



## Short Communication

# Identification of the selective corrosion existing at the seam weld of electric resistance-welded pipes



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## ABSTRACT

The selective corrosion existing at the seam weld of high frequency electric resistance welded pipes of carbon steel with low sulfur content in electrolyte solutions is revealed by localized electrochemical measurements. The seam weld, mainly consisted of ferrite, has more negative open circuit potential and higher anodic dissolution current density than the base metal consisting ferrite and pearlite. Between the seam weld and the base metal, there is a galvanic coupling effect accelerating the dissolution kinetics of the seam weld such that V-shaped corrosion groove preferentially occurs at the seam weld.

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## 1. Introduction

Electric resistance welding (ERW) using no weld filler wire is one of the lowest cost and highest efficiency pipe manufacturing technologies. ERW longitudinal seam welded pipe has been used in many applications, such as oil and gas pipelines [1,2], oil well casings [3] and coiled tube [4]. When these ERW pipes work in corrosive environments, serious selective corrosion exists in the seam weld [5–9] and causes premature and unexpected failures of ERW pipes [1,9,10]. This phenomenon, which is also known as selective seam weld corrosion with V-shaped corrosion damage or grooving corrosion, has been observed in environments ranging from seawater to soils and can proceed at very high rates. This grooving corrosion can be critical since it shortens the life of ERW steel pipes sometimes due to penetration that leads to leaks but also because the defect that tends to be formed during grooving corrosion is similar to a long, sharp notch which can act as the initiation site for fatigue and environmentally assisted cracking [11,12].

The grooving corrosion in plain carbon steel ERW pipes is attributed to, in many cases, non-metallic inclusion MnS [5]. The presence of MnS inclusions can lead to S-enriched portions of the surrounding ferrite phase during rapid heating and cooling in the ERW process. The welding area was said to be anodic in comparison to the base material hence forming a macro-cell between the narrow seam weld and the base metal. This macro-cell can lead to corrosion pits in the weld [5]. Despite efforts [6] to also reduce the sulfur content to relatively low values (less than 0.008 wt.%), ERW

pipes of a carbon steel and a micro-alloyed steel still appear to suffer from grooving corrosion problems in corrosive environments [13–15]. In this paper, localized electrochemical tests are used to characterize the micro-electrochemical activities at the seam weld of an ERW pipe in electrolyte, which establishes a mechanistic understanding of the selective seam weld corrosion. This may provide a more mechanistic insight into the fundamentals of ERW pipe failure related to the selective seam weld corrosion.

## 2. Experimental

Samples used in this research were cut from a  $\Phi 193.7$  mm  $\times$  7.34 mm high frequency ERW pipe manufactured by sheets of a carbon steel, with a chemical composition (wt.%): C 0.26, Si 0.22, Mn 1.29, S 0.002, P 0.016 and Fe balance. The pipe was subjected online heat treatment with peaking temperature of 930 °C and duration of 8 s only for the welding zone. During the process of post-weld heat treatment, the seam weld and the heat-affected zone were heated beyond the upper critical temperature ( $A_3$  point) and had been austenitized. The austenite was cooled in open air to produce ferrite with pearlite. The microstructure in the heat-affected zone was similar to the original microstructure of carbon steel sheets. The samples containing the seam weld were with dimension of 20 mm  $\times$  15 mm  $\times$  5 mm. The working surface was outer surface of the ERW pipe and was ground with 100–1000 grit emery paper.

The corrosion environments used in this work were aerated 3.5 wt.% NaCl with pH ranging from 6.8 to 7.3, oxygen-free 3.5 wt.% NaCl saturated by CO<sub>2</sub> with pH ranging from 6.2 to 6.6 and NS4 solution purged with 5% CO<sub>2</sub> balanced with N<sub>2</sub> with pH

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ranging from 6.4 to 6.8. The chemical composition of NS4 solution was:  $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$  0.181 g/L, KCl 0.122 g/L,  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  0.131 g/L and  $\text{NaHCO}_3$  0.483 g/L. The reason for selecting these environments is that ERW longitudinal seam welded pipe has been used in many environments ranging from seawater to soils.

Localized open circuit potential (OCP) was measured by a scanning reference electrode technique (SRET) [16], where a saturated KCl reference (SCE) with a  $50 \mu\text{m}$  tip moved above the steel electrode surface. The distance of the microreference electrode to the sample surface was kept at  $100 \mu\text{m}$ . The scanning rate was  $1 \text{ mm/min}$ . This measurement was done after the sample was immersed freely in the corrosive solution for 30 min.

Localized dissolution current density of the ERW pipe samples was measured by a scanning vibrating electrode technique (SVET) [17,18], where a Pt microelectrode with a  $100 \mu\text{m}$  tip vibrated above the steel electrode surface. The vibrating amplitude of the microelectrode was  $100 \mu\text{m}$  and the vibrating frequencies were  $200 \text{ Hz}$  in the direction normal to the electrode surface. The difference of potentials when the microelectrode was located at the vibrating peak and valley, respectively,  $\Delta E$ , was measured by an electrometer incorporated in M8812. The solution resistance between the vibrating peak and valley,  $R$ , is determined by

$$R = d/K \quad (1)$$

where  $d$  is the vibrating amplitude of the microelectrode ( $100 \mu\text{m}$ ) and  $K$  is the solution conductivity. The conductivity of the solutions was measured by DDS-370 conductivity meter. The measured conductivities are, respectively,  $56.12 \text{ mS/cm}$  for aerated 3.5 wt.% NaCl (close to  $55.4 \text{ mS/cm}$  in Refs. [19,20]),  $56.84 \text{ mS/cm}$  for oxygen-free 3.5 wt.% NaCl saturated by  $\text{CO}_2$  and  $1.179 \text{ mS/cm}$  for NS4 solution purged with 5%  $\text{CO}_2$  balanced with  $\text{N}_2$  (slightly higher than  $1.051 \text{ mS/cm}$  for NS4 solution in Ref. [21]). The SVET current density,  $i_{\text{svet}}$ , was then obtained by

$$i_{\text{svet}} = \Delta E/R \quad (2)$$

Galvanic current density between the seam weld and the base material,  $i_g$ , was measured by zero resistance ammeter. Two samples were used in this measurement. One was etched with 4 wt.%  $\text{HNO}_3$  ethanol solution to show the seam weld and to fix the accurate position of the seam weld. Then, the seam weld was taken as the exposed surface and other surfaces of the sample were sealed by epoxy resin. The same exposed surface of the base material in shape and area as the seam weld was done in another sample. Two samples, with a distance of the exposed surfaces being kept at  $30 \text{ mm}$ , were fitted together by a copper wire, in which a zero resistance ammeter was connected for measuring the galvanic current.

All the measurements above were conducted at room temperature of  $25 \text{ }^\circ\text{C}$ . A microcomputer was used for programming and data acquisition.

### 3. Results

Fig. 1 shows the OCP distribution maps across the seam weld and the base material measured in the corrosive solutions at  $25 \text{ }^\circ\text{C}$  by SRET. The microstructure graph of the seam weld after post-weld heat treatment shows that the bond line mainly consists of ferrite corresponding to previous investigations [10,13–15]. It is seen that the seam weld has more negative OCP values than the base material consisting of ferrite and pearlite, suggesting an increase of the surface activity of the weld metal in a given solution. This may be due to difference in the amount of pearlite or  $\text{FeC}_3$  phase that acts as a cathode phase. In fact, the microstructure in the welding zone after post-weld heat treatment should be determined by chemical composition such as carbon content.

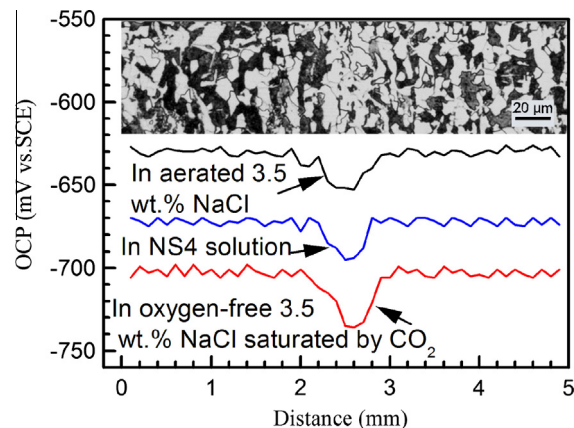


Fig. 1. OCP distributions across the seam weld in three solutions at  $25 \text{ }^\circ\text{C}$  and the microstructure of the seam weld etched in 4 wt.%  $\text{HNO}_3$  ethanol.

Carbon element loss exists in the welding zone caused by the rapid heating and cooling in processing of electric resistance welding [14] such that the amount of pearlite or  $\text{FeC}_3$  phase decreases in welding zone.

It should be pointed out that many fluctuations exist in OCP values of the base material measured by SRET. The fluctuations should depend on the microstructure as the micro SCE is applied. When the micro SCE moves above  $\text{FeC}_3$  phase that has more positive OCP value than ferrite phase, more positive OCP values will be measured. When the micro SCE moves above ferrite phase, more negative OCP values will be measured. The average OCP values of the base material are, respectively,  $-630 \text{ mV(SCE)}$  for aerated 3.5 wt.% NaCl,  $-702 \text{ mV(SCE)}$  for oxygen-free 3.5 wt.% NaCl saturated by  $\text{CO}_2$  and  $-672 \text{ mV(SCE)}$  for NS4 solution. As a result, the OCP value is strongly affected by the composition of electrolyte.

The OCP differences between the base material and the bonding line (minimum OCP value) are, respectively,  $23 \text{ mV}$  for aerated 3.5 wt.% NaCl,  $34 \text{ mV}$  for oxygen-free 3.5 wt.% NaCl saturated by  $\text{CO}_2$  and  $23 \text{ mV}$  for NS4 solution. Because the OCP difference is more than zero, the metal at the bonding line acts as anodic position, at which a corrosion groove appears [14].

Fig. 2 shows the current density distribution maps across the seam weld and the base material measured in the corrosive solutions at  $25 \text{ }^\circ\text{C}$  by SVET. Surface morphology of the corroded sample immersed in aerated stirred 3.5 wt.% NaCl at  $25 \text{ }^\circ\text{C}$  for 32 days shows that V-shaped selective corrosion occurs at the seam weld

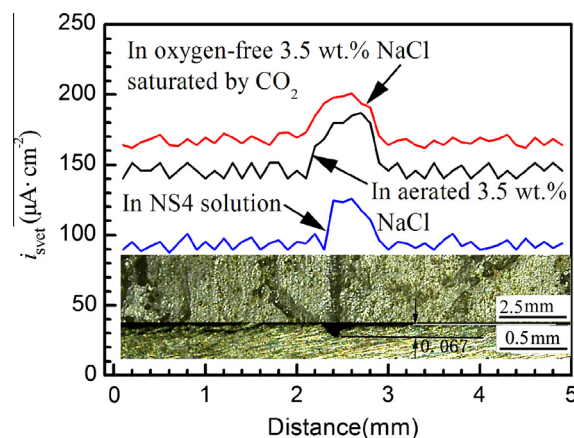


Fig. 2. Current density distributions across the weld in the corrosive solutions at  $25 \text{ }^\circ\text{C}$  and surface morphology of the corroded sample immersed in aerated stirred 3.5 wt.% NaCl at  $25 \text{ }^\circ\text{C}$  for 32 days.

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