

## Stress Corrosion Cracking Behavior of X100 Pipeline Steel under SRB Action in Acidic Soil Environment: Postprint

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### Abstract

The effect of sulfate-reducing bacteria (SRB) on the stress corrosion cracking (SCC) behavior of X100 pipeline steel in typical acidic soil (Yingtian soil simulated solution) was investigated using slow strain rate tensile (SSRT) tests and SEM. The results show that the SCC susceptibility of X100 steel base metal and weld in sterile Yingtian soil simulated solution is higher than that in the presence of bacteria. The fracture mode of X100 steel base metal and weld in both sterile and bacteria-containing acidic soil is transgranular SCC fracture, indicating that the presence of SRB inhibits the embrittlement of X100 steel, leading to reduced SCC susceptibility. This may be due to the ability of SRB to rapidly grow and reproduce on the surface of X100 steel and form a biofilm, which continuously accumulates and becomes denser with increasing time, thereby hindering the entry of corrosive Cl<sup>-</sup> into the steel substrate surface to a certain extent, resulting in a decrease in the SCC susceptibility of X100 steel.

### Full Text

## Stress Corrosion Cracking of X100 Pipeline Steel in Acidic Soil Environment Under SRB Action

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## Abstract

The effect of sulfate-reducing bacteria (SRB) on the stress corrosion cracking (SCC) behavior of X100 pipeline steel in a typical acidic soil environment (Yingtian soil simulated solution) was investigated using slow strain rate tensile (SSRT) tests and scanning electron microscopy (SEM). The results indicate that both the base metal and weld of X100 steel exhibit higher SCC susceptibility in sterile Yingtian soil simulated solution than in the solution containing SRB. The fracture mode is transgranular SCC for both conditions, suggesting that the presence of SRB inhibits embrittlement of X100 steel and reduces its SCC susceptibility. This may be attributed to the rapid growth and reproduction of SRB on the steel surface, forming a biofilm that progressively accumulates and becomes denser over time, thereby partially blocking corrosive chloride ions from reaching the steel substrate surface and reducing SCC susceptibility.

**Keywords:** X100 pipeline steel; Stress corrosion cracking; Sulfate-reducing bacteria; Acidic soil

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## Introduction

To meet China's growing energy demands while improving transportation efficiency and reducing pipeline construction costs, the adoption of high-pressure, large-diameter, high-grade pipeline steels represents an inevitable trend in oil and gas pipeline development. As an advanced reserve material, X100 pipeline steel will undoubtedly be used extensively in future long-distance pipeline construction in China due to its advantages of high strength, pressure resistance, and low economic cost. However, the soil corrosion resistance, stress corrosion cracking susceptibility, and fatigue performance of X100 pipeline steel are critical issues that must be addressed in applied fundamental research and are prerequisites for its successful application.

In the natural gas and petroleum processing industries, 74% of leakage accidents in gas transmission trunk lines and gathering pipelines are caused by corrosion, with 15%-30% of pipeline corrosion related to microbiologically influenced corrosion (MIC), which represents one of the primary corrosion forms in gathering and transmission pipelines. Analysis of numerous samples indicates that MIC of pipeline steel under disbonded coatings is often associated with sulfate-reducing bacteria (SRB), which are the most significant and destructive microorganisms causing soil corrosion of pipeline steel. Stress corrosion cracking (SCC) of pipelines in soil environments is one of the primary hazards leading to catastrophic rupture accidents, which have occurred in many countries worldwide. Among all corrosion accidents, pitting corrosion is the main factor causing internal and external corrosion of pipelines, and SRB activity can significantly alter the corrosion environment characteristics on metal surfaces under specific service conditions, resulting in severe pitting corrosion. Most SCC cracks originate from the bottom of pits on steel surfaces. Currently, MIC and SCC have

become the two main factors threatening the long-term safe operation of buried pipelines.

To understand and confirm whether correlation and synergy exist between MIC and SCC in steel corrosion processes, some corrosion researchers abroad are conducting studies in this area, while domestic reports remain scarce. Regarding corrosion research on X100 steel, current studies both domestically and internationally have primarily focused on its SCC resistance and soil corrosion performance in sterile environments. Therefore, investigating the SCC performance of X100 steel in actual soil environments containing SRB is both urgent and of significant practical engineering concern.

The southeastern region of China has a dense underground pipeline network and features red soil as a typical representative of acidic soils, characterized by compact structure, high water content, low oxygen content, and low pH values (3-5), which are extremely corrosive to materials and result in high localized corrosion susceptibility of pipeline steel in this environment. Therefore, this study investigates the stress corrosion cracking behavior of X100 pipeline steel in an acidic soil environment under SRB action using Yingtan soil simulated solution as the test medium, providing data support and reference for the engineering application of X100 steel in acidic soils.

## Experimental Procedures

### Materials and Sample Preparation

The material used in this study was X100 pipeline steel produced by Jinan Iron and Steel Company. Its chemical composition (mass fraction, %) was: C 0.04, Si 0.20, Mn 1.50, P 0.011, S 0.003, Mo 0.02, with Fe as the balance. The mechanical properties at room temperature were: tensile strength 850 MPa, yield strength 752 MPa, yield ratio 0.89, and elongation 24%.

SSRT tests were conducted using smooth plate-shaped specimens prepared according to GB/T 15970. Base metal specimens were oriented along the circumferential direction of the actual pipe to ensure the primary loading direction during testing matched the actual service condition. Welded joint specimens were taken from straight-seam welded pipe, with the weld located at the center of the gauge length. The specimens were ground sequentially with SiC waterproof abrasive paper up to 1500 grit, then degreased with acetone, rinsed with deionized water, dried, and stored for testing.

### Test Solution and SRB Culture

A typical acidic soil from China—the Yingtan soil environment—was selected as the simulated test medium. Based on the main physicochemical data of Yingtan soil, the simulated solution composition (mass fraction, %) was: 0.0084 Cl<sup>-</sup>, 0.0054 SO<sub>4</sub><sup>2-</sup>, 0.0010 HCO<sub>3</sub><sup>-</sup>, with a pH value of 4.36. The solution was

prepared using analytically pure NaCl, Na<sub>2</sub>SO<sub>4</sub>, and NaHCO<sub>3</sub> with deionized water.

The SRB strain used in the experiments was isolated from soil through enrichment cultivation. Modified Postgate's C medium was used for SRB enrichment, with the following composition: 0.5 g/L KH<sub>2</sub>PO<sub>4</sub>, 2.0 g/L MgSO<sub>4</sub>, 0.1 g/L CaCl<sub>2</sub>, 0.5 g/L Na<sub>2</sub>SO<sub>4</sub>, 1.0 g/L NH<sub>4</sub>Cl, 3.5 g/L sodium lactate, and 1.0 g/L yeast extract. The pH was adjusted to (7.2±0.2) using 1 mol/L NaOH solution. Prior to testing, the cultured SRB strain was activated in a 30°C incubator, and then 50 mL of bacterial suspension was inoculated into 950 mL of sterilized soil simulated solution.

### SSRT Testing and Evaluation

SSRT tests were performed using a Letry slow strain rate stress corrosion testing machine at a constant strain rate of  $1 \times 10^{-5}$  s<sup>-1</sup> and room temperature. One hour before SSRT testing, high-purity N<sub>2</sub> was purged through the inoculated Yingtan soil simulated solution to remove O<sub>2</sub> and prevent oxidation.

After testing, the specimens were first rinsed with deionized water to remove corrosion products from the surface, then the fracture surfaces were cleaned in an ultrasonic cleaner with acetone solution to remove surface corrosion products, dried, and stored in a desiccator. Fracture morphology was examined using a JSM-6390A scanning electron microscope (SEM).

After fracture, the SCC susceptibility of X100 steel in Yingtan soil simulated solution was evaluated using tensile strength loss ( $I_\sigma$ ), reduction of area loss ( $I_\psi$ ), and elongation loss ( $I_\delta$ ). The calculation formulas for  $I_\sigma$ ,  $I_\psi$ , and  $I_\delta$  are as follows:

$$I_\sigma = (1 - \sigma/\sigma_0) \times 100\% \quad (1)$$

$$I_\psi = (1 - \psi/\psi_0) \times 100\% \quad (2)$$

$$I_\delta = (1 - \delta/\delta_0) \times 100\% \quad (3)$$

where  $\sigma$  and  $\sigma_0$  are the tensile strength in solution and air, respectively;  $\psi$  and  $\psi_0$  are the reduction of area in solution and air, respectively; and  $\delta$  and  $\delta_0$  are the elongation in solution and air, respectively.

## Results and Discussion

### 2.1 SSRT Results

The stress-strain curves of X100 pipeline steel base metal and welded specimens in Yingtan soil simulated solution and air are shown in Figure 1 [Figure 1:

see original paper], and the stress corrosion parameters and results in different media are presented in Table 1 .

As seen in Figure 1 and Table 1, the strain, elongation, and reduction of area of X100 steel welded specimens in sterile Yingtan soil simulated solution are all smaller than those in the solution containing SRB. Based on the variations in  $I$ ,  $I$ , and  $I$ , the SCC susceptibility ranking of X100 steel is as follows:  $I$  (welded specimen with SRB) <  $I$  (sterile welded specimen) <  $I$  (sterile base metal specimen) <  $I$  (base metal specimen with SRB);  $I$  (welded specimen with SRB) <  $I$  (base metal specimen with SRB) <  $I$  (sterile base metal specimen) <  $I$  (sterile welded specimen); and  $I$  (sterile welded specimen) <  $I$  (welded specimen with SRB) <  $I$  (base metal specimen with SRB) <  $I$  (sterile base metal specimen). Comparison reveals that the variation patterns of  $I$ ,  $I$ , and  $I$  are not entirely consistent, making it difficult to establish a definitive relationship between the medium and SCC susceptibility. However, it can be confirmed that SCC susceptibility of X100 steel in sterile Yingtan soil simulated solution is generally greater than that in the solution containing SRB. Comparing  $I$ ,  $I$ , and  $I$  shows that  $I$  decreased by a maximum of 7.46%,  $I$  by 28.89%, and  $I$  by 4.12%, indicating that the effect of sterile versus SRB-containing Yingtan soil simulated solution on X100 pipeline steel primarily involves reduction of ductility rather than strength. The negative  $I$  value for X100 steel welded specimens tested in SRB-containing soil simulated solution indicates that the elongation in this environment is actually greater than in air. Furthermore, both  $I$  and  $I$  of welded specimens are significantly smaller than those of base metal specimens in SRB-containing solution, suggesting that SRB has a greater influence on the SCC susceptibility of welded specimens. Based on this analysis, the presence of SRB in Yingtan soil simulated solution inhibits embrittlement of X100 steel, thereby reducing its SCC susceptibility.

## 2.2 Fracture and Crack Morphology

Figure 2 [Figure 2: see original paper] shows the SSRT fracture morphologies of X100 pipeline steel base metal and weld in air. In air testing, both base metal and welded specimens exhibited obvious necking near the macroscopic fracture, with the base metal showing much more pronounced necking than the weld. The base metal fracture surface was perpendicular to the tensile axis, while the weld fracture surface was approximately  $45^\circ$  to the tensile axis, with the weld fracture being flatter than that of the base metal. The microscopic fracture morphologies of both base metal and weld were dominated by dimples, with those in the base metal being larger and deeper than in the weld. Microvoids existed between dimples, and some dimple walls showed obvious serpentine slip characteristics, indicating a dimple-microvoid type of ductile fracture typical of ductile failure. These observations demonstrate that SSRT testing of X100 pipeline steel in air involves plastic deformation. When stress exceeds the material's yield strength, plastic deformation begins, leading to dislocation pile-up at inclusions, precipitates, grain boundaries, and subgrain boundaries, which cre-

ates stress concentrations and subsequently forms microvoids. With increasing deformation, these microvoids coalesce and grow, eventually resulting in necking and fracture[18].

Figure 3 [Figure 3: see original paper] presents the macroscopic and microscopic SEM morphologies of SSRT fractures of X100 steel base metal in sterile and SRB-containing Yingtan soil simulated solutions. The macroscopic fractures show oblique fracture surfaces approximately  $45^\circ$  to the tensile axis in both conditions, with obvious necking observed. The necking was less pronounced in the sterile solution than in the SRB-containing solution. Microscopically, the fracture in sterile solution exhibited few dimples and microvoids along with localized brittle fracture features (Fig. 3a2), and numerous striped SCC cracks appeared on both sides of the fracture (Fig. 3a3), indicating a ductile/brittle mixed fracture and suggesting high SCC susceptibility of X100 steel base metal in sterile Yingtan soil simulated solution. In contrast, the fracture morphology in SRB-containing solution was dominated by dimples, showing ductile fracture characteristics (Fig. 3b2), although striped SCC cracks were present on the right side of the fracture, with dimple morphology surrounding the cracks (Fig. 3b3). This indicates that SCC susceptibility of X100 steel base metal in SRB-containing Yingtan soil simulated solution is lower than in sterile solution, demonstrating that SRB reduces SCC susceptibility.

Figure 4 [Figure 4: see original paper] shows the macroscopic and microscopic SEM morphologies of SSRT fractures of X100 steel weld in sterile and SRB-containing Yingtan soil simulated solutions. The macroscopic fractures exhibit oblique fracture surfaces approximately  $45^\circ$  to the tensile axis in both conditions, with obvious necking observed in SRB-containing solution and almost no necking in sterile solution. Microscopically, the fracture in sterile solution showed flat dimples in the edge region with obvious tear ridges between dimples, while the central region exhibited quasi-cleavage morphology with brittle characteristics, indicating a ductile/brittle mixed fracture and high SCC susceptibility of X100 steel weld in sterile Yingtan soil simulated solution. In SRB-containing solution, the fracture morphology was dominated by small dimples with few voids, showing ductile fracture characteristics, indicating lower SCC susceptibility of X100 steel weld in SRB-containing Yingtan soil simulated solution compared to sterile conditions. This demonstrates that SRB reduces SCC susceptibility of X100 steel welds.

A primary characteristic of stress corrosion is the presence of secondary cracks in addition to the main crack. Secondary cracks typically exhibit multiple nucleation sites, high density, and varying lengths and sizes. Generally, the presence of microcracks (secondary cracks) on the side surface of a tensile fracture specimen in corrosive media indicates SCC susceptibility of the material.

Figure 5 [Figure 5: see original paper] shows the side surface morphologies near the fracture of X100 pipeline steel base metal and weld tested in air. No secondary cracks are observed on the side surfaces of either base metal or weld fractures. Figure 6 [Figure 6: see original paper] presents the side surface mor-

phologies near the fracture of X100 pipeline steel base metal and weld tested in Yingtan simulated solution. Secondary cracks are present on the side surfaces of both base metal and weld fractures in both sterile and SRB-containing Yingtan soil simulated solutions, with some cracks having coalesced due to propagation. In sterile solution, secondary cracks propagate at 45° or perpendicular to the applied stress axis, while in SRB-containing solution, they propagate perpendicular to the stress axis. As seen in Figures 6a and 6c, secondary cracks extend in straight lines, indicating that the tensile fractures of X100 steel base metal and weld in sterile Yingtan soil simulated solution belong to transgranular SCC. Similarly, Figures 6b and 6d show that secondary cracks also extend in straight lines in SRB-containing solution, confirming that fractures in this environment are also transgranular SCC. Moreover, the density of secondary cracks is higher in sterile than in SRB-containing solution, and cracks are deeper in sterile conditions, indicating higher SCC susceptibility in sterile Yingtan soil simulated solution. This further demonstrates that SRB reduces SCC susceptibility of X100 steel.

The above analysis demonstrates that the presence of SRB reduces SCC susceptibility of X100 pipeline steel, which contradicts the common perception that “SRB are the most corrosive species among microorganisms to steel.” Hernandez et al.[19] reported that microorganisms do not always enhance corrosion; the same bacterial species may exhibit both corrosive and protective effects, with *Pseudomonas* being such an organism, and the 14 genera of SRB include the *Desulfovibrio* genus. Under certain conditions, the identical microorganisms can exhibit protective effects that slow corrosion.

Videla[20] comprehensively evaluated various mechanisms by which bacteria can mitigate or inhibit corrosion, focusing on three primary mechanisms: (1) neutralization of corrosive substances present in the environment; (2) formation of protective films on metals or stabilization of existing protective films; and (3) reduction of medium corrosivity. Therefore, corrosion mitigation may result from one of these mechanisms or a combination thereof. As an anaerobic bacterium, SRB can rapidly grow and reproduce in the O<sub>2</sub>-free Yingtan soil simulated solution, forming a biofilm that adheres to the X100 steel surface through extracellular polymeric substances. With increasing SSRT test duration, this biofilm continuously accumulates and becomes denser on the steel surface, partially blocking corrosive chloride ions from reaching the X100 steel substrate and thereby reducing SCC susceptibility.

## Conclusions

- (1) The strain, elongation, and reduction of area of X100 steel welded specimens in sterile Yingtan soil simulated solution are all smaller than those in the SRB-containing solution. Based on variations in  $\sigma$ ,  $\epsilon$ , and  $RA$ , it can be confirmed that SCC susceptibility of X100 steel in sterile Yingtan soil simulated solution is generally greater than in SRB-containing solution, indicating that SRB inhibits embrittlement of X100 steel and reduces its

SCC susceptibility.

- (2) X100 steel base metal and weld exhibit lower SCC susceptibility in SRB-containing Yingtan soil simulated solution than in sterile conditions, demonstrating that SRB reduces SCC susceptibility of both base metal and weld. The fracture mode of X100 steel base metal and weld in both sterile and SRB-containing Yingtan soil simulated solutions is transgranular SCC.
- (3) The mechanism by which SRB reduces SCC susceptibility of X100 steel base metal and weld may be that SRB rapidly reproduces and forms a biofilm in the O-free Yingtan soil simulated solution. This biofilm continuously accumulates and becomes denser over time, partially blocking corrosive chloride ions from reaching the X100 steel substrate surface and thereby reducing SCC susceptibility.

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