

Influence of Stray Alternating Current on Corrosion Behavior of Pipeline Steel in Near-Neutral pH Carbonate/Bicarbonate Solution

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Abstract — The Alternating current (AC) induced corrosion of pipeline steel was investigated in near-neutral pH carbonate/bicarbonate solution by potentiodynamic technique and weight loss test. It is found that superimposed AC is able to cause the negative shift of corrosion potential of pipeline steel, the severity of the polarization curve oscillation is proportional to the ratio of AC current density to DC current density, the most severe oscillation can be observed in the region near corrosion potential. The results of weight loss test indicated that the greater AC current density resulted in the higher AC-induced corrosion rate. The corrosion morphology viewed by optical camera and SEM showed that the form of corrosion is closely related to the magnitude of AC current density.

Keywords - Alternating current; pipeline steel; corrosion; polarization curve

I. INTRODUCTION

It is acknowledged [1-5] that most metallic materials or structures corroded at an accelerated rate due to the presence of stray alternating current (AC). The corrosion problems caused by stray AC on pipeline have received increasing attention from pipeline corrosion scientists during the last 30 years [4]. Generally, there are three AC sources [6] causing pipeline corrosion. Inductive coupling arises where pipeline has same route with powerline in length. Resistive coupling arises if pipeline is located at AC potential gradient caused by discharged current from grounding systems into earth. Capacitive coupling arises during pipeline construction when long pipeline is exposed in the air before burial. AC interference from high voltage transmission lines has been reported as one of the main factors to cause corrosion problems on buried pipelines by several distribution companies [7-10]. A harmful situation is when the high voltage lines and transmission pipelines parallel to each other for certain distance, particularly the pipeline steel coated with high dielectric coatings, like extruded polyethylene, polypropylene, or composite coating, if coating defects exist, these areas will subject to a severe AC induced corrosion, even under cathodic protection (CP) conditions [9,11,12]. However, CP criterion takes AC induced corrosion into consideration has not been established [12].

There has been a number of studies performed to investigate the corrosion effects of AC on steel [13-15], copper [2,4] nickel [3], etc. in acidic, sulfate, and seawater solutions. Most of the above research demonstrated that AC behaves as a depolarizer with the ability to reduce the polarization of both anode and cathode, as well as the electrochemical passivity. The reduced cell polarization or

passivity increases the corrosion rate. Even though the AC induced corrosion of common metallic materials in different solutions have been well investigated, little work has been performed on pipeline steel in simulated solution extracted from disbonded coating. Song and coworkers [6] reported that AC corrosion rate was affected not by AC voltage but by both of frequency and AC current density, AC corrosion rate increased linearly with effective AC current density. Literature review of AC induced corrosion on pipeline steel made by Wakelin and coworkers [9] revealed that corrosion did not occur at AC current densities of less than 20 A/m², while the corrosion is unpredictable at AC current densities of 20-100 A/m², the corrosion rate can be expected if the AC current densities are greater than 100 A/m². Linhardt and Ball [16] found that AC could induce pitting corrosion of pipeline steel in soil, interestingly, the pH of adhering soil collected from corroded pipeline surface were measured in the range 9 to 11, which is higher than the pH of soil (pH=8). It suggests that it is more practical to do the AC induced corrosion in simulated solution extract from disbonded coating, instead of soil.

In this work, the AC induced corrosion of pipeline steel in near-neutral pH carbonate/bicarbonate solution is studied by potentiodynamic technique and weight loss test, the effects of AC current density and the size of the coating defect on corrosion of the steel were determined. It is anticipated that this research would advance the understanding of AC induced corrosion of pipeline steel in near-neutral pH solution.

II. EXPERIMENTAL SETUP

A. Electrode and solution

All test specimens were fabricated from a sheet of X65 pipeline steel. The chemical composition (wt%) of X65 steel is: C 0.04, Si 0.2, Mn 1.5, P 0.011, S 0.003, Mo 0.02 and Fe balance. The specimens were precisely machined with a dimension of 10mm×10mm×9mm, three equivalent samples were prepared for each test. All the samples were subsequently polished with 600 grit, 800grit, and 1200 grit emery papers followed by cleaning with distilled water and acetone.

NS4 solution had been widely used to simulate the dilute electrolyte trapped between coating and the pipeline steel, with the chemical composition: 0.483 g/L NaHCO₃, 0.122 g/L KCl, 0.181 g/L CaCl₂·2H₂O, and 0.131 g/L MgSO₄·7H₂O. Prior to test, NS4 solution was purged with 5% CO₂/N₂ gas for 1 h to achieve an anaerobic and near-neutral pH condition (pH 6.8). The gas flow was maintained throughout the test. The solution was made from analytic grade reagents (Fisher Scientific) and ultra-pure water (18 MΩ cm in resistivity). All tests were conducted at room temperature (~22°C).

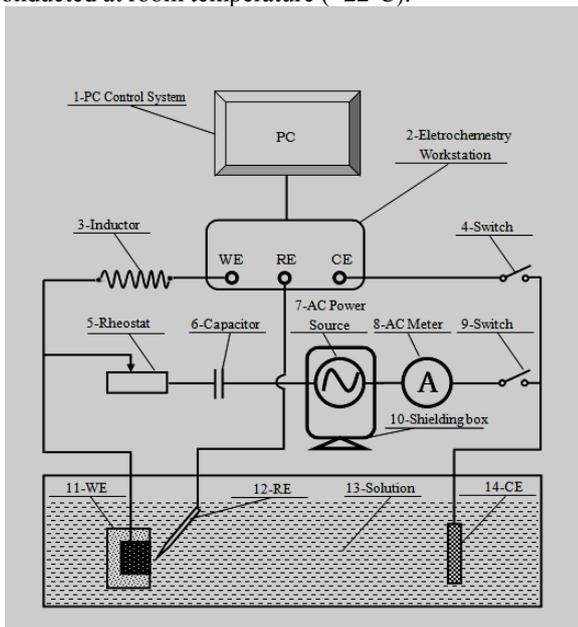


Fig.1 Schematic Diagram of the Apparatus for Investigating AC Induced Corrosion

B. Electrochemical measurements

Electrochemical measurements were performed using a Solartron 1280C electrochemical test system. A three-electrode test cell was used with the test specimen as working electrode, a platinum foil as counter electrode, and a saturated calomel electrode (SCE) as the reference electrode. The AC signal ($f=60\text{Hz}$) was applied between the working electrode and counter electrode, as shown in

Fig. 1, a rheostat was employed to adjust the AC current, and a capacitor was introduced to avoid the AC signal interfering with DC measurements, assuring the AC current flow only between working electrode and counter electrode instead of DC measurement circuit.

Prior to the electrochemical tests, the sample was conditioned for 30 min in the test solution at the corrosion potential to ensure that the steady state was reached. Potentiodynamic measurements were conducted at a scanning rate of 0.5mV/s under various AC current densities, six different AC current densities of 0A/m², 20A/m², 50A/m², 100A/m², 200A/m², and 500A/m² were chosen in the present work. All potentials are reported relative to the SCE.

C. Weight loss test

Weight loss test was performed to study the effects of AC on corrosion rate and corrosion morphology in near-neutral pH solution. The AC signal was applied between the working electrode and the counter electrode, the values of AC current densities chosen for weight loss tests are the same as that of the electrochemical measurements. Prior to each test, the specimen was cleaned with distilled water and acetone, dried, and then weighed using Satorius ED124S 4-digit electronic balance for gravimetric weight loss measurements. Weight loss tests were carried out for the duration of 48 h. After the completion of each test, the specimens were cleaned, and dipped briefly into a 50% (v/v) HCl solution according to ASTM procedure G1-81 to remove the corrosion products on the surface, rinsed and dried again, finally reweighed to get the resulting weight loss due to corrosion. The corrosion rate was reported in mm/a according to the obtained weight loss. Scanning electron microscope (SEM), combined with optical photography was used to characterize the corrosion morphology of the specimens after removal of corrosion products.

III. RESULTS AND DISCUSSION

A. Corrosion potential measurements on pipeline steel under interference of various AC current densities

Fig. 2 shows the corrosion potentials of pipeline steel measured in near-neutral pH solution under interference of various AC current densities. The corrosion potentials shifted to negative direction with the increasing of applied AC current densities. A number of studies [4,17-19] related to the influence of AC current on corrosion of metallic materials have concluded that the applied AC current could cause the negative shift of corrosion potential. Lalvani and Lin [18] proposed a model to derive the corrosion potential shift induced by applied AC current, the explanation in terms of mathematical equations are shown as follows:

$$E_{\text{corr,AC}} = E_{\text{corr,DC}} - \alpha \quad (1)$$

$$\alpha = \left(\frac{m_a m_c}{m_a - m_c} \right) \ln \left[\frac{\sum_{k=1}^{\infty} \frac{1}{(k!)^2} \left(\frac{E_p}{2m_c} \right)^{2k} + 1}{\sum_{k=1}^{\infty} \frac{1}{(k!)^2} \left(\frac{E_p}{2m_a} \right)^{2k} + 1} \right] \quad (2)$$

where $E_{corr, AC}$ and $E_{corr, DC}$ are the corrosion potentials with and without applied AC current, m_a and m_c are the anodic and cathodic Tafel slopes, respectively, E_p is the peak voltage of applied AC signal. The variation of corrosion potential caused by AC is a function of the ratio of anodic Tafel slope to cathodic Tafel slope ($r=m_a/m_c$) and E_p , and the corrosion potential shifted to negative direction as r and E_p increased. In the present work, it is seen that the variations of m_a and m_c are not obvious to cause the significant change of their ratio as presented in Fig. 3, therefore, the increase of E_p is a main contribution to the negative shift of corrosion potential, E_p is proportional to AC current density when the sample has a constantly exposed surface area in a given solution.

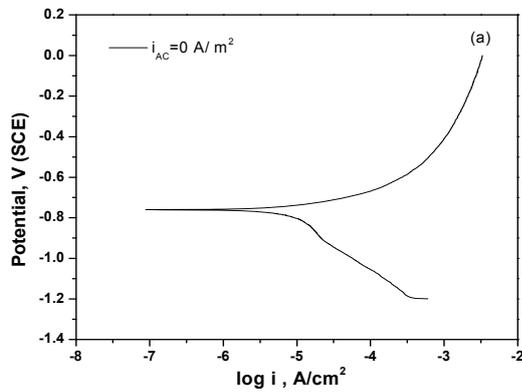


Fig.2 Corrosion Potentials of X65 Pipeline Steel under Interference of Various AC Current Densities

B. Polarization curves of pipeline steel under interference of various AC current densities

The corresponding polarization curves are shown in Fig. 3, there is no oscillation on polarization curve if AC current was not superimposed. The oscillations of polarization curves become more and more severe as superimposed AC current increased from Fig. 3 (b) to (f), particularly in the region near corrosion potential.

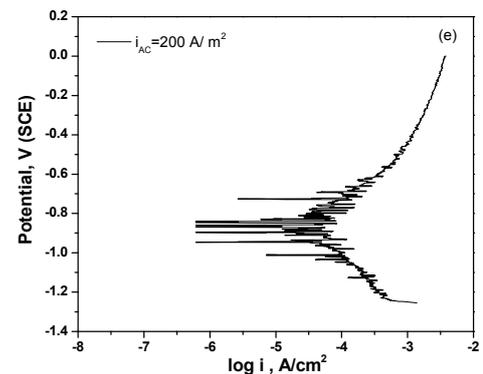
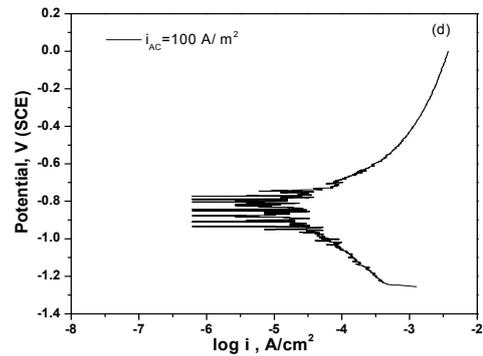
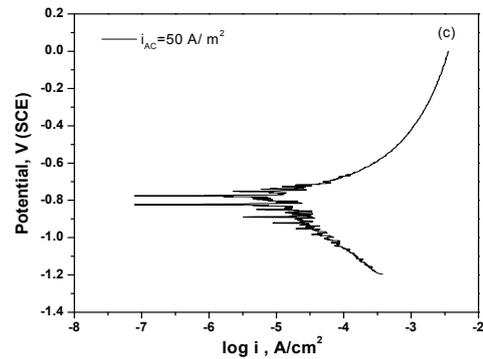
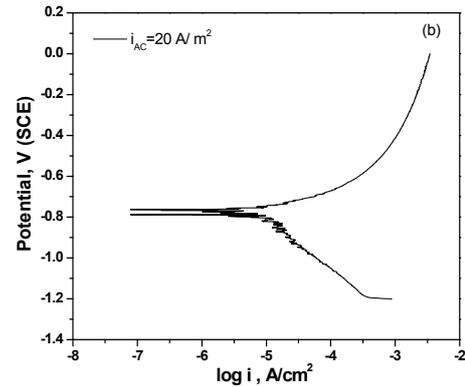
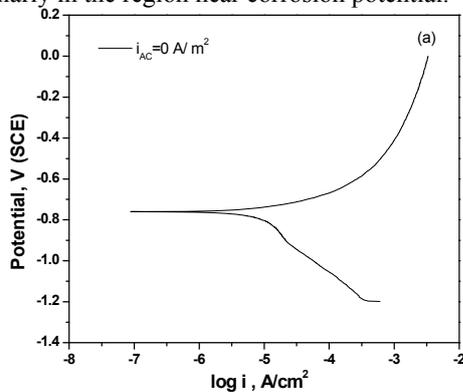


Figure 3 continues on the next page

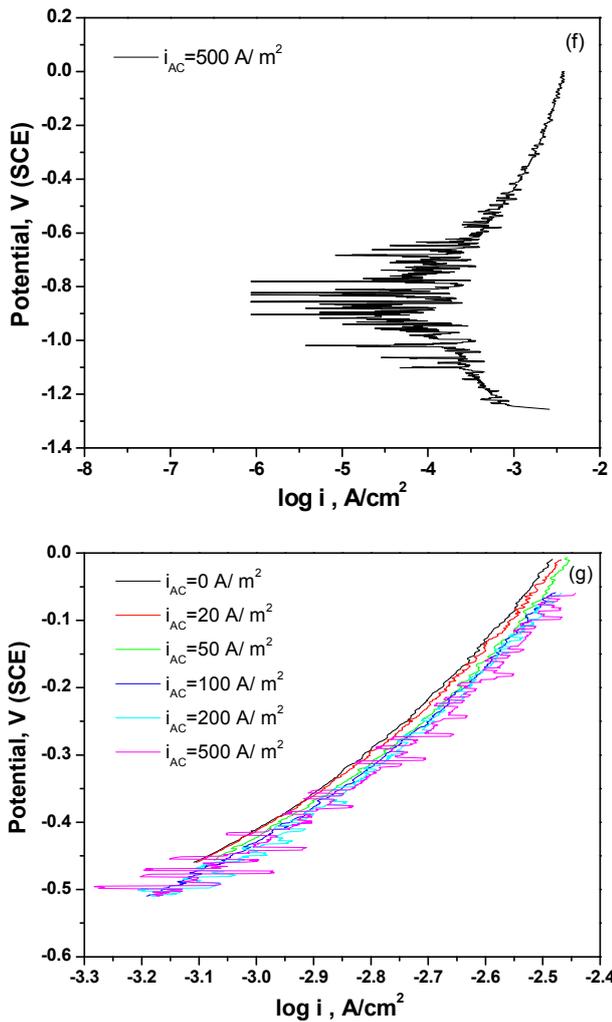


Fig.3 Polarization Curves of X65 Pipeline Steel under Interference of Various AC Current Densities

A portion of the anodic polarization curves at various AC current densities are replotted in Fig. 3 (g). It is seen that the curves shifted to the positive direction with the increase of AC current density. The enhanced anodic dissolution rate could be attributed to the superimposed AC caused the negative shift of corrosion potential and the increase of exchange current density, thermodynamically, the more negative the corrosion potential, the easier the corrosion occurs, and kinetically corrosion will take place in a higher rate if exchange current density increases. Apparently, the magnitude of the polarization curve oscillation is dependent on the ratio of AC current density to DC current density, which can be expressed as:

$$A_{DC} = K \frac{i_{AC}}{i_{DC}} \quad (3)$$

where A_{DC} is the magnitude of the oscillation, K is a coefficient, i_{AC} and i_{DC} are the AC current density and DC current density, respectively.

C. Effects of defect size on polarization behavior of coated pipeline steel at fixed AC current

Fig. 4 shows the corrosion potentials of coated pipeline steel with different coating defects in near-neutral pH solution under the interference of a fixed AC current ($I_{AC}=0.5mA$). It is seen that the corrosion potentials shifted to negative direction with the decreasing of defect size, the oscillations of corrosion potentials can be seen and became more obvious as the defect size decreased. The corresponding polarization curves are shown in Fig. 5, a significant shift of DC current density to positive direction can be observed as the defect size decreased. The severity of the oscillations of DC current densities in the polarization curves increased as the hole diameter decreased. There was no significant change on the shape of polarization curves at hole-1 at the given AC current.

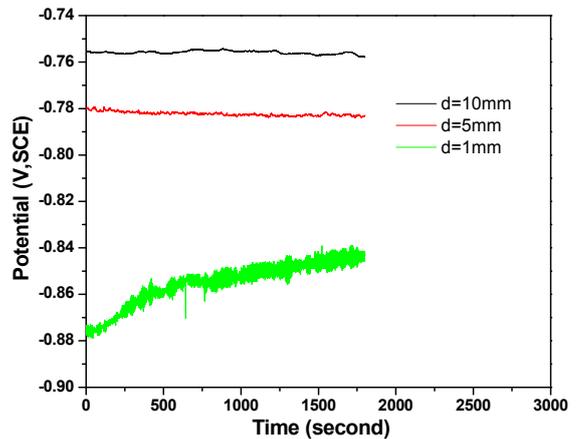


Fig.4 Corrosion potentials of X65 coated pipeline steel with defects under interference of a fixed AC current

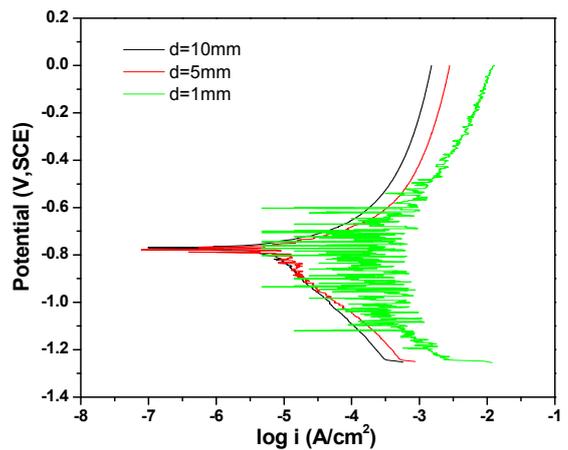


Fig.5 Polarization curves of X65 coated pipeline steel with defects under interference of a fixed AC current

If fixed AC current flows through a section of pipeline with several defects in different diameters, the corrosion behavior at different defects can be described by the polarization curves plotted in Fig. 5. At the given AC current, the smaller the defect is, the severer the corrosion will occur. This can be explained that AC current density is inversely proportional to defect area, i.e., AC current density in 1mm-hole was one hundred times compared to that of 10mm-hole, which led to less current density at 10mm-hole resulting in less influence on corrosion rate and passivity. It is indicated that the small defects are at potential high risk of corrosion with the presence of AC current at the beginning corrosion period. However, the corrosion products generated at small hole has increasing possibility to cause the “blocking effect” on AC current as the corrosion process developed.

D. Corrosion rate and morphology of pipeline steel under interference of various AC current densities

The corrosion rates of pipeline steel in near-neutral pH solution under interference of various AC current densities are plotted in Fig. 6. It is seen that the corrosion rate gradually increased with the AC current density. Fig. 7 and Fig. 8 show the corrosion morphologies of pipeline steel in near-neutral pH solution under interference of various AC current densities viewed by optical camera and SEM, respectively. It is seen that uniform corrosion occurred when AC current density is less than 500 A/m², a porous structure can be observed on sample surface at AC current densities of 100 and 200 A/m². If the AC current density reached 500 A/m², the sample undergoes pitting corrosion, the shape of corrosion pits is like a crater. The occurrence of pitting corrosion is possible in a non-passive environment if the superimposed AC current density is sufficiently high.

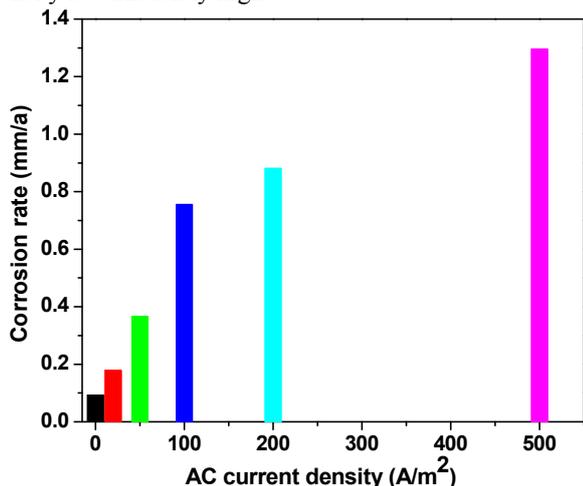


Fig.6 Corrosion Rates of X65 Pipeline Steel under Interference of Various AC Current Densities

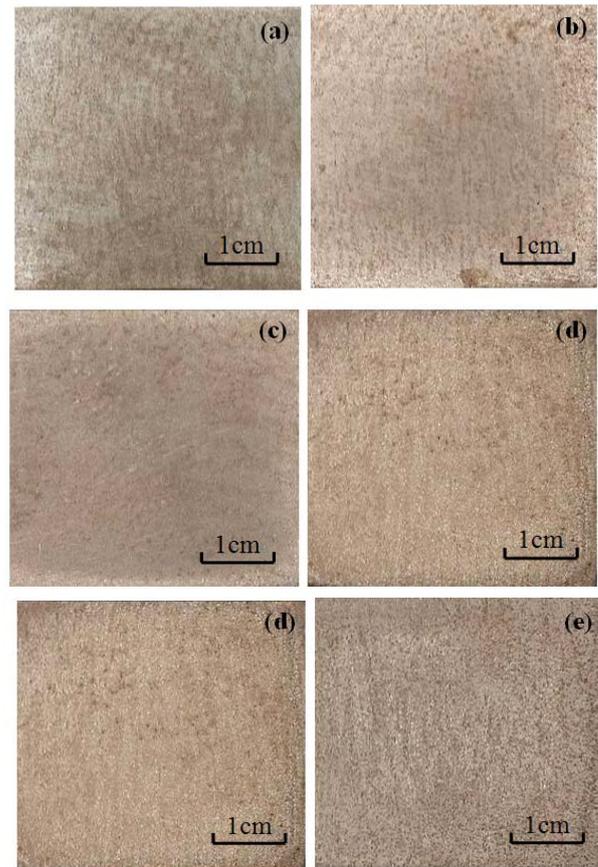


Fig.7 Optical Observation of X65 Pipeline Steel under Interference of Various AC Current Densities After Two-day test (a. 0 A/m²; b. 20 A/m²; c. 50A/m²; d. 100 A/m²; e. 200 A/m²; f. 500A/m²)

It is reported [6] that the amount of corrosion caused by AC current could be expressed as percentage of the amount of corrosion that would be caused by an equivalent intensity of DC current, generally, AC current causes less than 1% of the corrosion of the equivalent DC current. The relative low current efficiency in AC corrosion due to the fact that majority of AC current flow through electrical double layer capacitor causing charge and discharge as non-faradaic current, and only minority of AC current results in charge transfer causing corrosion as faradaic current [6, 13]. The corrosion rates shown in Fig. 6 indicated that superimposed AC current could accelerate corrosion process compared to that without applied AC current, the AC current densities expressed as percentages of equivalent DC current densities is shown in Table I, indicating that the corrosion rate caused by AC current was less than 1% of equivalent DC current.

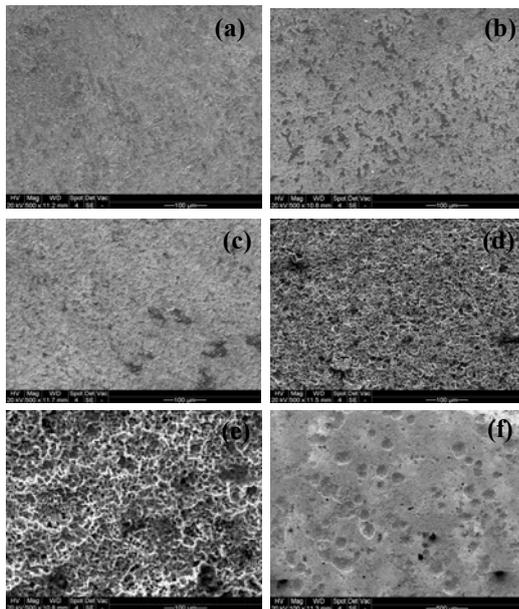


Fig.8 SEM Images of X65 Pipeline Steel under Interference of Various AC Current Densities After Two-day test (a. 0 A/m²; b. 20 A/m²; c. 50A/m²; d. 100 A/m²; e. 200 A/m²; f. 500A/m²)

TABLE I. AC CURRENT DENSITIES EXPRESSED AS THE PERCENTAGE OF EQUIVALENT DC CURRENT DENSITIES

AC current density/ A/m ²	0	20	50	100	200	500
Percentage of equivalent DC current density (%)	N/A	0.76	0.63	0.64	0.38	0.22

IV. CONCLUSIONS

(1) Applied AC current is able to cause the negative shift of corrosion potential of pipeline steel in near-neutral pH carbonate/bicarbonate solution. The greater the AC current density, the more negative the corrosion potential shifted.

(2) The polarization curve oscillation increased with the superimposed AC, the severity of oscillation is proportional to the ratio of AC current density to DC current density, the most severe oscillation occurred in the region near corrosion potential.

(3) Coated pipeline steel with small defect is at potential high risk of corrosion due to the fact that higher AC current density was generated at small defect with respect to big one at a fixed applied AC current.

(4) The greater the AC current density, the higher is the AC corrosion rate. The form of corrosion is closely related to the magnitude of AC current density. Localized

corrosion took place when the superimposed AC current density is greater than 500 A/m².

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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