Study on corrosion behavior of TWIP steel and properties of surface electroleless coatings

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Abstract

In this study, the corrosion behavior and corrosion resistance of TWIP (Twinning Induced Plasticity) steels in the industrial atmospheric environment were studied by dry-wet cycle immersion test and electrochemical experiments. The results showed that the corrosion rates of TWIP steel gradually decreased with the increase of corrosion time. A layer of corrosion products was formed on the surface of TWIP steel during alternating immersion accelerated corrosion process, whose main components were Fe3O4 and α-FeOOH. With the prolongation of corrosion time, the rust layer on the surface of TWIP steel had a certain protective effect on the steel matrix. The adherent and defect-free electroleless nickel–phosphorus (Ni-P) coatings were prepared on TWIP steels. Electrochemical test results showed the corrosion current density of the coating was about six times lower than that of TWIP steel substrate, indicating that the coating effectively improved corrosion resistance of TWIP steel and protected the steel substrate from erosion of corrosive ions. Additionally, the surface microhardness of TWIP steel was significantly increased after electroleless Ni-P plating treatment.

1. Introduction

TWIP (Twinning Induced Plasticity) steels are currently generating a lot of interest with potential applications for structural parts in the automotive industry, petroleum and natural gas industry due to their high energy absorption capacity, high elongation and high tensile strength [1]. At present, the main components of TWIP steels are Fe and Mn, and the content of manganese is generally 15%–30%. Some elements such as Al, Si, N, etc [2–5] are selectively added according to requirements. The addition of manganese and aluminum can significantly increase the stacking fault energy, which is beneficial to the formation of deformation twins. The mechanical twinning that occurs during the deformation of TWIP steels reduces the mean free path of dislocations and the austenite remains relatively stable, which could be interpreted as a dynamical Hall-Petch effect [6]. However, The TWIP steel has low corrosion resistance in chloride and acidic solutions due to high dissolution rate of high content Mn. The addition of silicon can increase the strength of TWIP steels after solid solution strengthening, but silicon has a negative effect on the combine between electroplating layer and substrate. A lot of systematic studies have been carried out on the mechanical behavior and mechanical properties of TWIP steels [7–9]. In order to further expand the application fields of TWIP steels, the study of surface properties of TWIP steels such as corrosion resistance, hardness and wear resistance in practical environment is also very important. So far, there were some studies made on corrosion behavior of TWIP steels in different aqueous solutions, stress corrosion behavior and high temperature oxidation of TWIP steels. K M Moon [10] studied the effect of Mn content on corrosion characteristics of lean Mn TWIP steel and concluded that pitting corrosion was observed in all samples. M Bobby Kannanet [11] stated TWIP steels showed highest corrosion susceptibility in acidic environment and the lowest corrosion susceptibility in the alkaline environment. Muhammed. Khalissi [12] made a conclusion that slow strain rate tension of the TWIP steel in...
Table 1. Chemical compositions of TWIP steel (wt%).

| Elements | Fe  | Mn  | S   | P   | Si  | C   | Al  |
|----------|-----|-----|-----|-----|-----|-----|-----|
| Content  | Balance | 18  | 0.002 | 0.016 | 0.5  | 0.6  | 2   |

3.5% NaCl resulted in stress corrosion cracking at a strain rate of $10^{-07} \text{ s}^{-1}$, whereas the higher strain rates produced exclusive mechanical fracture. Yuan X Y [13] studied the high-temperature oxidation behavior of a high-manganese TWIP steel, and the weight gain per unit area of experimental TWIP steel increased with the increase of oxidation temperature. However, there are few studies about the corrosion behavior and corrosion resistance of TWIP steels in the atmospheric environment. Nearly no investigation has been reported about the effect of corrosion products on the corrosion resistance of TWIP steels.

At present, the protection methods of TWIP steels against corrosion are mainly hot dip galvanizing, surface nitriding, laser cladding and electroless plating. Compared with the other methods, in the process of electroless plating, no external power is needed, and the coating has excellent profiling and brightness. In addition, electroless plating has low porosity and excellent adhesion [14, 15]. More importantly, in addition to excellent corrosion resistance, electroless Ni-P coating also has high hardness, which can greatly improve the wear-corrosion resistant property of TWIP steels in the special industrial application such as oil and gas pipelines, supporting materials for coalmine mining [16–18].

In the present study, the corrosion behavior of TWIP steels in the industrial atmospheric environment has been studied by alternating immersion experiment and electrochemical tests. It can be expected that Ni-P coatings might improve the surface properties of steels. Therefore, in this study nickel–phosphorus (Ni-P) coating on the TWIP steels were prepared by electroless coating and the surface properties of the coating were studied.

2. Material and methods

The experimental material was Fe–Mn–Al–C TWIP steel after cold rolling, and its chemical compositions are shown in table 1.

The sizes of tested samples are 50 mm × 30 mm × 2 mm and 10 mm × 10 mm × 2 mm, which are used in the alternating immersion test and electroless coating respectively. Prior to immersion, all the samples were mechanically ground to 1200# and polished, and then dried for 24 h after ultrasonic cleaning with ethanol and acetone.

The weight loss rates of TWIP steels after alternating immersion accelerated corrosion test were analyzed according to standard ISO8407 [19]. The samples to be tested were taken out after 24 h, 48 h, 72 h, 96 h of accelerated corrosion. Each cycle of the experiment included an immersion stage (12 min) and a dry stage (48 min). The samples were immersed in the 0.01 mol l$^{-1}$ NaHSO$_3$ solution at 35 °C and dried at 45 °C and (70 ± 2)% RH. In each case, five samples were used, one for electrochemical test, one for analysis of rust composition and morphology, and three for weight loss analysis. The corrosion morphology was observed with scanning electron microscope (Nova Nano SEM450) and electron probe micro-analyzer (JXA–8230 EPMA), and the composition of the corrosion product was analyzed by x-ray diffraction (Rigaku D/MAX2500PC XRD).

The rusty samples of 10 mm × 10 mm × 2 mm were subjected to encapsulation treatment with an acrylic resin to leave a working surface having an area of 1 cm$^2$. Electrochemical measurement was carried out using PAR2273 potentiostats. A platinum electrode, saturated calomel electrode and the encapsulated sample were used as counter electrode, reference electrode and working electrode respectively. The scanning range at room temperature was 0.5 mV s$^{-1}$ and the test solution was 0.01 mol l$^{-1}$ NaHSO$_3$.

In the electroless coatings test, the pre-treatment process before plating mainly included the steps of mechanical grinding, alkali washing and acid washing activation. Ni-P coatings were electrolessly deposited from an acidic hypophosphite-reduced nickel bath under a water bath condition. Nickel sulphate (NiSO$_4$ · 6H$_2$O) was used as the source of nickel, sodium hypophosphite (NaH$_2$PO$_2$ · H$_2$O) as the reducing agent, lactic acid (CH$_3$CH(OH)COOH) and acetic acid (CH$_3$COOH) as the complexing agents, and a little amount of thiourea as the stabilizing agent. The bath was operated in the PH 4.7 and temperature at 90 °C for the 2 h plating duration. The morphologies and corrosion resistance of the coating were studied by electron probe micro-analyzer (EPMA) and electrochemical measurements, respectively. The hardness of the substrate steel and coating were measured using micro Vickers hardness tester (TIME6610-M).
3. Results and discussion

3.1. Microstructures
TWIP steel is a typical austenitic steel, and its optical microscope morphology is shown in figure 1. It can be seen that the phase of TWIP steel is mainly single-phase austenite and the annealing twins are evenly distributed among them. Twins play an important role in the excellent mechanical properties of TWIP steels [20].

3.2. Corrosion kinetics
The weight loss rates of TWIP steels after corrosion were calculated by the following equation:

\[
W = \frac{G_0 - G_1}{2t(a \times b + a \times c + b \times c)}
\]

Where, \(W\) is average weight loss rate after corrosion, \(g \cdot m^{-2} \cdot h^{-1}\), \(G_0\) is the original weight of the sample, \(g\), \(G_1\) is the weight of the rusty sample after rust removal, \(g\), \(a\), \(b\) and \(c\) are the length, width and thickness of the sample respectively, \(m\), \(t\) is the corrosion time, \(h\).

The relationship between weight loss rates and corrosion time is shown in the figure 2. At the initial stage, the corrosion rate raised rapidly because of the directly reaction between steel substrate and corrosive medium. As corrosion proceeded, the rusty products on the steel were formed gradually, which can hinder corrosive
medium from eroding the substrate. As a result, the corrosion rate began to decrease gradually after 48 h of corrosion. The rust layer has a certain protective effect on the steel substrate.

Many researchers have predicted long-term atmospheric corrosion behavior of weathering steels and carbon steels using the following bilogarithmic law [21–24]:

\[ W = A \times t^n \]  

Where \( W \) is the weight loss, \( t \) is the test time, \( A \) and \( n \) are constants. \( A \) is the weight loss of the steel samples in the first corrosion cycle. If the values of \( A \) and \( n \) are known, long-term corrosion behavior can be predicted. This bilogarithmic law was applied to the prediction of corrosion behavior of most metal materials in the different atmospheric environments with reliability and authenticity [25].

The results fitted by the equation (2) are shown in figure 3. The value of \( n \) is related to the protective effect of the rust layer on the matrix. When \( n > 1 \), the rust layer has no protective effect on the substrate, and the corrosion rate is increasing sharply; \( n = 1 \), the mass loss curve is linear; \( n < 1 \) indicates the corrosion is a gradual slowing process, and the rust layer has protective effect on the substrate. In this study, the values of \( n \) and \( R\text{-}Square \) are 0.87055 and 0.98181 respectively, indicating that the rust layer on the surface of TWIP steel has a certain protective effect on the steel matrix, and the fitting results are in good agreement with the actual experimental results.

3.3. Analysis of surficial corrosion products

Figure 4 shows the surface morphologies of rust layer on TWIP steels after corrosion for 24 h, 48 h, 72 h and 96 h respectively. At the initial stage of corrosion (figure 4(a)), the corrosion products were agglomerated into particles. The rust layer was uneven and rough, which contained many dugs and microcracks. After 48 h of corrosion (figure 4(b)), the sizes of the surficial particles decreased, and the particles began to congregate together.

As can be seen from the enlarged image in figure 4(b), the surficial rust layer became more uniform as the corrosion time increases. When corroded for 72 h (figure 4(c)), the spherical particles grew larger and congregated into a flat rust layer, and the granular rust layer changed to uniform and lamellar pattern. However, some cracks are observed from the enlarged view in figure 4(c), which may result from stress release during the growth and transition of corrosion products as corrosion time increases. The rust layer on steel samples corroded for 96 h (figure 4(d)) became more compact and flat with much fewer cracks, which can inhibit the penetration of the corrosive ions to the steel substrate. Therefore, the corrosion rates of TWIP steel decreased due to the protective effect of the rust layer on the substrate.

Figure 5 shows the cross-sectional microscopic topographies of the rusty samples. The monolayer rust was formed on TWIP steels corroded for different time, which was different from the double rust layer on weathering steels in the same corrosive environment [26, 27]. In TWIP steels, alloying elements such as Cr, Cu and P are absent, which can promote stratification of corrosion products and enhance compactness of rust layer [28]. Furthermore, the thickness of the rust layer on TWIP steel did not increase with the increase of corrosion time. When the corrosion time was relatively short, the rust layer on the steel surface had the large cracks (as
Figure 4. The surface morphologies of rust layers on TWIP steel after 24 h (a), 48 h (b), 72 h (c) and 96 h (d) accelerated corrosion tests.

Figure 5. Cross-sectional morphologies of rust layers on TWIP steel corroded for different time: 24 h (a), 48 h (b), 72 h (c) and 96 h (d).
shown in figure 5(b)). New corrosion products were formed between the large cracks and steel base after a period of corrosion (as shown in figure 5(c)). The compactness, uniformity and adhesion of the rust layers were enhanced with the prolongation of corrosion time. The corrosion resistance of steel is not only related to alloy elements, but also to microstructures in the steels [29–31]. Although there is no corrosion-resistant alloy elements (Cu, Cr, Ni, et al) in the TWIP steel, TWIP steel has a single uniform austenite microstructure, which plays a role in the densification of rust layer. The electrochemical corrosion occurred uniformly on the TWIP steels with homogeneous microstructures, which caused no large volume expansion and large stress in the production process of corrosion products. This is advantageous for the formation of compact rust layers on the steels in the atmospheric corrosion process.

The composition of corrosion products on TWIP steels corroded for different cycles was analyzed by XRD, as shown in figure 6. In many articles [32], the corrosion products of test steels such as weathering steel, plain carbon steel and low alloy ultrahigh strength steel were considered to be α-FeOOH, γ-FeOOH and Fe₃O₄ in atmospheric environment, and β-FeOOH was found in the rust layer in the atmospheric environment containing chloride. The main compositions of the rust layer on TWIP steel are Fe₃O₄ and α-FeOOH in present study. Among them, Fe₃O₄ is a relatively high conductive oxide with a spinel structure. Qian [33–36] et al have drawn conclusions that the rust layer has protective effect on the substrate when the rust layer contains a large amount of α-FeOOH, which is thermodynamically stable and electrochemically inactive. Additionally, it can be seen from figure 6 that the peak intensity of corrosion products in the rust changed with increasing corrosion time. Therefore, there was the transformation of corrosion products in the cyclic wet/dry accelerated corrosion process. At the initial stage of corrosion, as the dissolution of TWIP steel, Fe was oxidized to Fe²⁺ and Fe(OH)₂, which was accompanied by the reduction reaction of oxygen. γ-FeOOH was formed by the further oxidation of Fe(OH)₂. In present study, no corrosion product γ-FeOOH was found in the XRD results of the rust layer, which may be due to the fact that γ-FeOOH was unstable and easily reduced to Fe₃O₄ [37]. In this experiment condition, α-FeOOH was easily formed via amorphous ferric oxyhydroxide in the slightly acidic solution. The rust layer composed of Fe₃O₄ and α-FeOOH has a certain protective effect on TWIP steel.

3.4. Electrochemical measurements
The corrosion process of TWIP steel in atmospheric environment simulated by dry-wet cyclic immersion accelerating corrosion is a typical electrochemical corrosion. The corrosion behavior and corrosion resistance of the steel samples can be well analyzed by electrochemical methods. Figure 7 shows the potentiodynamic polarization curves of rusty TWIP steel samples after accelerating corrosion in 0.01 mol l⁻¹ NaHSO₃ solution. As can be seen, both anodic and cathodic processes were electrode reactions controlled by active polarization, and there was no passivation in anode reaction. Corrosion current density (Icorr) and corrosion potential (Ecorr) of the steel samples can be determined by reverse extension method of tafel region from the polarization curves (as shown in table 2). It was obtained the corrosion currents and corrosion potentials of the TWIP steel samples in the corrosive medium changed with increasing corrosion time.
As the extension of corrosion time, the corrosion potentials of tested samples gradually shifted in the noble direction. The positive shift of corrosion potentials indicated that the corrosion tendency of steel samples decreased. Meanwhile, corrosion current density decreased, which has been suggested to be attributed to the formation of rusty products on the steel samples. Corrosion current density can indicate corrosion rate of the steel sample, further evaluate the protective properties of rust layer on the steel surface.

At the beginning of corrosion, the anode reaction was the dissolution of steel, and the cathode reaction was the reduction of hydrogen ions, accompanied by the reduction of a small amount of oxygen. With the extension of corrosion time, corrosion products were formed on the steel samples, and the cathodic reaction process was controlled by the reduction of ferric rust. From the fitting results in table 2, it is obtained that the corrosion current density of steel sample after corrosion of 24 h was large, indicating that the surface rust layer cannot effectively block the transfer of corrosive ions due to its loose structure with cracks. As the extension of corrosion time, the rust layer became more uniform and compact, had strong adhesion to the matrix, which inhibited the anodic reaction and led to a decrease in corrosion rate. The electrochemical results are consistent with the above weight loss and morphology observation of rust layer.

In order to further study the protective effect of rust layer, electrochemical impedance spectroscopy (EIS) technique was used in this study. Nyquist diagrams of the TWIP steels corroded for different time are presented in figure 8. For the rusty steel samples after 24 and 48 h accelerated test, the Nyquist diagrams are composed of two compressed capacitive semicircles and a low-frequency diffusion tail. Because the rust layer has the ability of charging and discharging and the ability of blocking ion-transfer, the capacitive arc at the high frequency region is considered to reflect the resistance and capacitance characteristics of the rust layer on TWIP steels. The capacitive arc in the intermediate frequency region is related to the charge-discharge and charge-transfer process of double electric layer on the interface between metal and electrolyte solution. The low-frequency diffusion tail indicates that the corrosion reaction is controlled by the diffusion process because of the formation of corrosion products. After 72 h accelerated test, the Nyquist diagrams of the steel samples are composed of two compressed capacitive semicircles. The diffusion tail disappears at the low frequency region, which may be due to the fact that the rust layer becomes denser and denser as the corrosion time increases.

![Potentiodynamic polarization curves of rusty steels corroded for different periods.](image)

**Figure 7.** Potentiodynamic polarization curves of rusty steels corroded for different periods.

| Corrosion Time (h) | Corrosion Potential (V) | Corrosion Current Density (A·cm⁻²) |
|------------------|------------------------|-----------------------------------|
| 24               | −0.881                 | 6.94 × 10⁻³                       |
| 48               | −0.842                 | 4.73 × 10⁻³                       |
| 72               | −0.826                 | 1.07 × 10⁻³                       |
| 96               | −0.792                 | 9.92 × 10⁻⁶                       |

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Based on the above analysis, two kinds of equivalent circuits were used to fit electrochemical impedance spectroscopy of the rusty steel samples in figure 8, which are shown in figure 9. The impedance spectroscopy of 24 h and 48 h rusty samples is fitted by using the equivalent circuit in figure 9(a) due to the appearing of diffusion tail. The equivalent circuit in figure 9(b) is applicable for the rusty samples corroded for 72 h and 96 h. In figure 9, Rs, Rf, and Rct denote solution resistance, rust layer resistance and charge transfer resistance, respectively. Due to the surface roughness and electric-field distribution heterogeneities in the metal/electrolyte interface, Q (constant phase angle element) was used to replace the pure capacitance, whose impedance is defined as \( Q_{\text{CPE}} = Y(j\omega)^n \), \( Y \) is model value of \( Q \) and \( n \) is dispersion coefficient, \( 0 < n < 1 \). \( Q_1 \) and \( Q_2 \) represent the rust capacitance and the double-layer capacitance with dispersion effect. \( W \) is Warburg impedance caused by diffusion process. The fitting parameters of impedance spectra of the samples for immersion different periods are listed in table 3. \( R_f \) and \( R_{ct} \) are the important parameters to evaluate the protective effect of rust layer. The total impedance is composed of the rust layer resistance \( R_f \) and charge-transfer resistance \( R_{ct} \), which corresponds to the radius of the capacitive arc in figure 8. It can be seen that \( R_f, R_{ct} \) values increase with the increase of corrosion time from table 3. It indicates that the inhibition of rust layer on charge-transfer and ion-migration is enhanced and the protective effect of rust layer on the matrix is improved with the extension of corrosion process.

### 3.5. Performance of electroless Ni-P coating

In order to improve the surface property of Fe-Mn-Al TWIP steels, electroless Ni-P coating was deposited on the TWIP steels in an optimized bath composition using Taguchi method. The plating bath composed of NiSO\(_4\)·6H\(_2\)O, 30 g l\(^{-1}\); NaH\(_2\)PO\(_2\)·H\(_2\)O, 35 g l\(^{-1}\); CH\(_3\)COONa, 15 g l\(^{-1}\); C\(_6\)H\(_8\)O\(_7\), 12 g l\(^{-1}\); H\(_2\)PO\(_2\) in the coating.
solution releases H\(^+\) and electrons by ionization and hydrolysis. Ni\(^{2+}\) ionized from the nickel sulfate is reduced to Ni, and H\(_2\)PO\(_2\)\(^-\) combines with H\(^+\) and electrons to form P and H\(_2\)O. The reduced P and Ni are deposited on the surface of the activated plated part to form a Ni-P coating\[38\]. Figure 10 shows the surface morphologies and cross-sectional morphologies of the electroless Ni-P coating on TWIP steel samples. At the same time, the composition of the coating was studied by energy spectrum analysis. The average thickness of the Ni-P coating obtained at a deposition time of 120 min was approximately 40 \(\mu\)m, which indicated a deposition speed of 20 \(\mu\)m h\(^{-1}\). It can be seen from the figure 10 that the surface of the coating has a hemispherical appearance, and the distribution is relatively uniform as a whole. From the cross-sectional morphology of the electroless plating samples, it is found that the coating is continuous and there is no gap between the coating and the substrate. There are no pores, cracks and other defects in the coating, which adheres to the substrate compactly. The thermal shock test has been carried out to further characterize the adhesion of the coating to the substrate. The samples were heated to 300 \(^\circ\)C in vacuum furnace for an hour, then cooled quickly with distilled water. It is found that the coating can resistant to two times thermal shock and the surface is smooth and uniform without blistering or peeling, which indicates that the Ni-P coating has a good mechanical bond with TWIP steel substrate. It can be inferred that a smooth, uniform and dense coating layer with about 88.9 wt% Ni and 11.1 wt% P was well formed on the TWIP steel substrate.

The microhardness values of the coated sample and TWIP steel under the load condition of 50 g were measured by using a micro Vickers hardness tester, as shown in figure 11. In order to ensure the accuracy of the data, they were the average values of the five points measured. As can be seen from the figure 11, the hardness of TWIP steel is 339.2 HV, and the hardness after electroless coating is 635.7 HV. The hardness of the coated

| Time/h | \(R_s/\Omega \cdot \text{cm}^2\) | \(Q_1 \cdot \text{Y} \cdot \text{F} \cdot \text{cm}^{-2}\) | \(Q_1 \cdot n\) | \(R_2/\Omega \cdot \text{cm}^2\) | \(Q_2 \cdot \text{Y} \cdot \text{F} \cdot \text{cm}^{-2}\) | \(Q_2 \cdot n\) | \(W/\Omega \cdot \text{cm}^2\) |
|--------|-----------------|-----------------|---------|-----------------|-----------------|---------|-----------------|
| 24     | 13.91           | 5.17            | 0.59    | 16              | 0.0098          | 0.8     | 58              | 0.0186        |
| 48     | 14.34           | 2.73            | 0.62    | 120             | 0.0045          | 0.56    | 218             | 0.0234        |
| 72     | 12.07           | 1.93            | 0.48    | 236             | 0.0043          | 0.5     | 874             | —              |
| 96     | 12.29           | 1.08            | 0.63    | 431             | 0.0021          | 0.71    | 932             | —              |

Figure 10. The surface micrograph (a), cross-section micrograph (b) and compositions (c) of Ni-P coatings.
sample is about two times that of the substrate. The strong Ni-P bonds were found to play important roles in the hardness of the coating [39].

Electrochemical experiments were carried out on the electroless coated sample and TWIP steel in a 3.5% NaCl aqueous solution respectively to obtain the polarization curves of figure 12.

The corrosion potential of the TWIP steel is about $-0.8$ V and the corrosion potential of the electroless coated sample is about $-0.4$ V. Compared with that of the TWIP steel substrate, the polarization curve of the coated sample positively shifts. The corrosion current density of the coating is $5.77 \mu A \cdot cm^{-2}$, and the corrosion current density of TWIP steel is $35.36 \mu A \cdot cm^{-2}$. The corrosion current density of TWIP steel is about seven times as much as that of the coating. The results show that the coating sample has low corrosion sensitivity and excellent corrosion resistance. According to the electrochemical studies, Ni-P coating can obviously improve corrosion resistance of TWIP steels in the corrosive environments. The formation of a uniform and dense coating can prevent the erosion of corrosive media to the steel substrate. It has been reported that the electroless Ni-P coating of high P content (>9 wt%) was amorphous structure without obvious crystalline defects such as dislocations and grain boundary, which had high corrosion resistance [40]. The high P content (11 wt%) in the coating in this study plays an important role on improving the corrosion resistance of Ni-P coatings, which can protect the TWIP steel from corrosion in the acid medium and neutral salt solution [41].

![Figure 11. Hardness comparison of TWIP steel and Ni-P coating.](image1)

![Figure 12. The polarization curves of TWIP steel and Ni-P coating in 3.5% NaCl solution.](image2)
4. Conclusions

(1) In the simulated industrial atmospheric environment, the corrosion rates of TWIP steels gradually decreased with the increase of corrosion time. A layer of corrosion products was formed on the surface of TWIP steel, whose main components were Fe₂O₄ and α-FeOOH. With the prolongation of corrosion time, corrosion potentials of the rusty steel samples increased and corrosion current decreased, indicating that the rust layer on the surface of TWIP steel has a certain protective effect on the steel matrix.

(2) The adherent and defect-free electroless nickel–phosphorus coatings were prepared on TWIP steels. Electroless coating formed a good mechanical bond with TWIP steel substrate. Electroless coating had a great improvement in the hardness and corrosion resistance of TWIP steel, which was attributed to high P content in the Ni-P coating.

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