Application of JFE-UHP™-15CR-125 and JFE-UHP™-17CR-110 to Enhanced Oil Recovery (Water Injection/Water Flooding)

KAMO Yuichi

Abstract:

Water Injection in which water, such as seawater, is injected into reservoir of oil has been conducted in order to enhance the recovery rate. Corrosion resistance against seawater is necessary for tubing materials used for seawater injection. JFE Steel has commercialized JFE-UHP™-15CR-125 and JFE-UHP™-17CR-110 as highly corrosion-resistant OCTG (Oil Country Tubular Goods) materials. Corrosion resistance of these materials was evaluated in the conditions simulating water injection. Most of the test were conducted at the location under higher temperature and higher amount of dissolved oxygen conditions which are possible operation conditions of water injection, because stainless steels have higher susceptibility to localized corrosion in the conditions. The result shows that corrosion rate of the materials was less than 0.006 mmly and the materials were free from localized corrosion in crevice-corrosion specimens, clarifying that JFE-UHP™-15CR-125 and JFE-UHP™-17CR-110 can be used for tubing materials for water injection.

1. Introduction

Crude oil is extracted by inserting steel tubes into geological formations (reservoirs). In the initial stages of production, crude oil can be extracted by the high pressure within the reservoir. However, as production progresses, the reservoir pressure declines and production ceases, despite some crude oil still remaining in the formation. Methods for extracting this residual crude oil are referred to as Enhanced Oil Recovery (EOR) techniques. One such method is Water Injection, also known as Water Flooding.

In the Water Injection method, water is injected into the reservoir to maintain the pressure, which helps to enhance the recovery rate of petroleum from the formation[1]. Since seawater is predominantly used for this injection[1], the steel pipes used to inject the water (injection pipes) must have high seawater corrosion resistance.

JFE Steel has commercialized highly-corrosion-resistant oil country tubular goods (OCTGs), specifically JFE-UHP™-15CR-125[2] (15CR steel) and JFE-UHP™-17CR-110[3,4] (17CR steel). This paper presents the results of an evaluation of the corrosion resistance of these steels in seawater simulating Water Injection conditions.

2. Environments in Water Injection

Figure 1 illustrates the operational environments of the Water Injection method, classified by the temperature and dissolved oxygen concentration in the seawater. The seawater used in Water Injection is usually deoxidized[5] because stainless steel is at a higher risk of localized corrosion in seawater with high dissolved oxygen concentrations[6]. Under the usual injection conditions, the inner surface temperature of the injection pipes remains below 40°C, and the dissolved oxygen concentration in the seawater is controlled to be below 20 ppb (Case (1) in Fig. 1). However, there is a possibility that seawater with a high dissolved oxygen concentration could be injected due to failure of the deoxygenation equipment during operation, increasing the risk of localized corrosion of the stainless steel. This risk scenario corresponds to Case (2) in Fig. 1. Similarly, if seawater injection stops due to failure of the injection equipment, the seawater inside the steel pipes can be heated by geothermal heat, causing the temperature of the seawater to rise. This scenario corresponds to Case (3) in Fig. 1. Generally, the risk of localized corrosion of stainless steel increases with rising temperature[7,8], which means the risk is higher in Case (3) than in Case (1). Case (4) represents the conditions where seawater with a high dissolved oxygen concentra-

† Originally published in *JFE GIHO* No. 54 (Aug. 2024), p. 18−22

Dr. Eng., Senior Researcher, Tubular Products & Casting Research Dept., Steel Res. Lab., JFE Steel

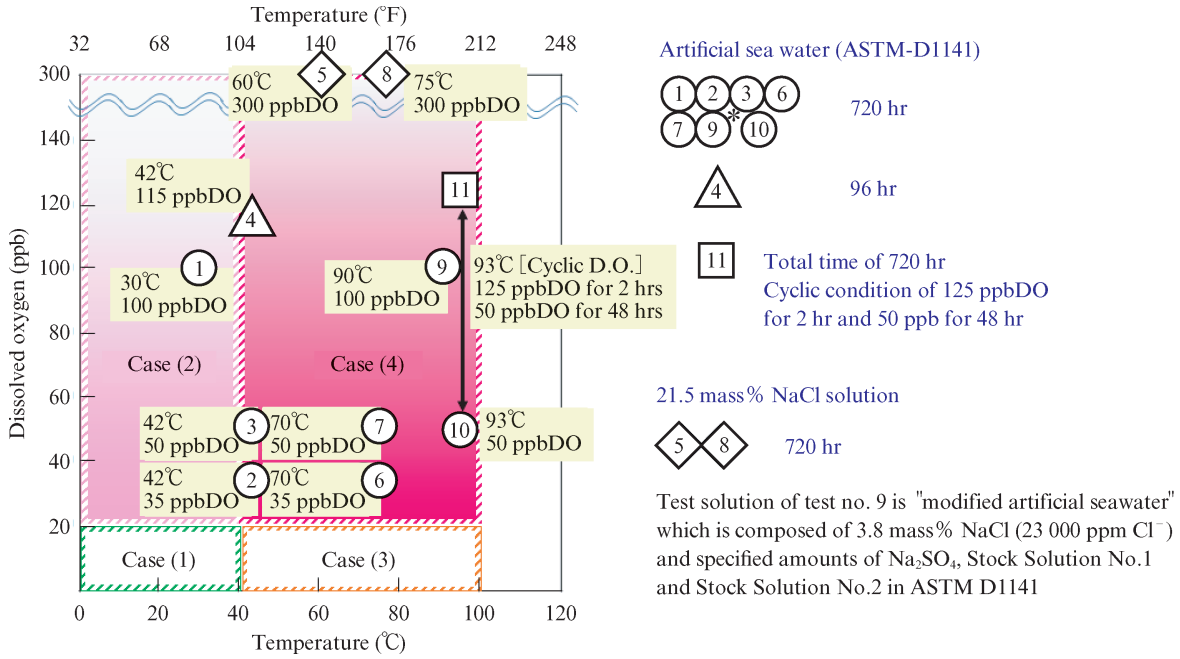


Fig. 1 Operation condition of water injection and corrosion test conditions

tion is injected, and injection is subsequently stopped. This scenario, characterized by both a high dissolved oxygen concentration and high temperature, poses the highest risk of localized corrosion in stainless steel during actual operation. In this study, the corrosion resistance evaluation focused primarily on the conditions of Case (4).

3. Evaluation of corrosion resistance in conditions simulating Water Injection

3.1 Experimental

3.1.1 Material

Table 1 shows the materials used for the evaluation, their representative compositions, and the Pitting Resistance Equivalent Number (PREN), which is an index calculated from the composition to indicate the resistance of the steel to localized corrosion. For comparison, the test materials also included L80–13CR steel (13CR steel), which is a martensitic 13Cr steel, and 22CR steel and 25CR steel, which are ferritic-austenitic duplex steels, in addition to the above-mentioned 15CR steel and 17CR steel. Seamless steel pipes manufactured by commercial mills were used as the test specimens.

3.1.2 Test specimens

Chapter 2 mentioned that localized corrosion is a significant corrosion risk for stainless steel in Water Injection environments. In actual wells, the steel tubes are connected using mechanical threaded joints, which create crevice structures at the threaded connections. These crevices are particularly prone to localized corrosion in stainless steel. Therefore, in this study, test specimens with crevice structures were subjected to corrosion testing.

The dimensions of the test specimens were 50 mm in length, 25 mm in width, and 3 mm in thickness. The

Table 1 Material information, and its chemical composition and values of PREN

Sample ID	UNS No	Yield Strength grade	C	Cr	Ni	Mo	Others	PREN
L80-13CR	S42000	80 ksi	0.2	13	-	-	-	13.0*
JFE-UHP™-15CR-125	S42625	125 ksi	0.03	15	6	3	1Cu-added	24.9*
JFE-UHP™-17CR-110	S42825	110 ksi	0.03	17	4.5	3	1Cu and 1W-added	28.6*
22CR-125	S31803	125 ksi	0.02	22	5	3	0.2N-added, Cold-drawn	35.1
25CR-125	S32760	125 ksi	0.02	25	6	3	0.6Cu-0.5W-0.3N, Cold-drawn	40.5

PREN = Cr + 3.3 × (Mo + 0.5 × W) + 16 × N

* N concentration was regarded as zero for calculation of PREN value of L80-13CR, 15CR-125 and 17CR-110.

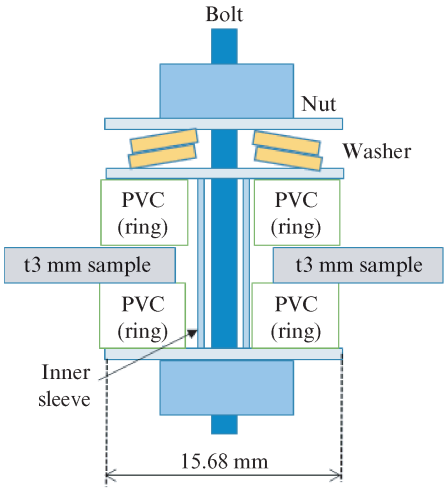


Fig. 2 Setup of crevice corrosion specimen

specimens were cut from the steel tubes. **Figure 2** shows the configuration of the crevice corrosion test specimens. Nonconductive PVC (polyvinyl chloride) rings were placed on both sides of the test specimens and pressed against the specimen surface by bolting from the outside, thereby creating crevices between the specimen surface and the PVC rings.

3.1.3 Corrosion test

Figure 1 also shows the corrosion test conditions used in this study, indicated by numerical symbols. The corrosion tests under conditions 1 to 10 were conducted for up to 720 hours. Under test condition 11, the dissolved oxygen concentration was alternated between 50 ppb for 48 hours and 125 ppb for 2 hours. This cycle was repeated until the testing time reaching 720 hours. This condition simulates the temporary increases in the dissolved oxygen concentration that occur during actual operation.

Figure 3 is a schematic diagram of the corrosion test apparatus. The test temperature was controlled by placing a glass container inside a temperature-controlled water bath. The temperature was monitored with a thermometer to ensure that the intended temperature was maintained throughout the test. The intended dissolved oxygen concentration was achieved by determining the appropriate N_2-O_2 gas mixture composition through thermodynamic equilibrium calculations. A membrane-type dissolved oxygen sensor was used to confirm that the desired dissolved oxygen concentration was maintained. After the specified corrosion period, the test specimens were examined for the presence of localized (crevice) corrosion after removing corrosion products. Specimens without localized corrosion were judged as "pass," while those with localized corrosion were judged as "fail." The average corrosion rate was also calculated based on the weight difference before and after the test (weight loss method).

3.1.4 Control of dissolved oxygen concentration at temperatures above 80°C

The dissolved oxygen concentration during the experiment was measured using a dissolved oxygen sensor. However, since the membrane-type dissolved oxygen sensor correctly measured temperatures lower than 80°C, the corrosion environment for temperatures exceeding 80°C was achieved as follows. **Figure 4** shows the relationship between the temperature and dissolved oxygen concentration when using various N_2-O_2 gas mixtures. Measurements of the dissolved oxygen concentration at temperatures ranging from 25°C to 80°C indicated that the relationship between the two variables changed exponentially.

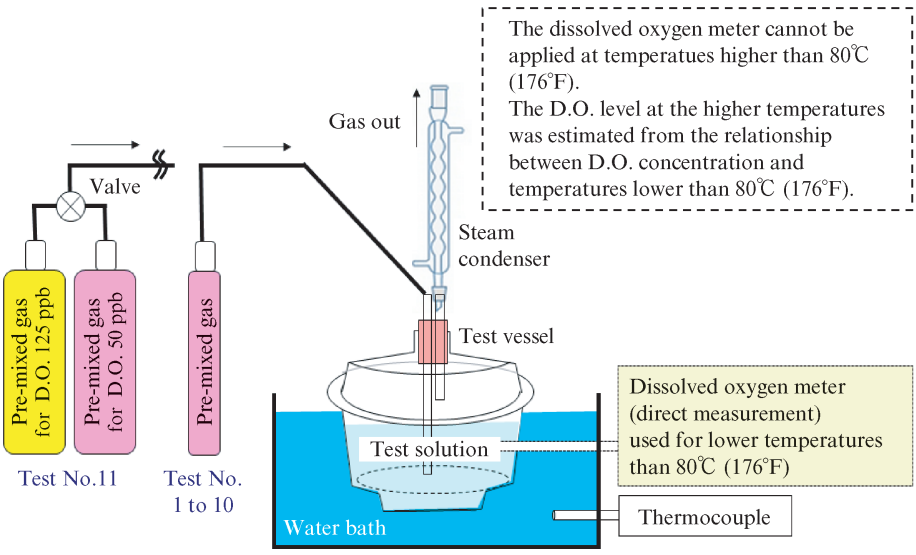


Fig. 3 Schematic illustration of apparatus of corrosion test

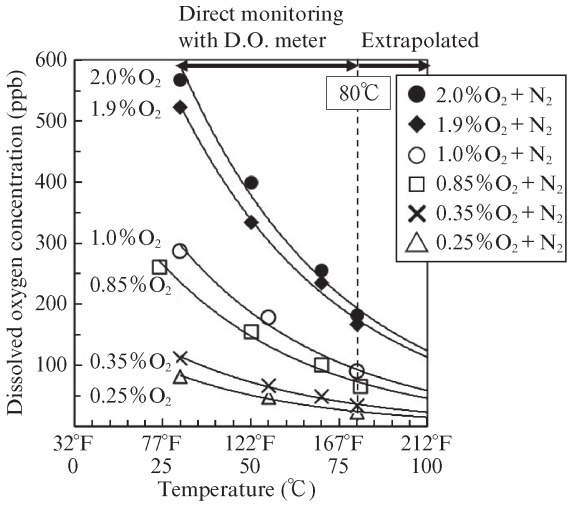


Fig. 4 Relationship between temperature and amount of dissolved oxygen for each N_2-O_2 mixture gas

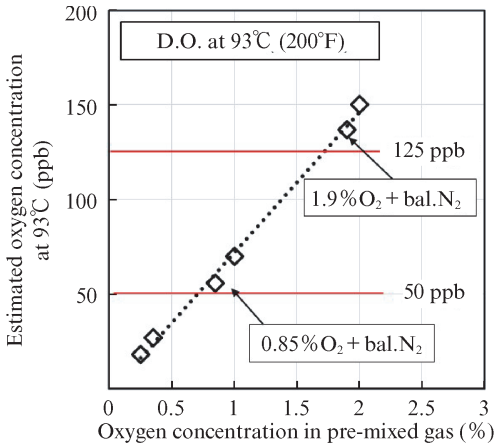


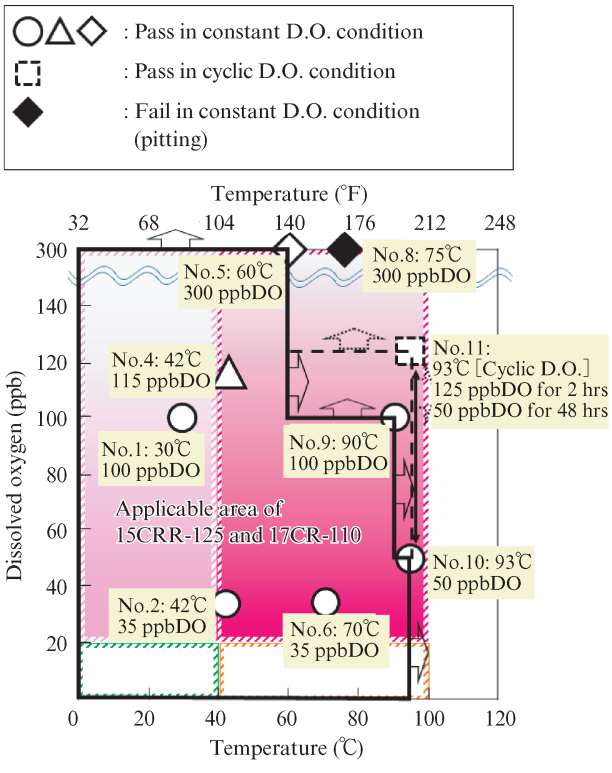
Fig. 5 Relationship between oxygen concentration in N_2-O_2 mixture gas and estimated amount of dissolved oxygen

The test condition at 93˚C is explained as an example for further explanation. Based on the fitted exponential relationships shown in Fig. 4, the dissolved oxygen concentration at 93˚C of the six mixed gases in the figure was estimated. **Figure 5** illustrates the relationship between the oxygen concentration of the N_2-O_2 gas mixture and the estimated dissolved oxygen concentration at 93˚C.

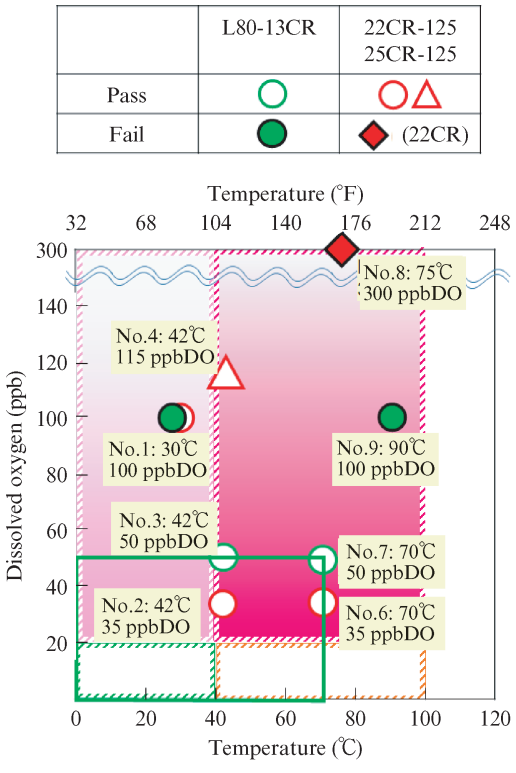
The relationship between the two variables was linear, confirming that it follows Henry's law. Based on these results, gas mixtures with 0.85% and 1.9% oxygen concentrations were used to achieve dissolved oxygen concentrations of 50 ppb and 125 ppb, respectively. The test conditions for 90˚C were determined by the same procedure.

3.2 Results and Discussion

Figure 6 shows the test results under each test condition. The open symbols indicate pass, while filled symbols indicate fail. The average corrosion rate for all steels in this evaluation was below 0.006 mm/y, which is



(a) 15CR-125 and 17CR-110



(b) L80-1CR, L80-13CR, 22CR-125 and 25CR-125

Fig. 6 Results of corrosion tests in simulated conditions of water injection

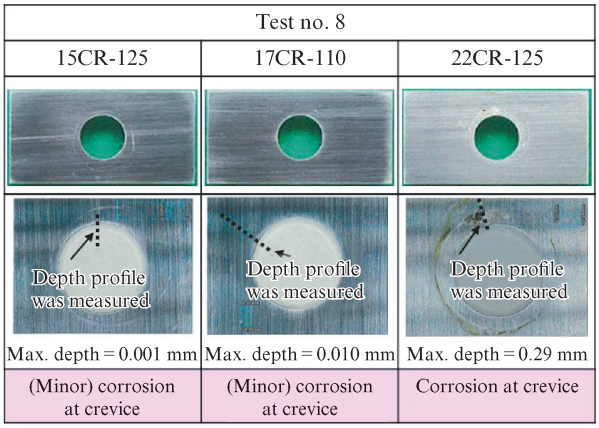


Fig. 7 Appearance of the specimens after the corrosion test in test condition of no.8

smaller than the pass/fail threshold of 0.127 mm/y (5 mil/y). Therefore, the pass/fail results in Fig. 6 correspond to the presence or absence of localized corrosion. As discussed in Chapter 2, higher dissolved oxygen concentrations and higher temperatures are expected to increase the likelihood of localized corrosion. Therefore, conditions with lower dissolved oxygen concentrations and lower temperatures than the test conditions for which pass judgments were obtained are considered to pass. The areas enclosed by bold lines in Fig. 6 indicate the applicable conditions for the 15CR steel and 17CR steel. The 15CR steel and 17CR steel are considered applicable in environments with dissolved oxygen concentrations of up to 125 ppb at 93°C in case of a temporary increase of the dissolved oxygen level.

On the other hand, localized corrosion occurred in the 15CR steel and 17CR steel under test condition 8, which involved an environment of 75°C and dissolved oxygen concentration of 300 ppb. **Figure 7** shows the appearance of the test specimens after the corrosion test. Circular marks were observed near the round hole in the center of the test specimens, indicating occurrence of crevice corrosion. The maximum depth measured with a digital microscope using the depth-of-focus method is also shown in Fig. 7. Although the depth was less than 10 μm, localized corrosion was present. As shown in Fig. 7, crevice corrosion also occurred in the 22CR steel under this condition. As indicated in Fig. 6, the 15CR steel and 17CR steel are applicable even in the Case (4) environment, which poses the highest risk of localized corrosion in Water Injection. It is generally thought that steels with a PREN value of 40 or higher are required for seawater environments under atmospheric conditions[9,10]. However, in deoxygenated seawater environments like those in Water Injection, the 15CR steel and 17CR steel are applicable even if the dissolved oxygen concentration rises to around 300 ppb.

4. Conclusion

In this paper, the corrosion resistance of JFE Steel's highly corrosion-resistant OCTG materials, JFE-UHP™-15CR-125 and JFE-UHP™-17CR-110, in Water Injection environments was evaluated, and the following results were obtained:

- The average corrosion rate calculated by the weight loss method was below 0.006 mm/y, which is smaller than the pass/fail threshold of 0.127 mm/y (5 mil/y).
- Even under high-temperature and high-dissolved oxygen concentration conditions, under which stainless steels are prone to crevice corrosion, no crevice corrosion occurred within the range of conditions tested here.
- Based on these results, it was concluded that JFE-UHP™-15CR-125 and JFE-UHP™-17CR-110 are suitable for use as injection pipes in Water Injection applications.

All figures and tables are used with permission by AMPP (©AMPP 2024, used with permission.)

References

1) Norwegian offshore directorate. https://www.sodir.no/en/facts/production/improved-oil-recovery-ior/water/ (accessed on 2024-10-22).
2) Kimura, M.; Yamazaki, Y.; Tamari, T.; Sakata, K.; Mochizuki, R. CORROSION 2005. paper no. 05108.
3) Kimura, M.; Shimamoto, K. Eurocorr 2011. p. 180.
4) Ishiguro, Y.; Suzuki, T.; Miyata, Y.; Kimura, M.; Nakahashi, T.; Sato, H.; Shimamoto, K. NACE CORROSION 2013. paper no. 2436.
5) GATE ENERGY website. https://www.gate.energy/the-brainery/fit-for-purpose-integrity-management-of-seawater-injection-systems (accessed on 2024-10-22)
6) Costa, E. M.; Dedavid, B. A.; Santos, C. A.; Lopes, N. F.; Fraccaro, C.; Pagartanidis, T.; Lovatto, L. P. Engineering Failure Analysis. 2023, vol. 144, p106955.
7) Ramana, K. V. S.; Anita, T.; Mandal, S.; Kaliappan, S.; Shaikh, H.; Sivaprasad, P. V.; Khatak, H. S. Materials & Design. 2009. vol. 30, no. 9, p. 3770–3775.
8) Ibrahim, M. A.; Abd El Rehim, S. S.; Hamza, M. M. Materials Chemistry and Physics. 2009, vol. 115, no. 1, p. 80–85.
9) Francis, R.; Hebdon, S. CORROSION 2015. paper no. 5446.
10) Standards Norway, NORSOK M-630, "Material data sheets and element data sheets for piping". p. 149 (2014).