CO₂ corrosion behavior of high-strength martensitic steel for marine riser exposed to CO₂-saturated salt solution

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Abstract

CO₂ corrosion is an inevitable problem of marine riser steel for oil and gas transportation. In the following work, the corrosion behavior was revealed in terms of microstructure characterization, corrosion kinetic curves, morphology and phase composition analysis of corrosion products, distribution characteristics of elements in corrosion products and electrochemical corrosion behavior. The results showed that FeCO₃ crystals gradually evolved from dispersed clusters to complete FeCO₃ layers with the extension of exposure time, which improved the protection ability of the corrosion product layer to the substrate. With the prolongation of corrosion time, the protective effect of the corrosion product layer on the substrate was gradually enhanced. The self-corrosion potential moved to the positive direction and the self-corrosion current density decreased. As a result, the corrosion rate gradually decreased and tended to be stable. The increase of corrosion-resistant elements content made the self-corrosion current density significantly decreased. The high content of corrosion-resistant elements effectively hindered the contact of corrosive ions with the substrate and inhibited the electrochemical corrosion reaction.

1. Introduction

With the continuous and deep exploitation of offshore oil and gas resources, the service performance of marine risers is required more and more strictly. Marine riser is the key equipment for oil and gas transmission, which should have good mechanical properties, hydrogen damage resistance and corrosion resistance [1, 2]. During the service of marine riser, CO₂ corrosion often occurs in the high-strength steel of marine riser due to the existence of carbon dioxide in oil and gas [3, 4]. CO₂ corrosion can lead to corrosion failure of marine riser, resulting in safety accidents. Therefore, CO₂ corrosion of marine riser steel has become a problem that cannot be ignored.

The CO₂ corrosion behavior of steel has aroused extensive attention. Many researchers have studied the CO₂ corrosion process of carbon steel and alloy steel. Some researchers [5, 6] studied the effect of corrosion product layer on electrochemical corrosion behavior. It was found that the ferrous carbonate crystal layer promoted the polarization impedance to increase significantly and made the potential shifts positively. Some literatures [7, 8] reviewed the information relating to FeCO₃ formation in the environment of oil and gas production. It found that the solubility of FeCO₃, environmental conditions, operating conditions, the material and interfacial properties of the steel all affect the thickness, density and protective properties of the FeCO₃ layer. Some researchers studied the effect of CO₂ corrosion product layer on corrosion behavior [9–11]. It was found that the corrosion products were generally divided into inner layer and outer layer, and the inner layer had stronger protection to the substrate than the outer layer. The compact and stable corrosion product layer can prevent the contact between the corrosion solution and the steel substrate, thus inhibiting the further corrosion. The
corrosion environment had a significant effect on the CO₂ corrosion behavior of high strength steel [12–14]. The influence of temperature on the corrosion rates and passivation was investigated and the results showed that the passivation effect of API-X100 pipeline steel became worse with the increase of temperature, the charge transfer resistance decreased and the corrosion current density increased. M. Honarvar Nazari [13] found that the thickness of FeCO₃ layer increased with increasing temperature and the optimum conditions for producing a compact and thick layer of FeCO₃ was obtained at temperature of 85 °C and pH 6.5. Xu Chen [14] studied effects of temperature on the corrosion behaviour of X70 steel in CO₂-containing formation water and pointed out that X70 steel showed the uniform corrosion in the temperature range of 30 °C–90 °C and the localized corrosion at 120 °C and 150 °C. The chemical composition and microstructure of steels also have obvious influence on the corrosion behavior of carbon dioxide [15–17]. Once a large number of corrosion-resistant elements such as Cr, Ni and Mo were added to the steel, the corrosion resistance of the steel would be significantly improved. The corrosion resistance of high strength steel can be improved by uniform microstructure with small residual stress.

Although the CO₂ corrosion behavior of high strength steel has received a lot of research and achieved many important results. The CO₂ corrosion behavior of martensitic high strength steel for marine riser is still unclear. At present, the research on high strength steel for marine riser mainly focuses on mechanical properties, vortex induced vibration and fatigue failure. The research on corrosion failure behavior is relatively less. Therefore, it is necessary to use environmental exposure test or electrochemical corrosion test to study the CO₂ behavior of high strength steel for marine riser. In this work, the hanging-piece corrosion test and electrochemical corrosion test were carried out on martensitic high strength steel for marine riser. Then the CO₂ corrosion behavior of the tested steel was analyzed from the aspects of corrosion kinetics curves, phase composition, morphology and structure of corrosion products, element distribution and polarization curves. This work is of great significance to improve the safety and reliability of marine riser service.

2. Experimental procedure

2.1. Material preparation

The chemical composition of tested steels are showed in Table 1, which demonstrated that the ratio of corrosion resistant elements of two tested steels was different. Figure 1 shows the schematic diagram of rolling and heat treatment process for tested steels. The rolling and heat treatment processes of two kinds of tested steels were the same. The billets with dimensions of 100 mm × 100 mm was hot rolled to plates with thickness of 12 mm and then cold rolled to 4 mm. Finally, the cold rolled plates was treated by quenching and tempering. The quenching

| Sample  | C   | Si  | Mn  | P   | S   | Cr  | Mo  | Ni  | Ti  | Nb  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.8Cr–0.8Mo | 0.070 | 0.240 | 0.520 | <0.005 | <0.002 | 0.810 | 0.801 | 0.250 | 0.011 | 0.050 |
| 1.3Cr–1.2Mo | 0.072 | 0.230 | 0.530 | <0.007 | <0.001 | 1.280 | 1.210 | 0.220 | 0.015 | 0.049 |

Figure 1. Schematic diagram of rolling and heat treatment process.
and tempering temperatures were 940 °C and 600 °C, respectively. Both quenching holding time and tempering holding time were 30 min.

2.2. Hanging-piece corrosion test
The hanging-piece corrosion test of tested steels were carried out in a high temperature and high pressure autoclave. The corrosion environment was 3.5 wt% NaCl solution containing saturated CO₂, and the test temperature was 90 °C. The dimension of samples for corrosion test was 30 mm × 20 mm × 4 mm. A hole with a diameter of 3 mm was drilled at one end of the sample to hang the sample. The corrosion test was divided into four corrosion periods, namely 1, 4, 8 and 12 days. Five parallel samples were used in each corrosion periods to ensure the reliability of the experimental results. The samples were taken from the autoclave for characterization and analysis after corrosion for 1, 4, 8 and 12 days, respectively. After the hanging-piece corrosion test, chemical cleaning method was used to remove the corrosion products formed on the sample surface. The chemical cleaning solution was 500 ml HCl + 500 ml H₂O + 15 g C₆H₁₂N₄. According to ASTM G1-03 (2011), the corrosion rate was calculated by weight loss method, and the corrosion rate was calculated by equation (1).

![Figure 2. Microstructure of 0.8Cr-0.8Mo steel: (a) SEM image; (b), (c) TEM images; (d) EDS analysis result of acicular precipitates; (e) EDS analysis result of spherical precipitates.](image-url)
where $CR$ is the average corrosion rate ($\text{mm/a}$), $\Delta m$ is the weight loss ($\text{g}$), $S$ is the area of the sample exposed to the solution ($\text{cm}^2$), $\rho$ is the density of the tested steel ($\text{g cm}^{-3}$), and $t$ is the exposure time ($\text{h}$).

### 2.3. Electrochemical corrosion test

According to the standard ASTM G3-14, the electrochemical corrosion test of corroded samples were conducted to study the protective ability of corrosion products generated at different corrosion periods. The electrochemical measurement of tested steel was carried out on the electrochemical workstation by using three electrode system. The sample with exposure area of 1 cm$^2$ was used as the working electrode. The saturated calomel electrode (SCE) was used as the reference electrode and the platinum electrode was acted as the counter electrode. Electrochemical measurements were performed at room temperature and the electrolyte solution was a 3.5 wt% NaCl solution. The scanning range of potentiodynamic polarization curve was $-250$–$250\ \text{mV}$ (relative to open circuit potential, $E_{OC}$), and the scanning rate was $0.5\ \text{mV s}^{-1}$. After the experiment, the polarization curve was analyzed by CView software.

### 3. Results and discussion

#### 3.1. Microstructural characteristics and mechanical properties

Figure 2 shows the microstructure of 0.8Cr–0.8Mo steel, which exhibited that the microstructure after quenching and tempering was tempered martensite. As shown in figures 2(b) and (c), TEM images indicated that most of tempered martensite maintained lath shape obviously, and a lot of high density dislocations appeared in lath. In addition, many spherical precipitates (marked with the red arrow) and acicular precipitates (marked with the blue arrow) were observed in the steel. The composition of precipitated phases was analyzed by EDS. Analysis results of acicular precipitates and spherical precipitates were showed in figures 2(d) and (e), respectively. The acicular precipitates were confirmed to be cementite and the spherical precipitates were niobium carbide. Figure 3 shows that the microstructure of 1.3Cr–1.2Mo steel was also tempered martensite. TEM images showed the fine structure of microstructure, which exhibited a clear lath shape. A large number of
spherical and ellipsoidal precipitates precipitated at the boundary and in the interior of laths. These precipitates were analyzed by EDS and the results showed that these particles were composite precipitates of niobium and titanium, namely \((\text{Nb, Ti})\). During the electrochemical corrosion of high strength steel, a large number of precipitates increased the number of microcells, resulting in violent electrochemical corrosion reaction, which had a certain impact on the electrochemical reaction \([18, 19]\).

Tensile strain-stress plots of tested steels are showed in figure 4 and detailed results of mechanical properties are showed in table 2. Due to the high content of alloying elements in 1.3Cr–1.2Mo steel, the yield strength and tensile strength of 1.3Cr–1.2Mo steel was higher than 0.8Cr–0.8Mo steel, but the total elongation was less than 0.8Cr–0.8Mo steel.

### 3.2. Corrosion kinetic curves

Figure 5 shows the corrosion kinetic curves of tested steels, which showed the variation of corrosion rate and mass loss with corrosion time, respectively. The corrosion kinetic curves of the two kinds of tested steels were

**Table 2. Mechanical properties of tested steels.**

| Sample        | YS (MPa) | UTS (MPa) | TEL (%) |
|---------------|----------|-----------|---------|
| 0.8Cr–0.8Mo   | 778      | 826       | 16.8    |
| 1.3Cr–1.2Mo   | 815      | 855       | 14.3    |
similar. With the prolongation of corrosion time, the weight loss of tested steels increased rapidly at first, and then increased slowly. The change trend of corrosion rate with corrosion time was opposite to corrosion weight loss. At the initial stage of corrosion, the corrosion rate was high, which indicated that the corrosion reaction was very violent. In the later stage of corrosion, the corrosion rate was low and tended to be stable, which indicated that the corrosion reaction was inhibited and the reaction was weak. Compared with 0.8Cr–0.8Mo steel, the
weight loss and corrosion rate of 1.3Cr–1.2Mo steel were relatively low due to the fact that more corrosion-resistant elements were added to the steel [20].

3.3. Phase composition of corrosion products
Figure 6 presents XRD patterns of corrosion products at different corrosion time. The XRD patterns of corrosion products formed on the surface of two tested steels were very similar, only the intensity of diffraction peaks was different. The phase analysis results of corrosion products showed that only ferrous carbonate (FeCO₃) was produced in the surface of tested steels. It indicated that the type of corrosion products mainly depended on the corrosion environment, and had nothing to do with the difference of composition for tested steels. Two different diffraction peaks of Fe and FeCO₃ were found on the XRD patterns, which indicated that the phases of the substrate and corrosion products were detected at the same time.

3.4. Morphology and structure of corrosion products
Figure 7 shows the surface morphology of corrosion products for 0.8Cr–0.8Mo steel at different corrosion time. After one day of corrosion, a large number of coarse FeCO₃ crystal particles was formed on the surface of the sample substrate. The FeCO₃ particles distributed in clusters on the surface of the substrate, and the complete FeCO₃ crystal layer was not formed, resulting in some substrate directly exposed to the corrosion environment. As shown in figure 7(b), a complete corrosion layer of FeCO₃ crystal layer had been formed on the substrate surface after 4 days. In addition, many new small-sized FeCO₃ crystals (marked with a red circle) generated on the surface of FeCO₃ crystal layer, which indicated that a large number of FeCO₃ crystals nucleated and grew on the surface of corrosion product layer. With the increase of exposure time in corrosive environment, more and more FeCO₃ particles were formed, thus forming a stable and dense corrosion product layer on the surface of the substrate. Figure 7(d) shows that many small pits (marked with a red arrow) appeared on the surface of FeCO₃ crystal particles. This phenomenon indicated that a small amount of FeCO₃ redissolved after a long time of corrosion immersion.

Figure 8. Surface morphology of corrosion products for 1.3Cr-1.2Mo steel at different corrosion time: (a) 1 day; (b) 4 days; (c) 8 days; (d) 12 days.
Figure 8 presents the surface morphology of corrosion products for 1.3Cr–1.2Mo steel at different corrosion time. The evolution of corrosion products morphology with corrosion time was similar to the 0.8Cr–0.8Mo steel. Figure 8(a) showed that the amount of FeCO₃ crystal particles formed on the substrate surface was obviously less than 0.8Cr–0.8Mo steel with the same corrosion time. With the extension of corrosion time, the distribution of FeCO₃ particles became compact and dense, and new FeCO₃ crystal particles (marked with red circles) were also generated continuously. Compared with 0.8Cr–0.8Mo steel, figure 8(d) showed that the surface layer of corrosion products for 1.3Cr–1.2Mo steel had lower porosity after corrosion for 12 days.

Cross-sectional morphology of corrosion products for 0.8Cr–0.8Mo steel at different corrosion time are showed in figure 9. The results show that the corrosion products layer appeared obvious delamination phenomenon at different corrosion time. Compared with the initial corrosion stage, the corrosion product layer at the later stage had fewer pores and cracks, and the compactness of corrosion products was obviously improved. With the extension of corrosion time, the corrosion depth gradually deepened, and the thickness of corrosion product layer became thicker. The increase of the compactness and thickness of the corrosion product layer was beneficial to hinder the diffusion and penetration of corrosive medium, thus inhibiting the corrosion reaction [21–23].

Figure 10 shows the cross-sectional morphology of corrosion products for 1.3Cr–1.2Mo steel at different corrosion time. The corrosion products near the substrate were seriously broken off, which was caused by the product layer falling off during the sample preparation for EPMA. Compared with 0.8Cr–0.8Mo steel, 1.3Cr–1.2Mo steel exhibited a more compact corrosion product layer, the corrosion product layer was relatively complete, and the pores and cracks were less. Therefore, the corrosion product formed on the surface of 1.3Cr–1.2Mo steel was more stable and compact, which had a stronger protective effect on the substrate. Compared with martensitic stainless steel, because the content of corrosion-resistant elements was less, a thin and dense passive film was not formed on the surface of the tested steel, but a thick corrosion product layer was formed. For conventional high carbon martensitic steel, due to its little corrosion-resistant elements, a thick and loose corrosion product layer would form on the substrate in the process of corrosion. Therefore, the corrosion product layer formed on the surface of the tested steel was more compact than conventional high carbon martensitic steel, which had a stronger protective effect on the substrate.
3.5. Distribution characteristics of elements in corrosion products

Figure 11 presents the elemental distribution on the cross-section of corrosion products for the 0.8Cr–0.8Mo steel after corrosion for 12 days. Figure 11 shows that corrosion resistant elements Cr, Mo and Ni were significantly enriched in the corrosion product layer. The Ni element was distributed in a strip shape at the boundary between the inner and outer corrosion products layer. Compared with Ni, the distribution of Cr and Mo was more uniform and had a higher concentration in the inner layer.
Mo was more uniform. Element Cr and Mo were enriched in the inner layer of corrosion products, especially near the substrate. The enrichment of corrosion-resistant elements effectively improved the protective ability of corrosion products layer to the substrate [24–26].

Figure 12 shows elemental distribution on the cross-section of corrosion products for 1.3Cr–1.2Mo steel after corrosion for 12 days. Similar to the 0.8Cr–0.8Mo steel, the corrosion resistant elements Cr, Mo and Ni were also significantly enriched in the corrosion product layer. Different from the 0.8Cr–0.8Mo steel, the enrichment area of corrosion-resistant elements was larger and the distribution was more uniform, which indicated that the corrosion-resistant elements are more abundant.

Schematic diagram of the CO₂ corrosion process is showed in figure 13. The corrosion process of high strength steel in CO₂ salt solution is a process of electrochemical reaction. The anodic reaction is mainly the dissolution process of Fe, and the cathodic reaction is mainly the formation of carbonate ion and bicarbonate ion. The reactions of anode and cathode are as follows [27–29]:

Figure 12. Elemental distribution on the cross-section of corrosion products for 1.3Cr–1.2Mo steel after corrosion for 12 days.

Figure 13. Schematic diagram of CO₂ corrosion process: (a) 0.8Cr–0.8Mo steel, 1 day; (b) 0.8Cr–0.8Mo steel, 12 days; (c) 1.3Cr–1.2Mo steel, 1 day; (d) 1.3Cr–1.2Mo steel, 12 days.
Anodic reaction:

\[
\text{Fe} = \text{Fe}^{2+} + 2e \quad (2)
\]
\[
\text{Fe} + \text{HCO}_3^- = \text{FeCO}_3 + \text{H}^+ + 2e \quad (3)
\]
\[
\text{Fe} + \text{CO}_3^{2-} = \text{FeCO}_3 + 2e \quad (4)
\]

Cathodic reaction:

\[
\text{H}_2\text{CO}_3 + e = \text{HCO}_3^- + \text{H}_\text{ad} \quad (5)
\]
\[
\text{HCO}_3^- + e = \text{CO}_3^{2-} + \text{H}_\text{ad} \quad (6)
\]
\[
\text{HCO}_3^- + \text{H}_\text{ad} + e = \text{CO}_3^{2-} + \text{H}_2 \quad (7)
\]

According to the electrochemical reaction equation, the Fe$^{2+}$ ions generated by anodic reaction will combine with CO$_3^{2-}$, HCO$_3^-$ ions generated by cathodic reaction to form FeCO$_3$. In the early stage of corrosion (1 day), the amount of FeCO$_3$ produced by the corrosion reaction was small, the corrosion product layer was thin, and the enrichment of corrosion-resistant elements near the substrate was relatively weak. In the later stage of corrosion (12 days), after long-term electrochemical reaction, a thick and compact corrosion product layer was formed on the substrate surface, and the inner layer of corrosion product appeared a significant enrichment of corrosion resistance elements. Corrosion resistant elements enriched in the corrosion product layer near the substrate, forming a solid shielding wall, which hindered the diffusion and penetration of ions in the process of electrochemical corrosion, thus hindering the contact between corrosive medium and substrate [30]. As a result,

### Table 3. Electrochemical parameters of the 0.8Cr-0.8Mo steel obtained by Tafel fitting.

| Steel          | $E_0$ (V) | $I_0$ (A cm$^{-2}$) | $b_a$ (mV dec$^{-1}$) | $b_c$ (mV dec$^{-1}$) |
|----------------|-----------|---------------------|-----------------------|-----------------------|
| 0.8Cr-0.8Mo    | 1 day     | -0.5263             | 4.598 x 10$^{-5}$     | 204.64                | -326.88              |
|                | 4 days    | -0.4332             | 4.326 x 10$^{-5}$     | 190.03                | -119.95              |
|                | 8 days    | -0.3166             | 3.104 x 10$^{-5}$     | 182.97                | -205.42              |
|                | 12 days   | -0.2707             | 1.775 x 10$^{-5}$     | 150.94                | -197.12              |

### Table 4. Electrochemical parameters of the 1.3Cr-1.2Mo steel obtained by Tafel fitting.

| Steel          | $E_0$ (V) | $I_0$ (A cm$^{-2}$) | $b_a$ (mV dec$^{-1}$) | $b_c$ (mV dec$^{-1}$) |
|----------------|-----------|---------------------|-----------------------|-----------------------|
| 1.3Cr-1.2Mo    | 1 day     | -0.417              | 1.286 x 10$^{-5}$     | 123.06                | -470.61              |
|                | 4 days    | -0.375              | 5.677 x 10$^{-6}$     | 249.14                | -376.24              |
|                | 8 days    | -0.295              | 4.415 x 10$^{-6}$     | 236.78                | -308.64              |
|                | 12 days   | -0.251              | 3.594 x 10$^{-6}$     | 228.15                | -231.41              |
the electrochemical reaction was inhibited and the substrate was protected from further corrosion. Under the same exposure time, the enrichment degree of corrosion resistant elements in corrosion products of the 1.3Cr–1.2Mo steel was higher than the 0.8Cr–0.8Mo steel, and the enrichment area was wider, resulting in a stronger barrier effect [20]. Therefore, the corrosion products of the 1.3Cr–1.2Mo steel had a stronger protective effect on the substrate, which made the corrosion resistance of the 1.3Cr–1.2Mo steel significantly improved.

3.6. Electrochemical corrosion behavior

Figure 14 shows potentiodynamic polarization curves of the tested steels at different corrosion time. Tafel extrapolation method was used to fit the polarization curves, and the relevant parameters obtained by Tafel fitting are shown in tables 3 and 4, respectively. With the extension of corrosion time, the polarization curves of the two steels showed a similar trend, that was, the self-corrosion current density ($I_0$) gradually decreased, and the self-corrosion potential ($E_0$) tended to move towards the positive direction. The anodic Tafel slope ($b_a$) showed an increasing trend, while the cathodic Tafel slope ($b_c$) showed a decreasing trend. The change trend of polarization parameters showed that the corrosion electrochemical reaction was inhibited with the prolongation of corrosion time [31–33]. During the corrosion process, the corrosion products on the surface of the substrate gradually became thicker and denser, which inhibited the diffusion of HCO$_3^-$, CO$_3^{2-}$ and chloride ions from the solution to the substrate, thus inhibiting the electrochemical reaction and gradually reducing the corrosion rate. Compared with the 0.8Cr–0.8Mo steel, the 1.3Cr–1.2Mo steel had lower self-corrosion current density, indicating that its corrosion resistance was better than the 0.8Cr–0.8Mo steel. The increase of the content of corrosion-resistant elements made the self-corrosion current density of the substrate decrease obviously, which indicated that the corrosion-resistant elements can inhibit the electrochemical reaction of the substrate and prevent Fe from losing electrons, thus improving the corrosion resistance of the substrate [34].

4. Conclusions

In this work, CO$_2$ corrosion behavior of high-strength martensitic steel for marine riser exposed to CO$_2$-saturated salt solution was investigated by hanging-piece corrosion test and electrochemical corrosion test. The following results were obtained according to the corrosion kinetics curves and the corrosion product analysis results.

(1) The formation of corrosion product FeCO$_3$ was independent of chemical composition and microstructure, and only depended on the corrosion environment. With the extension of exposure time, FeCO$_3$ crystals gradually evolved from dispersed clusters to complete FeCO$_3$ layers, which improved the protection ability of the corrosion product layer to the substrate.

(2) With the prolongation of corrosion time, the protective effect of the corrosion product layer on the substrate was gradually enhanced. The self-corrosion potential moved to the positive direction, the self-corrosion current density decreased, and the electrochemical reaction was inhibited, so that the corrosion rate of the tested steel gradually decreased and tended to be stable.

(3) With the content of corrosion-resistant elements increasing, the electron loss tendency of the substrate decreased and the self-corrosion current density significantly decreased. In addition, the high content of corrosion-resistant elements was more effective in hindering the contact of corrosive ions with the substrate and inhibiting the electrochemical corrosion reaction.

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Data availability statement

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

[1] Désamais N et al 2007 Use of high strength steel wires for flexible pipe in low sour service conditions: impact on deep water applications Proc. of the Sixteenth (2007) Int. Offshore and Polar Engineering Conf. (Lisbon, Portugal, July 1–6, 2007) 1033–8
[2] Zhang D et al 2019 Effect of microstructure refinement on hydrogen-induced damage behavior of low alloy high strength steel for flexible riser Mater. Sci. Eng. A 765 138278
[3] Liu Z et al 2016 Corrosion behaviour of low-alloy martensite steel exposed to vapour-saturated CO2 and CO2-saturated brine conditions, Electrochim. Acta 213 842–55
[4] Zhang D et al 2019 Corrosion behavior of high-strength steel for flexible riser exposed to CO2-saturated saline solution and CO2-saturated vapor environments Acta Metall. Sin. Engl. Lett. 32 607–17
[5] Zhang G et al 2017 Corrosion behaviour of N80 carbon steel in formation water under dynamic supercritical CO2 condition Corros. Sci. 120 107–20
[6] Hua Y et al 2019 The formation of FeCO3 and Fe3O4 on carbon steel and their protective capabilities against CO2 corrosion at elevated temperature and pressure Corros. Sci. 157 392–405
[7] Barker R et al 2018 A review of iron carbonate (FeCO3) formation in the oil and gas industry Corros. Sci. 142 312–41
[8] Burkle D et al 2017 In situ SR-XRD study of FeCO3 precipitation kinetics onto carbon steel in CO2-containing environments: the influence of brine pH Electrochim. Acta 255 127–44
[9] Azuma S et al 2013 The long-term corrosion behaviour of abandoned wells under CO2 geological storage conditions: (2) experimental results for corrosion of casing steel Energy Procedia 37 5793–803
[10] Guo S et al 2016 Characterization of corrosion scale formed on 3Cr steel in CO2-saturated formation water Corros. Sci. 110 123–33
[11] Wei L et al 2015 Formation mechanism and protective property of corrosion product scale on X70 steel under supercritical CO2 environment Corros. Sci. 100 604–20
[12] Eliyan F et al 2013 Influence of temperature on the corrosion behavior of API-X100 pipeline steel in 1-bar CO2–HCO3 solutions: an electrochemical study Mater. Chem. Phys. 140 508–15
[13] Honarvar Nazari M et al 2010 The effects of temperature and pH on the characteristics of corrosion product in CO2 corrosion of grade X70 steel Mater. Design 31 3559–63
[14] Chen X et al 2021 Effects of temperature on the corrosion behaviour of X70 steel in CO2-containing formation water J. Nat. Gas Sci. Eng. 88 103815
[15] Lopez D et al 2003 The influence of microstructure and chemical composition of carbon and low alloy steels in CO2 corrosion. a state-of-the-art appraisal Mater. Design 24 561–75
[16] Shibaeva T et al 2014 The effect of microstructure and non-metallic inclusions on corrosion behavior of low carbon steel in chloride containing solutions Corros. Sci. 80 299–308
[17] Xu L et al 2016 Effect of Cr content on the corrosion performance of low-Cr alloy steel in a CO2 environment Appl. Surf. Sci. 379 39–46
[18] Liu Z et al 2016 Corrosion behaviour of low-alloy martensite steel exposed to vapour-saturated CO2 and CO2-saturated brine conditions Electrochim. Acta 213 842–55
[19] Gao M et al 2011 The growth mechanism of CO2 corrosion product films Corros. Sci. 53 557–68
[20] Liu W et al 2014 Effect of alloy element on corrosion behavior of the huge crude oil storage tank steel in seawater J. Alloy. Compd. 598 198–204
[21] Zhang X et al 2014 Influence of outer rust layers on corrosion of carbon steel and weathering steel during wet-dry cycles Corros. Sci. 82 165–72
[22] Zhen-Guang et al 2015 Corrosion behavior of low-alloy pipeline steel with 1% Cr under CO2 condition Acta Metall. Sin. (Engl. Lett.) 28 739–47
[23] Kamimura T et al 2006 Composition and protective ability of rust layer formed on weathering steel exposed to various environments Corros. Sci. 48 7299–812
[24] Zhou Y et al 2013 Effects of Cr, Ni and Cu on the corrosion behavior of low carbon microalloying steel in a Cl− containing environment J. Mater. Sci. Technol. 29 168–74
[25] Zhou Y et al 2013 Corrosion behavior of rusted 550 MPa grade offshore platform steel J. Iron. Steel Res. Int. 20 66–73
[26] Doi et al 2020 In situ investigation of CO2 corrosion in Cr-containing steels in CO2-saturated salt solution at elevated temperatures and pressures Corros. Sci. 177 108931
[27] Liu Q et al 2014 Effects of chloride content on CO2 corrosion of carbon steel in simulated oil and gas well environments Corros. Sci. 84 165–71
[28] Ogundeke G et al 1986 Some observation on the corrosion of carbon steel in sour gas environments: effects of H2S and H2S/CO2/CH4/H2 mixtures Corrosion 42 71–8
[29] Eliyan F et al 2014 On the theory of CO2 corrosion reactions—investigating their interrelation with the corrosion products and API-X100 steel microstructure Corros. Sci. 85 380–93
[30] Cui Z et al 2004 Corrosion behavior of oil tube steels under conditions of multiphase flow saturated with super-critical carbon dioxide Mater. Lett. 58 10335–40
[31] Magaly Henriquez Gonzalez, et al 2013 Electrochemical investigation of the corrosion behavior of API 5L-X65 carbon steel in carbon dioxide medium Corrosion 69 1171–9
[32] Cheng Z et al 2016 Microstructure characteristic and electrochemical corrosion behavior of surface nano-crystallization modified carbon steel J. Iron. Steel Res. Int. 23 1281–9
[33] Eliyan F et al 2012 An electrochemical investigation on the effect of the chloride content on CO2 corrosion of API-X100 steel Corros. Sci. 64 37–43
[34] Zhang G et al 2009 On the fundamentals of electrochemical corrosion of X65 steel in CO2-containing formation water in the presence of acetic acid in petroleum production Corros. Sci. 51 87–94