Int. J. Electrochem. Sci., 17 **(2022)** Article Number: 220714, doi: 10.20964/2022.07.30

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Corrosion Behavior of N80 and 13Cr Steel in Presence of Imidazoline based Inhibitor in Three Different Acid Solutions

Li Li[1]*, Yukai liang*[1]*, Huaan Zheng*[1]*, Jifeng Song*[1]*, Juan Du*[2,*]*, Pingli liu*[2]

[1] CNOOC (China) Co., Ltd. Hainan Branch, Haikou, Hainan 570100, P R of China;
[2] School of Petroleum and Natural Gas Engineering, State Key Lab, Southwest Petroleum University, Chengdu, Sichuan 610500, P R of China
[*]E-mail: dujuanswpu@163.com

Received: 6 March 2022 / *Accepted:* 18 April 2022 / *Published:* 6 June 2022

In the paper, the corrosion behavior of N80 steel and 13Cr steel pipes caused by common acid liquids (5% HCl, 10% HAC, 10% CA) in oil field was analyzed. The corrosion and corrosion inhibition properties of N80 steel and 13Cr steel in acid solution with or without corrosion inhibitor were studied by electrochemical test and immersion test. The morphology of the corroded steel sheet was observed by scanning electron microscope (SEM). The results show that 13Cr Steel is seriously corroded in HCl solution, and the corrosion in organic acid HAC and CA solution is very low. The N80 steel is severely corroded in both inorganic (HCl) and organic acid (HAC and CA) solutions. The N80 steel and 13Cr steel are mainly pitted and spotted in acid solution. The inconsistency between impedance fitting and corrosion rate shows that the density and adsorption strength of the film have a great influence on the corrosion inhibition efficiency. The research results provide a theoretical basis for acidizing design of oil and gas wells. When the oil casing is Cr steel, HCl solution should be avoided in acidizing of oil and gas wells. The anti-corrosion of oil and gas wells acidification should be optimized from three aspects: steel type, acid type and corrosion inhibitor.

Keywords: N80 steel; 13Cr steel; acidizing; 5% HCl; 10% HAC; 10% CA; corrosion behavior

1. INTRODUCTION

In recent years, with the increasing demand for energy in the world, the development of oil and gas wells is also increasing [1, 2]. However, the possibility of discovering new large oil and gas fields every year is becoming smaller and smaller. In order to make effective use of limited resources, acidizing is an important stimulation measure in oil and gas field production [3, 4]. Acidizing is an effective measure to inject acid into the formation, remove the pollution near the bottom of the well, improve the formation permeability near the well, so as to improve oil and gas recovery [5]. However, in the process of acidification, the acid liquid will cause different degrees of corrosion to the tubing and casing [6].

Acidizing is a conventional and frequent stimulation treatment measure for oil and gas wells. Usually, the old wells have experienced acidizing for many times. The HCl solution is mostly used in oil and gas well acidification (low cost and wide source) [7, 8]. With the development of more high-temperature deep wells, acidizing will inevitably cause serious corrosion of pipelines and equipment [6, 9]. In order to reduce the serious corrosion caused by acidification, organic acids are more used to replace HCl solution, such as formic acid [10], acetic acid [11], citric acid, etc. The citric acid is widely used in sandstone reservoir acidification because citric acid can not only effectively replace HCl solution, but also has the ability to inhibit metal precipitation [11, 13].

The N80 and 13Cr steel are two kinds of materials widely used in oil fields [14-16]. In order to effectively protect the oil casing in the acidification process, more and more attention has been paid to the research on the corrosion behavior of oil casing in acid solution [17]. Imidazoline corrosion inhibitors are commonly used in the process of acidification. Its imidazoline ring is easily adsorbed on the metal surface as a positive reaction zone, and its ring structure has a geometric covering effect, forming a dense film on the metal surface [18]. The existing research focuses on the inhibition effect of different types of inhibitors in HCl solution [19, 20]. However, there is little discussion on the corrosion and inhibition of steel in the acid environment of petroleum industry.

In this paper, the corrosion behavior and anti-corrosion mechanism of N80 and 13Cr Steel with or without corrosion inhibitor in HCl / HAC / CA acid environment are studied by means of weight loss experiment, potentiodynamic polarization curve, electrochemical impedance spectroscopy and surface morphology analysis. The research results provide guidance for the optimization and adjustment of acid fluid system and anti-corrosion work of oil and gas wells with N80 and 13Cr Steel as oil casing.

2. EXPERIMENT

2.1 Materials

The chemical composition of N80 and 13Cr steel specimens (50 mm × 10 mm × 3 mm) used in this test is shown in Tab. 1. Hydrochloric acid (HCl), citric acid (CA), acetic acid (HAC) ethanol and acetone were obtained from Chengdu Kelon Chemical Reagent Company of China, and of analytical reagent grade. The oil based imidazoline (OI) was purchased from Chengdu acidification Petroleum Technology Development Co., Ltd.

Table 1. Chemical composition of N80 and 13Cr steel.

Steel	Alloy	C	Si	Mn	P	S	Cr	V	Al	Ni	Fe
N80	Wt%	0.34	0.22	1.55	0.18	0.013	0.14	0.13	0.02	-	Bal.
13Cr		0.02	0.3	-	-	0.5	13.8	-	-	6.2	Bal.

2.2 Corrosion experiment with the weight loss method

The fresh N80 and 13Cr steel was washed with acetone and ethyl alcohol and then dried in desiccators. Use vernier calipers to measure its length, width and height accurately, and weigh it with a balance. The weight loss experiments were performed by immersing the steel in the acid solution for different temperatures with and without inhibitors. The temperature is controlled by hh-2k constant temperature water bath. After 4 hours, the steel sheet was removed, wash it with deionized water, acetone and ethanol, dry it with desiccant and reweighed. The corrosion rate (C_R) was calculated using equation (1):

$$C_R = \frac{10^6 \Delta m}{St} \quad (1)$$

C_R ($g \cdot m^{-2} \cdot h^{-1}$) is the corrosion rate of each steel specimen, S (mm^2) is the surface area of the steel coupon, t (h) is the time of the corrosion reaction, and $\triangle m$ (g) is the weight loss of the steel specimen. The acid solution includes 1% HCl, 3% HCl, 5% HCl, 1% HAC, 5% HAC, 10% HAC, 1% CA, 5% CA and 10% CA. The weight loss test with or without 1% OI are carried out at 313K, 333K and 353K respectively.

The corrosion inhibition efficiency (IE) of the corrosion inhibitor was calculated using equation (2):

$$\mathrm{IE} = \frac{C_R - C_{Ri}}{C_R} \times 100 \quad (2)$$

C_R ($g \cdot m^{-2} \cdot h^{-1}$) and C_{Ri} ($g \cdot m^{-2} \cdot h^{-1}$) in equation (2) are the average corrosion rates with or without inhibitor, respectively.

2.3 Surface analysis of N80 and 13Cr steel

The microstructure of the N80 steel and 13Cr steel surface immersed in acid solution was assessed by scanning electron microscope (SEM, Quanta 450 produced by American FEI company), including 5% HCl, 10% HAC and 10% CA. The steel sheet was corroded in acid solution at 333K for 4 hours, then cleaned with deionized water and ethanol, and the corrosion products on the surface of the steel sheet were carefully removed with a brush.

2.4 Electrochemical measurements

Electrochemical measurements were executed with a CHI600 (Chenhua Instrument Company, Shanghai, China) electrochemical workstation. Standard silver chloride electrode was used as reference electrode, platinum electrode was used as auxiliary electrode, and the working electrode was 1 cm^2 (10 mm × 10 mm) steel.

Polarization and electrochemical impedance spectroscopy (EIS) were used to investigate the electrochemical corrosion behavior of N80 steel and 13Cr steel in acid solution at 333 K, including 5% HCl, 5% HCl + 1% OI, 10% HAC, 10% HAC + 1% OI, 10% CA, 10% CA + 1% OI. All electrochemical measurements were obtained 30 min later (or longer) in acid solution, after reaching a steady open-circuit potential. Potentiodynamic polarization curves were obtained at the scan rate of 1.0 mV·s-1 in the potential range from - 300 to + 300 mV. EIS measurements were carried out using AC signals of amplitude 5 mV peak-to-peak at the open circuit potential (Eoc) in the frequency range 10^5 Hz to 10^{-2} Hz.

3. RESULTS AND DISCUSSION

3.1 Weight loss measurements

3.1.1 Effect of different acid solution on corrosion of 13Cr / N80 stainless steel

The corrosion rates of 13Cr / N80 steel in different acid solutions at different temperatures were obtained by weight loss method and graphically showed by Fig. 1 and Fig. 2.

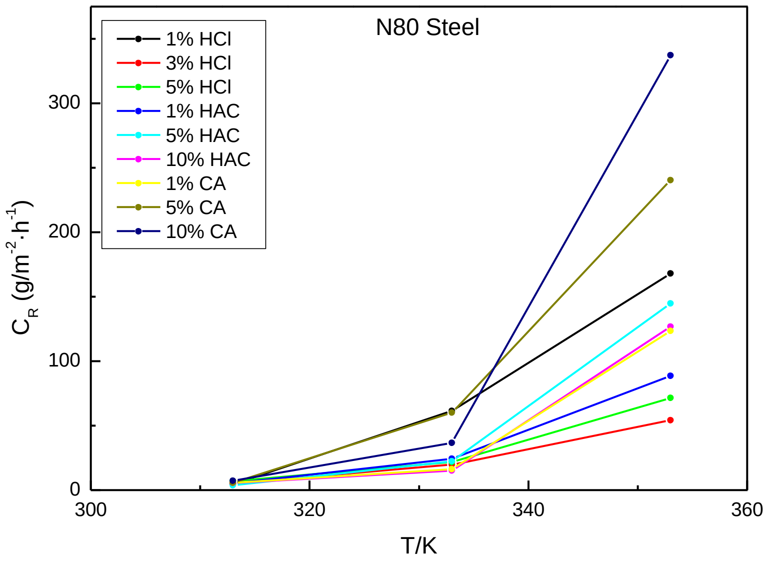


Figure 1. Corrosion rate of N80 steel in different acid solutions at different temperatures obtained by weight loss method for 4h

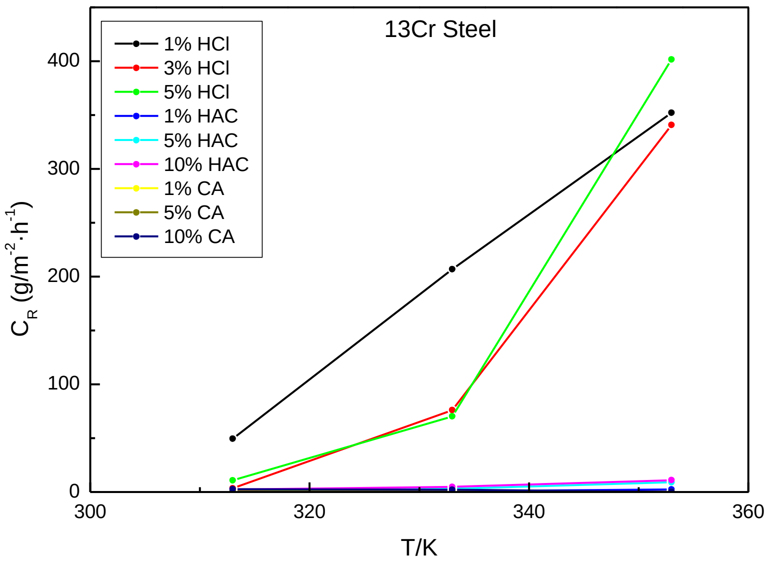


Figure 2. Corrosion rate of 13Cr steel in different acid solutions at different temperatures obtained by weight loss method for 4h

As shown in Fig. 1 and Fig. 2, the 13Cr steel is severely corroded in HCl solution because Cl^- will accelerate the corrosion of steel, which has been confirmed by previous studies [21-23]. The 13Cr steel corrosion is very low in HAC and CA solution, which may be attributed to the passive film formed on the surface of steel by organic acid [24]. The N80 steel has high corrosion rate in HCl, HAC and CA solution, especially in CA solution. The corrosion of steel increases with the increase of acid solution temperature, which is consistent with the results of previous studies [25-27]. Based on many previous studies, it is agreed that organic acids enhances the corrosion rate of mild steel by accelerating the cathodic (reduction) reaction [28-30]. The research results provide a theoretical basis for the selection of acid solution system for oil and gas well acidizing. If the oil casing is Cr steel, HCl should be avoided for oil and gas well acidizing, and it is suggested to use organic acid for acidizing operation. When acidizing oil and gas wells with N80 steel casing, corrosion inhibitor shall be selected.

3.1.2 Effect of inhibitor on corrosion rate

There are many effective measurements to reduce and control corrosion of steel caused by acid solution. Among which, adding corrosion inhibitor is the simplest, effective and commonly used measure in the oil industry [31-34]. In this paper, the corrosion inhibitor was used to inhibit the corrosion of acid solution on 13Cr / N80 stainless steel. The corrosion rate of 13Cr / N80 stainless steel in different acid solution at 353K was obtained by weight loss method and summarized in Tab. 2.

Table 2. Corrosion rate of 13Cr/N80 stainless steel and inhibition efficiency in different solution at 333 K obtained by weight loss method for 4h

material	Solution	C_R ($g/m^{-2}\cdot h^{-1}$)	IE %
N80	5% HCl	71.57	92.1
	5% HCl + 1% OI	5.643	
	10% HAC	126.6	96.3
	10% HAC + 1% OI	4.67	
	10% CA	337.3	92.3
	10% CA + 1% OI	25.94	
13Cr	5% HCl	401.6	92.8
	5% HCl + 1% OI	28.73	
	10% HAC	11.01	90.3
	10% HAC + 1% OI	1.066	
	10% CA	0.1842	34.7
	10% CA + 1% OI	0.1203	

The results showed in Tab. 2 indicated that the corrosion inhibitor can significantly reduce the corrosion rate of acid solution, and its corrosion inhibition efficiency is more than 90% at 333 K, except 13Cr in 10% CA solution. This is because the corrosion rate of 13Cr in 10% CA solution is very low. The corrosion inhibition rate of N80 steel in HCl, HAC and CA solutions is more than 92%, but the corrosion rate shows that organic acids have stronger corrosion to N80 than HCl solution, especially in CA solution. The 13Cr is easily corroded in HCl solution, but the corrosion rate in organic acid HAC and citric is very low. The OI is a common corrosion inhibitor in acidification [35-38]. The corrosion rate of 13Cr steel in 5% HCl + 1% OI solution is 36.13 g/m$^{-2}\cdot$h^{-1}, and the corrosion rate of N80 steel in 10% CA + 1% OI solution is 15.76 g/m$^{-2}\cdot$h^{-1}. However, the corrosion inhibition rates of both systems are greater than 90%. Therefore, the corrosion inhibition rate cannot be used as the selection standard of acid type, and it is necessary to use the corrosion rate as the selection standard. The acid type with strong corrosively to pipes does not need to be used, so the organic acid or chelate acid can be used to oil wells acidizing [39-40].

3.2 Electrochemical measurements

3.2.1 Polarization curve analysis

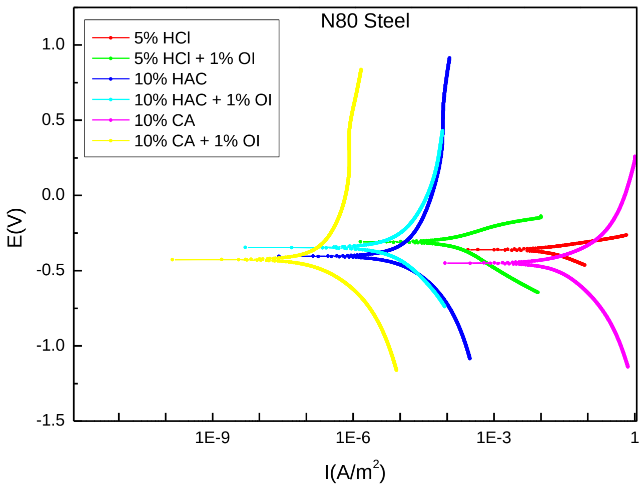


Figure 3. Polarization curves for N80 steel in different acid solution with and without inhibitor at 333 K

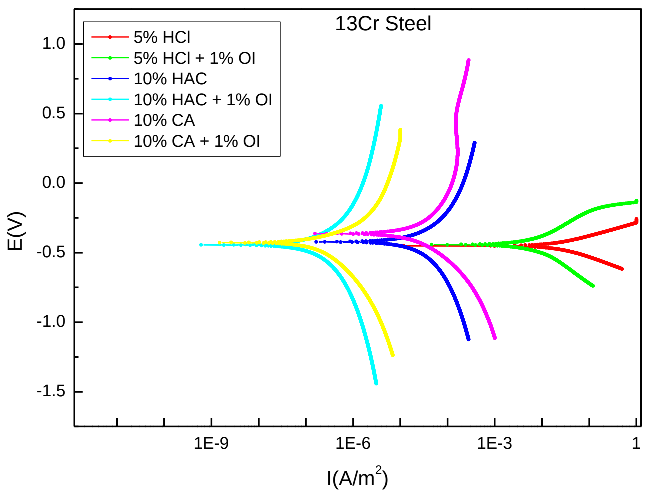


Figure 4. Polarization curves for 13Cr steel in different acid solution with and without inhibitor at 333 K

The polarization curves of N80 and 13Cr steel different acid solution at 333 K are shown in Fig. 3 and Fig. 4. The polarization parameters of N80 and 13Cr steel specimens are summarized in Tab. 3.

Table 3. Polarization parameters of N80 and 13Cr steel specimens in different acid solution with and without inhibitor at 333 K

Steel	System	E_{corr}(mV)	I_{corr}(mA/cm^2)	IEp
N80	5% HCl	-360	13.2	-
	5% HCl + 1% OI	-307	0.084	99.3%
	10% HAC	-405	0.0063	-
	10% HAC + 1% OI	-350	0.0049	22.2%
	10% CA	-454	17.456	-
	10% CA + 1% OI	-426	0.00012	99.9%
13Cr	5% HCl	-451	20.56	-
	5% HCl + 1% OI	-443	5.82	71.7%
	10% HAC	-428	0.021	-
	10% HAC + 1% OI	-448	0.00011	99.5%
	10% CA	-369	0.016	-
	10% CA + 1% OI	-431	0.00014	99.1%

To further confirm the results, the corrosion current density of steel was investigated using electrochemical station test polarization curves of N80 and 13Cr steel under different acid conditions. As shown in Fig. 3 and Fig. 4, the results show that the corrosion current density of N80 steel in 5% HCl and 10% CA solution is higher, but the corrosion current density of 13Cr is higher only in 5% HCl solution. The N80 steel polarization curve test shows, the corrosion potential of 5%HCl, 10%HAC and 10%CA moves forward after adding OI inhibitor, indicating that OI has a great influence on the anodic polarization curve. Related electrochemical parameters are listed in Tab. 3. The addition of OI to 5% HCl, 10% HAC and 10% CA can reduce the corrosion current density of N80 steel and inhibit the corrosion of pipe by acid, and OI can effectively inhibit the corrosion of acid to oil casing. The 13Cr steel polarization curve test shows after the addition of OI inhibitor, Ecorr of 5%HCl moves forward, indicating that OI has a greater influence on the anode polarization curve, while E of 10%HAC and 10%CA moves negatively, indicating that OI has a greater influence on the cathode polarization curve. Adding OI in 5% HCl, 10% HAC and 10% CA reduces the corrosion current density of 13Cr Steel, but the corrosion current density is still high in 5% HCl + 1% OI, which is consistent with the results of weight loss experiment, the HCl will cause serious corrosion of 13Cr. The OI is a typical adsorption corrosion inhibitor. The Ecorr of OI inhibitor changed in different directions in 6 groups, which indicated that the inhibition mechanism was influenced by inhibitor, environment and steel. According to previous studies, after the addition of OI, all Ecorr displacements in this paper are less than 85mV, which can inhibit both cathodic depolarization and anodic reaction. This is consistent with the results shown in the literature [35-38]. Therefore, the OI can effectively inhibit the corrosion of acid solution to pipeline equipment during acidification.

3.2.2 AC Impedance analysis

The EIS of N80 and 13Cr steels with and without OI inhibitor in 5%HCl, 10%HAC and 10%CA solutions were studied. The impedance measurements of the EIS experiment are presented in the form of Nyquist plots.

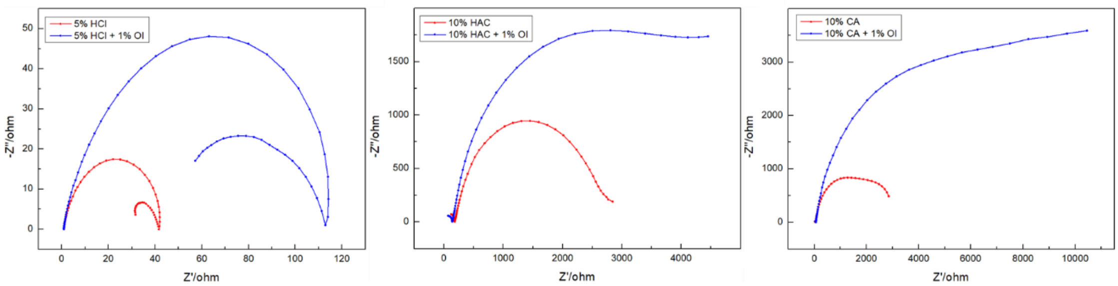


Figure 5. Nyquist curves for N80 steel immersed in different acid solution with and without inhibitor at 333 K

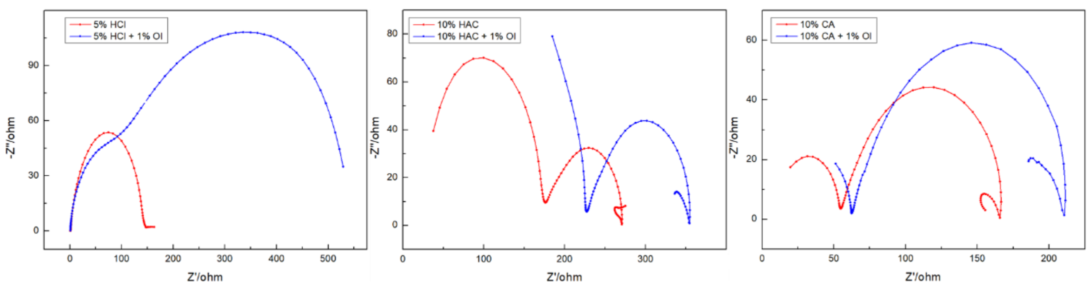


Figure 6. Nyquist curves for 13Cr steel immersed in different acid solution with and without inhibitor at 333 K

As shown in Fig. 5 and Fig. 6. The diameter of the semicircle represents the impedance of the steel in different acid solutions. The diameter of the semicircles of EIS Nyquist plot with OI containing acid are larger than that without OI, which addition of OI will increase the impedance of the acid system. These results suggest that the inhibitor OI can be adsorbed on the surface of the steel to form a protective film, which improves the transfer charge resistance value and prevents the acid solution from corroding the steel.

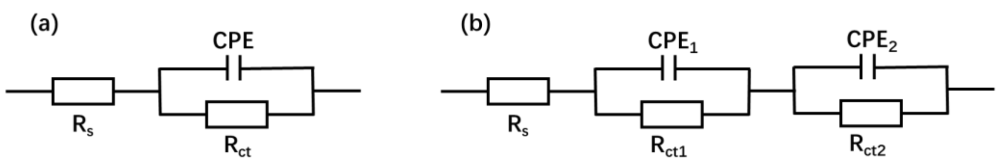


Figure 7. Equivalent electric circuit diagram used to fit the EIS data for (a) 5% HCl (b) 10% HAC, 10% CA, 5% HCl + 1% OI, 10%HAC + 1% OI and 10%CA + 1% OI

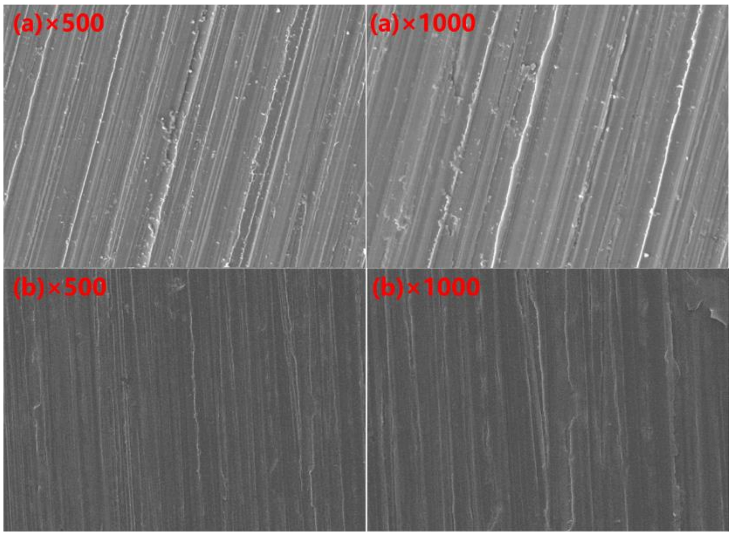
Table 4. Equivalent circuit parameters of EIS results at 333 K.

Steel	System	R_s (Ωcm^2)	R_{ct1} (Ωcm^2)	Q_1 ($\Omega^{-1}cm^{-2}s^n$)	n_1	R_{ct2} (Ωcm^2)	Q_2 ($\Omega^{-1}cm^{-2}s^n$)	n_2
N80	5% HCl	0.9104	-	-	-	38.83	4.959×10^{-5}	0.8771
	5% HCl + 1% OI	0.3162	102.5	3.228×10^{-4}	0.8673	0.8997	6.137×10^{-5}	1
	10% HAC	13.41	2560	2.552×10^{-4}	0.829	169.1	1.443×10^{-8}	0.9415
	10% HAC + 1% OI	14.99	126.2	3.116×10^{-8}	0.9387	5092	2.647×10^{-4}	0.8259
	10% CA	5.268	2702	2.719×10^{-4}	0.8253	40.89	1.663×10^{-7}	0.9227
	10% CA + 1% OI	10.61	10220	2.522×10^{-4}	0.8011	43.67	8.602×10^{-8}	0.9295
13Cr	5% HCl	0.9792	-	-	-	145.2	2.795×10^{-4}	0.8418
	5% HCl + 1% OI	0.707	82.32	1.098×10^{-5}	0.9018	427.3	4.645×10^{-4}	0.6637
	10% HAC	24.2	149.7	4.919×10^{-6}	0.9692	95.85	2.541×10^{-4}	0.7633
	10% HAC + 1% OI	15.55	228.4	8.489×10^{-9}	0.9244	120.6	2.148×10^{-4}	0.8011
	10% CA	9.523	106.9	2.397×10^{-4}	0.8567	45.85	1.301×10^{-7}	0.9464
	10% CA + 1% OI	6.013	144.1	2.725×10^{-4}	0.8474	63.46	6.501×10^{-8}	0.858

The equivalent circuit diagram obtained by fitting shown in Fig.7, circuit diagram a applies to 5%HCl and circuit diagram b applies to 5% HCl + 1% OI, 10% HAC ,10% HAC + 1% OI, 10% CA and 10% CA + 1% OI are interpreted by the equivalent electric circuits shown in Fig. 7b. The corresponding electrochemical parameters are given in Tab. 4. R_s is the solution resistance, R_{ct} represents the charge transfer resistance, and CPE is the constant phase element. The analysis of equivalent circuit parameters shows that: (a) In 5% HCl solution, the charge transfer resistance R_{ct} of 13Cr steel is greater than N80 steel, but the weight loss and polarization curve show that the 13Cr steel corrosion is greater than N80 steel. Previous studies have shown that 13Cr stainless steel has a dense amorphous Cr_2O_3 or $Cr(OH)_3$ passivation film on its surface, making the steel sheet more resistant to corrosion [21], so the R_{ct} value of 13Cr steel in this study is larger. But the Cl^- will promote the destruction of Cr corrosion inhibition film, resulting in serious pitting corrosion [28]. (b) In the 6 groups of acid solution systems of 13Cr and N80 steel corrosion experiments, there is little difference in R_s between the systems with and without OI, because the addition of 1% has little effect on the solution resistance. This is consistent with the data in the other literature of corrosion inhibitors [41-42]. (c) The R_{ct1} + R_{ct2} of with OI acid solutions are higher than those without OI, indicating that the corrosion inhibitor inhibits the charge transfer of steel corrosion. It also shows that the corrosion inhibitor forms a thin protective layer on the steel surface to prevent and slow down the corrosion reaction. (d) In 8 organic acid solutions, the R_{ct1} + R_{ct2} of N80 steel in acid solution are much larger than that of 13Cr steel, but the corrosion weight loss of 13Cr are less than that of N80, the results show that the corrosion strength cannot be judged by the magnitude of resistance, and it should also be related to the density and adsorption strength of the corrosion resistant film. And the results show that the corrosion resistance film formed of 13Cr steel is stronger than that of N80 steel. Therefore, it is necessary to optimize the material, acid solution and corrosion inhibitor for acidizing anticorrosion. Furthermore, it shows that the inorganic corrosion inhibition film of Cr has excellent corrosion inhibition performance, and it is suggested that the corrosion inhibitor can cooperate with both inorganic and organic films. (e) The R_{ct1} + R_{ct2} difference of 13Cr steel in organic acid solution with and without OI is small, because the corrosion of the organic acid is weak. (f) The morphology of Nyquist curves of the acid solution with and without corrosion inhibitor was similar, indicating that OI inhibitor did not change the corrosion mechanism of steel sheet by acid.

3.3 Corrosion morphologies of the N80 steel and 13Cr steel surface

The microscopic morphologies of the N80 steel and 13Cr steel after immersed in 5% HCl、10% HAC and 10% CA acid solution, were revealed by SEM and the results are shown in Fig. 8. As shown in Fig. 8a and Fig. 8b, the polished N80 steel and 13Cr steel surfaces exhibited sequential streaks and a smooth profile. However, the surface of N80 steel and 13Cr steel sheets soaked in acid solution became relatively blurred and the streaks disappeared. The Fig. 8c and Fig. 8d show that 5% HCl corrodes the steel seriously, especially 13Cr steel. The surface of N80 steel is corroded seriously and has big corrosion pit, while the surface of 13Cr steel is corroded integrally and has dense corrosion pit, therefore, the acidizing process must be corrosion protection, or for the strong corrosion environment to use weak acid instead of HCl solution. The Fig. 8e, Fig. 8f, Fig. 8g and Fig. 8h, show that the corrosion morphology of N80 steel and 13Cr steel in acetic acid and citric acid solution, the Fig. 8e and Fig. 8g are similar, the Fig. 8f and Fig. 8h are similar, this phenomenon shows that organic acid has similar corrosion behavior to N80 steel and 13Cr steel respectively. As shown in Fig. 8e and Fig. 8g, the HAC solution and CA solution can cause severe pitting corrosion on N80 steel, Fig. 8f and Fig. 8h show that the HAC solution and CA solution can cause slight pitting corrosion on 13Cr steel. This indicates that the organic acids cause serious corrosion to N80 steel and weak corrosion to 13Cr steel. This is consistent with the results of weightlessness tests. Organic or inorganic acids can cause severe corrosion of N80 material oil well, so must do a good job of protection measures when acidizing. The 13Cr material oil well, must be careful to use HCl solution.



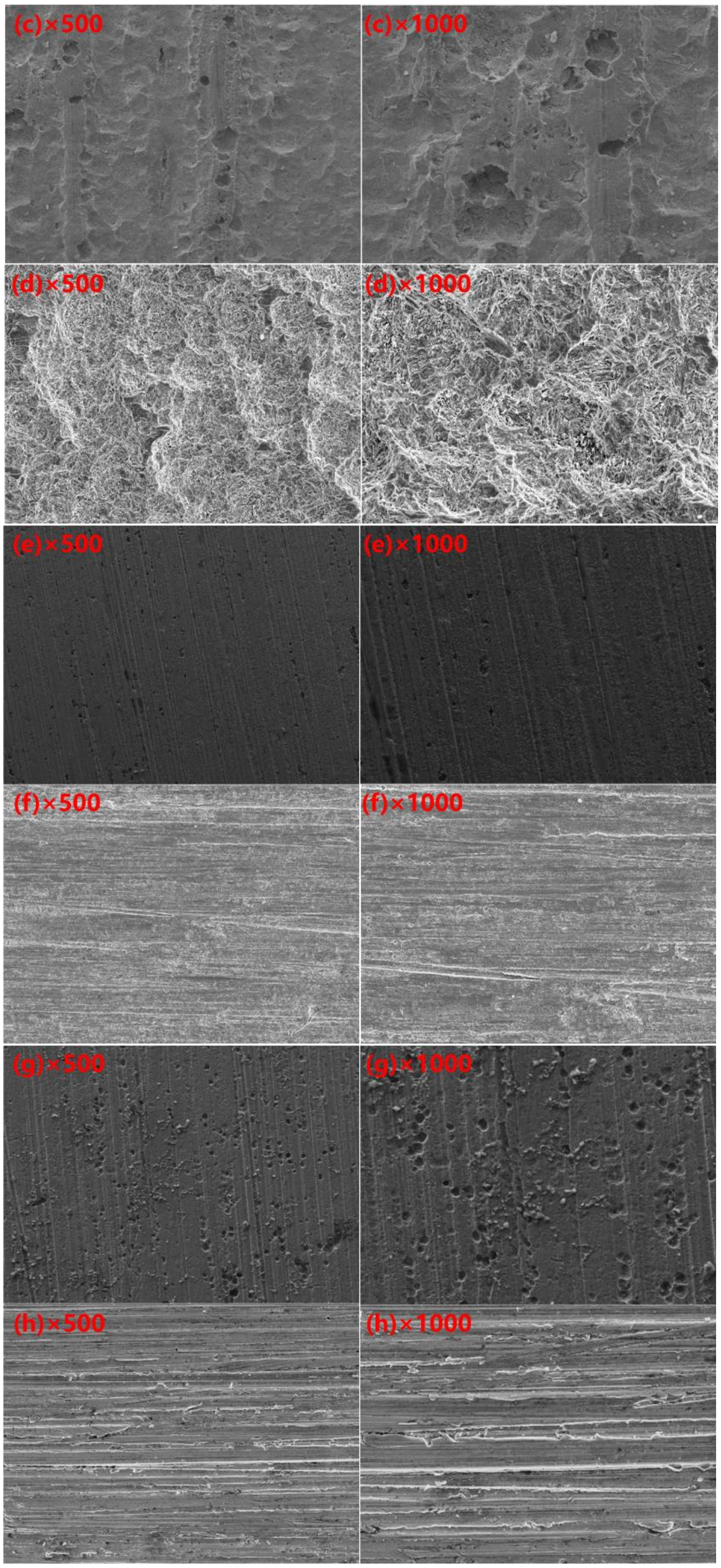


Figure 8. Scanning electron microscopy (SEM) image of the polished N80 steel surface (a), polished 13Cr steel surface (b), N80 steel after immersion in 5% HCl solution (c), 13Cr steel after immersion in 5% HCl solution (d), N80 steel after immersion in 10% HAC solution (e), 13Cr steel after immersion in 10% HAC solution (f), N80 steel after immersion in 10% CA solution (g) and 13Cr steel after immersion in 10% CA solution (h).

4. CONCLUSION

In summary, the corrosion behavior of N80 steel and 13Cr steel in 5% HCl, 10% HAC and 10% CA solution with or without OI inhibitor was studied. The corrosion rate, morphology and behavior were studied using weight loss method, SEM and an electrochemical station. The results showed that the corrosion of 13Cr steel is serious in HCl solution. Although Cr element has corrosion inhibition effect, Cl^- can destroy the oxide film of Cr. The corrosion of 13Cr steel was very low in HAC and CA solution. The corrosion of N80 steel in HCl, HAC and CA solution was serious, especially in CA solution. The surface of N80 steel in HCl solution was corroded into a large area pit, and that of 13Cr steel was corroded into a very dense pit. The organic acids can form pitting corrosion on steel surface and cause serious pitting corrosion on N80 steel. The inconsistence between impedance fitting and corrosion rate shows that the density and adsorption strength of the film have a great influence on the efficiency of corrosion inhibition. The research results provide a theoretical basis for the selection of acidizing acid solution types in oil and gas wells. When the oil casing is Cr steel, HCl solution should be avoided in acidizing of oil and gas wells. The acidizing of oil wells can not only take the corrosion inhibition rate as the standard of selecting acid type, and cannot choose the acid type which has strong corrosiveness to the oil tube, the corrosion protection of oil well should be optimized simultaneously from steel type, acid type and corrosion inhibitor.

References

1. M. Murshed and M.M. Tanha, *Energy Ecol. Environ.*, 6 (2021) 183-203.
2. A. Rahman, P. Dargusch and D. Wadley, *Renew. Sust. Energ. Rev.*, 144 (2021).
3. R.T.R. Carvalhoa, P.F. Oliveira, L.C.M. Palermo, A.A.G. Ferreira and C.R.E. Mansur, *Fuel*, 238 (2019) 75-85.
4. A.A. Garrouch and A.R. Jennings, *J. Pet. Sci. Eng.*, 158 (2017) 129-143.
5. P.L. Liu, H. Xue, L.Q. Zhao, Y.Y. Fu, Z.F. Luo and Z.Q. Qu, *J. Pet. Sci. Eng*, 132 (2015) 39-52.
6. X. Zhong, S. Yu, J. Hu, L. Chen, Y. Shi, Z. Zhang, S. Gao, D. Zeng and T. Shi, *Int. J. Electrochem. Sci.*, 12 (2017) 2875-2892.
7. N. Li, F. Zeng, J. Li, Q. Zhang, Y. Feng and P. Liu, *J. Nat. Gas Sci. Eng.*, 34 (2016) 792-802.
8. L.V. Hong, H.B. Mahmud, *IOP Conf. Ser.: Mater. Sci. Eng.*, (2017).
9. Y.H. Zhu, L. Q. Zhao, P.L. Liu and X. Qu, *Anti-Corros. Methods Mater.*, 66 (2019) 573-582.
10. F. Valentini, V. Kozell, C. Petrucci, A. Marrocchi, Y.L. Gu, D. Gelman and L. Vaccaro, *Energy Environ. Sci.*, 12 (2019) 2646-2664.
11. S. Divi, K.D. Efird and D. Spiller, *NACE - Int. Corros. Conf. Ser.*, (2017).
12. M.H. Alkhaldi, H.A. Nasr-El-Din and H.K. Sarma, *Can. Int. Pet. Conf., CIPC,* (2009).
13. N. Miyazaki, Y. Sugai, K. Sasaki, Y. Okamoto and C. Ouyang, *Soc. Pet. Eng. - Abu Dhabi Int. Pet. Exhib. Conf., ADIP*, (2018).
14. Y.Y. Li, Z.Z. Wang, X.P. Guo and G.A. Zhang, *Corros. Sci.*, 147 (2019) 260-272.
15. S.D. Zhu, A.Q. Fu, J. Miao, Z.F. Yin, G.S. Zhou and J.F. Wei, *Corros. Sci.*, 53 (2011) 3156-3165.
16. J. Du, J.H. Guo, L.Q. Zhao, Y.X. Chen, C.L. Liu and X.H. Meng, *Int. J. Electrochem. Sci.*, 13 (2018) 5810-5823.
17. R. Wang and S.J. Luo, *Corros. Sci.*, 68 (2013) 119-127.
18. J.G. Liu, Z. Wang, G. Gao, X. Fang and G. He, *Corrosion (Houston, TX, U. S.)*, 76 (2020).
19. L. Curkovic, M.F. Jelaca and S. Kurajica, *Corros. Sci.*, 50 (2008) 872-878.
20. J. Du, Y.N. He, P.L. Liu, Y.G. Liu, X.H. Meng and L.Q. Zhao, *Anti-Corros. Methods Mater.*, 66

(2019) 1-10.
21. P.L. Liu, Y.H. Zhu and L.Q. Zhao, *Anti-Corros. Methods Mater.*, 67 (2020) 557-564.
22. R. Puthalath, A. O. Surendranathan and C. Murthy, *Ind. Eng. Chem. Res.*, 53 (2013) 23–30.
23. J.T.Z. Amp and Y. Wang, *Pet. Sci. Technol.*, 30 (2012) 1851-1861.
24. S. Parsons, O. Poyntz-Wright, A. Kent and M.C. Mcmanus, *Mater. Today Sustainability*, 3-4 (2019) 100005.
25. M. Yadav, D. Behera and U. Sharma, *Corros. Eng. Sci. Technol.*, 48 (2013) 19-27.
26. S. Vishwanatham and N. Haldar, *Corros. Sci.*, 50 (2008) 2999-3004.
27. X. Zhang, M. Zhang, Z. Zhang, Q. Li, R. Lv and W. Wu, *J. Mol. Liq.*, 347 (2022) 117957.
28. J. Shen, *Int. J. Electrochem. Sci.*, 15 (2020) 10058-10080.
29. S. K. Singh and A. K. Mukherjee, *J. Mater. Sci. Technol.*, 26 (2010) 264-269.
30. T. Tran, B. Brown, S. Nešić and B. Tribollet, *Corrosion (Houston, TX, U. S.)*, 70 (2013) 223-229.
31. M. Yadav, D. Sharma and S. Kumar, *Korean J. Chem. Eng.*, 32 (2015) 993-1000.
32. D. L. Wang, Y.M. Li, T. Chang and A. Luo, *Colloids Surf., A*, 628 (2021).
33. M. Finsgar and J. Jackson, *Corros. Sci.*, 86 (2014) 17-41.
34. P.B. Raja, M. Ismail, S. Ghoreishiamiri, J. Mirza, M.C. Ismail, S. Kakooei and A.A. Rahim, *Chem. Eng. Commun.*, 203 (2016) 1145-1156.
35. J. Yang, L. Gao, X. Liu, W. Qin, C. Yin and J. Zhang, *SPE J.*, 21 (2016) 1743-1746.
36. T. Gu, P. Su, X. Liu, J. Zou, X. Zhang and Y. Hu, *J. Pet. Sci. Eng.*, 102 (2013) 41-46.
37. K. Zhang, B. Xu, W. Yang, X. Yin, Y. Liu and Y. Chen, *Corros. Sci.*, 90 (2015) 284-295.
38. J. Zhang, X.L. Gong, H.H. Yu and M. Du, *Corros. Sci.*, 53 (2011) 3324-3330.
39. L. Li, H.A. Nasr-El-Din, F.F. Chang and T. Lindvig, *Int. Pet. Technol. Conf., IPTC*, (2008).
40. I. Ivanishin and H. Samouei, *Proc. SPE Annu. Tech. Conf, Exhib.*, (2021).
41. S.H. Yoo, Y.W. Kim, K. Chung, S.Y. Baik and J.S. Kim, Corros. Sci., 59 (2012) 42-54.
42. I. Jevremovic, M. Singer, S. Nesic and V. Mikovi-Stankovi, Mater. Corros., 67 (2016) 756–768.