

Case Report

The effect of corrosion inhibitor on X-65 steel weldment in high flow rate conditions

Meyliana Wulandari^a, Nofrizal Nofrizal^{b,*}, Susan Impey^c, Konstantinos Georgarakis^c, Pandian Bothi Raja^d, M. Hazwan Hussin^d^a Department of Chemistry Education, Faculty of Educational Science, State Islamic University Syarif Hidayatullah, Jakarta, 15412, Indonesia^b Ministry of Energy and Mineral Resources, Lemigas, Jakarta 12230, Indonesia^c School of Manufacturing, Cranfield University, Wharley End, Cranfield, Bedford, MK43 0JR, UK^d School of Chemical Sciences, Universiti Sains Malaysia, Minden, 11800, Penang, Malaysia

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ABSTRACT

This study aims to determine the performance of a commercial corrosion inhibitor (mixture of ethanediol, 2-butoxy ethanol, and fatty acid amine) in inhibiting weldment corrosion. The inhibitor's effect on parent metals (PM), heat affected zone (HAZ), and weld metal (WM) has been investigated on the corrosion behaviour of X65-welded structures in brine solution (10 m/s) using submerged jet impingement (SJI) flow loops. The results show that inhibitors can reduce the corrosion rate by 10 times to 0.36 mm/y for WM. Linear polarization resistance and electrochemical impedance spectroscopy (EIS) show that the WM exhibited the highest corrosion rate.

1. Introduction

The oil and gas industry uses pipelines for oil and gas transportation over long distances [1]. According to the American Petroleum Institute (API), steel is a primary pipeline material that can be classified based on its chemical composition: carbon steel, alloyed steel, and stainless steel [2]. The carbon steel classification consists of X52, X65, X70, and X80. However, almost all oil and gas industries prefer X65 because of its good mechanical properties and low cost. Construction of pipeline transportation in the oil and gas industry requires welding, which combines metal structures by melting a filler material/weld metal. The parent metal is the base metal (PM). HAZ is a section of weldment that is affected by high temperatures [3]. Differences in the chemical composition and microstructure of PM, WM, and HAZ cause the galvanic effect. If the fluid in the pipeline reacts with CO₂, H₂S, and water to produce carbonic acid, known as “sweet corrosion” can damage the pipeline's construction and require significant funds to repair [4,5].

Corrosion prevention methods were practised in oil and gas industries, the first of which is using a protective layer (barrier). This method consists of coating and painting [6]. The weakness of painting is that heat and sunlight easily damage the layer [7]. The coating is to form a barrier, protecting the steel surface from the corrosive environment.

Inorganic coatings are rarely used due to environmental issues. Chitosan was extracted from Nila tilapia fish as an organic coating to protect ASTM A36 carbon steel surfaces using electrophoretic deposition (EPD) and dip coating (DC) techniques. This method produces high efficiency but is not resistant to high temperatures [8]. The third method is cathodic protection, which reduces the oxidation rate so the pipeline becomes the cathode. The fourth method is the use of corrosion inhibitors [9]. Inhibitors are chemical compounds in small amounts that are added to reduce the reaction between the metal and the environment [10]. Inhibitors can be applied without disrupting the production process. Inorganic inhibitors (including chromates, molybdates, phosphates, and nitrates) show good inhibition efficiency. However, these inhibitors are toxic to the environment [11].

Organic inhibitors show good anti-corrosion characteristics because heteroatom structures (nitrogen, oxygen, phosphorus, and sulfur) generate corrosion inhibition capability. N, O, P, and S atoms are the centre of adsorption for the metal and protect it from preferential weld corrosion [12,13]. The inhibitor compound binds the metal surface, forms the active layer, and subsequently reduces the corrosion rate. Due to organic corrosion inhibitors being essential for industry, studies on inhibitors are still being encouraged [14]. Bee wax propolis and durian peel have been reported to have an inhibition efficiency of >97 % on 304SS

* Corresponding author.

E-mail address: nofrizal.nof@esdm.go.id (N. Nofrizal).<https://doi.org/10.1016/j.csee.2024.100868>

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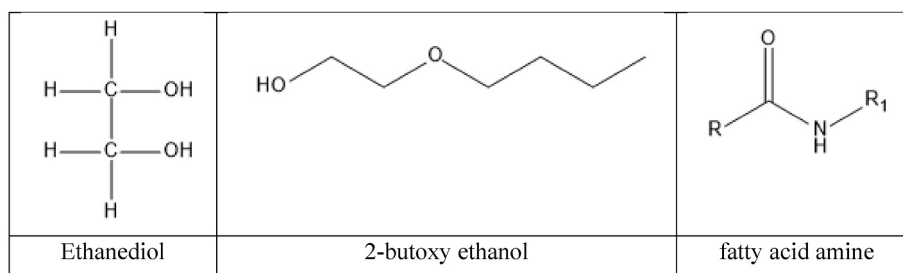


Fig. 1. The molecular structure of inhibitor (Ethanediol, 2-butoxy ethanol, and fatty acid amine).

Table 1

The composition of PM and WM (wt %).

	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb	Ti	N
PM	0.07	0.3	1.51	0.01	<0.005	0.02	0.01	0.39	0.037	0.26	0.02	<0.01	0.05
WM	0.07	0.3	1.59	0.01	0.007	0.03	0.11	0.27	<0.01	0.1	<0.01	<0.01	0.05

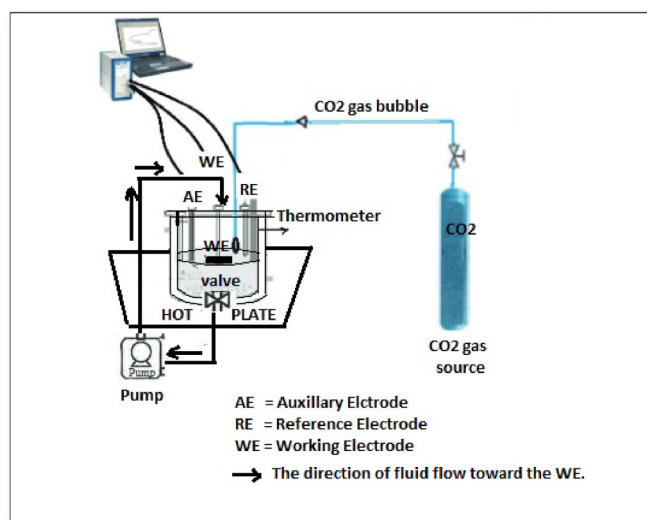


Fig. 2. The corrosion cell setup consists of a working electrode (weldment), reference (saturated calomel electrode), and auxiliary electrode (platinum) in 1 L of sea salt connected to a CO₂ gas source at ten m/s [20].

because it has flavonoid and antioxidant groups [15,16]. Various organic synthetic inhibitors have been studied as corrosion inhibitors, including hydrazides derivatives, benzotriazole, glutaraldehyde, 3-((5-mercapto-1,3,4-thiadiazol-2-yl)imino)indolin-2-one (MTIO) [17–19]. The inhibition efficiency of organic inhibitors is not as great as that of organic synthetic inhibitors. Hence, synthetic organic inhibitors were used in this study. In spite of several other heteroatom inhibitors that have been reported in the literature, the corrosion inhibition efficiency of the commercially available ethanediol, 2-butoxy ethanol, and

fatty acid amine has not been extensively studied. Ethanediol contains 2 –OH groups. 2-butoxy ethanol contains O and –OH atoms, while fatty acid amine contains O and N atoms. According to theory, N, O, P, and S atoms can act as metal adsorption centers (Fig. 1). The bond between the electron-donating group and the metal will produce a protective layer on the metal surface.

To simulate the actual fluid conditions, the submerged jet impingement method is the most suitable compared to other methods (rotating cage, recirculating flow loop, rotating cylinder electrode (RCE), and SJI). The SJI method allows simultaneous electrochemical measurements of all weldments in the same hydrodynamic region. Meanwhile, in this research, the effect of inhibitors on working electrodes located on the outer area was studied because they have a larger area, resulting in better repeatability. In this study, we investigated the effect of applying a novel inhibitor formulation on the SJI target in brine saturated with CO₂ with a flow rate of 10 m/s. Next, the corrosion rate between the PM, HAZ, and WM is monitored using galvanic measurements, linear polarization resistance, and electrochemical impedance spectroscopy. Later, surface morphology was screened via scanning electron microscope-energy dispersive X-Ray, focus ion beam, X-ray diffraction, and Raman spectroscopy.

2. Experimental

2.1. SJI target design

A 210 × 60 mm² area of submerged jet impingement (SJI) samples with 30 mm thickness were prepared using alloyed-arc welding from X65 steel. The X65 weldment was cut using electrical discharge machining (EDM) to produce WM, HAZ, and PM. Table 1 shows the composition of PM and WM.

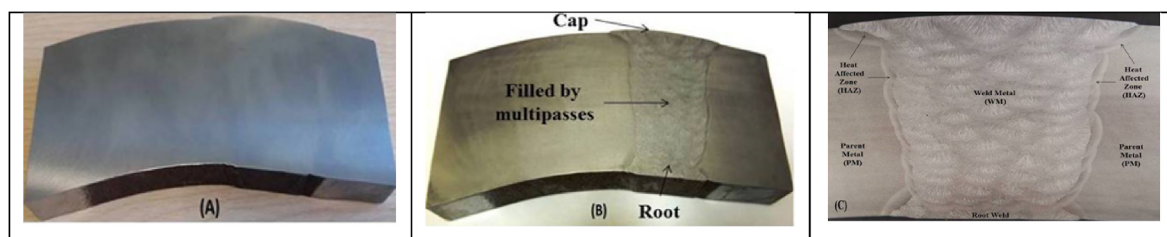


Fig. 3. Plate after welding (A), plate etched in 10 % nital (B), and the PM, the WM, and the HAZ macrostructures (C).

2.2. Corrosion cell setup

Figs. 2 and 3 show the corrosion cell setup and the macro photo images of PM, WM, and HAZ. The flow loop is filled with a working electrode (PM, WM, HAZ); the reference electrode used is a saturated calomel electrode, while platinum acts as an auxiliary electrode. The dissolved oxygen in the flow loop was removed with N₂ gas for 2 hours, and the CO₂ gas was continued at a flow rate of 10 m/s (30 °C). The inhibitor has been studied previously by optimizing several inhibitor concentrations (0–40 ppm), and the highest inhibitor efficiency was obtained at 30 ppm. The blank condition was run without using an inhibitor at 10 m/s.

2.3. Sea salt

A Tropic Marin sea salt used in this study contains calcium (1.1 %), chlorine (49 %), magnesium (3.5 %), potassium (1.1 %), sodium (27 %), and sulfur (2.2 %). The inhibitor concentration used in this study was only 30 ppm based on a preliminary experiment.

2.4. Electrochemical measurements

2.4.1. Galvanic measurements

Galvanic corrosion rate measurements were employed to determine the galvanic effect when several metals with different chemical compositions or microstructures are combined. Weldment is a condition where there are differences in chemical composition and microscopic structure between the parent material (PM), the heat-affected zone (HAZ), and the weld metal (WM). The large galvanic currents that occur in welding between PM, WM, and HAZ can sometimes cause severe local corrosion. The anodic and cathodic metal sites were immersed in the solution and purged for 3 hours with CO₂. Galvanic measurements are studied using a zero-resistance ammeter (Galvo-Gill 12) connected to a data logging PC (ACM Instrument, Grange-over-Sands, UK). The potential, temperature, and pressure used were about −740 mV (SCE), 28 °C (10 m/s), and 1 bar, respectively. The total of galvanic currents will be zero, as stated in Equations (1) and (2).

$$I_{PM} + I_{HAZ} + I_{WM} = 0 \quad 1$$

$$I_{HAZ} = -I_{PM} - I_{WM} \quad 2$$

The weld specimen area for PM, HAZ, and WM in the SJI target are 1.1383, 0.1439, 0.2878 cm², respectively. By calculating the current divided by the area (cm²), the corrosion rate in mm/y was calculated via using Equation (3).

$$1 \mu\text{A}/\text{cm}^2 = 0.01186 \text{ mm/y} \quad 3$$

2.4.2. The self-corrosion rate measurement

A potentiostat (ACM Instrument, Grange-over-Sands, UK) was used to measure the self-corrosion rate at 28 °C and 10 mV/min scan rate. The open circuit potential (OCP) was measured for 30 min to stabilize the steady-state potential with a potential scanned range from ±10 mV. The resulting curve is log I vs potential (mV), and the resulting slope/gradient shows the corrosion rate. Polarization resistance (Rp) was calculated using Equation (4).

$$I_{\text{corr}} = \beta / (R_p) \quad 4$$

Where: I_{corr} is the corrosion current (A/cm²), β is the LPR constant for the material (β value is 26), and R_p is the polarization resistance (Ωcm^2).

2.4.3. EIS measurements

EIS measurements were carried out using a computer-controlled potentiostat (ACM Instrument, Grange-over-Sands, UK) of potential

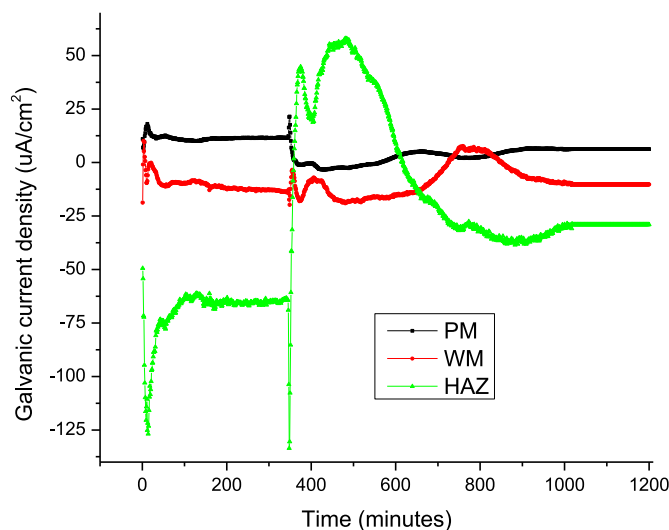


Fig. 4. The current density of PM, WM, HAZ in 1 L of sea salt and 30 ppm of inhibitor. The measurements are carried out at a potential of −740 mV (SCE), 28 °C, 10 m/s, and 1 bar.

from PM, HAZ, and WM over a frequency from 0.005 Hz to 20 kHz with a signal amplitude perturbation of 10 mV with AC potential. EIS data yields R_p and R_s . The corrosion rate was calculated using Equation (5).

$$R_{ct} = R_p - R_s \quad 5$$

Where: R_{ct} is the corrosion rate (mm/y), R_p is the polarization resistance, and R_s is the solution resistance.

2.5. Surface characterization

2.5.1. Scanning electron microscope-energy dispersive X-ray (SEM-EDX)

SEM-EDX analysis was carried out using the Philips-XL30 instrument and Oxford Instrument's Aztec software for data analysis. The samples were rinsed with isopropanol and dried prior to the analysis.

2.5.2. Focus ion beam (FIB) analysis

Characterization using FIB (TESCAN LYA3) was carried out to study the surface characteristics of the sample before and after corrosion. In order to get the conductive sample, the sample is coated with a 10 nm Pt coating. After that, the sample is shot with a 5 keV energy beam, which then produces an image.

2.5.3. X-ray diffraction (XRD)

The corroded sample obtained was characterized using the Siemens D5005 instrument with monochromatic radiation CuK α ($\lambda = 1.54056 \text{ \AA}$). After that, Fiffactplus XRD commander (version 2.4.1, 2005) software was used to analyze the data. XRD analysis was conducted with homogeneous powder (20 μm). The diffraction angle is calculated using Bragg's law in Equation (6).

$$n\lambda = 2d \sin \theta \quad 6$$

Where θ is the angle of the X-ray beam, d is the distance between the atomic planes in the crystal, and λ is the X-rays wavelength.

2.5.4. Raman analysis

A metal sample was located on a glass slide and viewed with a microscope (Olympus BX 40 equipped with a 100x objective lens. Raman (Jobin-Yvon LABRAM confocal-Raman spectrometer) has an Nd-YAG laser (100 mW, 532.2 nm) and diffraction gratings of 1800 grooves mm^{−1}. Analysis was conducted using Lap-spec 5 software with a scan rate between 0 until 2000 cm^{−1}. Data was analyzed by comparing the sample band with the standard band frequency.

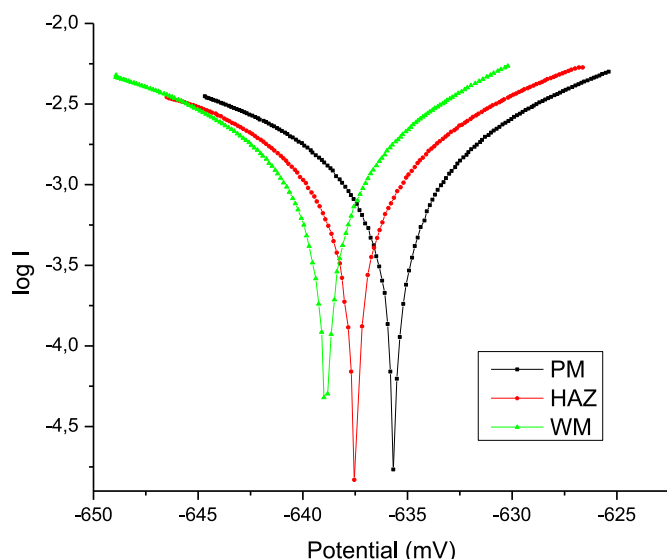


Fig. 5. Linear polarization resistance measurements of the weldment produce a Tafel plot of weldment in 1 L of sea salt in the presence of 30 ppm inhibitor. Measurements were carried out at 10 mV/min. The flow loop temperature is maintained at 28 °C and using inhibitor.

3. Results and discussion

3.1. Galvanic measurement

The galvanic current density of PM, WM, and HAZ in inhibited conditions with a flow rate of 10 m/s (corresponding to a shear stress of 280 Pa) were depicted in Fig. 4. This image shows that under no-flow conditions, when N₂ flows into the brine solution, the PM density looks stable at 12–15 $\mu\text{A}/\text{cm}^2$. The same trend is found with WM and HAZ, which shows that the current density is lower than PM's. This phenomenon is caused by forming an inhibitor film on the weld surface so that a spike in corrosion reactions does not occur as in uninhibited conditions [20]. After 400 minutes, the pump was turned on, and flowing conditions started. The HAZ, initially in a cathodic condition, changed to anodic while the PM and WM were in a cathodic condition. It may be due to the rupture of the inhibitor layer in the HAZ, which initiates a corrosion reaction.

After 600 minutes, the current density changed where the HAZ slowly moved towards the cathodic, and conversely, the WM shifted slightly towards the anodic zone. However, the WM current returns to the cathodic direction as the film layer re-forms on the weldment surface. The PM is in an anodic state at the end of the reaction and protects the WM and HAZ. The phenomenon shows, as the previous report, that the inhibitor works as expected, where the WM and HAZ are protected by PWC attacks [21]. It differs from the uninhibited condition where the weld experiences PWC as indicated by the high corrosion current density, namely 55 $\mu\text{A}/\text{cm}^2$ in the outer electrode regions [20].

Previous results also reported that there was a 20 % decrease in WM current density due to the use of inhibitors [22]. Similar results also reported the inhibitor application could reduce the corrosion current density from 150 to 20 $\mu\text{A}/\text{cm}^2$ [23].

3.2. Self-corrosion measurements

LPR measurements provided data on self-corrosion of the weldment. The material with the highest LPR has the lowest corrosion rate because LPR is inversely related to I_{corr} . In the uninhibited condition, the open circuit potential (OCP) data shows electrode potentials for WM, PM, and HAZ at –733, –729, and –730 mV, respectively. Meanwhile, the electrode potential is in an increasingly positive range for welding with

Table 2

Tafel plot characteristic of inhibited weldment (10 m/s).

	Weld section	E_{corr} (mV)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	Self-corrosion rate (mm/y)
Inhibited	PM	–652.8	22.6	0.26 ± 0.039
	HAZ	–656.3	24.4	0.28 ± 0.005
Blank	WM	–658.9	31.3	0.36 ± 0.005
	PM	–729.3	165.8	1.92 ± 0.19
	HAZ	–729.7	177.9	2.06 ± 0.22
	WM	–730.7	191.7	2.22 ± 0.27

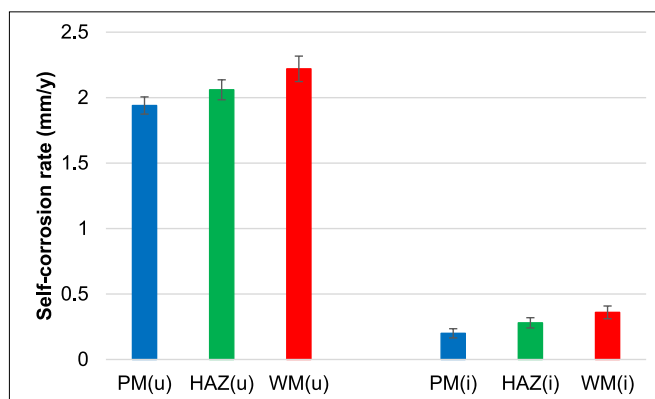


Fig. 6. The Self-corrosion rate of PM, HAZ, WM at 10 m/s and 28 °C (uncoupled electrode) where u: uninhibited, i: inhibited.

inhibited conditions, namely –635 to –640 mV (Fig. 5). An increasingly positive OCP value reveals a decrease in corrosion rate [24]. It shows that applying the inhibitor causes the OCP to shift positively. An increasingly positive OCP value will be equivalent to a decreasing corrosion rate, which is in accordance with previous research [25]. The inhibitors can be classified as a cathodic or anodic inhibitor when the potential shift between uninhibited and inhibited is greater than 85 mV. While the potential shift is less than 85 mV, the inhibitor can be classified as a mixed inhibitor [26]. In this research, the inhibitors used can be classified into the categories of inhibitor mixed mode.

Table 2 displays the corrosion current density data for each weldment (inhibited) obtained from the Tafel plot Fig. 5. The corrosion current density of PM, HAZ, and WM has increased from 22.6, 24.4, and 31.3 ($\mu\text{A}/\text{cm}^2$). The most negative corrosion potential shows the highest corrosion current density is the WM. This means that WM has the greatest corrosion rate. This phenomenon has been mentioned in previous works [27]. While, in uninhibited conditions, I_{corr} for the PM, the HAZ, and the WM are 165.8, 177.9, and 191.7 $\mu\text{A}/\text{cm}^2$, respectively. WM still has the highest I_{corr} , and WM is subject to corrosion [20].

Fig. 6 compares self-corrosion rates of PM, HAZ, and WM without inhibitors and with inhibitors. In the uninhibited condition, there was an increase in the self-corrosion rate of PM, HAZ, and WM to 1.92, 2.06, and 2.22 mm/y. The decrease in self-corrosion rate in weldment (metal loss) occurred after adding inhibitors to 0.26, 0.28, and 0.36 mm/y for PM, HAZ, and WM, respectively. With the addition of inhibitors, the self-corrosion rate in weldments decreases by around 80 % compared to without inhibitors. Previous reports supported the idea that the inhibitor used in weldment can reduce the corrosion rate by up to 80 % [28].

Based on Equations (7) and (8), the shear stress in this research is 280 Pa. Based on the results of this research, the rate of weldment corrosion (inhibited) at 30 °C and 280 Pa is 0.26, 0.28, and 0.36 mm/y for PM, HAZ, and WM. The corrosion rates can be compared when the previous report [22] uses the same measurement temperature as this study but with different inhibitors; the corrosion rate of PM, HAZ, and WM is Another study conducted using the RCE method [23] with a flow rate of 5000 rpm, a temperature of 70 °C, and a shear stress of 70 Pa; the

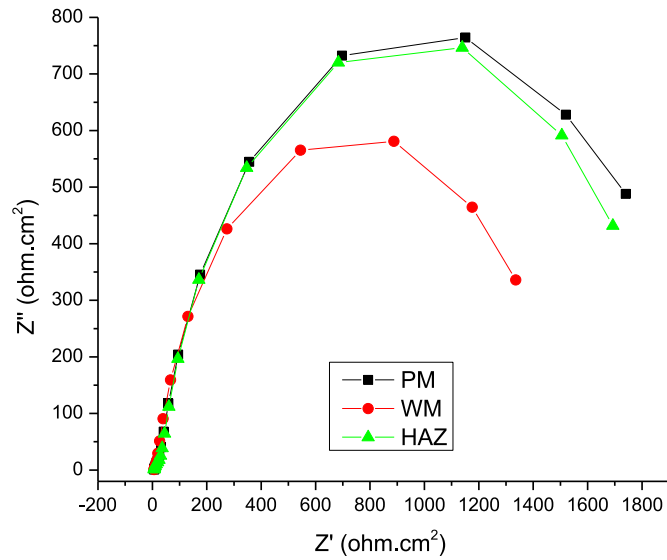


Fig. 7. The electrochemical impedance analysis produces a Nyquist plot for the PM, WM, and HAZ in the presence of 30 ppm inhibitor. The measurement were carried out at the OCP using 10 mV AC potential and 0.005 Hz to 20 kHz frequency.

Table 3

The comparison of LPR and EIS measurement in the inhibited and uninhibited weldment.

		Rs	Rp	Corrosion rate (mm/y) EIS	Corrosion rate (mm/y) LPR
Inhibited	PM	35 ± 1.2	1115	0.27 ± 0.043	0.26 ± 0.039
	HAZ	41 ± 1.6	1025	0.29 ± 0.049	0.28 ± 0.005
	WM	43 ± 1.9	860	0.35 ± 0.051	0.36 ± 0.005
	PM	4.8 ± 0.77	178.4	1.70 ± 0.14	1.82 ± 0.21
Blank	HAZ	5.8 ± 0.56	156.3	1.91 ± 0.13	2.06 ± 0.11
	WM	6.9 ± 0.81	138.5	2.12 ± 0.22	2.22 ± 0.25

corrosion rate can be compared with this study. It shows that the corrosion rate of PM, HAZ, and WM is 0.20, 0.24, 0.30 mm/y, 0.05, 0.15, 0.3 mm/y corrosion rate [29]. It can be concluded that this study is comparable to previous studies because it can reduce current density and corrosion rate.

$$\tau\omega = 0.179\rho Uo^2 Re^{-0.182} \left(\frac{r}{ro}\right)^{-2} \quad 7$$

The jet Reynold number is defined as:

$$Re = \frac{2roUo}{\eta} \quad 8$$

Where, r the radial distance from the jet centre line and r_o is the jet radius.

3.3. Electrochemical impedance spectroscopy (EIS)

The EIS measurements were depicted as a Nyquist plot, which studies the surface corrosion mechanism. The actual impedance/the resistive part (Z') is shown by X-axis, and the impedance/the capacitive part (Z'') is depicted by Y-axis. The EIS method was used to analyze the charge transfer resistance (R_{ct}) during the corrosion reaction. The solution

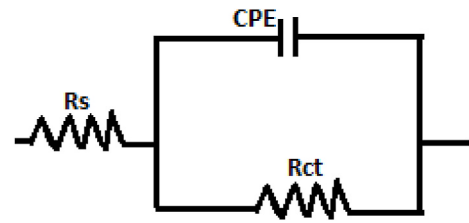


Fig. 8. Equivalent circuit to model impedance data.

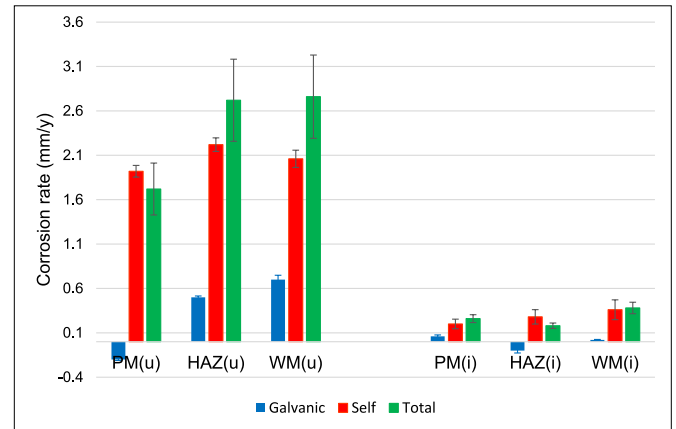


Fig. 9. The total corrosion rate of the PM, WM, and HAZ.

resistance (R_s) is equivalent to the LPR measurement's polarization resistance (R_p). The semi-circle diameter indicates the smallest R_p value, and it means that the corrosion rate is higher [30] as shown in Equation (9). Whereas, Equation (10) calculates the corrosion rate measurement.

$$R_p = \beta / (I_{corr}) \quad 9$$

$$\text{Corrosion rate (mm/y)} = 0.13 \times I_{corr} (\mu\text{A}/\text{cm}^2) \quad 10$$

In inhibited, the Nyquist plot does not form a full semicircle (Fig. 7). Unrestricted diffusion occurs called Warburg diffusion at an angle of 45°. Based on Table 3, the R_p value in WM (inhibited) shows the lowest value compared to PM and HAZ. This means that WM has the highest corrosion rate at 0.36 mm/y. Meanwhile, PM has the highest R_p and the lowest corrosion rate (0.26 mm/y). EIS data confirms that the LPR data and corrosion rates are not significantly different. EIS measurements are carried out using an equivalent circuit, as shown in Fig. 8.

Meanwhile, in uninhibited conditions, the Nyquist plot shows a semicircle diameter. This phenomenon is similar to previous research, which showed that the Nyquist plot semicircle diameter decreased due to the addition of inhibitors [31]. The charge transfer resistance (R_p) of WM is as low as 138.5 $\Omega \text{ cm}^2$, corresponding to 2.22 mm/y. PM has the highest R_p of 178.4 $\Omega \text{ cm}^2$ and the lowest corrosion rate of 1.82 mm/y. It can be concluded that EIS has the same corrosion rate trend as LPR.

3.4. Total corrosion rate

When self-corrosion is added to galvanic corrosion, the total corrosion rate is obtained. The total corrosion rate was calculated using Equation (11).

$$\text{Corrosion rate}_{\text{total}} = \text{Corrosion rate}_{\text{galvanic}} + \text{Corrosion rate}_{\text{self}} \quad 11$$

Fig. 9 shows the total corrosion rate for PM, HAZ, and WM (1.6, 2.6, 2.9 mm/y, respectively) in uninhibited conditions is higher than in inhibited conditions (0.2, 0.4 and 0.6 mm/y, respectively). It shows the occurrence of PWC in the weldment without adding inhibitors [32]. The

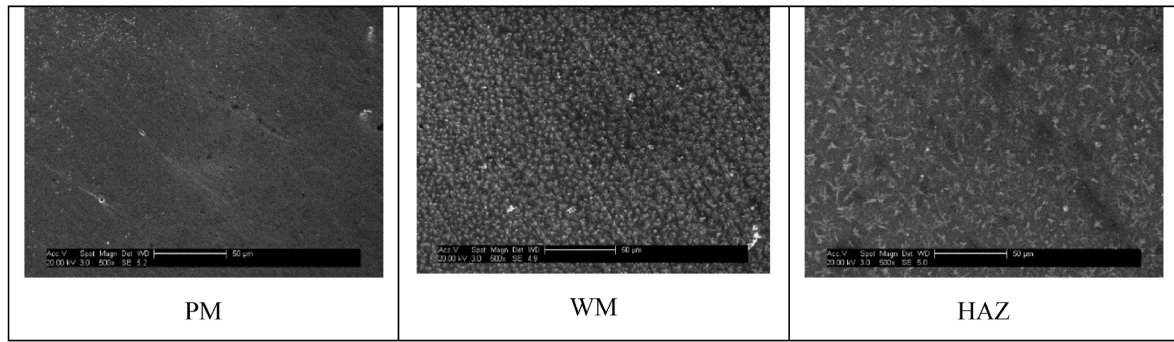


Fig. 10. The SEM morphology of the PM, WM, and HAZ in inhibited condition at 10 m/s.

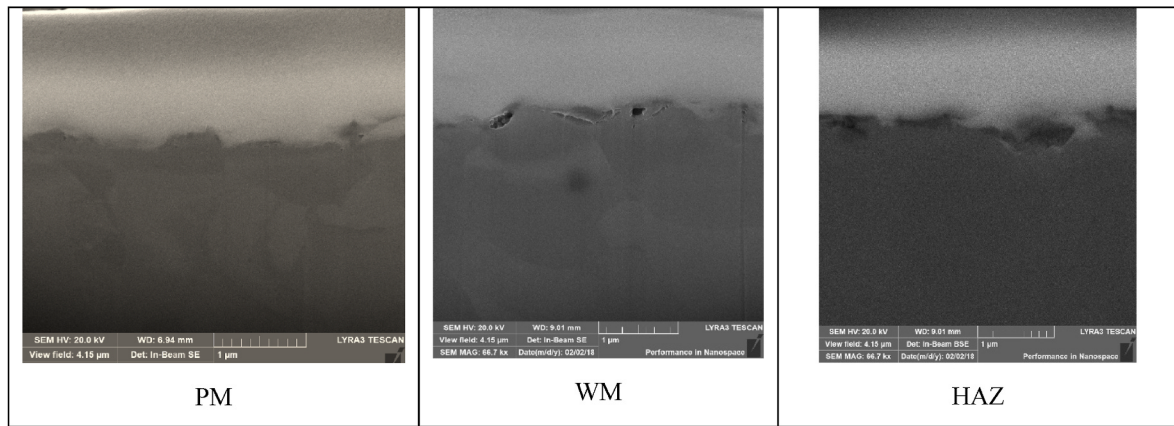


Fig. 11. The FIB analysis of PM 0.15 μm , WM 0.21 μm , HAZ 0.27 μm in inhibited condition (10 m/s).

uninhibited and inhibited conditions show that WM has the highest total corrosion rate compared to PM and HAZ. This is because WM has a material surface that is not homogeneous due to the welding process. HAZ has a higher total current density than PM because the HAZ area is small, so the current density is large. In the uninhibited condition, the galvanic corrosion rate of the PM is negative because the PM has a large area and a strong material structure, so it is resistant to corrosion attacks compared to WM and HAZ in the coupled condition. This can reduce the total rate of PM corrosion on uninhibited ones.

Meanwhile, negative galvanic current and inhibited conditions are found in the HAZ. This causes the inhibited condition's total HAZ corrosion rate value to be lower than WM. A similar observation was reported in the previous result, which reported that a negative value of the corrosion rate leads to a low corrosion rate [20].

3.5. Surface characterization

SEM morphology of PM and WM before adding the inhibitor shows significant material loss due to the formation of pits and cracks. The

inhibitor acts as a protective layer for the weldment so that the brine cannot flow through it because a thin layer of inhibitor protects it. After adding the inhibitor, the PM and WM surfaces were better protected. It can be concluded that the inhibitor can protect the weldment surface from preferential weld corrosion (PWC). Fig. 10 interpreted the SEM morphology of PM and WM in the inhibited condition. Compared with the uninhibited condition, PM and WM in the uninhibited condition crack propagation results in more metal surface contact with an acid solution, thus accelerating the dissolution of metals, as mentioned previously [33].

This surface morphology data supports electrochemistry measurements, namely that weldments not inhibited by corrosion inhibitors will form a porous structure, indicating the occurrence of PWC. This result is supported by previous research using inhibitors. When an inhibitor does not protect the weld, severe corrosion occurs. With the presence of an inhibitor, direct contact between the matrix and the corrosive medium is prevented, reducing the corrosion rate [34].

The thickness of the corrosion products can be analyzed with a focused ion beam. In uninhibited conditions, WM has a corrosion

Table 4
The chemical composition from EDX analysis of PM and WM.

Elements	PM (wt %)			WM (wt %)		
	Pure PM	Corroded PM uninhibited	Corroded PM inhibited	Pure WM	Corroded WM uninhibited	Corroded WM Inhibited
C	0.7	15.4	7.5	0.9	19.8	12.2
Si	0.1	0.2	0.2	0.3	0.2	0.2
Mn	1.6	1.4	1.4	1.7	1.6	1.6
Ni	0.3	0.4	0.4	0.2	0.3	0.3
Cu	0.2	0.3	0.3	0.2	0.2	0.2
Fe	97.1	82.3	90.2	96.7	77.9	85.5
Total	100	100	100	100	100	100

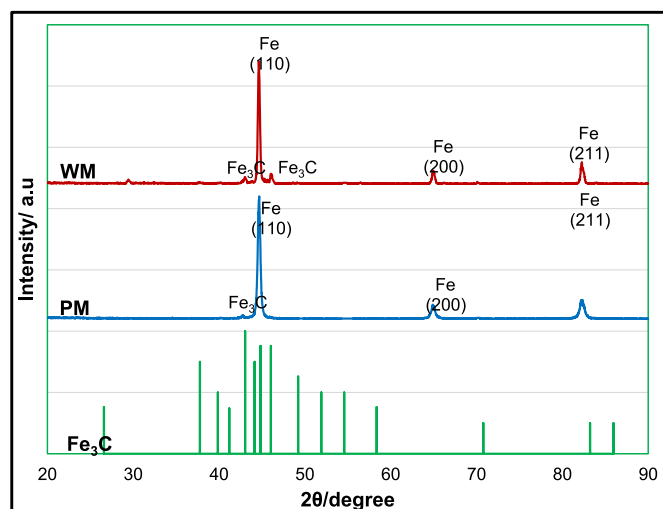


Fig. 12. X-ray diffraction spectra of inhibited PM and WM.

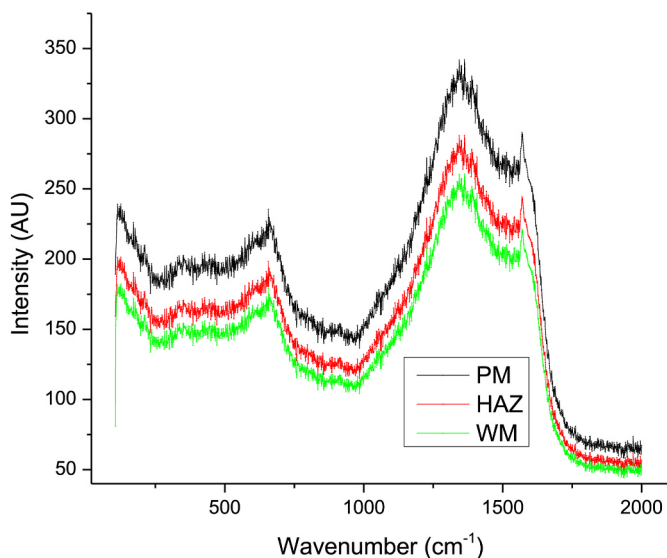


Fig. 13. Raman spectroscopy of the weldments in inhibited condition.

product thickness of 3.8 μm , PM 2.5–3 μm , and HAZ 3.1 μm . After the inhibitor was applied to the pipeline, the corrosion product thickness of the PM, WM, and HAZ became 0.15, 0.21, and 0.27 μm , respectively (Fig. 11). The thickness of the corrosion product was reduced ten times in the presence of the inhibitor, as previously mentioned in the literature [35].

Energy dispersive X-ray data (Table 4) shows a decrease in the wt % of PM carbon from 15.4 to 7.5 wt % in the presence of inhibitors. Meanwhile, the Fe content in PM is still higher with the inhibitor, namely 90.2 wt%, compared to without the inhibitor; PM has a Fe content of 82.3 wt%. WM shows the same trend. The Fe content for WM without inhibitors was 77.9 wt%, while WM with inhibitors was still able to maintain Fe levels of 85.5 wt%. These results are in agreement with previous report [36]. Carbon levels from WM in the inhibited condition were lower than in uninhibited WM. From the SEM-EDX results, it can be concluded that surface characterization supports electrochemical data.

Fig. 12 shows the XRD data of the PM and WM materials after adding the inhibitor. The PM and WM peak intensities were compared with the intensity of standard Fe_3C corrosion products. The weldment layer containing Fe_3C has disappeared from the microstructure. When

compared with uninhibited conditions, the Fe_3C peak appears at 2θ : 42°, 50°, 55°, 70° (PM). Meanwhile 2θ : 32°, 47°, 55°, 70° appear in WM [20, 21]. After the addition of inhibitor, 2θ : 42° still appeared in PM, and 2θ : 42°, 46° still appeared in WM. These XRD results are in good agreement with the earlier research [37].

Raman spectroscopy is used to identify corrosion product compounds using molecular vibration mode. Fig. 13 shows the relationship between wavenumber (cm^{-1}) vs intensity. Two sharp absorption peaks were obtained in all 1340 and 1580 cm^{-1} weldments. These two peaks show the Fe_3C (cementite) peak intensity between 250 and 330 AU in the inhibited condition. Meanwhile, in uninhibited conditions, the peak in Raman spectroscopy shows a sharper intensity at around 600 AU [20]. It is indicated that the presence of inhibitors can reduce corrosion by forming an active layer so that the intensity of corrosion products is reduced. It can be concluded that surface characterization data supports the above electrochemical measurement data.

4. Conclusion

This manuscript reports the inhibitor effect of a commercial corrosion inhibitor on the corrosion rate of PM, WM, and HAZ. This research discusses the effect of corrosion on coupled metal, which causes PWC to occur under high flow rate conditions which causes PWC. Studies that have been carried out include galvanic corrosion, self-corrosion rate, electrochemical impedance spectroscopy, total corrosion rate, and surface characterization. The inhibitor used can be applied in oilfield production because it can reduce the corrosion rate under flow conditions of 10 m/s. Based on measurements of the total corrosion rate, it was found that the highest corrosion rate was WM. Surface characterization supports electrochemical measurement data. Suggestions for further research: development of iron carbonate films and the application of submerged jet impingement to evaluate the preferential weld corrosion in flowing conditions at elevated temperatures. SJ1 used to conduct research in erosion-corrosion using different concentrations and sizes of suspended sand to simulate specific down-hole conditions that are very demanding for effective corrosion inhibition. Studies on the effective inhibitor concentration in different environments such as H_2S , and acetic acid environments. Research with dissimilar welded joint configurations and compositions was produced, which are typical of application in oilfield environments.

CRedit authorship contribution statement

Meyliana Wulandari: Writing – original draft. **Nofrizal Nofrizal:** Investigation, Data curation. **Susan Impey:** Supervision. **Konstantinos Georgarakis:** Supervision. **Pandian Bothi Raja:** Writing – review & editing. **M. Hazwan Hussin:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Wulandari, Meyliana; Nofrizal, Nofrizal; Impey, Susan A.; Georgarakis, Konstantinos; Raja, Pandian Bothi ...

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