Effect of controlled cooling process on the atmospheric corrosion behaviour of HRB400E hot rolled rebar

Zhen Qian, Si-qian Bao, Yong-qing Zhang, Xue-hai Qian, Xue-liang Chen, Lei Feng and Ming-quan Li

1 The State Key Laboratory of Refractories and Metallurgy, Wuhan University of Science and Technology, Wuhan 430081, People’s Republic of China
2 CITIC Microalloying Technology Centre, CITIC Metals Ltd, Beijing 100004, People’s Republic of China
3 Technology Center of Liuzhou Iron and Steel Company Ltd, Liuzhou Iron and Steel Company Ltd, Liuzhou 545000, People’s Republic of China

E-mail: baosiqian@163.com

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Abstract
To address the problem of rusting of reinforcing bars that occurs in industry, the aim is to control the denseness of the iron oxide skin by changing the controlled cooling process without increasing the production cost, thereby improving the corrosion resistance of the bars. In this paper, the effect of different cooling control processes on the industrial atmospheric corrosion behaviour of HRB400E hot-rolled rebar was investigated using alternating wet and dry corrosion tests. The morphology and structure of iron oxide on the surface and cross-section of the rebar were observed using scanning electron microscopy (SEM) and field emission electron probe microanalysis (EPMA); the corrosion products and electrochemical behaviour of the specimens after alternating wet and dry tests were compared using x-ray diffraction analysis (XRD) and electrochemical methods. The results showed that the hot-rolled rebar without controlled cooling had a dense surface, a thicker iron oxide skin and a tighter bond between the iron oxide skin and the substrate; the corrosion rate of the hot-rolled rebar without controlled cooling was less than that of the rebar with controlled cooling in the alternating wet and dry corrosion tests; the corrosion products mainly consisted of \( \alpha \)-FeOOH, \( \gamma \)-FeOOH and Fe\(_3\)O\(_4\); the self-corrosion potential and rust layer resistance of the hot rolled rebar without controlled cooling after rolling are higher than those of the controlled cooling bars, showing good corrosion resistance.

1. Introduction
HRB400E hot rolled rebar is widely used as a common steel in the industrial and construction industries. With the rapid development of industry, the concentration of sulphur-containing compounds in the atmosphere is increasing, forming acid rain that corrodes the steel matrix, accelerating the corrosion rate of the bars and leading to a reduction in the quality and serviceability of the bars [1]. As a result, there has been increasing concern in recent years about the resulting problems.

After rolling, the surface of the hot rolled rebar will form iron oxide during the cooling process. Iron oxide can isolate the rebar substrate from direct contact with air to a certain extent, which has a certain protective effect on the substrate. Collazo A et al [2] found that the presence of dense iron oxide slowed the corrosion rate of the steel plate substrate. Dong C F et al [3] investigated the electrochemical corrosion behaviour of hot rolled steel with iron oxide in NaCl solution by EIS, dynamic potential polarisation and surface characterisation. The results show that the dense iron oxide skin protects the underlying steel from corrosion. Cheng M et al [4] used Raman spectroscopy and x-ray diffraction for the physical phase analysis of the iron oxide and corrosion products and found that the corrosion products were mainly \( \gamma \)-FeOOH, Fe\(_3\)O\(_4\), FeOOH and \( \gamma \)-Fe\(_2\)O\(_3\). Cao G M et al [5] through the polarization curve and AC impedance spectrum (EIS) comparison analysis at the same time with the
help of Tafel extrapolation method to fit the self-corrosion potential is more positive, the specimens occur corrosion tendency is smaller; and the lower the self-corrosion current, the specimens occur corrosion rate is slower. Dong J H et al [6] studied the evolution of corrosion products of weathering steel by simulating an industrial atmospheric environment with alternating wet and dry indoor conditions and found that as the corrosion time increased, the corrosion rate of weathering steel decreased, the $\alpha$-FeOOH content increased and the corrosion resistance of the rust layer improved. Although accelerated indoor corrosion cannot fully simulate the corrosion of materials in a natural environment, the method is still a powerful tool for pre-mouth studies of material corrosion. Sun B et al [7] also found through alternating wet and dry experiments that in the initial stages of corrosion, corrosion products nucleate and form an external rust layer. As the thickness of the outer rust layer increases, corrosion products develop on the defect. As cracks in the oxide skin expand, an internal rust layer forms in the local craters. In the later stages of corrosion this erodes the scale and extends into the substrate. At this stage, the protective effect of the oxide skin is lost. More studies have also reported that iron oxide has a protective effect on the substrate to improve rust resistance, but differences in the cooling process will affect the shape and structure of the oxide [8, 9]. According to field reports, the iron oxide surface of the rolled and chilled bars was rough and dark with a few cracks visible to the naked eye, while the surface of the non-chilled bars was smooth, shiny and dense. After cooling, the iron oxide is thin and poorly bonded to the substrate under the same conditions, and there are obvious cracks on the surface of the iron oxide, especially where the substrate is bonded to the cross-rib of the bar, which is prone to electrochemical corrosion during storage and transport. In addition, there are stress concentrations and residual stresses in the joint between the matrix and the cross-rib of the bar after cooling, and the residual stresses caused by controlled cooling may be even greater, which will aggravate the corrosion of the bar later on.

In recent years, more and more attention has been paid to HRB400E hot-rolled rebar, but most of the research has focused on its mechanical properties. Therefore, it is important to study and improve the corrosion resistance of HRB400E hot-rolled rebar and to investigate the mechanism of corrosion. In this paper, the effect of the controlled cooling process on the corrosion resistance of HRB400E hot-rolled rebar under industrial atmospheric conditions is investigated by simulating the industrial atmospheric environment through alternating wet and dry cycle corrosion tests, and the difference in corrosion resistance between the controlled and uncontrolled cooling process conditions is compared, which has certain guiding significance in solving the corrosion problems of rebar arising in industry.

2. Experimental materials and methods

The material for this experiment was taken from HRB400E hot-rolled rebar from a domestic steel mill, and three specimens were obtained by using different controlled cooling processes, with the chemical composition (in mass fraction) shown in table 1. The addition of a small amount of Nb to the specimen reduces the Mn and Si content to reduce costs and can compensate for the loss of strength caused by the reduction of Mn and Si through fine grain strengthening and precipitation strengthening of Nb. The hot rolling process parameters for the specimens shown in table 2. Controlled cooling of the steel bars is generally divided into three stages: before entering the finishing roll, after the finishing roll and on the cold bed stage. HRB400E-1 and HRB400E-2 are post-rolling controlled cooling specimens (HRB400E-2 on the cooling bed temperature is not controlled), HRB400E-3 is post-rolling uncontrolled cooling specimens. Using an EDM cutter, 10 mm specimens were cut along the cross-section of the specimen for surface and cross-sectional morphology and electrochemical testing.
and 55 mm specimens were cut along the cross-section for alternating wet and dry tests, corrosion weight gain analysis and x-ray diffraction (XRD) analysis of the rust layer.

The three specimens were inlaid with epoxy resin, sanded in turn with 400# to 2000# sandpaper, polished and etched with 2% (mass fraction) hydrochloric acid in alcohol solution, and observed for surface and cross-sectional morphology using field emission scanning electron microscopy (SEM, FEI Nova nano 400). The SEM-observed specimens were cut into 1/4 circles by wire cutting, inlaid with conductive inlays, sandpapered, polished, etched and then placed in a field emission electron probe microanalyzer (Field-Emission Electron Probe Micro Analyzer) for scanning, followed by importing the collected data into EPMA-Browser software for analysis.

The alternating wet and dry corrosion test was carried out in a spray chamber model F/YW-60 (where the temperature was maintained at 35 °C for 24h, the corrosion spray for 12h and the drying for 12h), and a 0.052% NaHSO3 (mass fraction) solution was used for the alternating wet and dry corrosion in order to simulate an industrial atmosphere. The physical phase analysis of the rust layer on the surface of the specimens after 240 h of alternating wet and dry corrosion was carried out with the aid of an x-ray diffraction (XRD) analyser (XRD, PANalytical Xpert PRO MPD) using a Cu target with a scanning range of 10° to 90°, a voltage and current of 40 kV and 40 mA respectively, a step size of 0.033° and a scanning speed of 1. The electrochemical measurements were carried out using a three-electrode system, with Pt as the auxiliary electrode, saturated glycerol as the reference electrode and three test steels as the working electrodes. The polarisation curves and AC impedance spectra of the specimens were measured in 0.052% NaHSO3 solution using a CHI600B electrochemical workstation and fitted to their electrochemical impedance spectra using ZView electrochemical analysis software.

3. Results and analysis

3.1. Analysis of the denseness and structure of the iron oxide in the original sample of the specimen steel

The surface microscopic morphology of the three specimen steels is shown in figure 1. The surface of HRB400E-1 shows obvious cracks and gaps; the surface of HRB400E-2 has only a few cracks and a relatively flat surface; while the surface of HRB400E-3 is the densest. It can be seen that there are more cracks and crevices on the surface of the specimen when it is controlled cold after rolling, and these cracks provide channels for corrosive media such as O2 and HSO3−, which are not conducive to the protection of the base metal, which will directly affect its later corrosion resistance. From figure 1(b) it can be seen that increasing the upper cooling bed temperature can reduce the cracks on the surface of the steel; the surface quality of the specimen steel is good when the cooling is not controlled after rolling.

In order to further analyse the denseness of the iron oxide, we observed the cross-sectional iron oxide morphology of the original specimen steel. The microscopic morphology of the iron oxide of the specimen steel is shown in figure 2, which shows that the thickness of the iron oxide is HRB400E-3 > HRB400E-2 > HRB400E-1, and the tightness of the iron oxide bond with the substrate is much better for HRB400E-3 and HRB400E-2 specimens than for HRB400E-1. Some studies have shown that the thicker the iron oxide and the tighter the bond with the substrate, the more effective it is in preventing galvanic corrosion of the steel. The thicker the skin, the tighter the bond with the substrate, the more effective it is in preventing galvanic corrosion of the reinforcement. The iron oxide skin is best and most tightly bound to the substrate for uncontrolled chilled bars after rolling; it is less tightly bound for controlled chilled bars after rolling, but the thickness and tightness of the iron oxide skin increases as the bed temperature increases.
After controlled cooling of the reinforcement, the iron oxide is thinner and less well bonded to the matrix under the same conditions, and the surface of the iron oxide is visibly cracked, especially at the bond between the matrix and the cross-rib of the reinforcement, which is prone to electrochemical corrosion during later storage and transport. In addition, there are stress concentrations and residual stresses in the joint between the matrix and the cross-rib of the bar after cooling, and the residual stresses caused by controlled cooling may be even greater, which can aggravate the corrosion of the bar later on.

Figure 3 shows the EPMA analysis of the iron oxide of HRB400E-2. From the energy spectrum, it can be seen that the iron oxide is mainly composed of three elements, Fe, O and Si. In general the iron oxide skin consists of three layers, the thinner Fe₂O₃ on the outside and the thicker Fe₃O₄ and FeO in the middle. The distribution of the Si elements can be clearly seen in the diagram as a bright layer at the combination of the iron oxide skin and the collective, i.e. an enrichment of Si oxides occurs here, and it was found that there is a continuous thin layer of Fe₂SiO₄ close to the matrix side.

3.2. Simulation of industrial atmospheric corrosion weight gain curves

The corrosion weight gain test involves weighing the corrosion specimens for each cycle and calculating their corrosion rate, calculated according to equation (1).


\[
\text{Corrosion rate} = \frac{(m_i - m_0)}{s \cdot t}
\]

Where: \(m_i\) for the mass of the specimen with corrosion products (mg), \(m_0\) for the mass of the specimen before corrosion (mg), \(s\) for the side area of the specimen (cm\(^2\)), \(t\) for the test time (h).

Simulation of industrial atmospheric corrosion in different periods of the three specimens of steel weight gain curve shown in figure 4, from the figure can be seen in the three specimens of steel in the industrial atmosphere corrosion rate change law is basically the same. Corrosion at the early stage, due to the steel surface of iron oxide directly in contact with the corrosion fluid, iron oxide is easy to chemical reaction, so the initial corrosion rate of the three specimens change faster. By the middle of the test is mainly electrochemical corrosion, the surface of the iron oxide has generated a layer of rust, the generation of rust layer to slow down the corrosion effect, so that the corrosion rate in the middle of the corrosion began to decline. In the later stages of corrosion, the corrosion rate of all three specimens is slowing down. Due to the difference in the denseness and thickness of the three specimens of iron oxide, so the corrosion weight gain curve produced by the obvious gap. Analysis of the corrosion weight gain curve, the size of the corrosion rate of the specimen steel: HRB400E-1 > HRB400E-2 > HRB400E-3, it can be seen that after rolling without control cooling significantly reduces the corrosion rate of the steel.

### 3.3. Simulating the macroscopic shape of steel reinforcement in an industrial atmosphere

After alternating wet and dry tests, figure 5 shows the macroscopic surface appearance of the three specimen steels at different corrosion times. When the corrosion time is 48h, the sample steel cross-rib appears slightly corroded, a small amount of rust at the base, at this time the colour of the rust layer is yellow, with the corrosion test time is extended, the colour of the rust layer gradually deepened, 144h after the rust layer is brown, at this time, HRB400E-1 and HRB400E-2 two specimens appear large area corrosion, but HRB400E-2 situation is relatively good, HRB400E-3 only a small amount of rust. HRB400E-3 showed only a small amount of corrosion. After 240 h of alternating wet and dry, the rust layer turned dark brown, HRB400E-1 was covered with rust but the rust layer was thin, HRB400E-2 could still see blue-black iron oxide with the naked eye, and HRB400E-3 showed a small area of corrosion. From the macroscopic morphology of the reinforcement, it can be seen that the protective effect of the iron oxide on the reinforcement is different for the same corrosion cycle with different controlled cooling processes, which is consistent with the findings of the corrosion weight gain curve above.

### 3.4. XRD analysis of simulated industrial atmospheric corrosion products

The XRD of the specimen steel as is shown in figure 6(a) shows that the iron oxide of the specimen steel is mainly composed of Fe\(_3\)O\(_4\), FeO and Fe\(_2\)O\(_3\), which is similar to the energy spectrum results of EPMA above.

The composition of the rust layers of the three specimen steels was analysed using XRD after 240h of alternating wet and dry tests. The XRD diffractograms given in figure 6(b) show that the rust layers of the different experimental steel specimens did not differ in composition and that the rust layers consisted mainly of \(\alpha\)-FeOOH, \(\gamma\)-FeOOH, Fe\(_3\)O\(_4\) and a small amount of FeO [12].

Although there is no difference in the phase composition of the rust layer, the volume fraction of each phase varies greatly. The physical phase analysis of the rust layer after simulating industrial atmospheric corrosion for 240h is shown in table 3. \(\alpha/\gamma\) can be used as an indicator of the degree of protection of the rust layer of
Figure 5. Macroscopic appearance of the sample steel after corrosion for 48h, 144h and 240h.

Figure 6. XRD pattern of the rust layer after simulated industrial atmospheric corrosion for 240h: (a) specimen steel as is; (b) corrosion for 240h.

Table 3. Physical phase analysis of the rust layer after 240h of simulated industrial atmospheric corrosion.

| Sample       | α-FeOOH | γ-FeOOH | Fe₃O₄  | α/γ  |
|--------------|---------|---------|--------|------|
| HRB400E-1    | 42%     | 13%     | 45%    | 0.7241|
| HRB400E-2    | 43%     | 11%     | 46%    | 0.7544|
| HRB400E-3    | 47%     | 8%      | 45%    | 0.8868|
HRB400E hot-rolled rebar in the atmosphere, the higher the value, the higher the stability of the rust layer and the stronger the shielding effect of the rust layer. In the formula, \( \alpha \) refers to the content of FeOOH and \( \gamma^- \) refers to the total amount of FeOOH, Fe\(_2\)O\(_4\), and FeO (small amounts of FeO are negligible). The \( \alpha/\gamma^- \) values for the three specimen steels can be obtained by semi-quantitative XRD analysis. As can be seen from the table 3, HRB400E-3 has the highest value, indicating that HRB400E-3 has the highest rust layer stability, i.e. the rust layer has the strongest shielding effect, indicating that the generated \( \alpha^- \) FeOOH and Fe\(_2\)O\(_4\) inhibit the corrosion rate of the reinforcement.

The specific corrosion process is as follows:

In the initial phase of the alternating wet and dry test, HSO\(_3^-\) in NaHSO\(_3\) solution and water react on the surface of the specimen and the electrochemical corrosion process begins according to the following reaction:

\[
\text{HSO}_3^- \rightarrow \text{H}^+ + \text{SO}_3^{2-} \\
\text{HSO}_3^- + \frac{1}{2}\text{O}_2 \rightarrow \text{H}^+ + \text{SO}_4^{2-}
\]

The H\(^+\) generated will react with FeO, Fe\(_2\)O\(_3\), and Fe\(_3\)O\(_4\) in the iron oxide skin, at which point the anodic dissolution reaction occurs on the surface of the iron oxide to generate Fe\(^{2+}\), which reacts as follows:

\[
\text{FeO} + 2\text{H}^+ \rightarrow \text{Fe}^{2+} + \text{H}_2\text{O} \\
\text{Fe}_2\text{O}_3 + 6\text{H}^+ + 2e^- \rightarrow 2\text{Fe}^{2+} + 3\text{H}_2\text{O} \\
\text{Fe}_3\text{O}_4 + 8\text{H}^+ + 2e^- \rightarrow 3\text{Fe}^{2+} + 4\text{H}_2\text{O}
\]

The depolarisation of oxygen in the cathodic region culminates in OH\(^-\), as shown in the following reaction [13]:

\[
\text{O}_2 + 2\text{H}_2\text{O} + 4e^- \rightarrow 4\text{OH}^-
\]

Fe\(^{2+}\) generated at the anode and OH\(^-\) generated at the cathode react rapidly to form Fe(OH)\(_2\), but Fe(OH)\(_2\) is extremely unstable and is easily oxidised to Fe(OH)\(_3\) in the presence of oxygen and water. The higher corrosion rate leads to depletion of oxygen and induces the formation of Fe\(_2\)O\(_4\). In this experiment, the pH of the sample steel surface changed under alternating wet and dry conditions, with \( \gamma^- \) FeOOH forming rapidly on the sample surface as the pH approached 7. With the continuous generation of \( \gamma^- \) FeOOH, the H\(^+\) concentration also increased, at which time the pH value decreased and Fe\(^{2+}\) adsorbed on the surface of \( \gamma^- \) FeOOH, accelerating the dissolution of \( \gamma^- \) FeOOH and its conversion into \( \alpha^- \) FeOOH and Fe\(_2\)O\(_4\) [14]. The generation of \( \alpha^- \) FeOOH and Fe\(_2\)O\(_4\) played an important role in inhibiting the corrosion process of the specimen steel.

In the atmospheric environment, the corrosion mechanism of steel bars is: in the early stage of corrosion, the corrosion products at the iron oxide surface defects are the most, and the longer the corrosion time, the outer rust layer will gradually form. By the middle of corrosion, the outer rust layer increases, the corrosion products formed at the iron oxide defects become larger, thus forming cracks at the iron oxide defects and spreading to the substrate, forming the inner rust layer. In the late stages of corrosion as the thickness of the outer rust layer increases, the bonding surface will be formed at the inner rust layer, at which point the iron oxide skin lost its protective role.

### 3.5. Simulating the electrochemical characteristics of industrial atmospheric corrosion

#### 3.5.1. Polarisation curves

Figure 7(a) shows the polarisation curves of the three specimens of steel in 0.052% NaHSO\(_3\) solution, and table 4 shows the corresponding electrochemical parameters. It can be seen that the shape of the polarisation curves of the specimens is basically the same, indicating that the presence of iron oxide only reduces the current of the cathodic and anodic reactions, and does not change the cathodic and anodic reaction mechanism. The self-corrosion potential is HRB400E-3, HRB400E-2, and HRB400E-1 in descending order, while the self-corrosion current is the opposite. The more positive the self-corrosion potential, indicating that the specimen has less corrosion potential is HRB400E-3, HRB400E-2, and HRB400E-1 in descending order, while the self-corrosion rate leads to depletion of oxygen and induces the formation of Fe\(_3\)O\(_4\). In this experiment, the pH of the sample surface changed under alternating wet and dry conditions, with small amounts of FeO are negligible.

The polarisation curve of the specimen steel in 0.052% NaHSO\(_3\) solution after 240h of simulated industrial atmospheric corrosion is shown in figure 7(b) and the electrochemical parameters are shown in table 5.

The polarisation curves at this time compared with the polarisation curves of the original sample of the test steel, the self-corrosion potential are moving in the positive direction, indicating that under the alternating wet and dry conditions, the rust layer of the test sample has a certain inhibitory effect on the NaHSO\(_3\) solution. With the self-corrosion potential moving in the positive direction, the resulting rust layer inhibited the anodic reaction and the cathodic process was accelerated. The initial corrosion products on the surface of the test steel were mainly Fe\(^{2+}\) and Fe\(^{3+}\), which were uniformly covered on the surface of the specimen steel after accumulating to a certain amount, and the corrosion current of the anode was reduced. At the same time,
because the accumulated Fe\(^{3+}\) amorphous oxide can occur cathodic reduction as well as due to its own crystallization generated γ-FeOOH is also difficult to occur cathodic reduction, in the case of its increasing number led to cathodic reduction current with the increase of dry and wet corrosion test cycle and increase. At this stage, the formation of α-FeOOH is also mainly from the crystallization reaction of Fe\(^{2+}\) and Fe\(^{3+}\) oxides. During the alternating wet and dry corrosion tests, when the γ-FeOOH on the surface accumulates to a certain amount, a crystallographic transformation can occur to generate α-FeOOH. This increases the reaction pathway for α-FeOOH formation on the surface and also accelerates the formation of α-FeOOH \[15\]. From the surface morphology of the test steel, it can be found that, with the increase in time of alternating wet and dry, the anodic polarisation behaviour is inhibited by the hindering effect of the rust layer on the ions due to the gradual increase in the corrosion product α-FeOOH accumulated on the surface and the stabilisation of its nature \[16\], and as the corrosion proceeds, the weight gain of the specimen shows a trend of relative decrease due to the gradual increase in α-FeOOH. The corrosion currents and self-corrosion potentials shown in table 5 show that the three types of steel rust protection: HRB400E-3 > HRB400E-2 > HRB400E-1, which is consistent with the weight gain results.

### 3.5.2. AC impedance mapping

Using ZView electrochemical analysis software to fit the electrochemical impedance spectrum of the specimens after 240h of alternating wet and dry corrosion tests, the fitted equivalent circuit is shown in figure 8 (where Rs is the solution resistance; CPE1 is the double layer capacitance formed by the rust layer and the electrolyte; CPE2 is the double layer capacitance formed by the substrate and the infiltrated electrolyte; Rt is the rust layer resistance; Rp is the charge transfer resistance of the substrate dissolution reaction transfer resistance. Rs+Rt is used as an indicator to assess the corrosion performance of the specimens, with larger values indicating greater resistance to corrosion of the steel bars \[17\], the fitted parameters are shown in table 6.

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**Table 4.** Electrochemical parameters of the original sample of specimen steel.

| Sample   | Self-corrosive potential/V | Corrosion current/A | Cathodic tafel slope | Anodic tafel slope |
|----------|----------------------------|---------------------|----------------------|--------------------|
| HRB400E-1 | −0.789                    | 4.471 × 10\(^{-4}\) | −7.512               | 2.442              |
| HRB400E-2 | −0.729                    | 1.165 × 10\(^{-4}\) | −7.327               | 2.458              |
| HRB400E-3 | −0.531                    | 1.672 × 10\(^{-5}\) | −5.089               | 4.936              |

**Table 5.** Electrochemical parameters of the sample steel after corrosion for 240h.

| Sample   | Self-corrosive potential/V | Corrosion current/A | Cathodic tafel slope | Anodic tafel slope |
|----------|----------------------------|---------------------|----------------------|--------------------|
| HRB400E-1 | −0.726                    | 1.046 × 10\(^{-4}\) | −7.070               | 2.580              |
| HRB400E-2 | −0.639                    | 2.730 × 10\(^{-5}\) | −6.563               | 3.961              |
| HRB400E-3 | −0.431                    | 1.284 × 10\(^{-5}\) | −5.076               | 5.077              |

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![Figure 7. Polarization curves of specimen steel in 0.052% NaHSO\(_3\) solution: (a) Specimen steel original sample; (b) corrosion for 240h.](image-url)
Figure 9 is the AC impedance spectrum of the three specimen steels in 0.052% NaHSO₃ solution after simulating industrial atmospheric corrosion for 240 h. After 240 h of alternating wet and dry tests, the surface of the specimen has been covered with rust, and the surface has generated a rust layer that can impede the passage of ions to a certain extent. When the rust layer is generated on the surface, due to the looseness of the rust layer, two double electric layers exist between the working electrode (specimen steel) and the solution: one consisting of the substrate and the electrolyte that penetrates to the surface of the substrate, and the other consisting of the rust layer and the electrolyte. The Nyquist plot of the AC impedance spectrum of a specimen corroded for 240 h is a compressed capacitive arc at high frequencies and has significant diffusion characteristics at low frequencies, when a diffusion tail appears in the low frequency region of the complex plane impedance spectrum. The Nyquist plot of the capacitive resistance arc is extended so that the capacitive resistance arc intersects with the real impedance axis, and the coordinate value of the intersection of the extension line and the real impedance is the magnitude of Rs + Rt (solution resistance + rust layer resistance). From the fitting results in Table 6 it can be seen that since the solution resistance Rs of each electrode is almost the same under the same experimental conditions, the test steel rust layer resistance is in the following order: HRB400E-3 > HRB400E-2 > HRB400E-1. HRB400E-3 has the highest rust layer resistance, which indicates the best corrosion resistance.

The Bode diagram is a better method to assess the performance of the corrosion product layer, so a Bode diagram corresponding to the Nyquist diagram is also given in this paper. Both the Nyquist and Bode diagrams clearly show that after 240 h of simulated industrial atmospheric corrosion, the rust layer resistance of HRB400E-3 is the highest, the rust layer resistance of HRB400E-1 is the lowest and the rust layer resistance of HRB400E-2 is between the two. When microscopic observations were made above, it was found that HRB400E-1 had multiple cracks and gaps on its surface and that the iron oxide was poorly bonded to the substrate, which was the cause of its lowest resistance, while HRB400E-3 had a dense and thicker iron oxide surface and the

| Sample     | Rs/Ω | Rt/Ω | Rp/Ω | Rs+Rt/Ω |
|------------|------|------|------|---------|
| HRB400E-1  | 49.66| 897.3| 3459 | 946.96  |
| HRB400E-2  | 47.54| 1185 | 879.6| 1232.54 |
| HRB400E-3  | 52.48| 1931 | 1073 | 1983.48 |

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highest chance of the appearance of the protective $\alpha$-FeOOH, which determined that HRB400E-3 had the best corrosion resistance. Therefore, the steel bars have better corrosion resistance without controlled cooling.

4. Conclusion

(1) SEM characteristics showed that the hot rolled rebar without controlled cooling had a dense surface, a thicker iron oxide skin and a tighter bond between the iron oxide skin and the substrate, while under controlled cooling conditions, increasing the upper cooling bed temperature helped to improve the denseness of the iron oxide skin of the rebar.

(2) After the industrial atmospheric corrosion test, the corrosion products were mainly composed of $\alpha$-FeOOH, $\gamma$-FeOOH and Fe$_3$O$_4$ according to XRD analysis, and the corrosion weight gain analysis revealed that the corrosion rate of the rebar without controlled cooling after rolling was less than that of the rebar with controlled cooling.

(3) The electrochemical results show that the self-corrosion potential and rust layer resistance of the uncontrolled-cooled rebar after rolling are higher than those of the controlled-cooled rebar, showing good corrosion resistance; the self-corrosion potential of the three specimens after corrosion for 240 h is shifted in a positive direction compared with the initial specimens and the corrosion current is reduced, which indicates that the generation of $\alpha$-FeOOH and Fe$_3$O$_4$ successfully inhibits the corrosion rate of the rebar.

(4) The comprehensive study shows that the thickness and denseness of the iron oxide directly affects the corrosion resistance of the reinforcement, and that it is beneficial to enhance the corrosion resistance of the reinforcement in industry by appropriately reducing the cooling strength through water and increasing the upper cooling bed temperature.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Zhen Qian @ https://orcid.org/0000-0001-7185-4589

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