Corrosion Behavior of High-Strength Steel for Flexible Riser Exposed to CO₂-Saturated Saline Solution and CO₂-Saturated Vapor Environments

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Abstract

The corrosion behavior of high-strength steel used for flexible riser exposed to CO₂-saturated saline solution and CO₂-saturated vapor environments was studied through immersion experiment and electrochemical corrosion experiment. The corrosion behavior and mechanism of the tested steel were analyzed on the basis of corrosion kinetics, nature of corrosion products, corrosion product morphology, elemental distribution and polarization curves. The experimental results showed that the microstructure of the tested steel was bainitic microstructure. The corrosive activity of the tested steel exposed to CO₂-saturated vapor environment was significantly lower than that exposed to CO₂-saturated saline solution environment. On prolonging the exposure time, the corrosion rate gradually decreased, the corrosion heterogeneity increased, and the dimensions of FeCO₃ crystals gradually became small. At later stages of corrosion, the corrosion current density decreased significantly and the anodic Tafel slope increased, indicating that the corrosion process was strongly inhibited. The corrosion mechanism of low-alloy steel with bainitic microstructure was proposed based on experimental results.

Keywords Flexible riser · High-strength bainitic steel · CO₂ corrosion · Electrochemical behavior

1 Introduction

During the service process of pipeline steels used for transporting oil and gas, CO₂ corrosion is a common corrosion, and it is also a prominent problem that limits the development of oil and gas industry. When pipeline steel is used for oil and gas transportation or carbon capture and

storage (CCS, a potentially effective and promising solution to counter the threat of climate change), it inevitably contacts with CO₂ [1, 2]. CO₂ dissolves in water to form carbonic acid, causing severe corrosion to the steel substrate. It is easy to cause corrosion failure and safety accidents. Therefore, it is extremely necessary to study the CO₂ corrosion behavior of pipeline steel.

As a new type of pipeline, flexible riser is widely used for the transportation of oil and gas in ocean environment and the transportation of CO₂ in CCS technology [3, 4]. Compared with traditional steel pipe, flexible riser has the outstanding advantages of cost-effectiveness, corrosion resistance and fatigue resistance [5, 6]. The flexible riser is a multi-wall composite pipe made up of carcass layer, armor layer and polymer layer [7, 8]. The armor layer is the core layer of flexible riser, which is made of high-strength steel to reduce weight, and increase flexibility and fatigue life [9, 10]. During the service process of flexible risers, the temperature of armor layer varies typically from 20 to 130 °C [11], which depends on the operating conditions and thermal properties of the structure. Meanwhile, CO₂ or carbonic acid inevitably permeates into the armor layer,

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resulting in CO₂ corrosion of the armor material, namely high-strength steel. Therefore, it is very important to study CO₂ corrosion of high-strength steel used for flexible riser exposed to high-temperature high-pressure environment.

Previous studies confirmed that CO₂ corrosion process in high-temperature and high-pressure environment is complex and depends on many factors such as corrosion environment, chemical composition and microstructure of the tested steel, morphology and structure of corrosion products [12–14]. During the corrosion process of steel exposed to CO₂-containing saline solution, when the concentration of Fe²⁺ and CO₃²⁻ in solution exceeds the solubility product of ferrous carbonate, ferrous carbonate crystals are formed [15, 16]. Ferrous carbonate is the main corrosion product of carbon dioxide corrosion. The compact and stable corrosion product adheres to the surface of the steel substrate, which significantly inhibits the electrochemical reaction and reduces the corrosion rate. The addition of corrosion-resistant elements Cr, Ni and Mo in the steel enhances the self-corrosion potential of the substrate and reduces the corrosion activity [17, 18]. At the same time, the corrosion-resistant elements tend to accumulate in the corrosion products and promote the formation of dense corrosion products to protect the substrate [19, 20]. Chloride ions in saline solution have strong penetration ability, which can destroy the CO₂ corrosion product film and accelerate the dissolution of steel substrate [21, 22]. The temperature and pH of CO₂ corrosion environment have a significant effect on the corrosion process. Sim et al. [23] found that with the increase in temperature, the corrosion rate of X65 pipeline steel increased first and then decreased. With the decrease in pH and the increase in CO₂ partial pressure, the corrosion rate also increases significantly.

Previous studies on CO₂ corrosion behavior of pipeline steels exposed to high-temperature high-pressure environment provided many important findings. However, the CO₂ corrosion behavior of high-strength bainitic steel used for flexible riser in high-temperature and high-pressure environment is not systematically studied. The CO₂ corrosion mechanism of bainitic structure is rarely reported. Therefore, the corrosion behavior of high-strength bainitic steel used for flexible riser exposed to different high-temperature high-pressure CO₂ environments (CO₂-saturated saline solution and CO₂-saturated vapor environments) is studied in this paper. The corrosion mechanism is also revealed in terms of corrosion kinetics, corrosion product composition, corrosion products characterization, elemental distribution and electrochemical analysis.

2 Experimental

2.1 Materials

The tested steel was melted in a high-frequency vacuum induction furnace and forged into slabs. The chemical composition of the slab is listed in Table 1. The slab was homogenized at 1200 °C for 1 h and then hot-rolled to a plate with 10 mm thickness.

All corrosion specimens were cut from the hot-rolled plate. The dimensions of immersion corrosion test samples were 30 mm × 20 mm × 5 mm. Before the immersion test, the surface of all specimens were mechanically ground using a series of SiC abrasive paper up to grade 1200 grit, followed by ultrasonic cleaning with acetone and ethanol to remove dirt and grease, respectively. All specimens were weighed on an electronic balance with a precision of 0.1 mg before immersion corrosion test. After the experiment, corrosion products attached to the surface of samples were removed by immersion in a chemical solution (500 mL H₂O + 500 mL HCl + 5 g C₆H₁₂N₄). Subsequently, the samples were cleaned with ethanol and weighed again to calculate the weight loss.

2.2 Immersion Test

The immersion corrosion test was carried out in a high-temperature high-pressure autoclave. The upper part of the autoclave is CO₂-saturated vapor environment, and the lower part is the CO₂-saturated saline solution environment. As shown in Fig. 1, the tested steel was exposed to the above-mentioned two different environments, respectively. The corrosion medium is 3.5 wt% NaCl solution, and the test temperature is 90 °C. Before specimens were exposed to the autoclave, the corrosion solution was purged with nitrogen for 90 min, and then, the CO₂ was injected into the solution for 60 min to deoxygenate. The specimens were suspended in CO₂-saturated saline solution and CO₂-saturated vapor environments, respectively. During the test, CO₂ was continuously injected into the solution through the gas inlet and the pressure in the autoclave was maintained at 1.2 MPa. The specimens were successively taken out from autoclave for analysis after different immersions, 24 h, 96 h, 192 h and 288 h.

2.3 Electrochemical Measurements

The electrochemical measurements were taken in an electrochemical work station with a three-electrode cell system. The test specimens with an exposed area of 1 cm² were used as the working electrode. A saturated calomel electrode (SCE) was used as the reference electrode, and a

Table 1 Chemical composition of the tested steel (wt%)

C	Si	Mn	P	S	Cr + Mo + Ni	Nb	Ti	Fe
0.08	0.19	0.52	< 0.005	< 0.003	2.0	0.05	0.011	Balance

Fig. 1 Schematic diagram of corrosive device

platinum electrode was utilized as the counter electrode. The electrolyte solution was 3.5 wt% NaCl solution. The potentiodynamic polarization curve was measured from – 250 to 250 mV with respect to the open-circuit potential (vs. E_{oc}) at a sweep rate of 0.5 mV/s.

2.4 Material Characterization and Analysis

Microstructure morphology of the tested steel was analyzed by optical microscope (OM, OLYMPUS) and electron probe micro-analyzer (EPMA, JEOL-8530). The composition of corrosion products was detected by X-ray diffractometer (XRD, D/MAX 2400) with a CuK α target and scanning step of 0.04°. The surface morphology of corrosion products was analyzed by field emission scanning electron microscope (FE-SEM, ZEISS ULTRA 55). 3D surface morphology of the tested steel after removing corrosion products was obtained using confocal laser scanning microscope (CLSM, VL2000DX-SVF17SP & 15FTC). The cross-sectional morphology and elemental distribution of corrosion products were observed by electron probe micro-analyzer (EPMA). The polarization curve parameters were fitted using Tafel extrapolation approach by CView software.

3 Results

3.1 Microstructure

The microstructure of the tested steel is shown in Fig. 2. OM micrograph and SEM micrograph show that the microstructure is bainite. Bainite is composed of ferrite and cementite. Ferrite and cementite have different electric potential and energy, respectively. Thus, their effects on electrochemical reaction during corrosion are also different. According to the galvanic corrosion theory, two phases with different corrosion potentials in the same solution

produce contact corrosion due to the different electrochemical activity. The dissolution rate of the phase with low potential is accelerated, and the phase with low potential acts as the anode of the corrosion system. The dissolution rate of the phase with high potential is decreased simultaneously, and the phase with high potential acts as the cathode of the corrosion system. The effect of microstructure characteristics on CO₂ corrosion is discussed in detail in the following sections.

3.2 Corrosion Kinetics

The corrosion rate is obtained by measuring the mass loss of tested steels after the immersion test. The corrosion rate (CR, mm/y) was calculated using the following Eq. (1) according to standard ASTM G1-03:

$$CR = \frac{87,600 \Delta m}{t \rho S}, \quad (1)$$

where Δm is the mass loss (g), t is the immersion time (h), ρ is the density of the tested steel (7.85 g/cm³), and S is the exposed area of the specimen (cm²).

Corrosion kinetics curves of the tested steel exposed to CO₂-saturated saline solution and CO₂-saturated vapor environments are shown in Fig. 3a, b, respectively. According to the mass loss curves and corrosion rate curves, the trend in the change of corrosion kinetics of the tested steel is similar for the two environments. On prolonging the exposure time, the mass loss gradually increases, and the corrosion rate gradually decreases. Both of them tend to be stable in the end. During the initial stage of corrosion (24–96 h), mass loss increased rapidly while corrosion rate fell rapidly due to the active corrosion reaction. With the continuous corrosion of the tested steel (96–288 h), the surface of the substrate is formed with protective corrosion products, which inhibits the active corrosion reaction. Therefore, the mass loss slowly increased, and the corrosion rate gradually decreased. Figure 3 shows that the corrosion rate of the tested steel exposed to CO₂-saturated saline solution is much larger than that exposed to CO₂-saturated vapor environment. Therefore, the corrosion of the tested steel in the CO₂-saturated saline solution is more serious.

3.3 Corrosion Products Composition

The nature of corrosion products was detected by X-ray diffractometer, and the experimental result is shown in

Fig. 2 Microstructure of the tested steel: **a** OM micrograph, **b** SEM micrograph

Fig. 3 Corrosion kinetics curves of the tested steel exposed to different environments: **a** CO_2 -saturated saline solution environment; **b** CO_2 -saturated vapor environment

Fig. 4 XRD patterns of corrosion products: **a** CO_2 -saturated saline solution environment; **b** CO_2 -saturated vapor environment

Fig. 4. The XRD pattern shows that only the diffraction peak of ferrous carbonate (FeCO_3) appears on the specimen surface in CO_2 -saturated saline solution environment (Fig. 4a), indicating that the corrosion product is FeCO_3 . Figure 4b shows that the diffraction peaks of FeCO_3 and the diffraction peaks of Fe appear simultaneously on the specimen surface in CO_2 -saturated vapor environment.

This is due to the fact that the corrosion product film is thin in CO_2 -saturated vapor environment. As a result, the diffraction peaks of Fe appear in XRD patterns.

Fig. 5 Surface morphology of corrosion products exposed to CO₂-saturated saline solution environment **a, b** CO₂-saturated vapor environment **c, d**: **a** 24 h; **b** 288 h; **c** 24 h; **d** 288 h

3.4 Surface Morphologies of Corrosion Products

Surface morphology of corrosion products is shown in Fig. 5, and corrosion products (FeCO₃) present crystals of cubic shape. Figure 5a, b shows the morphological changes of corrosion products (FeCO₃) at different corrosion period exposed to CO₂-saturated saline solution. After exposure for 24 h in the corrosion solution (Fig. 5a), a large number of FeCO₃ crystals are formed on the surface of steel substrate. FeCO₃ crystals that dispersed on the surface of the substrate did not completely cover the substrate. At this time, the protective capability of corrosion products is too weak to protect the substrate from further corrosion. After a long period (Fig. 5b), the dense and compact FeCO₃ crystals completely cover the substrate surface. Compared with the initial stage of corrosion (Fig. 5a), the size of these crystals decreases significantly and no pores, cracks appear between these crystals. The corrosion products film effectively blocks the corrosive ion from penetrating into the substrate and reduces the activity of corrosion reaction, which makes the corrosion rate gradually decrease and tends to be stable [24]. When the tested steel is exposed to

the CO₂-saturated vapor environment (Fig. 5c, d), the corrosion products (FeCO₃) formed on the surface of substrate are small and dense. At the initial stage of corrosion (Fig. 5c), the substrate surface is completely covered with a dense corrosion product film, but the size of the FeCO₃ crystal is different. At the later stage of corrosion (Fig. 5d), the corrosion products are more compact and stable, and the size of FeCO₃ crystal is similar. Compared with the CO₂-saturated saline solution environment, the size of the FeCO₃ crystal generated in the CO₂-saturated vapor environment is smaller, and the contact and stacking of the crystals is more compact.

3.5 3D Surface Morphology of the Tested Steel After Removing Corrosion Products

Figure 6 shows 3D surface morphology of the tested steel after removing corrosion products. The color change in the picture represents the height variation of the specimen surface on the Z axis. The red region represents the convex part of the surface, while the blue region corresponds to the corrosion pit. At the initial stage of corrosion (Fig. 6a, c),

Fig. 6 3D surface morphologies of the tested steel after removing corrosion products exposed to CO₂-saturated saline solution environment **a**, **b** CO₂-saturated vapor environment **c**, **d**: **a** 24 h; **b** 288 h; **c** 24 h; **d** 288 h

the corrosion of the substrate surface is relatively uniform, and no large and deep corrosion pits are found. After a long time of corrosion (Fig. 6b, d), the corrosion heterogeneity on the substrate surface is remarkable, and many corrosion pits appear on the substrate surface. After exposure for 288 h, many large and deep corrosion pits appear on the surface of the substrate when the steel is exposed to the CO₂-saturated saline solution (Fig. 6b). But the tested steel surface of the CO₂-saturated vapor environment only appears some small and shallow corrosion pits (Fig. 6d). It indicates that the corrosion heterogeneity of the tested steel of the CO₂-saturated saline solution environment is more serious under the same corrosion time.

3.6 Cross-Sectional Morphologies and Elemental Distribution in Corrosion Products

Figure 7 presents cross-sectional morphology of corrosion products exposed to CO₂-saturated saline solution (Fig. 7a, b) and CO₂-saturated vapor environments (Fig. 7c, d). On increase in exposure time, the layer of corrosion products

on the substrate surface becomes thicker and denser. Thick and dense corrosion products show strong protection ability, effectively inhibit corrosion reaction and promote the decline of corrosion rate. It is found that the layer of corrosion products generated on the tested steel surface of the CO₂-saturated saline solution environment is much thicker than that of the CO₂-saturated vapor environment. It reflects that the corrosion process of the tested steel in the CO₂-saturated saline solution is more serious.

Figure 8 shows the distribution of elements in corrosion products analyzed by EPMA when the tested steel is exposed to CO₂-saturated saline solution for 288 h. The results of elemental distribution showed that Cr, Mo and Ni are significantly enriched in corrosion products. Cr accumulates in the inner corrosion products layer near the steel substrate and not appear in the outer layer of corrosion products. Mo is also mainly concentrated in the inner layer of corrosion products, and a small amount of Mo is enriched in the outer layer of corrosion products. Ni is mainly enriched in the middle part of corrosion products. The enrichment of corrosion-resistant elements (Cr, Ni, Mo) in

Fig. 7 Cross section morphology of corrosion products exposed to CO₂-saturated saline solution environment **a, b** CO₂-saturated vapor environment **c, d**: **a** 24 h; **b** 288 h; **c** 24 h; **d** 288 h

Fig. 8 Distribution of elements in corrosion products exposed to CO₂-saturated saline solution for 288 h

corrosion products enhances the compactness and stability of corrosion products, which acts as a barrier and effectively prevents the penetration of corrosive substances into the substrate [25].

Figure 9 presents the distribution of elements in corrosion products exposed to CO₂-saturated vapor environment for 288 h. The results showed that Cr is slightly enriched in the corrosion products, while Mo and Ni did not show significant enrichment in the corrosion products. It is indicated that the corrosion-resistant elements (Cr, Ni, Mo) have less influence on the corrosion products in the CO₂-saturated vapor environment.

3.7 Electrochemical Behavior

Figure 10 shows polarization curves of the tested steel exposed to CO₂-saturated saline solution environment (Fig. 10a) and CO₂-saturated vapor environment (Fig. 10b). The polarization curve parameters were fitted using Tafel extrapolation approach, and fitting results including corrosion potential (E_{corr}), corrosion current density (I_{corr}), anodic Tafel constant (b_a) and cathodic Tafel constant (b_c) are listed in Table 2. With the increase in corrosion time, the corrosion current density (I_{corr}) of the tested steel decreases and the corrosion potential (E_{corr}) presents an opposite trend in two different environments. It indicates that the electrochemical reaction becomes weaker and weaker with the extension of corrosion time, and the

corrosion rate decreases accordingly. Table 2 shows that the anodic Tafel constant of the tested steel at the later stage of corrosion significantly increases in two corrosion environments, indicating that the formation of corrosion products inhibits the anodic dissolution [26]. Thus, the corrosion current density is reduced. Compared with the corrosion current density of the tested steel in two different environments, it is found that the corrosion current density of CO₂-saturated vapor environment is smaller than that of CO₂-saturated saline solution environment at identical exposure time. It is attributed to the strong protection capability and low permeability of corrosion products formed on the substrate surface of the CO₂-saturated vapor environment.

4 Discussion

It is widely known that corrosive carbonates are formed when carbon dioxide dissolves in water. The equilibrium reactions occurring during carbon dioxide dissolution process are given by the following equations [12, 27]:

Fig. 9 Distribution of elements in corrosion products exposed to CO₂-saturated vapor environment for 288 h

Fig. 10 Polarization curves of the tested steel exposed to different environments: **a** CO₂-saturated saline solution environment; **b** CO₂-saturated vapor environment

Table 2 Polarization parameters of the tested steel exposed to different environments

Specimen	E_{corr} (mV)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	b_a (mV/dec)	b_c (mV/dec)
CO ₂ -saturated saline solution environment (h)				
24	− 478.58	62.29	140.59	− 169.19
96	− 412.99	45.07	152.13	− 255.04
192	− 387.03	24.87	160.36	− 186.23
288	− 359.38	14.84	236.12	− 224.46
CO ₂ -saturated vapor environment (h)				
24	− 395.35	37.34	183.56	− 389.89
96	− 416.57	23.51	144.40	297.39
192	− 331.30	18.49	177.75	− 255.79
288	− 359.17	14.04	303.80	− 315.86

When the tested steel is exposed to CO₂-containing solution or vapor environment, active electrochemical reaction occurs on the steel substrate surface. The related electrochemical reactions occurring during the corrosion process are the following equations [21, 28–30]:

Anodic reactions:

Cathodic reactions:

According to the above reaction equations, the Fe²⁺ ions produced by anodic reaction and the CO₃^{2−}, HCO₃[−]

produced by the cathode reaction mutually combine to form FeCO₃. The formation of FeCO₃ is explained using Eqs. (11) and (12).

During the formation process of FeCO₃, when the concentration of [Fe²⁺] and [CO₃^{2−}] exceeds the [Fe²⁺][CO₃^{2−}] solubility product (K_{sp}), the FeCO₃ crystals nucleate and precipitate on the steel substrate surface. The nucleation and growth of FeCO₃ crystals are illustrated by the following Eqs. (13–16) [22, 31].

$$I = Bn \exp\left(\frac{-16\pi r^2 \Omega_s^2}{3k^3 T^3 \sigma^2}\right), \quad (13)$$

$$R = hv \exp\left(\frac{-Q_f}{kT}\right) \sigma, \quad (14)$$

$$\sigma = \frac{Q - Q_{\text{eq}}}{Q_{\text{eq}}} = S - 1, \quad (15)$$

$$S = \frac{C_{\text{Fe}^{2+}} \cdot C_{\text{CO}_3^{2-}}}{K_{\text{sp}}}, \quad (16)$$

where I is the rate of nucleation, R is the rate of growth, and σ and S are the relative supersaturation and supersaturation of FeCO₃, respectively. B is the rate at which atoms are added to the nucleus, n is the number of molecules per volume, Ω_s is the molecule volume, r is the critical nucleus radius, k is the Boltzmann constant, T is the temperature, h is the interplanar spacing, v is the vibrational frequency of molecules, and Q_f is the activation energy. Q is the FeCO₃ concentration of the solution at any instant, Q_{eq} is the equilibrium solubility of FeCO₃, $C_{\text{Fe}^{2+}}$ is the concentration of Fe²⁺, and $C_{\text{CO}_3^{2-}}$ is the concentration of CO₃^{2−}.

At the initial stage of corrosion, the corrosion medium directly contacts with the steel substrate; thus, the

Fig. 11 Schematic diagram of CO₂ corrosion process of bainitic microstructure

electrochemical reaction is very active, resulting in the formation of high concentration of Fe^{2+} and CO_3^{2-} . However, the solubility product of FeCO_3 is low, which led to high supersaturation (σ) of FeCO_3 at this stage. According to Eqs. (13) and (14), the nucleation rate of FeCO_3 is low and the crystal growth is predominant at this time. Therefore, as is shown in Fig. 5a, c, the crystal size of FeCO_3 generated on the substrate surface is large and the porosity between the crystals is high.

With increase in corrosion time, the crystals of FeCO_3 are constantly formed and gradually covered the whole substrate surface, resulting in weakening of the electrochemical reaction and a decrease in relative supersaturation (σ). Crystal nucleation is predominant at this moment, thus forming a large number of small-size crystals. Figure 5c, d shows that the crystal size of FeCO_3 is indeed small and the porosity between the small-size crystals is low after a long period of corrosion. The corrosion product formed under this condition is more compact and protective.

In CO₂-saturated saline solution environment, a large amount of chlorine ions exist in the solution. Due to the catalysis of chloride ions, it can promote the dissolution of iron on the substrate and accelerate the corrosion process [21, 32]. The ionic radius of chloride ion is small, and its permeability is strong. It easily penetrates into corrosion products, reduces the densification of corrosion products and reduces the binding ability of corrosion products and steel substrate, leading to the decrease in the protection ability of corrosion products to the substrate and aggravating the degree of carbon dioxide corrosion. Therefore, the corrosion current density of CO₂-saturated vapor environment is smaller than that of CO₂-saturated saline solution environment at identical exposure time.

A schematic diagram of CO₂ corrosion process for low-alloy steel with bainitic microstructure is shown in Fig. 11. Bainite is a combination of ferrite and cementite. In the electrochemical reaction process, ferrite is anode and iron is dissolved in the anode. Cementite is the cathode position and remains in the process of reaction because of its low hydrogen overvoltage and metallic conduction [31, 33]. At

the initial stage of corrosion (Fig. 11a), Fe^{2+} combines with CO_3^{2-} and forms FeCO_3 crystals with large size. Large-size FeCO_3 crystals adhere to the surface of the substrate. During the later stage of corrosion (Fig. 11b), ferrite dissolves in large quantities, and residual cementite distributes on the substrate surface and in corrosion products. A large number of small FeCO_3 crystals are generated on the surface of the substrate, forming a dense corrosion product layer.

Compared to the pearlitic microstructure, the bainitic microstructure is more uniform, the carbide is finer, and the distribution is more uniform. Therefore, the corrosion rate and the corrosion inhomogeneity of bainite are much lower than those of pearlite. The corrosion products formed on the surface of bainitic microstructure are more compact and smooth, with fewer voids and cracks, and have stronger protection to the steel substrate [28, 34]. In the process of CO₂ corrosion of pearlitic microstructure, the carbide acts as the cathode and the ferrite acts as the anode. Because carbides have a lamellar shape, a larger area of the cathode region is formed. The existence of the large cathode region promotes the dissolution of anode (ferrite), accelerates the corrosion process and leads to the inhomogeneity in corrosion. In the bainitic microstructure, the fine dispersion of carbides does not promote the dissolution of ferrite [35].

5 Conclusions

In this study, CO₂ corrosion behavior of high-strength steel used for flexible riser exposed to high-temperature and high-pressure environment was studied. Experimental results show that the corrosion current density and corrosion rate of the tested steel exposed to CO₂-saturated vapor environment are significantly lower than those exposed to CO₂-saturated saline solution environment. The corrosion products in the two environments are mainly FeCO_3 , and the size of FeCO_3 decreases with the increased exposure time. During the corrosion process, the alloying elements Cr, Ni, Mo are enriched in the corrosion products, which

promote the formation of compact protective layer. With increase in exposure time, the corrosion products become thick and compact, the corrosion current density decreases significantly, and the anodic Tafel slope increases, which indicates that the anodic dissolution is strongly inhibited and the corrosion activity becomes weak.

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