

Electrochemical mechanism of stress corrosion cracking of API X70 pipeline steel under different AC frequencies

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HIGHLIGHTS

- A fundamental understanding of SCC mechanism under AC interference at different frequencies is investigated.
- The processes of Faraday and non-Faraday derived from the AC are discussed in detailed.
- Catalytic effect of various AC frequencies on SCC behavior is proposed.

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ABSTRACT

Electrochemical and SCC behaviour of X70 pipeline steel samples were investigated under various AC frequencies to elucidate the mechanistic aspects of the alternating current (AC)-assisted stress corrosion cracking (SCC) of pipeline steels in simulated seawater solutions. Results indicate that AC serves as a critical influencing factor on SCC of X70 pipeline steel by accelerating the mass transfer and in-situ-O₂-generation, and hydrogen evolution due to the non-Faraday and Faraday potential of AC, respectively. The electrochemical reactions show a maximum rate around 30 Hz, which is attributed to the periodic effect of AC frequency on the different processes; a similar trend is observed in SCC behaviour with increase in AC frequency. AC catalyses both the anodic dissolution (AD) and hydrogen evolution reactions, and greatly increases the SCC susceptibility resulting from the combined effect of increased AD and hydrogen embrittlement (HE) on the SCC process.

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1. Introduction

In recent years, with the development of offshore oil/gas fields and offshore oil industry, submarine pipelines are being increasingly used for transporting marine oil and gas [1–4]. The marine environment causes the corrosion of submarine pipelines, and this effect is especially pronounced on the defects in the undercoating, which are subjected to high loop and/or residual stresses, as a result of which stress corrosion cracking (SCC) is easily initiated. To date, numerous cases of SCC of land oil and gas pipelines have been reported [5–14]. Most of the time, SCC behaviour is observed under the dis-bonded coating, where open defects are formed by the synergistic effect of environmental factors and dynamic stress under cathode stripping [15–25]. Even though off-shore pipelines also suffer from similar coating defects and cathodic protection

(CP) conditions, the risk of SCC in submarine pipelines is increased due to harsher environment, i.e., corrosive solutions, loop stress, residual stress, perennial waves, and sea currents.

Moreover, with the rapid development of electric power and oil/gas transportation industries, and other energy transmission systems, the effects of stray current attract tremendous interest in coastal and offshore areas. These problems are concentrated around the so-called “public corridor” in the local area and further exacerbate SCC behaviour of submarine pipelines [26–30]. Therefore, understanding stray current-induced corrosion, especially stress corrosion under alternating current (AC) conditions, may be one of the key issues in the corrosion protection of inshore and offshore pipelines.

Basically, some AC-induced corrosion mechanisms have been proposed, i.e., irreversibility effect of anode reaction [30], Faraday rectification effect [31], depolarization effect of anodic reaction [32], oscillating effect of AC voltage at metal/dielectric interface [33]. Recently, many mechanism researches are conducted

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experimentally and theoretically on the stray current corrosion under various conditions [3,34–43]. For example, Goidanich et al. [34,35] reported the effects of AC on corrosion kinetics parameters of electrochemical process, i.e., Tafel slope and exchange current density, depended on the corrosion system and AC current density. Tang et al. [43] pointed out that AC enhanced the dissolution of magnesium and a polarity reversal was observed on a magnesium sacrificial anode in the presence of AC current density of 100 A/m^2 (or larger). A mechanism for this polarity reversal was proposed. In addition, another explanation was that the asymmetry of anodic (β_a) and cathodic (β_c) Tafel slopes (ratio, $r = \beta_a/\beta_c \neq 1$) significantly affected the AC-induced corrosion mechanism [44–47]. However, a detailed understanding of AC-induced corrosion mechanism has been limited due to unsteady kinetics of electrochemical processes under stray AC. It is significant from the point of view of fundamental studies and urgent in engineering to reveal the influence of AC on SCC and understand the underlying mechanisms. Since the AC signal is a function of time, the influence of AC on electrochemical kinetics can be revealed by changing the frequency of the applied AC. Therefore, it is expected that the fundamental mechanism of AC-induced corrosion can be revealed by investigating the change of corrosion and electrochemical behaviour under different frequencies.

In this work, the impact of different AC frequencies on both electrochemical and SCC behaviour of X70 pipeline steel in simulated seawater environment was studied using dynamic potential polarization curves, immersion tests, and slow strain rate tensile tests (SSRTs), to analyse the electrochemical mechanism of SCC and its relation to corrosion morphology.

2. Experimental procedures

2.1. Materials and test solutions

The test specimens were fabricated from a hot-rolled plate of API X70 pipeline steel, of which, the chemical composition (wt.%) is shown in Table 1. The microstructure of the steel mainly consists of polygonal ferrite grains and fine

martensite-austenite phases (distributed in the intergranular regions, Fig. 1). The test solution was a simulated seawater solution prepared in accordance with the ASTM D1141 national standard and contained 24.53 g/L NaCl, 5.2 g/L MgCl_2 , 4.09 g/L Na_2SO_4 , 1.16 g/L CaCl_2 , 0.695 g/L KCl, and 0.201 g/L NaHCO_3 . The solution was prepared using analytical grade reagents and deionized water and its pH was 8.0. All tests were conducted at room temperature ($22^\circ\text{C} \pm 1^\circ\text{C}$).

2.2. Electrochemical measurements

The electrodes, with an exposure area of $10 \text{ mm} \times 10 \text{ mm}$ as the working surface, were mounted using epoxy. The working area was ground to 1500 grit emery paper and successively cleaned with distilled water and acetone using an ultrasonic cleaner.

Electrochemical tests were conducted, using a PARSTAT 2273 electrochemical workstation, in a three-electrode cell system composed of electrochemical testing and analog circuits. The AC superimposed circuit was independent of the direct current (DC) measurement circuit. The AC was measured with a clamp meter as a root-mean-square value. In this system, specimens of X70 pipeline steel were tested as working electrodes; a platinum plate was used as the counter electrode, a saturated calomel electrode (SCE) was the reference electrode, and a graphite electrode was the counter electrode of the AC analog circuit. A schematic of the polarization curve test and a diagram of the specimen in the loaded state are shown in Fig. 2, and diagram of electrochemical measurements is in accordance with that reported by Zhu et al. [40]. The function generator AT1645-3 model was employed to generate the sine wave AC signal of 100 A/m^2 to the specimens at different frequencies. The sine wave AC with a density of 100 A/m^2 , which was considered to be high enough to cause SCC damage to pipeline steel [42], was applied between the working electrode and the graphite electrode (Fig. 2). The AC density was maintained at 100 A/m^2 using a rheostat and a fuse was used to ensure the safety of electrochemical test circuits, in the event of current overload. Additionally, the inductor (L, 4.2H) was controlled to prevent the influence of AC on the test process of the electrochemical workstation and a capacitor (C, 500 μF) was used to prevent interference of the two circuits and ensure that the two circuits were almost independent of each other. After the device was set up, the AC signal was applied to the sample to obtain the equilibrium-state value of the corrosion potential. Dynamic potential polarization curves were generated by fast and slow scanning under 30 Hz (100 A/m^2) AC and the potential was scanned in the range $-2.0 V_{\text{SCE}}$ to $1.6 V_{\text{SCE}}$ under no-stress conditions. Conventional dynamic potential polarization curves were traced at a scanning rate of 0.5 mV/s from $-1.2 V_{\text{SCE}}$ to $-0.4 V_{\text{SCE}}$ under conditions of stress. The polarization curve tests were repeated three times.

Prior to EIS measurements, the sample was immersed for different periods in simulated seawater under 30 Hz (100 A/m^2) of AC. The EIS tests were conducted at scanning frequencies ranging from 0.01 Hz to 100 kHz, after switching off the

Table 1
Chemical composition of X70 pipeline steel.

Material	Chemical composition										
	C	Si	Mn	S	Cr	Al	P	Ni	Mo	Cu	Fe
Wt.%	0.045	0.24	1.48	0.001	0.031	0.01	0.017	0.16	0.23	0.21	balance

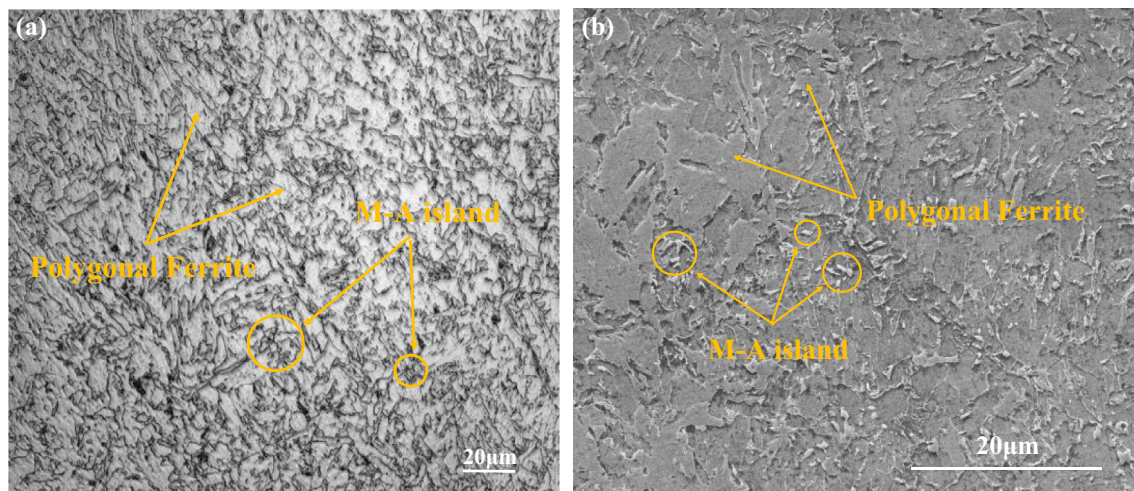


Fig. 1. (a) Optional and (b) SEM microstructural images of X70 pipeline steel in test.

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