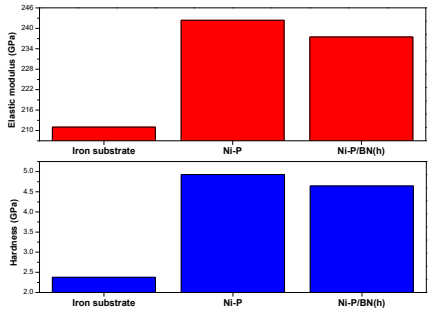


*Fig. 6. (a) Hardness and (b) elastic modulus of the steel substrate, the Ni–P coating, and the Ni–P/h-BN composite coating.*

### 3.5. Tribological behavior

Fig. 7 shows the variation in the coefficient of friction and wear loss of the steel substrate, the Ni–P coating, and the Ni–P/h-BN composite coating under dry reciprocating wear tests. The results demonstrate that the Ni–P/h-BN composite coating exhibited the lowest coefficient of friction, which was reduced by approximately 45% compared with the Ni–P coating and by about 58% compared with the steel substrate. Furthermore, its wear loss was reduced by 38% and 75%, respectively, indicating that h-BN can effectively enhance the wear resistance of the coating. This result is primarily associated with the unique layered crystal structure of h-BN. Since the interlayers of h-BN are mainly bonded by weak Van der Waals forces, interlayer slip readily occurs along the crystal planes during the wear process, thereby reducing the shear resistance at the contact interface. Moreover, during repeated sliding, some h-BN particles are gradually extruded from the interior of the coating and become uniformly distributed on the wear track surface, forming a transfer film with low shear strength that can effectively separate the direct metallic contact between the counterface ball and the coating.

On the other hand, the transfer film can also be regarded as a third-body layer, which can absorb part of the frictional energy and reduce the local contact stress, causing the wear mechanism to gradually transform from severe adhesive wear to mild abrasive wear. Consequently, both the coefficient of friction and the wear loss can be simultaneously reduced. In addition, although the hardness of the Ni–P/h-BN coating was slightly lower than that of the Ni–P coating, its overall wear resistance was significantly improved, indicating that the tribological performance is predominantly governed by the self-lubricating capability rather than solely determined by hardness. Recent studies on self-lubricating composite coatings have also pointed out that an appropriate amount of h-BN can form a stable lubricating film on the worn surface, thus effectively prolonging the service life of the coating.

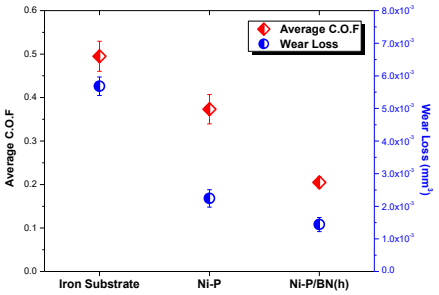


*Fig. 7. Coefficient of friction and wear loss of the steel substrate, the Ni–P coating, and the Ni–P/h-BN composite coating as a function of sliding distance.*

### 3.6. Corrosion behavior

Fig. 8 shows the potentiodynamic polarization curves of the steel substrate, the Ni–P coating, and the Ni–P/h-BN composite coating in a 3.5 wt.% NaCl solution. The results indicate that the corrosion potentials of both the Ni–P and Ni–P/h-BN composite coatings were significantly higher than that of the steel substrate, while the corrosion current densities were markedly reduced, demonstrating that the electroless Ni–P coating provides an effective corrosion protection effect. It is noteworthy that after the addition of h-BN, the corrosion potential and corrosion current density were close to those of the Ni–P coating, indicating that the incorporation of h-BN did not degrade the corrosion resistance of the coating. This result can be attributed to three main reasons. First, the Ni–P coating in this study maintained a high-phosphorus amorphous structure with a

low number of grain boundaries; therefore, corrosive media are less likely to rapidly diffuse along the grain boundaries. Second, SEM observations revealed that h-BN was uniformly distributed within the coating without causing apparent porosity or cracks, thereby preserving the coating compactness. Finally, h-BN possesses excellent chemical stability and can exist as an inert second phase in the Ni–P matrix, hardly participating in electrochemical corrosion reactions, and thus does not create new corrosion pathways. In summary, the Ni–P/h-BN composite coating in this study exhibits a combination of low friction, high wear resistance, and good corrosion resistance, demonstrating its potential for application in surface protection of molds, sliding parts, and precision machinery.

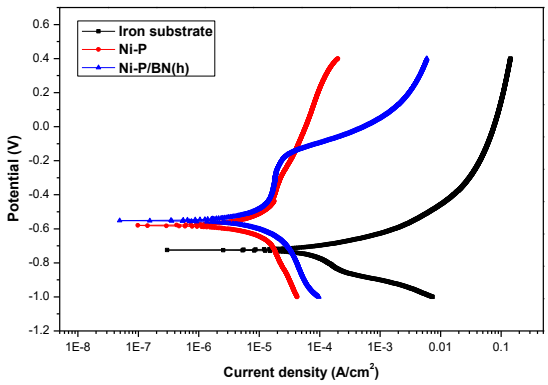


*Fig. 8. Polarization curves of the steel substrate, the Ni–P coating, and the Ni–P/h-BN composite coating.*

### 3.7. Comparison with recent studies

To further evaluate the performance of the Ni–P/h-BN composite coating prepared in this study, the obtained results were compared with those of recent related studies on nickel-based composite coatings, as shown in Table 4. In recent years, functional particles such as SiC, $Al_2O_3$, $MoS_2$, graphene, and h-BN have been predominantly employed as reinforcing phases to enhance the wear resistance, corrosion resistance, and mechanical properties of the coatings. Although different reinforcing materials can improve the coating properties, their strengthening mechanisms are distinct. Compared with high-hardness ceramic particles (e.g., SiC, $Al_2O_3$), h-BN is a typical layered solid lubricant material. Its primary mechanism is not to increase the coating hardness but to form a lubricating film (transfer film) with low shear strength during the friction process, reducing the shear stress at the contact interface and thereby effectively decreasing the coefficient of friction and wear loss. Although the hardness of the Ni–P/h-BN composite coating in this study was slightly lower than that of the conventional Ni–P coating, its coefficient of friction was reduced by approximately 45% and its wear loss by about 38%, indicating that its wear resistance mainly originates from the self-lubricating effect rather than from a mere increase in hardness. This result is consistent with the trends observed in recent studies on Ni–hBN composite coatings and self-lubricating coatings.

Table 4. Performance comparison with recent related studies.

| Study | Coating system | Main reinforcing phase | Hardness change | Coefficient of friction | Wear resistance | Corrosion resistance |
|---|---|---|---|---|---|---|
| [27] | Ni–P–$MoS_2$–$Al_2O_3$ | $MoS_2$+$Al_2O_3$ | ↑ | Decreased | Improved | Improved |
| [28] | Ni–hBN | h-BN | ↑ | Reduced by approximately 42% | Improved | Improved |
| [23] | Ni–hBN（Heat treatment） | h-BN | ↑ | Reduced by approximately 42% | | |
| This study | Ni–P/h-BN | h-BN | Slightly decreased（4.92→4.64 GPa） | Reduced by approximately 45% | Wear loss reduced by 38% | Maintained good corrosion resistance |

Furthermore, the polarization tests in this study revealed that the addition of h-BN did not degrade the corrosion resistance of the Ni–P coating, which is presumed to be related to the fact that the amorphous

structure of Ni–P remained intact and h-BN was uniformly dispersed. Recent studies have also indicated that when h-BN is uniformly dispersed in the coating without forming porosity, the corrosion resistance of the composite coating can be maintained or even improved. Therefore, h-BN not only serves as a solid lubricant phase but can also provide a corrosion protection effect. In summary, the Ni–P/h-BN composite coating prepared in this study combines good wear resistance, self-lubricating capability, and corrosion resistance, demonstrating promising application potential for sliding parts, molds, precision machinery, and high-wear-resistance engineering components.

## IV. CONCLUSIONS

In this study, Ni–P and Ni–P/h-BN composite coatings were successfully prepared on steel substrates via electroless deposition, and the effects of h-BN particles on the microstructure, mechanical properties, tribological behavior, and corrosion resistance of the coatings were investigated. Based on the results of SEM, XRD, AFM, nanoindentation, wear tests, and electrochemical polarization measurements, the following conclusions can be drawn:

(1) h-BN particles can be successfully and uniformly co-deposited into the Ni–P matrix via electroless deposition to form a Ni–P/h-BN composite coating. XRD analysis revealed that the addition of h-BN did not alter the original amorphous structure of the Ni–P coating, indicating that h-BN mainly exists as a second-phase particle within the coating rather than modifying the crystal structure of the Ni–P matrix.

(2) After the incorporation of h-BN particles, the surface roughness of the coating increased from 0.42 ± 0.02 μm to 1.49 ± 0.11 μm. Both SEM and AFM results showed that the h-BN particles were uniformly dispersed on the coating surface without evident agglomeration, demonstrating that the CTAB surfactant and stirring conditions provided an effective dispersion effect, which was beneficial for the formation of a uniform composite coating.

(3) The nanohardness of the Ni–P/h-BN composite coating slightly decreased from 4.92 GPa to 4.64 GPa, and the elastic modulus also decreased slightly. This is mainly attributed to the low shear strength of the layered h-BN crystals, which increased the local plastic deformability of the coating. However, the extent of hardness reduction was limited, indicating that the addition of h-BN did not compromise the overall mechanical integrity of the Ni–P coating.

(4) In dry wear tests, the average coefficient of friction of the Ni–P/h-BN composite coating was reduced by approximately 45% and the wear loss by about 38% compared with the Ni–P coating. This result confirms that h-BN can form a transfer film with low shear strength during the wear process, effectively reducing the frictional resistance and wear rate at the contact interface, thereby endowing the coating with excellent self-lubricating capability. Recent studies on self-lubricating Ni–P composite coatings have also indicated that the uniform dispersion of the solid lubricant phase and the formation of a stable transfer film are key mechanisms for enhancing wear resistance.

(5) The electrochemical polarization test results showed that the corrosion potential and corrosion current density of the Ni–P/h-BN composite coating were close to those of the Ni–P coating, indicating that the incorporation of h-BN particles did not degrade the corrosion resistance of the coating. This phenomenon is primarily attributed to the fact that the Ni–P matrix maintained its amorphous structure and the h-BN particles were uniformly dispersed without causing apparent porosity or cracks, thus preserving the coating compactness and barrier effect. Recent studies have also pointed out that uniformly dispersed second-phase particles can help maintain or even improve the corrosion resistance of Ni–P composite coatings in chloride-containing environments.

(6) In summary, the Ni–P/h-BN composite coating prepared in this study exhibits a combination of good self-lubricating capability, wear resistance, and corrosion resistance, demonstrating that h-BN is an effective reinforcing phase for enhancing the overall performance of electroless Ni–P coatings. It holds promising potential for surface protection applications in precision machinery, sliding parts, molds, and high-wear-resistance engineering components. Future work can further investigate the effects of different h-BN contents, nanosized h-BN particles, and heat treatment conditions on the microstructure and service performance of the coatings, in order to establish optimized process parameters and expand their industrial applications.

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