

An experimental and simulation screening of X-65 steel weldment corrosion in high flow rate conditions

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Abstract

Over many decades, the oil and gas industry has encountered significant challenges due to weldment corrosion. The issue of internal-pipeline local corrosion at the welded joint region has garnered significant concern, especially due to the combined impact of high shear stress and electrochemical corrosion. This combination can lead to pipeline rupture with relative ease. Hence, a new approach to screen the flow corrosion of X-65 steel via electrochemical methods, predicting fluid shear stress and velocity using computational fluid dynamic (CFD) simulation is positively tested and presented here. For that, the X-65 steel specimens were cut/ designed as the inner, centre, and outer electrodes of the target to analyse the Weld Metal (WM), Heat Affected Zone (HAZ), and Parent Metal (PM). Electrochemical screening was carried out simultaneously at a flow of 10 m/s using a brine solution saturated with CO₂. The PM and HAZ will corrode less than the WM, in some cases at 30–23% of the rate of the WM. Thus in an environment of uninhibited brine saturated with CO₂ at 10 m/s, preferential weld corrosion (PWC) is expected to occur. In addition, the surface morphology screening (scanning electron microscope with energy dispersive x-ray analysis, X-Ray diffraction, focus ion beam, raman spectroscopy) was employed to monitor the corrosion damage on the metal surface and also to support the electrochemical measurements (linear polarization resistance, galvanic measurement, and electrochemical impedance spectroscopy).

Keywords

Computational fluid dynamics, Electrochemical, Heat affected zone, Parent metal, Weld metal

1. Introduction

Steel is a mixture of iron and carbon. Carbon steel (CS) contains about 0.2–2.1% carbon, 0.6% copper, 1.65% manganese, and 0.6% silicone. The American Petroleum Institute (API) divides CS into several grades, namely X52, X65, X70, and X80 [1]. Among these grades, X65 is predominantly used because it has good mechanical strength and low cost [2]. Hence, this material is abundantly used in the oil and gas industry for transportation processes. Oil/gas mining and storage pipes mandatorily require a welding process to combine two metals using heat, which causes the two metals to melt and fuse together [3], [4]. This welding part is very susceptible to localized and galvanic corrosion attacks. Galvanic corrosion that occurs will result in Preferential Weld Corrosion (PWC) problems.

Undersea oil and gas mining requires various pipelines transporting oil and gas across long distances [5]. The US Gulf of Mexico (GoM) has hosted more than 72,000 km of pipeline installation from 1952 to 2017 and 26,000 miles (42,000 km) [6]. Transportation of oil and gas by pipeline has always been a significant financial concern because of the high chance of corrosion [7]. When corrosion occurs, it can significantly impact the economy and environment [8], [9]. PM, HAZ, and WM of the weldment in oil and gas industries will be subjected to galvanic corrosion [10], [11], [12] because of the different microstructures and compositions of each metal [12]. It can be found in off-shore gas production in many countries [13]. Scientists are currently addressing the enormous losses caused by PWC [14]. If WM and HAZ are in an anodic position to PM, metal loss (localized corrosion) will occur [15]. So, the PM must be in the anodic position due to a large area to prevent the PWC [16]. Hence, this research aims to study the corrosion rate in the weldment structure.

Researchers have developed various methods to analyse the flow effect on corrosion in carbon steel. These methods include a recirculating flow loop, rotating cage, rotating cylinder electrode (RCE), and submerged jet impingement (SJI) [17], [18]. Among these techniques, SJI was chosen because it was proven to be more reliable than other methods. It can be used in the oil and gas industry to apply high wall shear stress. Furthermore, SJI has also been used to successfully study weldment behavior (PM, HAZ, WM) using X65 [19], [20], [21]. At flow rates of 5 and 10 m/s, WM and HAZ are protected, and PM is subjected to PWC. However, there is a current reversal under certain conditions, thereby accelerating the corrosion rate. The previous study focused on electrodes in the inner position. This is considered because this position has higher hydrodynamics. The result showed that at flow rates of 5 and 10 m/s, WM and HAZ are protected, and PM is subjected to PWC [19].

In this study, the corrosion performance of the weldment in the inner, outer, and centre positions is reported to study the effect of different flow rates in each area of the weldment. It is known that the hydrodynamic velocity decreased from the inner, outer, and centre, respectively. The rate of galvanic corrosion needs to be analysed to study the activity of the corrosion rate when two metals are combined. At the same time, the self-corrosion rate is carried out to see the corrosion activity of each weldment so that the total corrosion (total of the galvanic corrosion and self-corrosion) can be known. EIS measurement is essential to determine the corrosion rate. To support the experimental data in the laboratory, fluid dynamic velocity, and shear stress profiles using computational fluid dynamics (CFD) analysis were also studied. The simulation was carried out in the outer, inner, and centre electrode positions. This analysis explains how fluid velocity affects the electrode surface when a corrosion reaction occurs. This research is used to study the flow corrosion of the weldment in oil and gas companies, which is applicable in welding procedures during production and distribution

processes. This work screens the characteristics of weldment corrosion in the centre, inner, and outer areas, which have different turbulence.

2. Experimental

2.1. Design of SJI target

The welding material plates of size $210 \times 60 \text{ mm}^2$ area dimensions and 30 mm thickness (Fig. 1) were employed for the analysis. Fig. 1A shows the plate's condition after welding is complete. Fig. 1B shows the welding conditions after adding 10% nital to see the welding microstructure. Fig. 1C is the detailed microstructure of PM, WM, and HAZ. This target is made up of carefully selected fragments of the parent metal, the heat-affected zone, and the weld metal.

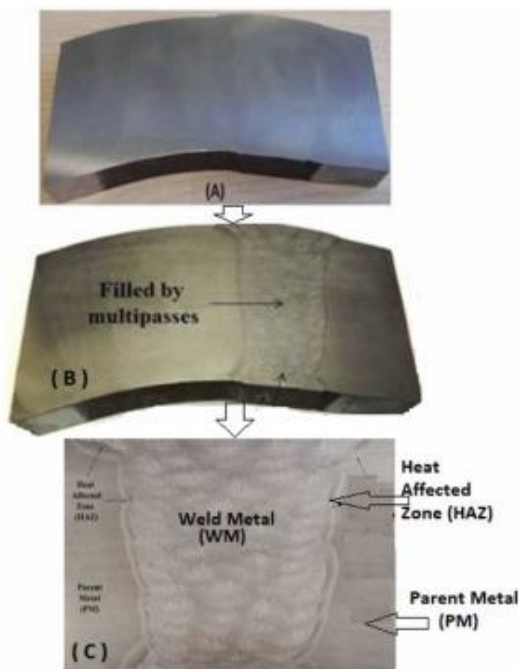


Fig. 1. Plate after welding (A), plate etched in 10% nital (B), and the PM, the WM, and the HAZ macrostructures (C).

2.2. Corrosion cell setup

The target of SJI was glazed with abrasive paper (grades from 240 until 1200 grid), cleaned with aquades, then 2-propanol to put off the unwanted grease and dried. After that, it was deposited under a 5 mm jet nozzle inside the flow loop. The target SJI (PM, WM, HAZ acts as working electrode/WE) is included in the flow loop and connected to a reference electrode (saturated calomel electrode/SCE) and an auxiliary electrode/AE (platinum) (Fig. 2) [22]. The flow loop is attached with electrochemical tools to analyse the corrosion process. Then, N_2 gas flowed into the brine solution to remove the dissolved oxygen. After about 2 hours, CO_2 was continuously supplied with one bar of partial pressure, and a pH of 4.0 as a test solution was observed during the experiments. The temperature was set at $28\text{--}30^\circ\text{C}$ (10 m/s).

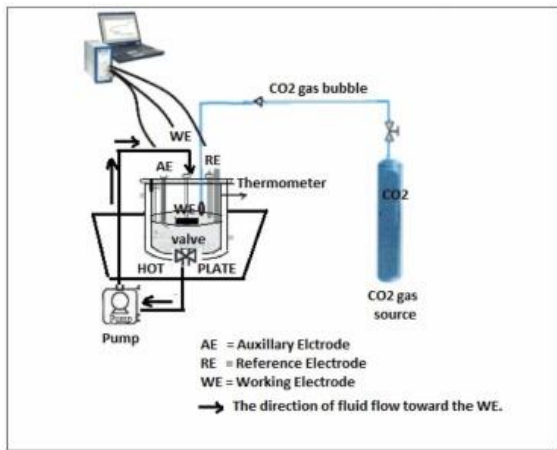


Fig. 2. Electrochemical Set-up for corrosion monitoring.

2.3. Electrochemical measurements

2.3.1. Galvanic measurements

The metal was immersed in a brine solution and purged with CO₂ for 3 hours, which generated cathodic/anodic sites over the metal surface. Then, the galvanic measurement for each electrode is done using a zero-resistance ammeter (ZRA) connected to a computer. The potential used was about -740 mV (SCE). The electrode setup can be seen in Fig. 3. The temperature was set at $28-30^{\circ}\text{C}$ (10 m/s), and the pressure used was 1 bar. The total of galvanic currents will be zero ((1), (2)): Table 1.

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

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

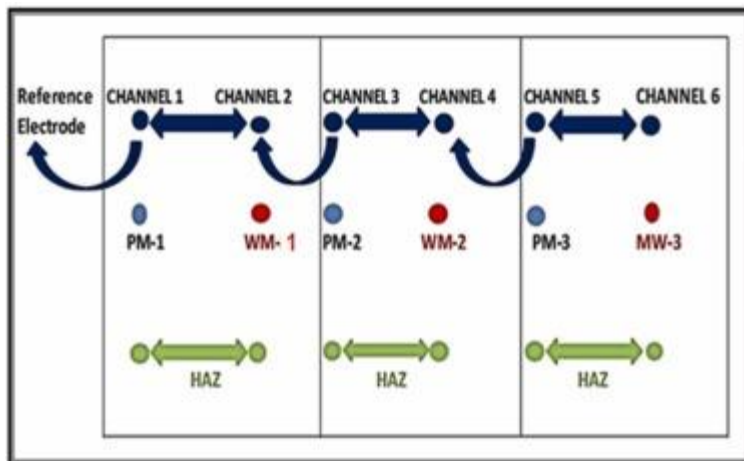


Fig. 3. The electrical connection of the working electrodes to ZRA.

Table 1. Electrode area in SJI target.

Empty Cell	Weld specimens (cm ²)		
Empty Cell	PM	WM	HAZ
Outer	1.1383	0.2878	0.1439
Inner	0.6829	0.1727	0.0864
Centre	0.1492	0.0314	0.0154

The corrosion rate at each electrode is obtained from the calculated current divided by the area (cm²) and then converted to mm/y according to Eq. 3:

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

2.3.2. The measurements of self-corrosion rate

LPR measurement produces the Self-Corrosion Rate of each electrode. The scan is performed at a potential of ± 10 mV from the open circuit potential (OCP) [23]. The plot obtained is the log I vs potential (mV) in a straight line where the slope can be determined. The corrosion rate is obtained from the slope/gradient value. During the measurement, the temperature is kept constant at 28°C and scanned every 10 mV/minute. The polarization resistance (Rp) is calculated based on Eq. 4.

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

Where:

I_{corr} = corrosion current (A/cm²)

β = the LPR constant for the material (β value is 26)

R_p = polarisation resistance (Ωcm^2)

2.3.3. EIS measurements

The cell attached to a computer and a potentiostat was used to gain more information on the electrochemical interaction between the welds. EIS parameters were used with an amplitude of 10 mV, AC potential, and 0.005 Hz to 20 kHz of frequency. From EIS measurement, the Rp and Rs are obtained—the corrosion rate calculation in mm/year from Eq. 5.(5)

$$R_{\text{ct}} = R_p - R_s$$

Where:

R_{ct} = corrosion rate (mm/year)

R_p = polarization resistance

R_s = solution resistance

2.4. Computational fluid dynamic parameters

The “3D Flow” Commercial CFD Software is used to study the fluid flowing across the target at 2–20 m/s. From this software, the fluid flow velocity, shear stress, and shear velocity can be determined when impacted by a jet directed at 90 degrees to the target surface with a specific jet velocity.

The CFD parameters used are as follows: cell size - 0.3 mm, initial water temperature - 25°C, pressure - 101325 Pa, and the turbulence model employed was the Renormalized group (RNG). Annular electrodes are placed at three different characteristic regions, as shown in schematic Fig. 8, Fig. 9, Fig. 10, Fig. 11, Fig. 12, Fig. 13. The centre electrode (C) is placed at a radius 0–2.5 mm from the centre of the target and the inner electrode (I) at 6.5–8.5 mm, while the outer electrode (O) is at 11.5–13.5 mm from the target centre. The nozzle is 5 mm in diameter, (nozzle radius of 2.5 mm) and positioned at a fixed distance (H) 5 mm from the target (Fig. 4).

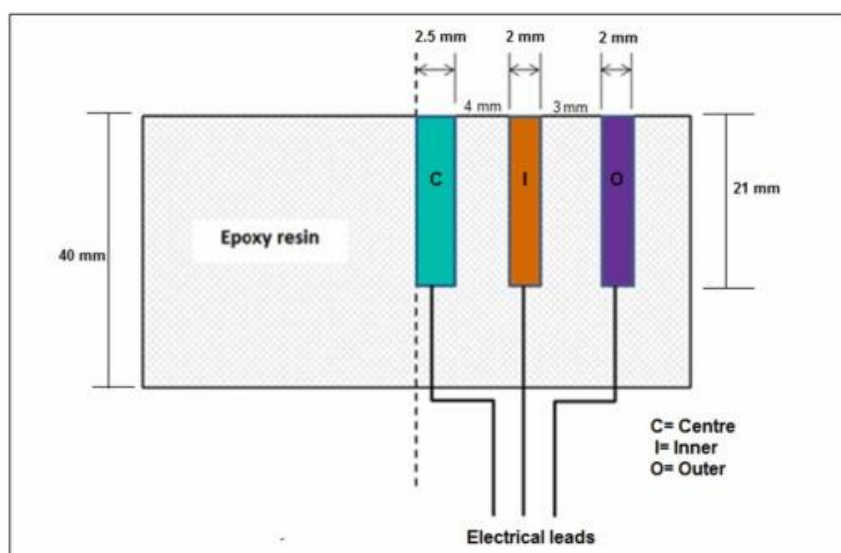


Fig. 4. Experimental set-up of electrodes within the target surface exposed to jet impingement from the vertical nozzle.

2.5. Surface characterization

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

Before analysis, the corroded sample was rinsed and cleaned with isopropanol and deionised water, dried, and stored in a desiccator prior to the SEM analysis. Analysis was performed using the Philips-XL30 with energy dispersive x-ray (EDX), and the data obtained was analysed with Oxford Instrument's very own Aztec software.

2.5.2. XRD analysis

XRD aims to determine the chemical composition of corrosion products by interpreting the material's crystal structure and also to support electrochemical measurements. This study reports XRD Analysis (Siemens D5005 instrument) with CuK α at a wavelength of 1.5406 Å

and Fiffrafractplus XRD commander (version 2.4.1, 2005) software. Samples are pulverized to homogeneous powder (20 μm) before the XRD analysis. Bragg's law is used to understand the diffraction angle (Eq. (6)) [24]:

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

where:

θ = angle of the X-ray beam

d = distance between the atomic planes in the crystal

λ = wavelength of X-rays

2.5.3. Focus ion beam

Focus ion beam measurements using a single BIM FIB TESCAN LYA3 using an energy beam of 5 keV. Gallium ions are used to mill the sample surface. Ions dig into the specimen surface and cut thin sections. Before analysis in the microscopic chamber, the samples were coated with a thin layer of Pt coating ($\sim 10 - 20 \text{ nm}$) to make them conductive. The interaction of the ion beam with the sample results in the generation of secondary electrons, which can be used for imaging.

2.5.4. Raman spectroscopy

Raman spectroscopy was performed in Jobin-Yvon LABRAM confocal-Raman spectrometer, which is equipped with an Nd-YAG laser (100 mW, 532.2 nm) and diffraction gratings of 1800 grooves mm^{-1} . The corroded sample ($1 \times 1 \text{ cm}^2$) is placed on a glass slide, and sample viewing is carried out with an Olympus BX 40 microscope fitted with a 100x objective lens and then analysed through Lap-spec 5 software with a scan rate of between 0 and 2000 cm^{-1} . After that, the interpretation of the raman band was compared with the standard frequency band.

3. Results and discussion

3.1. Galvanic corrosion measurements

SJI targets are immersed into the flow loop, and studies are conducted for each PM, HAZ, and WM. Measurements are taken on the outer, inner, and centre simultaneously. So, there are a total of 9 electrodes on the target. The currents from PM to HAZ as well as WM to HAZ are recorded into the six ports of ZRA. The corrosion current density in PM, WM, and HAZ is shown in Fig. 5.

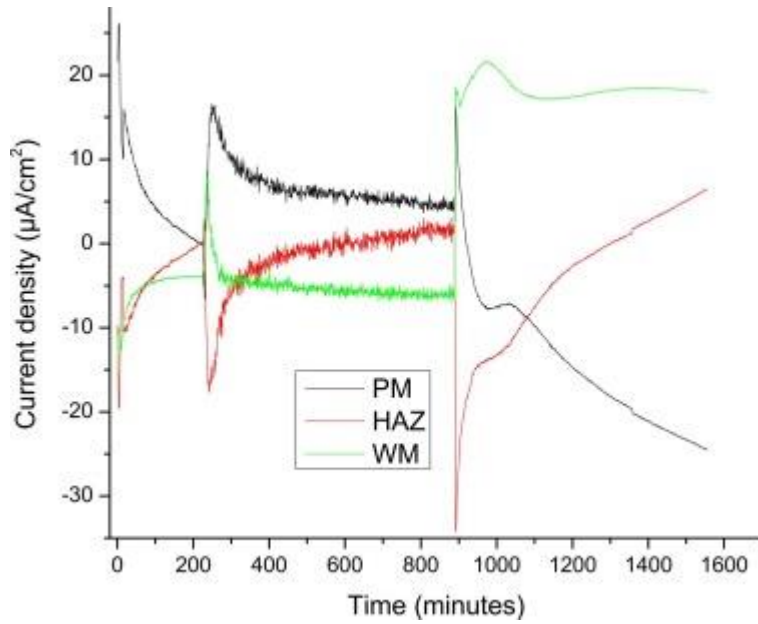


Fig. 5. Typical galvanic current density of outer weld sections. Deaerated with N₂ (0–200 min), saturated with CO₂ (200–900 min), saturated with CO₂ and 10 m/s (900–1600 min).

The galvanic current density in the brine solution flowed with CO₂ is higher than that of N₂. It means that X65 weldment steel is susceptible to galvanic corrosion. The current density for WM (in the inner, centre, and outer electrodes) remained constant in the cathodic area until 1000 minutes. It is probably due to the achievement of equilibrium on the surface, which depends on the exchange rate of ions towards the surface and the formation of a film on the surface. This film serves to protect the weld from corrosion. PM also experienced a decrease in cathodic current density to near zero after being saturated with CO₂. It is likely the formation of a carbonate layer. This result is consistent with previous research where PM remained in the cathodic current while WM remained in the anodic current after several hours in CO₂ conditions [25], [26].

When the brine solution flows at 10 m/s, the galvanic current of WM is the highest and experiences PWC. HAZ (green line) has increased in anodic behavior for all the electrodes. The corrosion current densities obtained after 1600 min for WM are 30, 90, and 55 $\mu\text{A}/\text{cm}^2$ in the centre, inner, and outer electrode regions, respectively. High corrosion damage occurs on the inner electrode, according to previous research [21]. In contrast, the centre electrode has the lowest current density because of low turbulence in this area.

3.2. Self-corrosion measurements (Uncoupled)

LPR is inversely proportional to corrosion current, I_{corr} . Therefore, the material that has the highest LPR has the lowest corrosion rate [27]. Tafel plots for each weldment can be seen in Fig. 6. The potential (E_{corr}) with the log of the density of current (I_{corr}) for PM, HAZ, and WM taken from LPR measurements. The open circuit potentials (OCP) are -733 , -729 , and -730 mV, respectively, for WM, PM, and HAZ in the outer ring. Increasing positive OCP indicates that there is a decrease in the corrosion rate. It can be confirmed that the WM is more electronegative than the PM and HAZ.

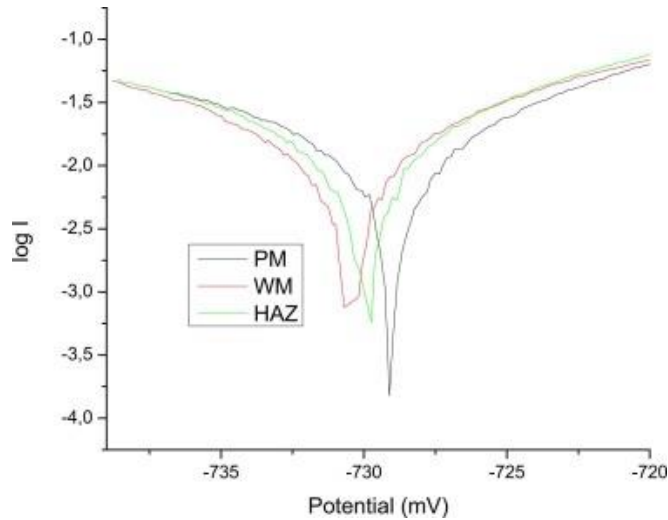


Fig. 6. The PM, HAZ, and WM Tafel Plot in the outer ring.

Table 2 shows the LPR measurement of the outer, inner, and centre electrodes. The corrosion potential (E_{corr}) was found to be more negative (more reactive) and close to each other. Corrosion may occur as indicated by a drop potential [28]. All the electrodes might have the same chemical composition but differ only in microstructure. WM shows the highest corrosion rate for all the electrode regions. So, WM has lower corrosion resistance. It can be related to the composition of WM, which contains the lowest Ni composition (0.24%) compared with PM (0.36%). The highest WM corrosion rate of 2.52 mm/y was found on the inner electrode. In addition, the inner electrode shows the highest self-corrosion rate compared to the outer and centre electrodes. The highest corrosion rate is due to the interaction of cations and anions of CO_2 saturated brine water that become significant [29], [30]. The corrosion current density (I_{corr}) ranges from 132 to 217 $\mu A/cm^2$. This phenomenon can occur due to flow conditions that allow intensive mass transfer from metal to electrolyte.

Table 2. LPR Measurement.

Empty Cell	Weld section	E_{corr} (mV)	I_{corr} ($\mu A/cm^2$)	Self-corrosion rate (mm/y)
Outer	PM	-729.3	165.8	1.92±0.19
Empty Cell	HAZ	-729.7	177.9	2.06±0.22
Empty Cell	WM	-730.7	191.7	2.22±0.27
Inner	PM	-729.7	193.4	2.24±0.21
Empty Cell	HAZ	-730.1	206.5	2.39±0.26
Empty Cell	WM	-731.1	217.7	2.52±0.34
Centre	PM	-729.0	132.1	1.53±0.25
Empty Cell	HAZ	-729.1	142.5	1.65±0.23
Empty Cell	WM	-730.1	147.7	1.71±0.18

Previous research reported that uninhibited conditions at the flow of 11 m/s produce a self-corrosion rate for PM, WM, HAZ 4.70, 5.30, and 6.02 mm/y, respectively [14]. Oxygen is more likely to cause the value of the self-corrosion rate from previous research to become more significant.

3.3. EIS measurements

The measurement of EIS is used to study the corrosion mechanism that occurs on the surface. EIS complements LPR measurement and confirms self-corrosion rate in PM, WM, and HAZ. EIS measurement data was obtained from the Nyquist plot. Nyquist plots for uncoupled PM, HAZ, and WM in the outer ring are described in Fig. 7 and Table 3.

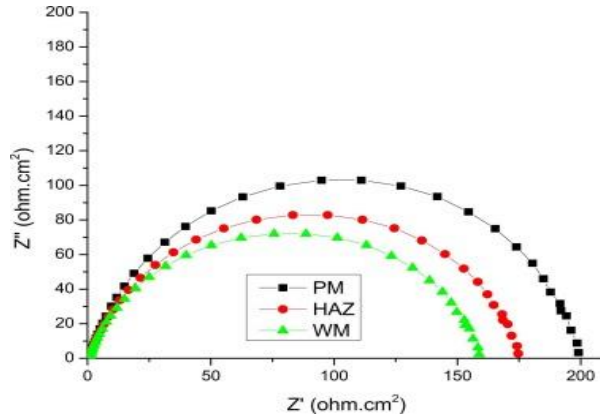


Fig. 7. PM, HAZ, and WM Nyquist Plot in the outer ring.

Table 3. Analysis of Electrochemical Impedance Spectroscopy (10 m/s).

Empty Cell	Weld section	Rs	Rp	corrosion rate (mm/y)
Outer	PM	4.7±0.76	194.9	1.71±0.19
Empty Cell	HAZ	5.6±0.57	177.1	1.90±0.22
Empty Cell	WM	6.8±0.82	157.4	2.11±0.27
Inner	PM	4.2±0.66	147.4	2.22±0.43
Empty Cell	HAZ	51±0.87	142.5	2.34±0.29
Empty Cell	WM	5.8±0.99	132.4	2.55±0.94
Centre	PM	4.9±0.49	213.2	1.56±0.55
Empty Cell	HAZ	5.9±0.91	183.5	1.67±0.93
Empty Cell	WM	6.4±0.89	167.7	1.73±0.88

The Nyquist plot shows the magnitude and direction of the impedance vector at a particular frequency. The x-axis, Z' is the actual impedance or the resistive part, while y-axis, Z'' is the impedance or the capacitive part. The semicircle diameter extrapolated defines the charge transfer resistance (R_{ct}). It means the transfer of electrons present on the surface and is inversely proportional to the corrosion rate. R_s describes the solution resistance. It is equivalent to LPR measurements' polarization resistance (R_p) value. The smallest semi-circle diameter shows the lowest R_p ($R_s + R_{ct}$) and the highest corrosion rate (Eq. (7)). While the corrosion rate measurement can be calculated from Eq. 8.

$$R_p = \beta / I_{corr} \quad (7)$$

$$\text{Corrosion rate (mm/y)} = 0.13 \times I_{corr} (\mu\text{A/cm}^2) \quad (8)$$

Fig. 7 shows WM has a smaller semicircle than PM and HAZ, so the WM self-corrosion rate is the highest (Fig. 5). WM has the smallest charge transfer resistance compared to PM. The PM corrosion rate is the lowest, while the WM corrosion rate is the highest because the PM has the largest semi-circle. The quantitative values of $R_s + R_{ct}$ (Table 3) agree with the LPR measurements. From EIS, in outer ring, PM, HAZ, and WM, corrosion rates are 1.71; 1.90; 2.11 mm/y, respectively. While from the LPR, PM, HAZ, and WM's corrosion rate is 1.92, 2.05, 2.22 mm/y. The corrosion rate for the inner and centre ring achieved from LPR and IES data show the same pattern. It shows that the results of the IES and LPR reinforce each other. The usefulness of these data permits the analysis of the alternating current (AC) impedance data, which are based on modelling a corrosion process by an electrical circuit (Fig. 8).

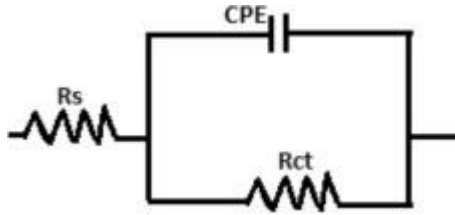


Fig. 8. Electrical equivalent circuit for AC impedance measurement.

3.4. Total corrosion rate

The total corrosion rate is the sum of the uncoupled (Linear Polarisation Resistance) and coupled (galvanic current), as shown in Fig. 9. The galvanic current of the PM for all the electrodes has a negative value because it is protected by the WM and HAZ currents, so the corrosion rate becomes negative. Our study's findings agree with the findings of the earlier report, which stated that increasing pressure causes corrosion and minimises erosion [31]. While, WM (in green) has the highest total corrosion rate for each of the electrodes. It means that PM and HAZ are more protected from corrosion than WM. The total corrosion rate of WM in the outer, inner, and centre are 2.8, 3.3, and 2.5 mm/y, respectively. The inner electrode corrodes faster than other areas, possibly due to higher local turbulence in the inner electrode.

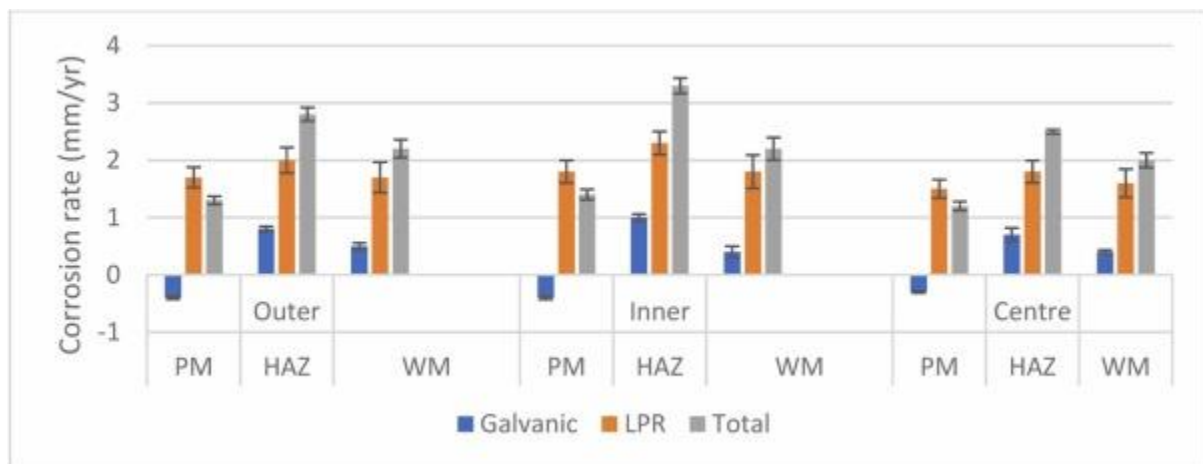


Fig. 9. The total corrosion rate of the weldment in the outer, inner, and centre electrode.

3.5. CFD simulation

The results obtained from the laboratory were then compared with a computational fluid dynamic (CFD) simulation using commercial CFD software (Fig. 10). The software can predict fluid shear stress and velocity. The surface of the target SJI has a different velocity, which influences the corrosion process. Simulations were carried out at 0–10 m/s velocities and shear stress of 0–140 Pa. From the colours, it is clear that blue to light blue is the centre area, and the region with the highest velocity (yellow-red) is an inner electrode. At the same time, the outer region (green to blue) shows intermediate low turbulence. This result is similar to the previous research [21].

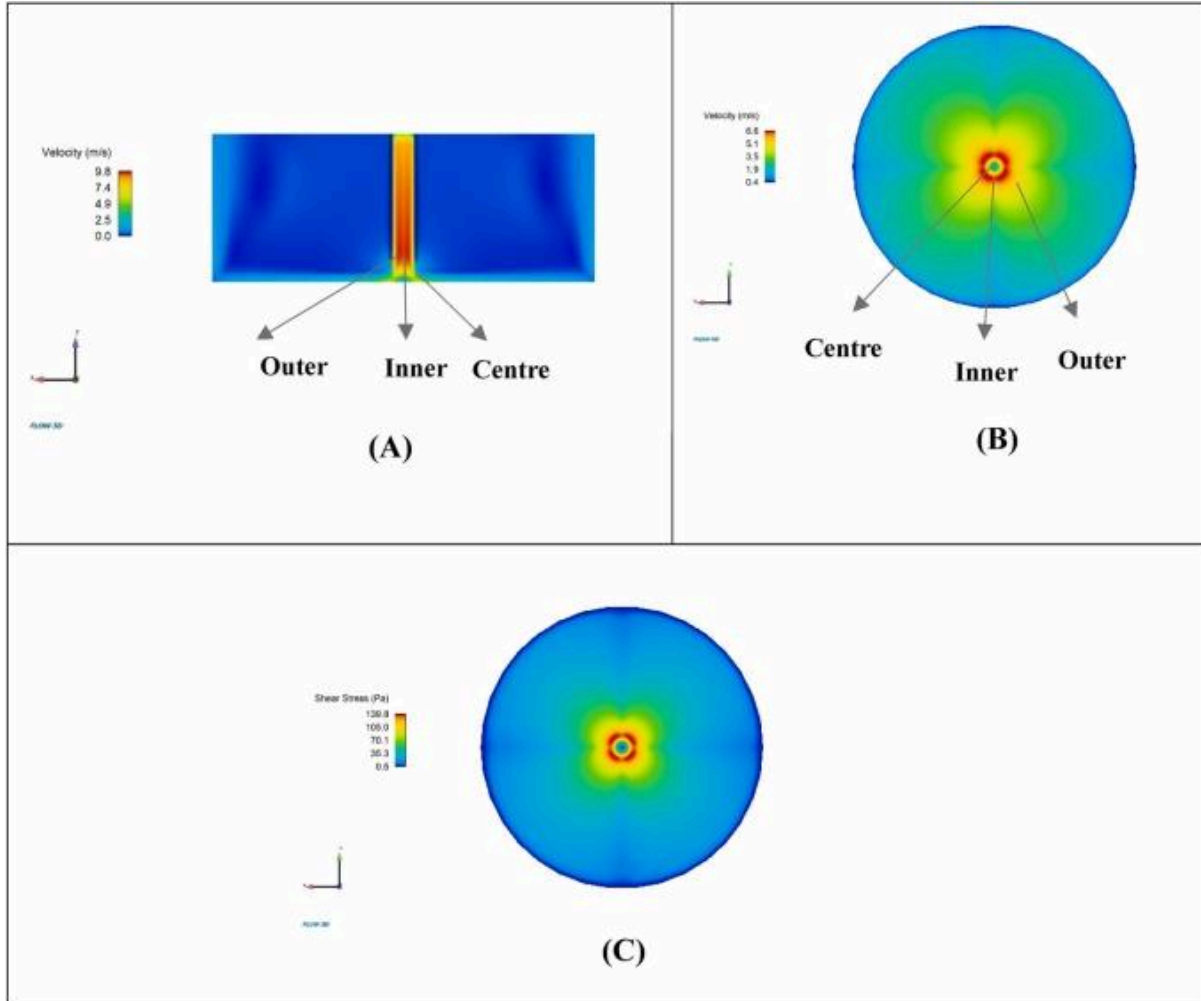


Fig. 10. 2D CFD simulation of fluid characteristic distribution at 10 m/s with (A) 90° of jet flow rate impinging on target, (B) the velocity profile (C) the shear stress of the SJI target.

CFD analysis produces PM velocity and shear stress simulations (Table 4). The centre electrode shows the lowest velocity and shear stress compared to the inner and outer electrodes. Meanwhile, the inner electrode indicates the highest shear stress and velocity, followed by the outer electrode. When the velocity increases, the shear stress also increases [32]. In the CFD simulation, the jet velocities applied are 2, 5, and 10 m/s. As a result, the range of velocities at the centre electrode ranges from 0.5 to 2.5 m/s, the inner electrode's velocity increases from 0.9 to 4.9 m/s, and then the velocities decrease again at the outer electrode 0.7–3.6 m/s.

Table 4. The velocity and shear stress data.

Empty Cell	Centre		Inner		Outer	
	Velocity (m/s)	Shear stress (Pa)	Velocity (m/s)	Shear stress (Pa)	Velocity (m/s)	Shear stress (Pa)
2 m/s	0.5±0.4	2.4±2.3	0.9±0.05	5.2±0.5	0.7±0.24	2.9±0.21
5 m/s	1.3±0.9	10.5±10.1	2.5±0.12	25.1±2.2	1.8±0.07	14.2±1.0
10 m/s	2.5±1.8	32.7±22.9	4.9±0.24	84±7.4	3.6±0.14	47.6±3.34

Fig. 11 shows a significant increase in shear stress on electrodes with a radius of 0–2.5 mm with a maximum velocity of 6.4 m/s. Shear stress in the centre region increased until it reached a maximum of 130 Pa (inner electrode). There is a small inflection visible in the shear stress curve so that the peak intensity is lower at the outer edge of the electrode. It causes the activity at the electrode to decrease as the radius increases. Then, for the inner and outer electrodes, the velocity, shear stress, and shear velocity decrease gradually.

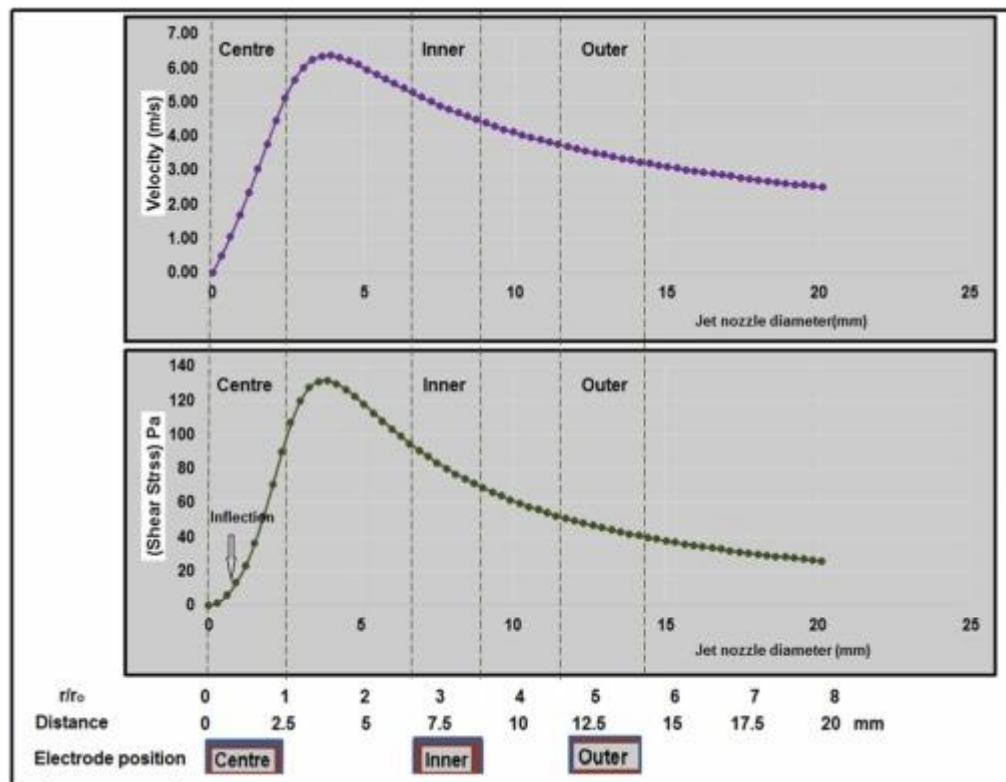


Fig. 11. The Estimated shear stress and velocity with radial position from the target centre, $r=0$ to outer edge.

The simulation of CFD is then compared with the laboratory experimental results. The PM corrosion rates are 1.5, 2.2, and 1.9 mm/y at the centre, inner, and outer (10 m/s). It can be concluded that the corrosion rate depends on the position of the electrode. The inner electrode has the highest corrosion rate because it is in the highest hydrodynamic condition compared to the centre and outer. The hydrodynamic effect is minimum when there is no velocity (0 m/s), as shown by the corrosion rate in the inner, outer, and centre equal to 1 mm/y. When the

velocity increases from 2, 5, 8, and 10 m/s, the turbulence becomes higher, thereby the mass transfer rate increases. Therefore, the corrosion rate increases. The high flow velocity (10 m/s) is accompanied by a high concentration of electroactive species leads to more corroded [33]. The experimental results are consistent with the simulation of CFD for the centre, outer, and inner electrodes. This result is in accordance with previous research [34], [35].

3.6. Surface characterization

The SEM images below (Fig. 12) show that the WM and HAZ surfaces are more damaged than the PM. The formation of pits and cracks is more severe than PM, causing more significant material loss [36]. EDX analysis is used to determine the chemical composition of the weldment. The results showed that PM's C content (wt%) increased after being corroded, initially from 0.7 to 15.4, while the Fe content (wt%) decreased when PM experienced corrosion from 97.1 to 82.3. Likewise, WM showed the same trend, with C content (wt%) increasing from 0.9 to 19.8 and Fe content, initially 77.9, decreasing to 19.8. Table 4 shows the chemical composition of the weldment. Fe concentration in WM decreased more than in PM.

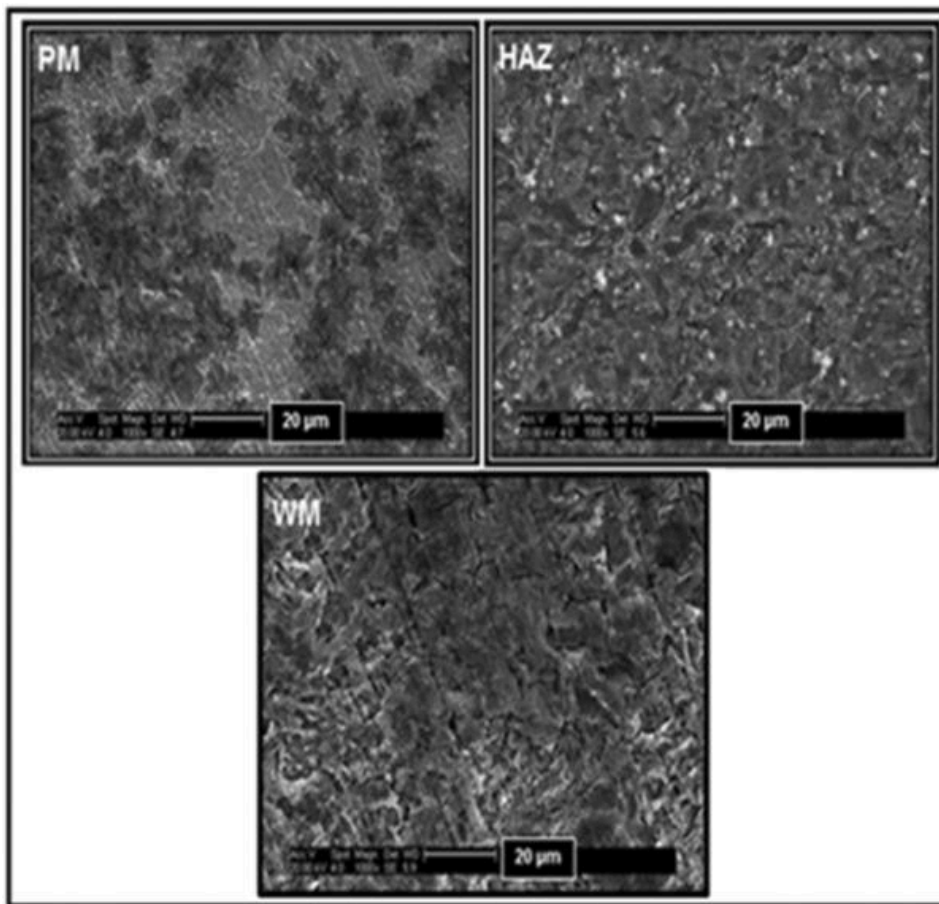


Fig. 12. Scanning electron microscopy of the weldment at 10 m/s.

The X65 pipeline steel is basically composed of pearlite and ferrite [37]. Fig. 13 shows the XRD data of the corrosion products. Based on the results, it was found that the peak of the sample was cementite (Fe_3C). This is in accordance with several references where the corrosion product is generally a cementite compound [38]. High peak intensity at 45 °C was also reported

by previous research [39]. Cementite seems to separate from ferrite-pearlite after Fe dissolves into Fe^{2+} .

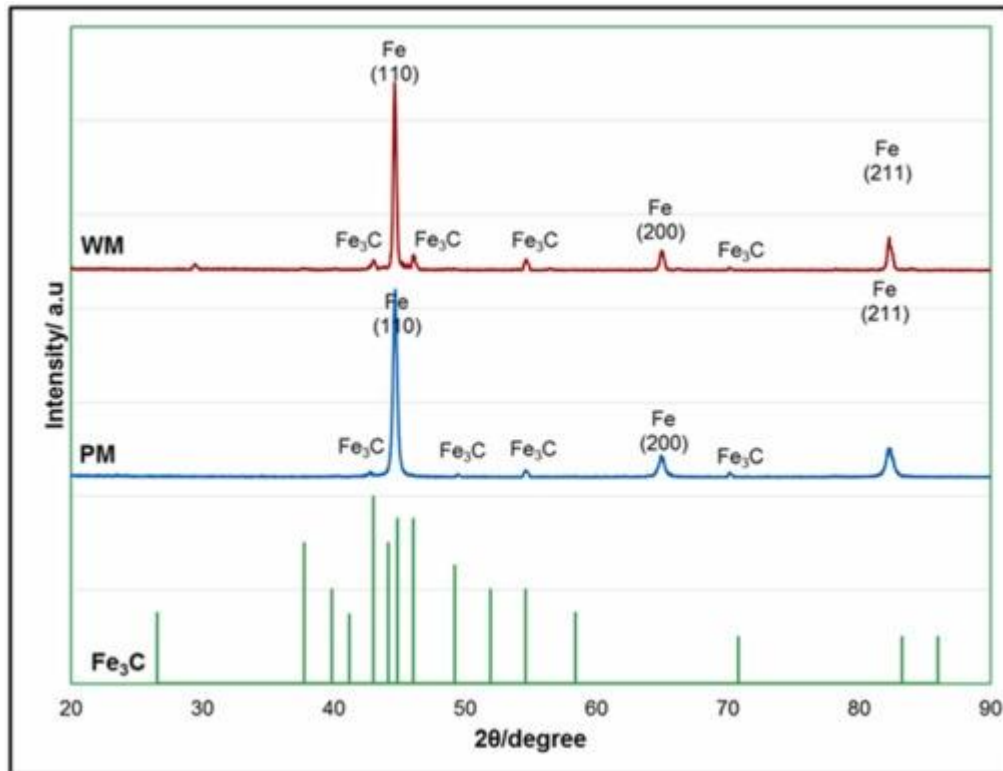


Fig. 13. X-Ray diffraction spectra of the corroded weldment.

FIB analysis is carried out to observe the depleted zone. WM has a thickness of 3.8 μm and PM 2.5–3 μm (Fig. 14A and B) and is 10 times greater than in no-flow conditions, namely around 0.3–0.6 μm (data not shown). This data supports the electrochemical measurement data mentioned above and in accordance with previously reported research. The high flow-rate enhances the local mass transportation and leads to corrosion [40].

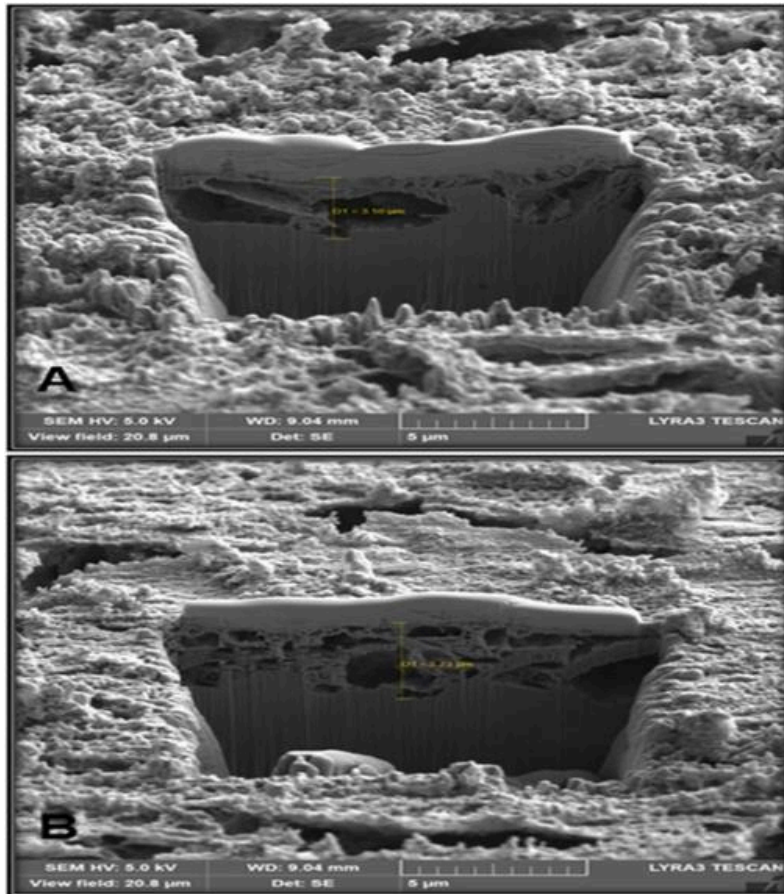


Fig. 14. The FIB micrograph of the PM (A) and the WM (B) in uninhibited 10 m/s saturated with CO_2 .

Raman analysis of WM, PM, and HAZ is shown in Fig. 15. The shift is between 200 until 2000 cm^{-1} . Two strong peaks at 1360 and 1575 cm^{-1} indicate the presence of cementite. This data supports the results of the XRD analysis.

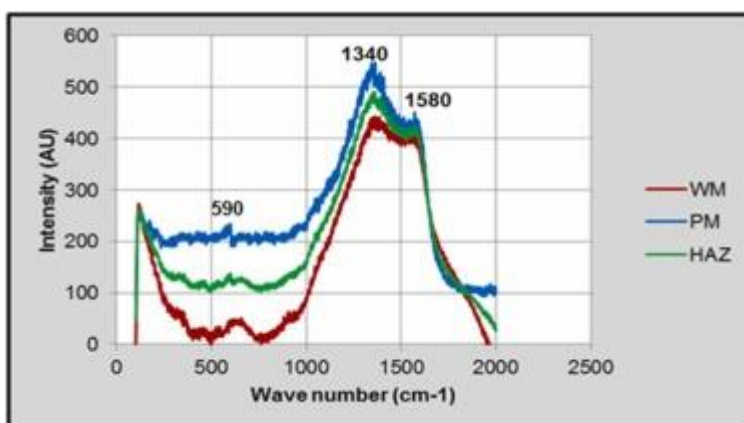


Fig. 15. Raman peaks characteristic of cementite.

The reduction of iron oxide leads to the formation of carbon and iron carbide (cementite). The microstructure of the X65 pipeline steel is composed of ferrite and pearlite. The cementite (Fe_3C) is seen in the pearlite. The cementite formed on the sample surface functions as a barrier

to carbon diffusion because the carbon diffusion coefficient in iron carbide is lower than that of pure iron. It causes carbon to accumulate on the surface and cementite to decompose [41].

4. Conclusion

The corrosion performance of the SJI target with artificial seawater samples purged with CO₂ at 10 m/s has been studied. Experimentally, LPR measurements showed that WM has the highest corrosion rate of 2.52 mm/y, which was found on the inner electrode. The inner electrode shows the highest self-corrosion rate compared to the outer and centre electrodes. From EIS, in outer ring, PM, HAZ, and WM, corrosion rates are 1.71; 1.90; 2.11 mm/y, respectively. While from the LPR, PM, HAZ, and WM's corrosion rate is 1.92, 2.05, 2.22 mm/y. The result is that WM is more corroded, and PM is more protected. The total corrosion rate of WM in the outer, inner, and centre are 2.8, 3.3, and 2.5 mm/y, respectively. The inner electrode corrodes faster than other areas, possibly due to higher local turbulence in the inner electrode. CFD simulation showed that velocity is directly proportional to shear stress. The PM's centre, outer, and inner regions have been simulated for their shear stress and velocity and their effect on the corrosion progress. The highest corrosion rate belongs to the inner region. Surface characterization was studied using SEM-EDX, XRD, FIB, and Raman, which shows the formation of cementite corrosion products.

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