



Research Article

Corrosion behavior of N80 tubing steel in the produced water

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ABSTRACT

One of the most common problems encountered in the oil industry is the microbiologically induced corrosion (MIC) of steel equipment by the produced water (PW). In this aspect, PW sample, which is known to contain microorganisms, was taken from Adıyaman oil field and used in corrosion tests of N80 tubing steel. Two different laboratory scale systems, test (with non-sterile PW) and control (with sterile PW), were set up and operated at 70°C over 720 h. For corrosion analysis, the coupons were removed from the laboratory-scale systems at certain time intervals and, gravimetric and electrochemical analyses were carried out. The surface of the coupons was examined by scanning electron microscopy (SEM). The corrosion rates of the test coupons obtained from gravimetric analyses were higher than the control ones during the experiment, and the test coupons were 1.46 times more corroded at the end of the experiment. Additionally, it was determined that the current values of the test coupons were significantly higher than those in the control system ($p < 0.05$). The results of corrosion analyses pointed out that N80 steel was corroded microbiologically. SEM analysis showed that microorganisms were present among the corrosion products. The corrosion data obtained from the control system also indicated that the PW was aggressive for N80 steel.

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INTRODUCTION

The produced water (PW) is a mixture of the formation water, naturally found in the oil reservoir, and injection water, injected water into the reservoir for oil recovery

[1]. The chemical composition of PW is specific to the oil reservoir from which it is extracted because the different factors, such as reservoir conditions (i.e. geological formation), well structure, age of the well, and extracted product, may affect the constituents of PW. Generally, PW may

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contain inorganic substances (e.g. calcium, sodium, chloride, potassium, sulphate, carbon dioxide, hydrogen sulphide), organic compounds, including volatile aromatic compounds (benzene, ethylbenzene, toluene, etc.), polycyclic aromatic hydrocarbons (PAHs) (e.g. naphthalene), phenol compounds, organic acids and additives, condensates, petroleum gases, sand and corrosion products [2, 3].

In oil industry, corrosion occurs with very different corrosive effects originating from PW. Electrochemical corrosion is very common due to the presence of an aqueous system in the environment [4]. Major corrosion mechanisms include sour corrosion, hydrogen crevice corrosion, microbiologically induced corrosion (MIC) etc. [5, 6]. MIC refers to metal degradation caused by corrosion reactions that occur directly with the microbial metabolic activities or indirectly with the secretion of chemically reactive products [7]. MIC is the result of a series of highly complex, interacting reactions carried out by different bacterial species [8, 9]. The ability of microorganisms to survive in oil reservoirs depends on the chemical composition and physical properties of the ecosystem. The major factors affecting the physicochemical structure of the reservoir environment are temperature, salinity, pH values and the redox potential of the environment, as well as the presence of electron donors and acceptors in the environment [10]. Microorganisms can accelerate corrosion by forming a biofilm, producing extracellular polysaccharide substances (EPS), producing deposits under which is a favorable environment for the development of crevice corrosion, creating a corrosive acidic environment with own metabolic products, breaking down the chemicals added to the environment to prevent corrosion, by directly affecting (accelerating cathodic or anodic reactions) corrosion reactions [8, 11].

Carbon steel is commonly used metal in the oil industry (storage tanks, crude pipelines, etc.), although it has low corrosion resistance [12]. The reason for this may be due to its highly developed technology and advantages in terms of cost-effectiveness [13]. The carbon steels such as N80, P110, Q235 etc. are generally preferred in studies conducted to investigate the corrosion of carbon steel used in the oil industry [13-15].

The oil content in different countries in the world differs in terms of both chemical and microorganism diversity and density. Therefore, every oil field is special in itself and microorganism-based corrosion problems should be handled as specific to the oil fields where the trouble arised. Adiyaman region is one of the important oil production regions of Türkiye and known to have intense corrosion problems. In addition, as revealed in our previous study [16], the oil PW taken from this region is rich in mixed bacterial population. In this context, it was aimed to reveal whether the microorganisms in the PW have a role in the corrosion of N80 steel, which is frequently used material both in the region and in general oil production activities, in the present study. For this purpose, N80 steel was exposed to PW taken from Adiyaman oil field over 720 h. The corrosion

behavior of N80 steel was investigated by performing electrochemical and gravimetric analyses at certain sampling times. Scanning electron microscopy (SEM) analysis was applied to examine the coupon surfaces.

MATERIALS AND METHODS

PW Sampling and Analyses

PW was used as working solution in the experiments. The PW sample known to be rich in bacterial content was taken from Adiyaman oil field located in the Southeastern Anatolia Region of Türkiye [16]. The sample was collected under aseptic conditions in sterile 500 mL serum bottles and the bottles were immediately capped to prevent oxygen inlet. Temperature and conductivity data of the PW were obtained from Türkiye Petrolleri Anonim Ortaklığı (TPAO), and some physicochemical parameters (alkaline, conductivity, total chlorine, dissolved oxygen, etc.) were analysed by AEM Environmental Laboratory.

Test Material

N80 steel, which is frequently used as tubing material, was used as test material [14]. N80 steel was supplied by Adiyaman Regional Directorate of TPAO as an unused tubing pipe prepared according to the American Petroleum Institute (API) standards. The N80 steel consists of the following chemical composition (wt.%): Fe 97.60, Mn 1.18, Ni 0.56, Si 0.285, C 0.24, Cr 0.104, P 0.0189, S 0.0157, Mo 0.015, Cu 0.012. The coupons (6×5×21 mm) were cutted from the tubing pipe (Figure 1) and then were drilled from one edge to form a 2.5 mm diameter hole. After all the coupon surfaces were polished with emery papers (180, 240, 320, 400, 600, 800 grit), the coupons were washed, dried and stored in a desiccator until use.

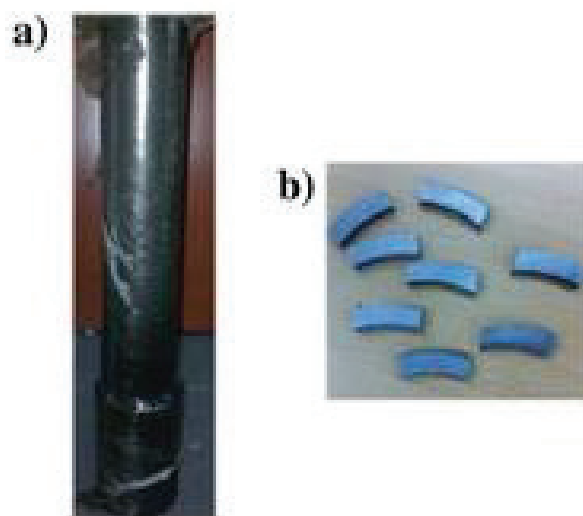


Figure 1. The tubing pipe (a) and the coupons obtained from the tubing pipe (b).

The corrosion behavior of N80 steel was detected by both gravimetric and electrochemical methods. Therefore, the coupons were prepared separately as required by these analyses. The coupons to be used in gravimetric analysis were weighed. For electrochemical analysis, the coupons were coated with an epoxy zinc phosphate primer (Moravia, Türkiye) and then with an epoxy final coating (Moravia, Türkiye) to leave an area of 1 cm² on a surface in contact with the PW sample. Afterwards, the epoxy coated areas on the surfaces were finally covered with silicone. All the coupons were sterilized by UV (UVC, 254 nm, 15 W) for 15 min.

Installation and Operation of Experimental Systems

In order to perform the corrosion experiments, a test system on a laboratory scale was set up, which included a sterile 1 L glass beaker, a grid as coupon bearer, and N80 steel coupons. The PW sample was used as the working solution. The coupons attached to the carrier grid were located into the glass beaker under aseptic conditions. The system was operated uninterruptedly at 70°C over 720 h. A magnetic stirrer (IKA C-MAG HS 10) set at 150 rpm was used to mix the working solution during the process. As soon as the coupons were exposed to the PW sample, the experiment began (0 h of exposure). From the moment that the coupons were exposed to the PW sample, the experimental period began to run. A control system was simultaneously installed and operated under the same conditions with the test system. Sterile PW sample (without microorganism) was used as the working solution in the control system. Sterility control was carried out in terms of anaerobic and aerobic bacteria by inoculating of the sterile PW onto R2A agar and sodium thioglycolate agar, respectively, at each measurement time.

Corrosion analyses were performed with the coupons taken from the test and control systems at certain sampling times (24, 48, 72, 96, 144, 168, 336 and 720 h) by both gravimetric and electrochemical methods. Additionally, electrochemical measurements were applied also at 504th h of exposure. SEM analysis was carried out to observe the surface of the coupons.

Gravimetric Analysis

For the weight loss measurement, three coupons were taken from both of the systems. Clarke's solution was used to remove corrosion products from the coupons' surfaces [17]. Then they were dried in the Pasteur oven. After the weight loss of the coupons were determined, the corrosion rates were calculated with the formula given in the equation below [17].

Corrosion rate (V_{corr}) was calculated in mpy (miles/year) and represented 1 mile thinning in one year (1 mile = 0.0254 mm)

$$V_{\text{corr}} \text{ (mpy)}: (K \times W) / (A \times t \times d)$$

K: 3.45×10^6 (constant for mpy)

d: density of coupon (g/cm³)

W: weight loss (g)

A: surface area (cm²)

t: experimental time of (h)

Electrochemical Analysis

Electrochemical measurements were performed in a conventional three-electrode corrosion cell by means of a potentiostat/galvanostat device (Gamry, Interface 1000, USA). The N80 steel coupons was used as the working electrode, while the counter electrode was carbon rods and a saturated calomel electrode (SCE) was used as the reference. After open circuit potential (OCP) values of the coupons were measured, potentiodynamic curves were obtained. The potentiodynamic polarization scans were conducted from -1.000 V to -0.400 V at a scanning rate of 1mV/s. After potentiodynamic polarization tests, corrosion potential (E_{corr}) and corrosion current (i_{corr}) were determined. Electrochemical measurements were carried out at certain times (24, 48, 72, 96, 144, 168, 336, 504 and 720 h). For each measurement, a coupon was removed from the test and control systems.

SEM Analysis

The surfaces of the coupons were analysed by SEM. The coupons were fixed with 2.5% glutaraldehyde, then gradually dehydrated in ethanol series (30%, 50%, 80%, and 95%) for 10 min and finally dried in air [18]. Images were taken by a scanning electron microscope (FEI Quanta 450 FEG, magnification range: from $6 \times$ to $10^6 \times$) after the dried samples were coated with gold.

Statistical Analysis

SPSS Statistics Version 24.0 software was used for the statistical analyses. The relationship between the test and control data obtained by gravimetric and electrochemical methods was determined by the Pearson and Spearman correlation coefficients test. Also, the numerical status and comparison of the test and control data obtained by gravimetric and electrochemical methods in terms of means were determined with the t-test and Mann Whitney U test. Except where otherwise stated, p values of 0.05 were used to determine statistical significance for all analyses.

RESULTS AND DISCUSSION

Produced Water

The results of the physicochemical analysis of the PW sample are presented in Table 1. The temperature of the PW was 70°C and therefore the systems were operated at this temperature. Although Mn and Cl contents were found to be lower, the other analysed parameters were typical for PW.

It has been reported that while the PWs contain SO_4^{2-} up to several thousand mg/L, the dissolved oxygen amount is generally low, the Fe content varies from trace amounts

Table 1. Some physicochemical parameters of the PW

Parameter	Unit	Result
Total Alkalinity	mg/L	416.8
HCO ₃ ⁻	mg/L	416.8
Dissolved Oxygen	mg/L	8.14
Fe ⁺²	mg/L	0.091
PO ₄ ⁻³	mg/L	<1
H ₂ S	mg/L	<0.1
Conductivity	ms/cm	30.2
Mn ⁺²	µg/L	56.8
NO ₃ ⁻	mg/L	<1
NO ₂ ⁻	mg/L	<0.05
CO ₂	mg/L	<10
SO ₄ ⁻²	mg/L	673.52
Total Dissolved Solids (TDS)	mg/L	18256
Total Fe	mg/L	2.35
Total Cl	mg/L	0.63

to 1 mg/L, the PO₄⁻³ content is generally less than 1 mg/L. Also, the Mn content has been reported to range from 1 to 6 mg/, the Cl content has been usually at high (200000 mg/L or more) concentrations, and the NH₄ content can be variable [19].

Despite harsh conditions in oil reservoirs (e.g. low oxygen, high salinity, high temperature,), many microorganisms with different metabolic capabilities are able to survive in the oil reservoir environment [20]. The identified microbial groups in oil fields are sulfate reducing bacteria (SRB) [21], sulfur oxidising bacteria [22], methanogens [23], fermentative microorganisms [24], acetogens [25], nitrate reducers [26], manganese reducers [27], iron reducers [28], and hydrocarbon degraders [29]. Although the microbial community composition may differ significantly in reservoirs located in remote geographical areas, it is likely that microbial groups with similar metabolic activity can be seen in the reservoirs, located in the same region, due to having similar physicochemical reservoir conditions. For instance, nitrate-reducing and hydrocarbon-degrading *Pseudomonas stutzeri*, was reported to be abundant in oil-associated environments (e.g. PW) of south-eastern Türkiye, including Adıyaman [30], Diyarbakır [31] and Batman regions [32]. Apart from nitrate-reducers and hydrocarbon-degraders, fermentative bacteria (e.g. *Thermovirga*, *Petrotoga*), acetogens (e.g. *Acetobacterium*, *Proteiniphilum*) and sulfate reducers (e.g. *Desulfosporosinus*, *Desulfovibrio*, *Thermodesulfovibrio*, *Desulfotomaculum*) were also detected in the Diyarbakır oil fields located in southeastern Türkiye [33]. In addition, not only Diyarbakır but also Adıyaman oil fields harbor fermentative bacteria (e.g. *Thermovirga*, *Geotoga*, *Sphaerochaeta*) and SRB (e.g. *Desulfovibrio*, *Paucidesulfovibrio*, *Oleidesulfovibrio*) [16].

The viability and metabolic activity of oil microorganisms in the PW. Different types of microorganisms require different mineral nutrients such as macronutrients including carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), sulphur (S), chlorine (Cl), iron (Fe) elements, and micronutrients including manganese (Mn) for growth. The microorganisms derive these elements in different chemical forms found in PW. For example, SRB derive S from SO₄⁻² or nitrate-reducing bacteria derive N from NO₃⁻ [34]. Especially, the high SO₄⁻² content (673.52 mg/L) detected in the PW in the present study may point out the high probability presence of the SRB in the reservoir.

Corrosion Analyses

At the end of the analyses, a thick black layer was observed on the surface of the test coupon, while it was observed that this layer was red in the control coupons (Figure 2). SEM images revealed that the corrosion products accumulated on the test coupons were in a sandy structure and in layers on top of each other (Figure 3).

It was observed that the corrosion products accumulated on the surface of both test and control coupons in a short time, and these products completely covered the surface and thickened over time (Figure 2). Formation of thicker corrosion product on the surface of the coupons with the increased immersion time may be an indication of that the layer formed was not protective and therefore the corrosion process of N80 steel continued. Wang et al. [35] investigated the effect of PW at different temperatures on corrosion and found out that the corrosion rate increased proportionally at temperatures up to 70°C, but not proportionally when the temperature reached 80°C -90°C. They suggested that a protective corrosion product layer forms on the surface of the metal at temperatures above 70°C.

After the removal of the corrosion products, numerous pits were observed on the test coupon surface (Figure 4a).

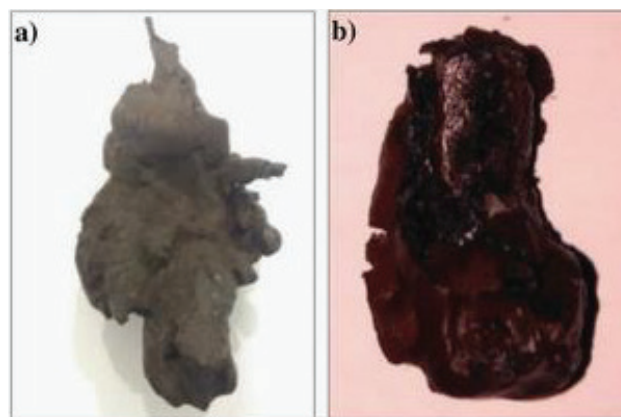


Figure 2. Macroscopic views of the corrosion products formed on the test (a) and control (b) coupons exposed to the PW.

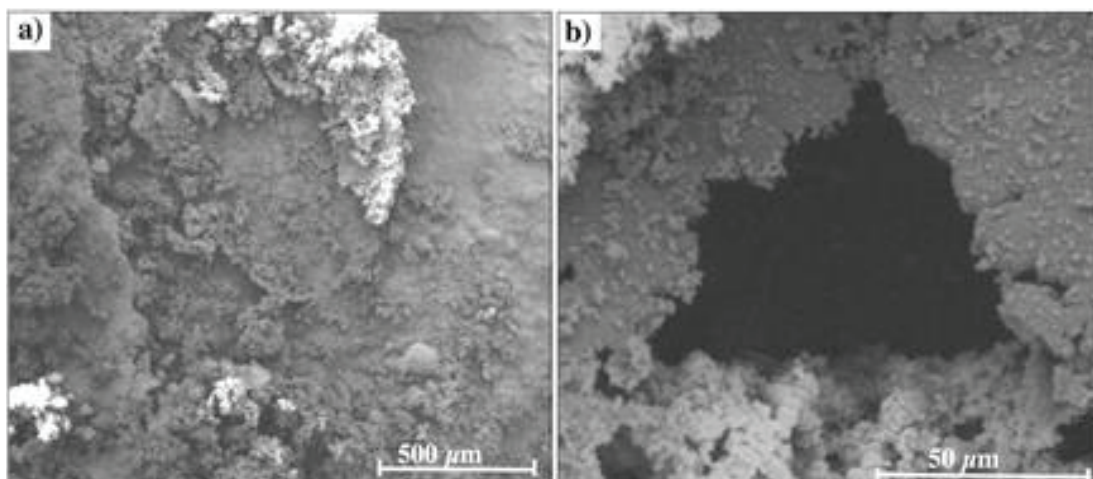


Figure 3. SEM micrographs of the corrosion products formed on the test coupon. a) Bar=500 μm , b) Bar=50 μm .

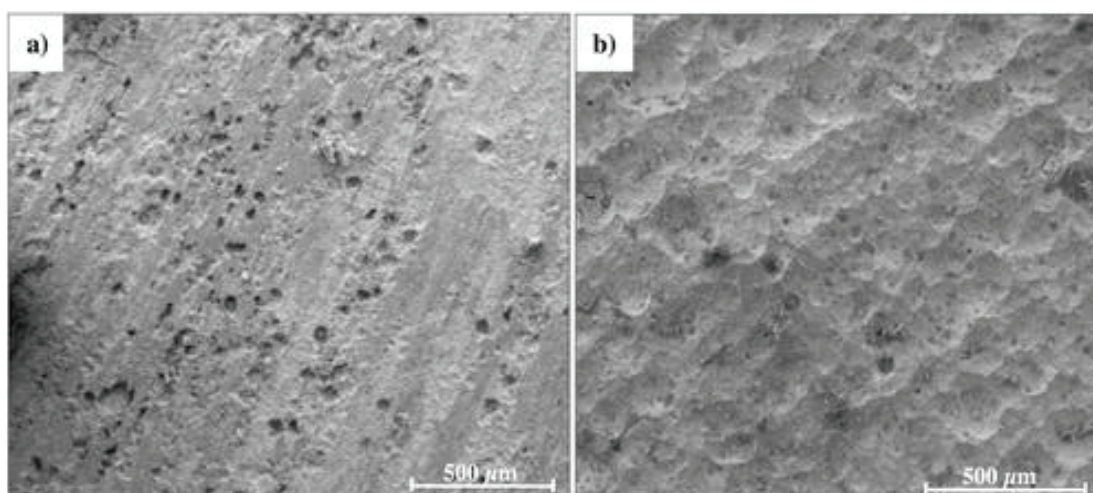


Figure 4. SEM micrographs of the test (a) and control (b) coupons after removal of corrosion products (Bars=500 μm).

However, pits were also observed on the control coupon surface, albeit less in number than on the test ones (Figure 4b). It was also detected that the surface topography of the control coupon was different from that of the test coupon. The pits formed on the surface of the control coupons may be due to the physicochemical content of the PW (Table 1). It was reported that the intense salt content causes pits on steel surfaces [36, 37]. Liu et al. [3] notified that CO_2 causes corrosion of N80 steel. Perez [38] also reported that CO_2 , temperature, pH, H_2S , O_2 and organic acids cause corrosion in the oil industry, either being alone or in their interactions. In addition, Craig [39] notified that the water amount in the oil content increases the corrosive potential of the solution due to the conductivity. Moreover, Gonzalez-Rodriguez et al. [40] reported that, the passive

film on the surface of the metal deteriorates and anodic dissolution begins in the presence of high amounts of HCO_3^- .

Gravimetric Analysis

The results of the weight loss and corrosion rate of the coupons are given in Table 2. It was determined that the weight loss values both of the test and control coupons increased with time ($p < 0.01$ and $p < 0.01$, respectively), and the highest values were detected as $0.1598 \pm 0.0038 \text{ g/cm}^2$ and $0.1030 \pm 0.0040 \text{ g/cm}^2$ at the end of the experiment, respectively. The highest corrosion rate in the test coupons was determined as $25.55 \pm 2.10 \text{ mpy}$ after 24 h of exposure, and then decreases and increases in the values were determined during the experiment. The corrosion rate of the test coupons at the end of the experiment was determined as $19.07 \pm 1.82 \text{ mpy}$. In the control coupons, the corrosion rate varied during the experiment and the highest value was

Table 2. The weight losses and corrosion rates of the N80 steel coupons over the experiment

Time (h)	Weight loss, g/cm ²		Corrosion rate, mpy		
	Test system	Control system	Test system	Control system	Test / Control
24	0.0070 ± 0.0002	0.0031 ± 0.0001	25.55 ± 2.10	10.97 ± 0.98	2.33
48	0.0083 ± 0.0004	0.0057 ± 0.0002	15.81 ± 1.15	10.46 ± 1.01	1.51
72	0.0104 ± 0.0010	0.0073 ± 0.0002	13.30 ± 1.89	9.30 ± 1.21	1.43
96	0.0185 ± 0.0012	0.0173 ± 0.0011	17.75 ± 2.13	16.52 ± 1.30	1.07
144	0.0295 ± 0.0005	0.0248 ± 0.0010	18.21 ± 1.92	15.27 ± 1.93	1.19
168	0.0298 ± 0.0011	0.0274 ± 0.0021	15.75 ± 1.75	14.49 ± 2.01	1.09
336	0.0617 ± 0.0021	0.0546 ± 0.0019	16.75 ± 1.16	15.17 ± 1.80	1.10
720	0.1598 ± 0.0038	0.1030 ± 0.0040	19.07 ± 1.82	13.07 ± 1.72	1.46

± Standard deviation.

measured as 16.52 ± 1.30 mpy after 96 h of exposure. The corrosion rate of the control coupons was determined as 13.07 ± 1.72 mpy at the end of the experiment. It was determined that the corrosion rates of the test coupons were higher than those of the control until the end of the experiment, and the test coupons were corroded 1.46 times more than the control coupons after 720 h of exposure (Table 2). This result may indicate that microorganisms are responsible for the corrosion of the N80 steel.

Electrochemical Analysis

Although the electrochemical measurements were made over the 720 h-period of exposure, accurate data could be obtained at the last after 504 h of exposure because of the intense corrosion products on the coupon surfaces. The potentiodynamic polarization curves are shown in Figure 5. E_{corr} values of the coupons in the both systems varied during the experiment (Table 3). On the other hand, when compared with the control coupons, the E_{corr} values of the

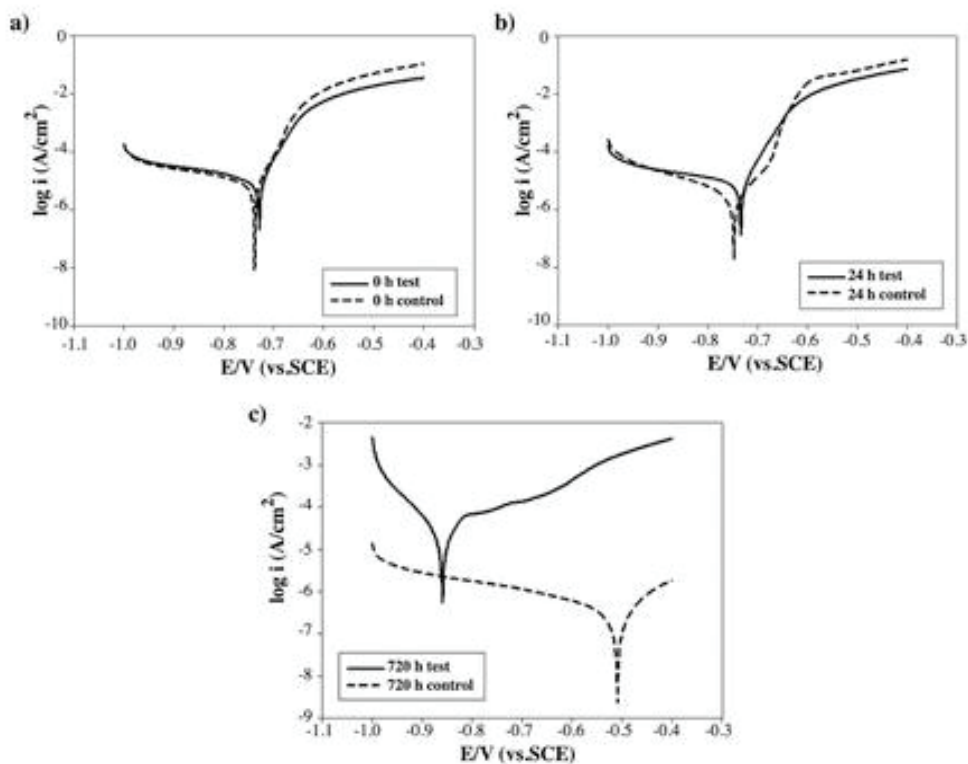
**Figure 5.** The potentiodynamic polarization curves of the test and control coupons exposed to the PW. a) 0 h, b) 24 h, c) 504 h.

Table 3. Electrochemical parameters of the N80 steel coupons in the test and control systems over 720 h

Time (h)	E_{corr} (V)		i_{corr} ($\mu\text{A}/\text{cm}^2$)	
	test	control	test	control
0	-0.729	-0.739	12.33	4.06
24	-0.734	-0.748	8.97	3.38
48	-0.749	-0.795	8.53	3.26
72	-0.762	-0.817	7.00	6.52
96	-0.796	-0.750	5.38	2.84
144	-0.795	-0.826	9.20	2.24
168	-0.805	-0.830	13.11	4.35
336	-0.811	-0.796	42.20	30.77
720	-0.859	-0.509	17.15	0.17

test coupons generally shifted to more positive values was determined. The most negative value of the test coupon was determined as -0.888 V after 504 h of exposure (Table 3, Figure 5c). Additionally, the current density (i_{corr}) values of the test coupons decreased until 96 h of exposure and then started to increase until the end of the experiment and was determined after 504 h of exposure as 151.30 $\mu\text{A}/\text{cm}^2$. The polarization curve belong to 504 h of exposure may indicate that cathodic reaction increased and cathodic depolarization produced on N80 steel in the presence of consortium. Indeed, similar findings for MIC of N80 steel by SRB were reported by Song et al. [41]. On the other hand, i_{corr} values of the control coupons varied during the experiment and was determined after 504 h of exposure as 29.84 $\mu\text{A}/\text{cm}^2$. It was detected that the i_{corr} values of the test coupons were

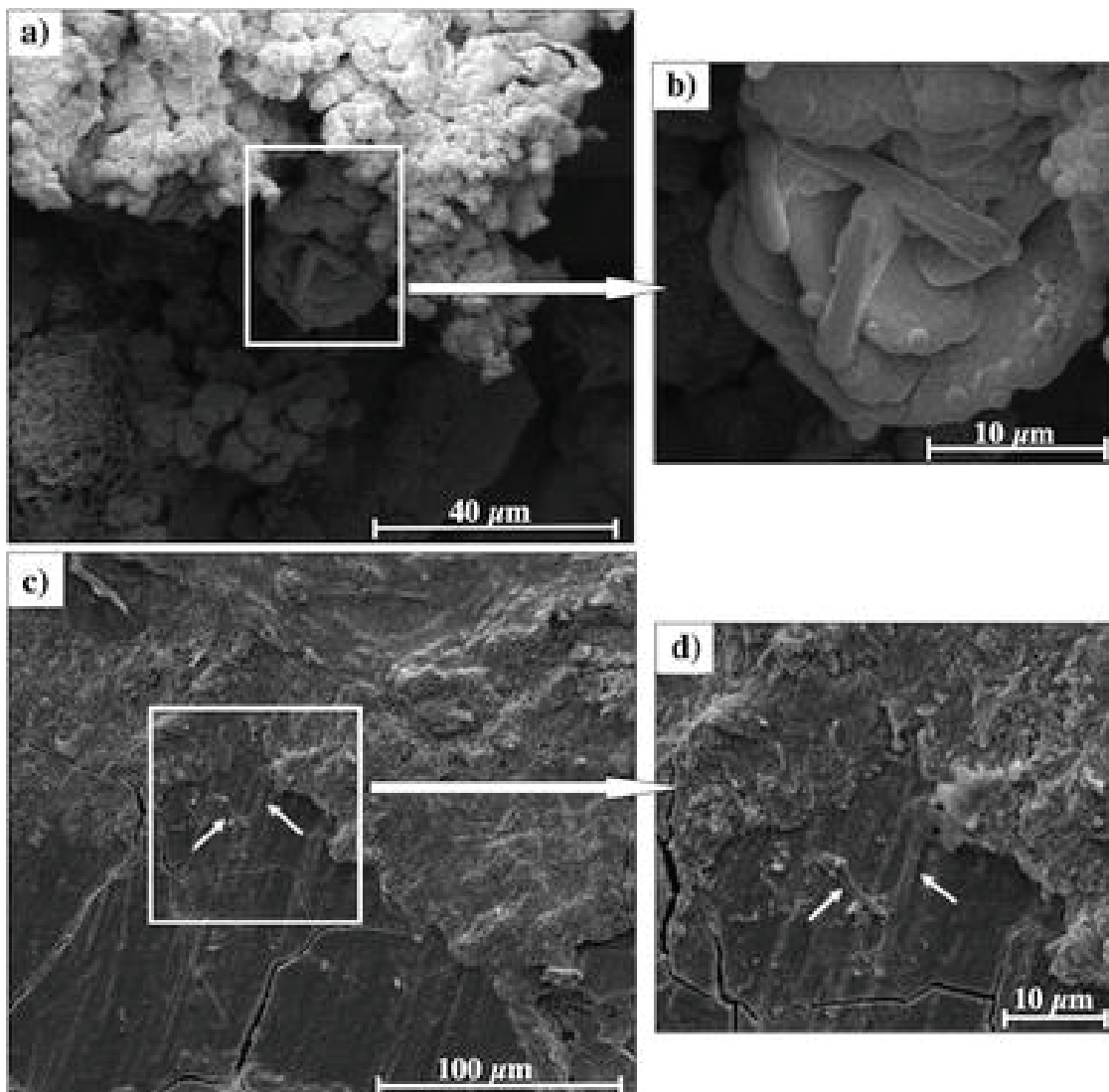


Figure 6. SEM micrographs of the microorganisms in the corrosion products on the surface of coupons in the test system (Arrows indicate microorganisms). a) Bar= $40\mu\text{m}$, b) Bar= $10\mu\text{m}$, c) Bar= $100\mu\text{m}$, d) Bar= $10\mu\text{m}$.

significantly higher than the control ones during the experiment ($p < 0.05$).

The findings obtained from the electrochemical and gravimetric experiments could be interpreted as microorganisms encouraged the corrosion of N80 steel. It may be caused by the metabolic processes of microorganisms. Indeed, SEM images shows the presence of microorganisms on the coupon surface (Figure 6). Nevertheless, it was not clearly investigated which groups of microorganisms affect the corrosion behavior of N80 steel, nor how they were involved in the process. To the knowledge of the authors, although the corrosive effect of the mixed consortium of microorganisms in PW was investigated in different carbon steels such as API 5L [42, 43], L245 [44], and L360 [45], no similar study has been found showing the effect on the corrosion of N80 steel. However, Song et al. [41] investigated corrosion behavior of N80 steel exposed to pure SRB strains isolated from oilfield PW using gravimetric and electrochemical methods during 5 and 3 days, respectively. In line with the findings obtained from both analyses, they stated that SRB corroded the N80 steel. The corrosion rate according to the weight loss was 0.0093 mm/y in the presence of SRB. It was noticed that the reported data were even lower than the values obtained after 96 h of exposure (day 4) in the present study. This may be because the diverse mixed microbial community in the present study exhibited different corrosion mechanisms. Indeed mixed-culture microorganisms can form synergistic biofilms that are more tenacious when compared with the biofilms of single-strain microorganism [46].

In order to propound the corrosion mechanisms for N80 steel exposed to PW with mixed consortium, it is primarily necessary to determine corrosion-related microorganism groups that are actively present on the metal surface and even in the corrosion products. The microbial groups leading to MIC in oil associated environments mainly include SRB, sulfur-oxidizing bacteria (SOB), iron-reducing bacteria (IRB), iron-oxidizing bacteria (IOB), acid-producing bacteria (APB), nitrate-reducing bacteria (NRB), and slime-forming bacteria (SFB) [47]. Anaerobic SRB considered as the main culprits of corrosion failures of carbon steel structures due to anoxic reservoir conditions. SRB utilize sulfur compounds, such as sulfate (SO_4^{2-}), thiosulfate ($\text{S}_2\text{O}_3^{2-}$), and sulfite (SO_3^{2-}) and, as well as sulfur (S^0) to sulfide (H_2S) [48]. In the oil field steel pipe, high SO_4^{2-} concentrations of PW can facilitate SRB growth, causing not only faster corrosion of the steel, but also blocking the reservoir due to H_2S and FeS produced by SRB [47]. Extensive researches revealed that numerous factors are associated with SRB-induced MIC, including bacterial metabolic activity as well as various corrosion mechanisms such as cathodic depolarization [49], iron sulfide precipitation [50], a volatile phosphorus compound [51], Fe-binding exopolymers [52], electron-MIC (EMIC) and chemical-MIC (CMIC) [53], and the extracellular electron transfer-MIC (EET-MIC) [54, 55].

Within this scope, bacteria associated with biocorrosion were reported in the PW taken from the reservoir in Adiyaman oil field with corrosion problem in wellhead equipments [56]. In the reported study, SO_4^{2-} amount in the PW was measured as 170 mg/L, and SRB species, including *Desulfovibrio* genus (e.g., *D. dechloracetivorans*) and *Desulfovibrio*-like bacteria (e.g., *Paucidesulfovibrio capillatus*, *Paucidesulfovibrio longus*, and *Oleidesulfovibrio alaskensis*) were detected in the enrichments obtained from the PW. In addition, besides SRB, H_2S generating bacteria, such as *Geotoga* and *Thermovirga*, were also detected in these enrichments. Members of *Geotoga* and *Thermovirga* genera, known as fermenters, may contribute to MIC by reducing elemental sulfur with the hydrogen they produce to H_2S , a corrosive product [57, 58]. Considering the present study, it can be interpreted that the relatively higher amount of SO_4^{2-} detected in the PW (673.52 mg/L) may stimulate SRB growth in the PW and thus encourage SRB to have a significant impact on the corrosion of N80 steel.

CONCLUSION

While this study reveals the scientific importance of the studies carried out with a mixed microbial consortium in its natural environment, it will also serve as a reference for future studies on MIC control in oil environment.

Based on the obtained data, the conclusions can be drawn as follows:

- According to the electrochemical and gravimetric corrosion test results, the N80 steel was microbiologically corroded.
- The formation of thick corrosion layers on the surfaces of both test and control coupons together with the occurring of pits on the control coupons indicated that the PW was aggressive for the N80 steel.
- In line with the corrosion data obtained, the question of whether the use of N80 steel as tubing steel is economical and long-lasting comes to the fore. Therefore, more experimental studies are needed to clarify this interpretation.

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DATA AVAILABILITY STATEMENT

It is confirmed by the authors that the data supporting the findings of the study are available in the article. In accordance with reasonable requests, the raw data supporting the findings of this study are available from the corresponding author.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare in regard to the research, authorship, and/or publication of this article.

ETHICS

The publication of this manuscript has no ethical problems exist.

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