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Microbiological corrosion of pipeline steel under yield stress in soil environment

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ABSTRACT

Microbiological corrosion induced by sulfate-reducing bacteria (SRB) of X80 steel under yield stress was studied by EIS, SEM and XPS in a soil environment. The activities of SRB stimulate the generation of secondary pitting on the bottom of wide shallow pits and near micro-crack tips on the specimen with yield stress. Yield stress enhances the stress concentration, promoting the growth of micro-cracks in the inoculated environment. With the assistance of synergistic effect of SRB and yield stress, corrosion of the steel can process easily during the repetition of SRB induced secondary pitting, anodic dissolution and formation of the passive layer.

1. Introduction

It has been well accepted that microbiological corrosion (MC) is one of the most damaging failure mode for buried pipeline in soils [1–3]. As is reported in soil, more than 20% of pipeline failures were related to the microorganisms [4]. Sulfate reducing bacteria (SRB), iron reducing/oxidizing bacteria and CO_2 reducing bacteria are the typical microorganisms associated with pipeline corrosion [5]. Among them, MC induced by SRB is the most widespread in soil environment [6,7] and several mechanism have been proposed, including but not limited to cathodic depolarization [8], local corrosive cell [9], metabolite induced corrosion [10].

Bacteria induced cracking has been observed in field [11–14]. The simultaneous effects of stress corrosion cracking (SCC) and SRB were responsible for the fracture and leakage of an API 5L X52 pipeline in the northern part of Iran in 2004 [13]. SCC was the main failure mechanism, while SRB had intensified pitting corrosion and had important roles in crack development [13]. In the SCC diagnostics of trunk pipelines in Russia, the crack depths of the pipelines were mostly related to the counts of SRB and denitrifying bacteria [14]. SRB has been used as an indicator for estimating the stress corrosion activity in certain soil-climatic zones [14]. Under simulated field conditions, associations of SRB with acid-forming bacteria accelerated the growth of SCC [15]. On the other hand, microbiologically assisted SCC has also been demonstrated via electrochemical frequency modulation [16] and slow strain rate tests (SSRT) [17–20]. All these observations indicate the effect of SRB activities on SCC of metals, but so far, no mechanism was proposed to explain their interactions in corrosion process. Therefore, further studies on effect of SRB on SCC are necessary to clarify their interactions.

In our recent paper, the individual and simultaneous effects of elastic stress (75% $\sigma_{0.2}$) and SRB on corrosion of X80 steel were conducted [21]. The results show that both elastic stress and activity of SRB enhance corrosion of the steel. The activities of SRB induce the initiation of pits, and the applied elastic stress keep and promote the growth of pits [21]. The most interesting phenomenon is that, in condition of elastic stress and the presence of SRB, a cluster of tiny secondary corrosion pitting were observed at the bottom of the primary pitting [21]. What would happen if the applied stress reaches the yield point of the steel? The mechanoelectrochemical effect developed on the metal will become significant under plastic strain condition compared to the elastic stress condition [22,23]. Besides, under plastic stress, SCC failure and cracks were observed on X70 [24] and X80 [25] pipeline steel. However, to the best of our knowledge, there are no reports to deal with the corrosion behavior of pipeline steel under plastic stress in the presence of SRB.

The aim of this paper is to investigate the SRB induced corrosion behavior of API X80 pipeline steel under yield stress. An improved loading system was designed to keep a constant environmental temperature and to renew the solutions in the test cells.

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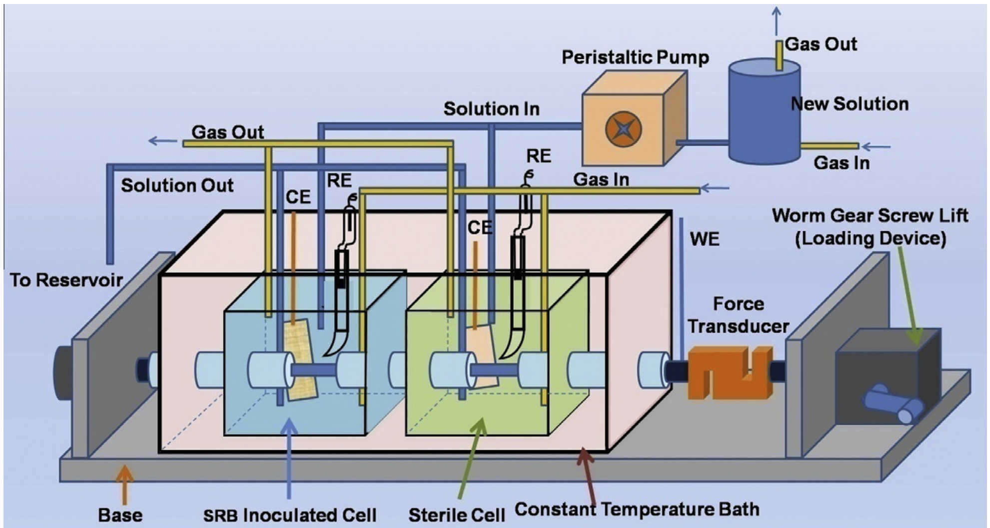

Fig. 1. Schematic diagram of the near-constant load system.

Electrochemical techniques, scanning electron microscope (SEM) and X-ray photoelectron spectroscopy (XPS) were applied to evaluate the corrosion behavior of the steel in different environments. The synergistic effects of yield stress and activity of SRB on corrosion of the pipeline steel were also discussed.

2. Experimental method

2.1. Design and construction of the improved loading system

Fig. 1 shows the improved loading system [21] for this investigation, which combined a worm gear screw lift (JWSS-2T, Hangzhou Jinwanli Machinery Factory) and a force transducer (PST-1000 kg, Keli Transducers Co., Ltd.). Two plexiglass cells were used to provide two different environments in one experiment: the sterile environment and the inoculated environment in this experiment. Two solution inlets and two outlets were used to renew the two solutions combined with a peristaltic pump, providing the nutrient that supports the growth of SRB for the long-term experiment. Two gas inlets and two outlets were used to remove the oxygen from the solutions, while another one inlet and one outlet to remove the oxygen in the new solution, providing the anaerobic environmental conditions for the growth and development of SRB. The environmental temperature was kept to 30 ± 2 °C by a water bath. More detailed information can be obtained in our previous paper [21].

2.2. Specimen, soil solution and microorganism

Material used in the present study was API X80 steel with the chemical composition (wt.%) given in Table 1. Table 2 presents the mechanical properties of the steel determined by tensile test in air. The yielding and tensile strengths of the steel are 650.7 MPa and 694.3 MPa, respectively. The tensile specimen used in this work is the same as in the previous paper [21]. Prior to the experiment, the work surfaces of the specimen were abraded with a series of grit papers (400#, 600#, 800#, and 1000#), and cleaned in acetone and alcohol, and then dried by a hair drier.

A meadow soil used in this work was collected at Shenyang, PR China (41°45′48.31″N, 123°27′11.12″E) [26,27]. The physicochemical property of the soil is given in Table 3. The soils were dried at 105 °C for 10 h, ground and pass through a sieve with 1 mm diameter openings. The soil solution was prepared by filtering the solution with the water/soil ratio of 1:1. The soil solution was autoclaved at 121 °C for 20 min and stored at 4 °C for use.

Table 1
Chemical compositions of X80 pipeline steel (wt.%).

C	Mn	Si	P	S	Mo	Ni	Cr
0.07	1.82	0.19	0.007	0.023	0.010	0.17	0.026
Cu	V	Nb	Ti	Al	N	B	Fe
0.020	0.002	0.056	0.012	0.028	0.004	0.0001	Bal.

Table 2
Mechanical properties of X80 pipeline steel in air.

Steel	$\sigma_{0.2}$ (MPa)	σ_b (MPa)	ψ	$\sigma_{0.2}/\sigma_b$
API 5L X80	650.7	694.3	71%	0.94

The same SRB strain (*desulfovibrio desulfuricans*) and medium were used as described in previous paper [28]. The API RP-38 medium was composed of $MgSO_4{\cdot}7H_2O$ (0.2 g/L), KH_2PO_4 (0.5 g/L), NaCl (10.0 g/L), ascorbic acid (1.0 g/L), sodium lactate (4.0 g/L), yeast extract (1.0 g/L) and $Fe(NH_4)_2$ $(SO_4)_2$ (0.02 g/L). The pH value of the culture solution was regulated between 7.0 and 7.2 by 1 mol/L NaOH. SRB number was determined by the three tube multiple most probable number (MPN) method according to the American Society of Testing Materials (ASTM) Standard D4412-84. Prior to the experiment, SRB strains were activated in an incubator for 12 h.

Two specimens were connected in series between the three axles and loaded slowly to 100% $\sigma_{0.2}$ (650.7 MPa, 7808 N for the two specimens). Then the two specimens were sealed with paraffin wax leaving a working area of 2 × 1.6 cm^2. Another two specimens were sealed in the same way and placed near the loaded specimens. Then the two chambers and the four specimens were sterilized by ultraviolet ray, and then the two chambers were sealed immediately with paraffin wax. The sterile soil solution (950 mL) was transferred into the two sealed chambers, respectively. Pure N_2 was bubbled into the soil solutions for about 2 h prior the test, and then the two gas inlets were sealed. After that, 50 mL strain and 50 mL medium were transferred into the two plexiglass chambers, respectively. Finally, the peristaltic pump was turned on to renew the solutions throughout the experiment. In this paper,