Corrosion behaviour of X80 pipeline steel welded joint in H2O-saturated supercritical-CO2 environment

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Received: 22 September 2019 / Accepted: 27 November 2019 / Published: 31 December 2019

In this work, the corrosion behaviour of an X80 carbon steel welded joint in a H2O-saturated supercritical-CO2 (SC-CO2) environment (40°C, 10 MPa) was studied with SEM, XRD and electrochemical techniques. The results showed that different zones (base metal (BM), fine grain heat affected zone (FHAZ), coarse grain heat affected zone (CHAZ) and weld metal (WM)) of the X80 welded joint were corroded in the SC-CO2 environment, and FeCO3 corrosion product film is formed on the surface. However, different zones exhibited different corrosion behaviours, as related to its different microstructures. The most serious zones of corrosion appeared at coarse grain heat affected zone (CGHAZ) and fine grain heat affected zone (FGHAZ), which exhibited higher proportion of pearlite. Whereas, BM and WM with higher content of ferritic were slightly corroded.

Keywords: supercritical CO2, X80 carbon steel, welded joint, corrosion behaviour, CCS

1. INTRODUCTION

Fossil energy such as coal and oil are still the main energy source in the world today[1-3], as illustrated in Table 1. Thus, large amounts of greenhouse gas such as carbon dioxide are emitted since the current economic development is heavily dependent on fossil energy. The use of carbon capture and storage (CCS) technology can save enterprises 25% in cost[2]. Currently, CCS is the main technology to achieve reductions in carbon-intensive emissions for industries such as electricity and coal; furthermore, it is also the main choice for mitigating climate change, which is cited by major global gas emission reduction schemes[3]. To achieve the goal of limiting the temperature increase as stated from the Paris Agreement to “far below” 2°C, more than 2,000 CCS projects need to be
established by 2040, and there are only 17 CCS projects which are currently in operation (up to
2017)[2,4]. CCS has been operated in Europe, America and other regions for many years, and projects
in Asia, Africa and other countries such as China and Japan are gradually starting to be established and
operated rapidly.

Table 1. Energy composition of the United States, China and the world in 2016

<table>
<thead>
<tr>
<th>Energy composition</th>
<th>United States</th>
<th>China</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil equivalent</td>
<td>Oil equivalent</td>
<td>Oil equivalent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proportion/%</td>
<td>Proportion/%</td>
<td>Proportion/%</td>
</tr>
<tr>
<td>Oil</td>
<td>8.631</td>
<td>37.98</td>
<td>6.443</td>
</tr>
<tr>
<td>Natural gas</td>
<td>7.163</td>
<td>31.52</td>
<td>3.095</td>
</tr>
<tr>
<td>Coal</td>
<td>3.584</td>
<td>15.77</td>
<td>19.329</td>
</tr>
<tr>
<td>Nuclear energy</td>
<td>1.918</td>
<td>8.44</td>
<td>0.554</td>
</tr>
<tr>
<td>Hydropower</td>
<td>0.592</td>
<td>2.60</td>
<td>2.646</td>
</tr>
<tr>
<td>Regenerable</td>
<td>0.838</td>
<td>3.69</td>
<td>0.871</td>
</tr>
<tr>
<td>Total</td>
<td>22.726</td>
<td>100.00</td>
<td>32.938</td>
</tr>
</tbody>
</table>

In CCS, SC-CO$_2$ is the best transport phase of CO$_2$ because of its excellent transport and flow
characteristics and is widely used in actual production abroad[5]. Pipeline transportation of
supercritical CO$_2$ is considered as a more economical and reliable transportation method[6]. At
present, SC-CO$_2$ pipelines are still transported by carbon steel pipes[7]. A comparative analysis shows
that the corrosion rate rating of carbon steel materials such as X70 is high in a SC-CO$_2$ environment.
The service environment in production operations is far more complex than the experimental
environment, and there exist high risk of pipeline leakage and other failure problems. According to
statistics, the frequency of CO$_2$ leakage per 1000 km of pipeline is 0.32, which is much higher than
that of oil and gas pipelines, which is 0.17[7].

Sewed steel pipelines (straight seam steel pipes and spiral steel pipes) are often used in pipeline
construction, and also connected by welds. However, the uneven heating of a welded joint caused by
the welding thermal cycle difference will lead to more serious corrosion, which will directly lead to
safety accidents such as pipeline leakage, furthermore damage and even personal injury[8-9].
According to the reports, most leakage accidents of CO$_2$ pipelines are caused by corrosion and
welding. [10-12] At present, the research on the corrosion of welded joints mainly focuses on that
occurred in conventional environments, such as soil, aqueous solution, NaCl solution and simulated
seawater. There is little research on the corrosion of welded joints in SC-CO$_2$ environments. It is
becoming more urgent to study the corrosion of welded joints in a SC-CO$_2$ environment due to the demand in the future from transportation of SC-CO$_2$ in CCS.

In this study, an X80 pipe welded joint consisted of base metal (BM), fine grain heat affected zone (FGHAZ), coarse grain heat affected zone (CGHAZ) and weld metal (WM) was used as the research object. The corrosion of different zones of the welded joint in the SC-CO$_2$ environment containing saturated water was studied with an electrochemical techniques and SEM and XRD. The results can provide a theoretical basis and supporting data for corrosion protection at the welded joint of a SC-CO$_2$ pipeline. This is of great significance for reducing the risk of leakage in the welded joint zone of a SC-CO$_2$ pipeline and improving the safety and integrity of the pipeline.

2. EXPERIMENTAL

2.1 Material and method

The welded joint of X80 pipeline steel was selected as the test material in this research. First, the welded joint was cut into a 20-mm wide block sample along the welding direction. Then, the welded sample splices were then ground using 240, 600, 1000, 1200, 1500 and 2000 grit silicon carbide sand papers, followed by polishing with 1μm diamond suspension abrasive. Finally, the polished surface was corroded with a 4% nitric acid alcohol solution. The treated specimen is shown in Fig. 1. In addition, the boundary lines between BM and FGHAZ, FGHAZ and CGHAZ, and CGHAZ and WM could be clearly seen in Fig. 1. The sheet specimens of the WM, CGHAZ, FGHAZ and BM were obtained by a wire cutting method where the sample was cut along the boundary line at the central position of each zone. The sliced samples were identified and calibrated by an optical metallographic microscope (OLYMPUS, QX71) to ensure that the exposed surface was completely the required target zone.

Figure 1. Distribution zones of the X80 carbon steel welded joint.
The identified sheet specimen was cut into a sample with a size of 4 mm × 5 mm × 1 mm by a wire electric discharge machine. All the specimens were degreased and then rinsed with deionized water and acetone before epoxy pouring. After that, the specimens were placed in a silicone mould to make its exposed area 20 mm², and the remaining faces were sealed with epoxy resin. Five immersion test specimens were prepared for each zone, so a total of 20 test modules were required for these four zones. The specimens of each zone were sanded with abrasive paper from stage to stage (240, 600, 1200), washed with deionized water, wiped with acetone, blown with cold air, and then stored under vacuum before the immersion corrosion test.

2.2 Immersion corrosion experiment

The immersion corrosion experiment was tested in a Cortest 5 L high-pressure autoclave with a pressure of 10 MPa at 40°C for 120 h. Before the corrosion test, 1 L deionized water was added into the autoclave, then the samples were quickly placed inside and installed. Next, the autoclave was sealed, and then it was deoxygenated for 6 h by passing high purity N₂ (99.99%) through the apparatus to ensure that the SC-CO₂ was saturated with H₂O throughout the test. The timing was started after the temperature and pressure was raised to the required stable conditions for 3 h. All immersion corrosion tests were performed under static conditions. Four samples were taken from each zone for the immersion corrosion test.

2.3 Electrochemical measurements

Electrochemical workstation (CHI 660E) was applied to carried out electrochemical corrosion tests on the sample by using a three-electrode system in a 3.5% NaCl aqueous solution at 40°C under ambient pressure. The samples of the different zones before and after were corroded in SC-CO₂ were used as the working electrode (WE), a platinum electrode was the counter electrode (CE), and a Ag/AgCl electrode (3.5 M KCl) was the reference electrode (RE). The open circuit potential (OCP) measurements were taken over a 3600s duration of continuous monitoring. The polarization curve measurements were performed when the OCP fluctuation was less than 0.5 mV/min. The polarization curve measurements were performed from -250 mV to 250 mV vs. OCP with a scan rate of 0.5 mV/s.

2.4 Structural analysis of corrosion products

The organization of the structure, corrosion morphology, and corrosion product compositions of the sample were analysed by means of scanning electron microscopy (SEM) and X-ray diffractometry (XRD).
3. RESULTS

3.1 Analysis of the welded joint microstructures

An optical microscope (OM) was used to examine the microstructures of the X80 carbon steel welded joint, including the BM, FGHAZ, CGHAZ, and WZ, as shown in Fig. 2. Fig. 2a shows that the BM microstructure is composed of polygonal ferrite (PF) and quasi-polygonal ferrites (QF), and there are a large number of finely granular M-A islands diffused in the interior and along the grain boundaries of the QF.

Fig. 2b shows the metallographic microstructure of the FGHAZ. The FGHAZ structure mainly consists of pearlite (P), a small amount of QF and a very small amount of PF. Additionally, it contains a small amount of fine M-A islands. The FGHAZ is obtained by slow cooling after the temperature reaches 1000°C during the welding process.

![OM morphologies of different zones in the X80 carbon steel welded joint: (a) BM, (b) FGHAZ, (c) CGHAZ, and (d) WZ.](image)

As shown in Fig. 2c, the structure of the CGHAZ consists of P and bainite ferrite (BF), and the M-A islands are distributed at the lath of the BF. The temperature in this zone can reach above 1300°C during the welding process, which leads to its thick grain size and extremely uneven distribution. The transformation mechanism of BF is a shear and diffusion mixed phase transition [13], which has a high
dislocation density. The microalloy compound, nitride, and carbide are dissolved since the CGHAZ is heated to a higher austenitizing temperature during the welding process, resulting in an obvious increase in grain size.

As shown in Fig. 2d, the structure of the WZ consists of acicular ferrite (AF) and a very small amount of widmanstatten ferrite (WF). In addition, the WM contains a small number of M-A islands.

The acicular ferrite is an intragranular nucleated ferrite intermingled and induced by a nonmetal in the weld metal. The grain boundary is distributed at a small angle with a large dislocation density.

3.2 XRD analysis

Fig. 3 shows the XRD test results of each zone sample of the X80 carbon steel welded joint after corrosion for 120 h in a H$_2$O-saturated SC-CO$_2$ phase.

![XRD diagram](image)

**Figure 3.** XRD of the X80 carbon steel welded joint after corrosion for 120 h in a H$_2$O-saturated SC-CO$_2$ phase

The analysis results show that there are obvious Fe and FeCO$_3$ phases for corrosion scale formed on the surface of each sample after corrosion. This shows that the corrosion products of the sample in a SC-CO$_2$ environment is FeCO$_3$, which is the same as that in an ordinary CO$_2$ environment for carbon steel[14]. The intensity of Fe and FeCO$_3$ peaks on the surface of the 4 zone specimens are
different, which may be caused by the different coverage situation on the sample surfaces by FeCO$_3$ generated from the corrosion. The stronger the intensity of the FeCO$_3$ peak, the more FeCO$_3$ product formed on the surface of the specimen. As shown in Fig. 3, the strongest FeCO$_3$ peak on the sample surface of the four zones is the CGHAZ, followed by that of the FGHAZ; there is not much difference of peak intensity between the BM and the WM. This indicates that the thickest layer of FeCO$_3$ generated by corrosion on the sample surface is with the CGHAZ, the FGHAZ has the second thickest layer, and then there is just a few FeCO$_3$ formed on the BM and the WM.

### 3.3 Corrosion morphology

Fig. 4 shows the SEM surface morphology of each zone specimen of the X80 welded joint corroded in the CO$_2$ phase of the SC-CO$_2$ for 120 h. As seen from Fig. 4, flake-like FeCO$_3$ crystals were adsorbed on the surface of each sample. The coverage of FeCO$_3$ on the sample surface of different zones is different, which may be related to the microstructures difference at different zones. The FeCO$_3$ formed at BM (Fig. 4a, 4b), FGHAZ (Fig. 4c, 4d), and WM (Fig. 4g, 4h) are distributed independently in an island shape. It is not shown any thick and continuous corrosion product layer overlying their surface. FeCO$_3$ islands on the surface of the FGHAZ is larger, and the FeCO$_3$ islands in the BM and the WM are more but with smaller size. In addition, there is a flat and continuous FeCO$_3$ film on the surface of the specimen outside of the island. As shown in Figures 4e and 4f, the CGHAZ samples were most severely corroded among zones of the welded joint. The FeCO$_3$ islands was resulted from the corrosion to form a polycrystalline multilayer crystalline film, which covers almost completely on the sample surface.

However, there are a large number of pores on both the FeCO$_3$ islands on the sample surface of each zone. The surface of the polycrystalline FeCO$_3$ film becomes the potential initiation location of local corrosion.
Figure 4. SEM surface morphologies of the X80 carbon steel welded joint after corrosion in a H₂O-saturated SC-CO₂ phase for 120 h: (a and b) BM, (c and d) FGHAZ, (e and f) CGHAZ, and (g and h) WM.

3.4 Open circuit potential

Figure 5 shows the OCP variation graphs for each zone of the welded joint in a 3.5% NaCl aqueous solution before and after corrosion in SC-CO₂, along with the corrosion time. As shown in Fig. 5a and 5b, the OCP of each zone of the welded joint before and after corrosion decreased with time in the 3.5% NaCl aqueous solution, and the OCP of CGHAZ decreased the most. The OCP tends to be stable after immersion for 1 h. The OCP of CGHAZ was the lowest, followed by that of the FGHAZ, BM and WM. Thus, the FGHAZ and the BM are the second highest, and the WM has the
highest OCP. In addition, the OCP of the samples of each zone is higher than that before corrosion. It shows that the corrosion product film (FeCO₃) formed by corrosion of the X80 welded joint in an SC-CO₂ environment has a certain protective effect on the metal matrix.

**Figure 5.** Time dependence of OCP with the X80 carbon steel welded joint before (a) and after (b) SC-CO₂ corrosion in a 3.5% NaCl aqueous solution.

### 3.5 Polarization curve measurements

Fig. 6 shows the polarization curves of the four zones in the X80 carbon steel welded joint before and after SC-CO₂ corrosion in a 3.5% NaCl aqueous solution. It can be seen from Fig. 6a that the reaction of the four regions in the 3.5% NaCl aqueous solution before the SC-CO₂ corrosion were controlled under active polarization. Fig. 6b shows that passivity appeared in the zone curves after corrosion in a H₂O-saturated SC-CO₂ phase in 3.5% NaCl solution. This is because the metal samples have generated a protective FeCO₃ film on their surface after corrosion in the SC-CO₂ environment. The FeCO₃ film breaks at a higher polarization potential[15]. As the FeCO₃ generated on different zones corroded in the SC-CO₂ environment have different film microstructure, different zones show different degrees of passivation. As for different zones after corroded, the passivation of the CGHAZ and the FGHAZ is stronger than that of the BM and the WM. However, as a whole, the passivation phenomenon caused by the existence of FeCO₃ film is weak.

Table 2 shows the results of the polarization curve parameter fitting of the samples in each zone before and after SC-CO₂ corrosion in a 3.5% NaCl solution. The fitting results were obtained by a Tafel curve extrapolation. According to the corrosion current density (I_corr) in the fitting result the corrosion rate is calculated by formula (1). It can be seen from the fitting results that the corrosion potential (E_corr) of the samples in each zone after corrosion in the SC-CO₂ environment is lower than that before corrosion, and the I_corr is higher than that before corrosion. This shows that although the FeCO₃ film formed on the surface of the metal sample has a slight protective effect, there may be more holes and gaps on the surface of the film, which is a potential danger for inducing local corrosion.

\[
V(\text{mm/aa}) = \frac{0.00327 \times I_{\text{corr}} (\mu A/cm^2) \times A}{n \times D(g/cm^3)}
\]  \hspace{1cm} (1)
Where $V$ represents the corrosion rate for the metallic material, $A$ represents the atomic mass of the reactant, $n$ represents the number of electrons gained or lost, and $D$ represents the density of the metal materials. In this work, $A$ takes the atomic weight of Fe, which is 55.8. $D$ takes the ordinary carbon steel density value of 7.8 g/cm$^3$.

![Figure 6. Polarization curves of the X80 carbon steel welded joint before (a) and after (b) SC-CO$_2$ corrosion in a 3.5% NaCl aqueous solution.](image)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Zone</th>
<th>$E_{\text{corr}}$ (V vs. Ag/AgCl (3.5 M KCl))</th>
<th>$I_{\text{corr}}$ (μA/cm$^2$)</th>
<th>Corrosion rate (mm/a)</th>
<th>Corrosion level (NACE RP0775-2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before the corrosion</td>
<td>BM</td>
<td>-0.606</td>
<td>9.77</td>
<td>0.114</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>FGHAZ</td>
<td>-0.655</td>
<td>28.4</td>
<td>0.332</td>
<td>Extremely serious</td>
</tr>
<tr>
<td></td>
<td>CGHAZ</td>
<td>-0.704</td>
<td>35.5</td>
<td>0.414</td>
<td>Extremely serious</td>
</tr>
<tr>
<td></td>
<td>WM</td>
<td>-0.615</td>
<td>8.59</td>
<td>0.100</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>BM</td>
<td>-0.707</td>
<td>13.7</td>
<td>0.160</td>
<td>Serious</td>
</tr>
<tr>
<td>After the corrosion</td>
<td>FGHAZ</td>
<td>-0.750</td>
<td>50.6</td>
<td>0.592</td>
<td>Extremely serious</td>
</tr>
<tr>
<td></td>
<td>CGHAZ</td>
<td>-0.798</td>
<td>62.3</td>
<td>0.729</td>
<td>Extremely serious</td>
</tr>
<tr>
<td></td>
<td>WM</td>
<td>-0.711</td>
<td>10.6</td>
<td>0.124</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

4. DISCUSSION

The corrosion behaviour of the X80 welded joints in a SC-CO$_2$ environment is the same as that in other H$_2$O-saturated CO$_2$ phase environments[16]. When carbon steel is in a H$_2$O-saturated supercritical-CO$_2$ environment, even if the metal is in the SC-CO$_2$ phase, there is still a free water film
Precipitated by condensation on its surface[17]. The CO₂ in the environment combines with this free water to form carbonic acid, which causes corrosion on the surface of the metal base. In addition, the water film deposited on the metal surface is supersaturated because the water solubility of supercritical CO₂ is extremely small. According to a model calculation[18] of the pH value of supercritical CO₂, the pH of a H₂O-saturated SC-CO₂ environment is approximately 3. The corrosion mechanism of the X80 welded joint is the same as that of X70 and other carbon steel materials in a H₂O-saturated SC-CO₂ environment, which is an electrochemical reaction. The reaction principle is[19]:

First, CO₂ dissolves in H₂O to form carbonic acid:

\[ H_2O (l) + CO_2 (g) ⇌ H_2CO_3 (aq) \]  \hspace{1cm} (2)

Then, the carbonic acid will react in the water to cause an ionization reaction, which releases H⁺, HCO₃⁻, and CO₃²⁻:

\[ H_2CO_3 (aq) ⇌ HCO_3^- + H^+ \]  \hspace{1cm} (3)

\[ HCO_3^- ⇌ CO_3^{2-} + H^+ \]  \hspace{1cm} (4)

As the pH value of the H₂O-saturated SC-CO₂ environment is low and at approximately 3, the cathode reaction acts as a reducing agent for H⁺ produced by a secondary ionization of carbonic acid and that is how the direct hydrogen evolution reaction occurs[20].

\[ 2H^+ + e^- \rightarrow H_2 \]  \hspace{1cm} (5)

The anodic reaction is the dissolution reaction of the carbon steel in an acidic solution:

\[ Fe \rightarrow Fe^{2+} + 2e^- \]  \hspace{1cm} (6)

Therefore, the total corrosion reaction equation of carbon steel in a H₂O-saturated SC-CO₂ environment is:

\[ Fe + H_2CO_3 \rightarrow Fe^{2+} + CO_3^{2-} + H_2 \]  \hspace{1cm} (7)

In this work, during the actual corrosion of the CO₂ phase in a H₂O-saturated SC-CO₂ environment, there will be extremely uneven condensed water deposited on the surface of the metal. The condensed water will first adsorb to the metal surface in tiny droplets to cause electrochemical corrosion. Meanwhile, the metal at the droplet is used as a cathode, and the nearby metal is used as an anode, so the FeCO₃ formed by the reaction is adsorbed around the reaction site. These FeCO₃ grains will provide a nucleation site for the FeCO₃ generated by subsequent reactions. In addition, the FeCO₃ generated by subsequent corrosion will precipitate and grow along this location. However, there are large holes and gaps among these FeCO₃ grains (as shown in Fig. 3), and the electrolyte in the corrosive environment can enter into the pores and reach the metal surface. The anode zone is only a small metal matrix in the pores and is much smaller than that of the cathode zone, which results in a sharp increase of the corrosion rate and causes severe corrosion unevenly distributed in local regions.

Due to the non-uniformity of the microstructure of the metal material, accelerated corrosion dissolution at a local location is caused[21-23]. Kobayashi's research found that the corrosion-resistant area of the HAZ in the pipeline welded joint is much lower than the tube BM [24]. Also, the HAZ acts as an anode region for galvanic corrosion, and the corrosion rate will corrode faster than the weld zone and the substrate zone[25]. In this work, the corrosion specimens of the different zones are quite different in the SC-CO₂ environment, which is related to the difference in metallographic structure of each zone[26]. According to the research conclusions of Wang et al. [27], a Kelvin potential was measured in the X80 simulated welded joint region. It was found that a structure composed entirely of
pearlite had the lowest Kelvin potential (about -0.78 V to -0.49 V), which slightly increased when ferrite was doped in the structure (about -0.49 V to -0.42 V). Moreover, as shown in formula (8), the composition of ferrite has the highest Kelvin potential (about -0.42 V to -0.27 V). Thus, the self-corrosion potential \( E_{\text{corr}} \) of the material is proportional to the Kelvin potential in a corrosive environment[28-29].

This indicates that in the structure of the X80 welded joint, the corrosion potential of ferrite is higher than that of pearlite, and the doping of ferrite in pearlite can enhance the corrosion potential of the material.

\[
E_{\text{corr}} = (\frac{W_{\text{ref}}}{F} - \frac{E_{\text{ref}}}{2}) + \varphi
\]  
(8)

where \( W_{\text{ref}} \) represents work function for the reference electrode, \( \frac{E_{\text{ref}}}{2} \) represents the half-cell potential of the reference electrode, \( F \) represents the Faraday constant, and \( \varphi \) represents the Kelvin potential.

Comparing the various zone structures of the X80 welded joint in this test, it is found that the CGHAZ is dominated by a pearlite and bainitic ferrite, which contain a coarse grain. The corrosion potential of the pearlite is lower than that of the other structures in the corrosive environment. In addition, the coarse grains further reduce the corrosion potential of the CGHAZ, which makes it have a large corrosive tendency. The FGHAZ is mainly composed of P with a low corrosion potential and also contains QF and PF. The corrosion potential of the FGHAZ can be appropriately increased as these two kinds of ferrite are doped into the pearlite, which also lowers the corrosion tendency. The BM is mainly composed of ferrite structures such as PF and QF, and the WM is mainly AF.

As both of these regions are mainly composed of ferrite structure with higher corrosion potential, and with no pearlite of lower corrosion potential among them, the corrosion potentials of the BM and the WM are higher than those of the FGHAZ and CGHAZ, and their corrosion tendencies are the least of all.

5. CONCLUSIONS

(1) In an X80 welded joint, the BM is composed of polygonal ferrite (PF) and quasi-polygonal ferrite (QF), and there are a large number of fine granular M-A islands distributed in the interior and along the grain boundaries of the QF. The FGHAZ structure consists of pearlite (P), a small amount of QF and PF, and contains a small number of fine M-A islands. The CGHAZ is composed of P and bainitic ferrite (BF), and a small number of M-A islands are distributed at the lath of the BF. In addition, the crystal grains of the CGHAZ are coarse. The WM structure consists of acicular ferrite (AF) and a very small amount of widmanstatten ferrite (WF), which also contains a small number of M-A islands.

(2) There is a big difference in the corrosion conditions among the various regions of the X80 welded joint in the H\(_2\)O-saturated SC-CO\(_2\) environment (40°C, 10 MPa). The most severely corroded zone is the CGHAZ, followed by that of the FGHAZ, and then the WM and BM.
(3) The microstructure differences of the different zones in the X80 welded joint lead to differences in the corrosion degree. More serious corrosion occurred in the SC-CO$_2$ environment when pearlite accounted for the majority phase of the X80 carbon steel (such as that of the CGHAZ). Less corrosion happened as the ferrite content of the X80 carbon steel increased (such as that of the FGHAZ). The corrosion in the SC-CO$_2$ environment was relatively slight when the ferrite accounts for the majority phase in the X80 carbon steel (such as that of the BM and WM).

ACKNOWLEDGEMENTS
The authors would like to acknowledge the financial support from the Research Foundation of Chongqing University of Science & Technology (CK2016Z09), the Natural Science Foundation Project of CQ CSTC (cstc2019jcyj-msxmX0181 & cstc2019jcyj-msxmX0188) and the Transfer Program of Institutions of Higher Education in Chongqing (KJZH17136).

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