Comparative study on the corrosion behaviour of Lord Razor Blade Steel (LRBS) in aqueous environments

Nobl F. El Boraeia and Magdy A. M. Ibrahimb

aDepartment of Chemistry, Faculty of Education, Ain Shams University, Cairo, Egypt; bDepartment of Chemistry, Faculty of Science, Ain Shams University, Cairo, Egypt

ABSTRACT

The corrosion resistance of Lord Razor Blade Steel (LRBS) specimens made of low carbon steel has been compared in aqueous borate (pH 9.0), 1.0 M NaOH and 0.5 M NaCl solutions at 25°C. The investigation was accomplished utilizing potentiodynamic polarization curves (PPC’s), cyclic potentiodynamic polarization (CPP), electrochemical impedance spectroscopy (EIS), open circuit potential (OCP) and chronoamperometric (j-t transients) techniques, complemented by SEM study. The study was also carried out on mild steel (MS) for comparison. It was found that the corrosion resistance of LRBS specimens in the borate solution is higher than that in NaCl and NaOH solutions. Moreover, the LRBS specimens possess a higher corrosion resistance than the MS in the same tested solutions.

1. Introduction

Due to its high flexibility, low carbon steel is ideal for applications in which precision is chief. It is less prone to corrosion than other types of steel due to its reduced carbon content. Steel alloys are the most important materials in our daily life due to their mechanical strength, easy manufacture, weldability, formability, reasonable cost and wide applications [1].

Corrosion is an undesirable phenomenon that involves the deterioration of metallic materials and shortens their life. The most regular example of corrosion is the development of rust on steel. Most corrosion processes are of an electrochemical type and involve two reactions on the surface of the corroding metal. One of the reactions is the dissolution of iron (oxidation). The other is a reduction of oxygen (reduction reaction). The products of the electrochemical reactions can react with each other non-electrochemically to produce the final product (e.g. rust) [2]. However, the corrosion resistance of steel depends on the steel composition as well as on the environments. Moreover, the presence of aggressive Cl− ions plays an important role in the corrosion process. Chloride ions in the solution could help to remove the metal cations accumulated on the anode by forming soluble compounds, and this participates in an accelerated anodic reaction and thus faster rusting of the metals.

Therefore, the objective of this research is to assess the disparity in the corrosion behavior of Lord Razor Blade Steel (LRBS) in aqueous borate, 1.0 M NaOH and 0.5 M NaCl solutions, particularly it is widely used in Egypt with a suitable price. Comparing the corrosion behavior of LRBS with mild steel (MS) in the same tested solutions are also reported.

2. Experimental details

2.1. Materials and electrolyte solutions

The low carbon steel used for the manufacture of Razor Blade specimens was supplied from Sweden by the Lord company in Egypt. It has the following chemical composition (wt.%): C 0.02, Mn 1.11, Co 1.65 Cr 12.99 and rest are Fe. Lord company is one of the most famous companies in Egypt for producing Razor Blade at a reasonable price. On the other hand, the mild steel (MS) specimens used for comparison have the following chemical composition (wt. %): C 0.2, Mn 0.9, P 0.05 and the rest are Fe. Before the corrosion test, all specimens were manually polished with emery papers of increasing smoothness up to 2000 grit, washed with double distilled water and rinsed with acetone. The electrolytes; aqueous borate (0.05 M H3BO3 and 0.05 M Na₂B4O7) (pH 9.0), 1.0 M NaOH and 0.5 M (3% weight) NaCl solutions were prepared with double-distilled water. Most of the experiments were carried out at ambient temperature (25°C), however, various temperatures (25–65°C) were used in the case of NaCl solutions and its effect on the pitting potential.
2.2. Electrochemical measurements

The electrochemical measurements were conducted using Interface 1000 Gamry Instrument Potentiostat/Galvanostat/ZRA and the software used was Gamry Echem Analyst Version 6.11. A three-electrode cell assembly was used. The working electrodes were made of steel strips (LRBS or MS) fixed in Araldite holders to give an available surface area of 1.26 cm². A new specimen for each corrosive media test was used. A platinum wire was used as counter electrode and Ag/AgCl electrode was used as a reference electrode. The electrochemical tests have performed in aerated solutions. The working electrode was immersed in the test solution for 30 min before the electrochemical measurements. The potentiodynamic polarization curves (PPC’s) were carried out, in the potential range of $-1.5$–$0.6$ V at a scan rate of 5 mV s$^{-1}$, while cyclic potentiodynamic polarization (CPP) was traced in the potential range of $-1.5$ to $+0.85$ V at a scan rate of 5 mV s$^{-1}$. The sweeping potential was started at $-1.5$ V and progressed in a positive direction. The electrochemical impedance spectroscopy (EIS) measurements were performed at OCP over a frequency range of 100 kHz to 0.01 Hz with an amplitude of 5 mV peak-to-peak. On the other hand, chronoamperometric (current–time) curves, at different anodic step potentials, and different NaCl concentrations were recorded for a period of 120 s.

2.3. Surface morphology

The surface morphology of LRBS specimens before and after the potentiodynamic measurements in different aqueous solutions was investigated using scanning electron microscopy model Shimadzu supper-scan SSX-550.

3. Results and discussion

3.1. Potentiodynamic polarization curves (PPC’s)

The PPC’s for LRBS specimens as well as for MS in aqueous borate buffer (pH 9.0), 1.0 M NaOH and 0.5 M NaCl solutions were displayed in Figures 1 and 2 respectively. The electrochemical corrosion parameters deduced from these figures are collected in Tables 1 and 2. The data show that both LRBS and MS exhibit an active–passive behavior in NaOH and borate solutions. However, in NaCl solution both the two specimens (LRBS and MS) exhibit active–passive-transpassive behavior and characterized by a shorter potential domain of passivity.

It is obvious that the corrosion potential $E_{\text{corr}}$ of LRBS specimen in aqueous borate solution is nobler than those in NaCl and in NaOH solutions ($-E_{\text{corr}} = 688, 880$ and $1040$ mV for borate, NaCl and NaOH solutions respectively). Also, MS possesses a similar trend ($-E_{\text{corr}} = 700, 938, 1080$ mV for borate, NaCl and NaOH solutions respectively). Also, $E_{\text{corr}}$ values for LRBS specimens in the tested solutions are lower than their values for MS. Moreover, the values of $j_{\text{corr}}$ and corrosion rate $C_R$ (milli inches per year, mpy) listed in Tables 1 and 2, for LRBS and MS in NaOH indicates that the rate of corrosion of LBSR in NaOH is higher than that in NaCl and borate solutions. This means also that MS is more corroded in the tested solutions than LRBS specimens. It is widely recognized that the presence of other elements such as Cr and Co in LRBS specimens reinforced the corrosion resistance of LRBS in comparison with MS [3,4].

On the other hand, LRBS possesses the highest value of passivity current, $j_{\text{pass}}$ (1.58 mA cm$^{-2}$) (measured at $-0.5$ V) in NaOH solution and the lowest value in an aqueous borate solution (0.021 mA cm$^{-2}$) (Table 1).

Figure 1. Potentiodynamic polarization curves for LRBS in aqueous borate, 1.0 M NaOH and 0.5 M NaCl solutions.
A similar trend was recorded in the case of MS. The MS possesses the highest value of $j_{\text{pass}}$ (1.98 mA cm$^{-2}$) in NaOH solution and possesses the lowest value in an aqueous borate solution (0.019 mA cm$^{-2}$) (Table 2).

This indicates that the NaOH solution is more aggressive than NaCl and borate solutions. This could be attributed to the fact that the steel surface suffers from pitting corrosion in NaCl solution and after pitting, repassivation occurs which protects the steel surface. It is worthwhile to mention that the small anodic peak appears in the passive region, it’s potential varied depending on the medium, is associated with the active peak of steel [5].

The polarization resistance $R_p$ values for LRBS and MS corrosion were calculated from the Stern–Geary equation [6] using the electrochemical corrosion parameters listed in Tables 1 and 2 as follows:

$$R_p = 1/j_{\text{corr}} [\beta_c \times \beta_a/2.303(\beta_c + \beta_a)]$$

where $\beta_a$ and $\beta_c$ are the anodic and cathodic Tafel slopes respectively. The data explores that LRBS and MS in borate solution exhibit the highest polarization resistance $R_p$ and the lowest $j_{\text{corr}}$ while in NaOH solution they exhibit the lowest polarization resistance and the highest $j_{\text{corr}}$.

Therefore, according to the previous data of $j_{\text{corr}}$, $E_{\text{corr}}$, and $R_p$, the corrosion resistance of LRBS and MS in the tested solutions can be arranged as follows: borate > NaCl > NaOH.

On the other hand, the profile of the PPC’s in the presence of Cl$^-$ ions are distinguished for localized corrosion and passivity breakdown (Figures 1 and 2). Moreover, the passivity domains became shorter in Cl$^-$ solution and the breakdown of the passive layer in case of MS occurs earlier than in the case of LRBS. It is well known that Cl$^-$ ions are aggressive plenty to strike steel and initiate pitting [7,8].

Figure 3 displays linear sweep voltammetry curves of LRBS specimens in different NaCl concentrations (0.3 – 1.0 M). The measurements were carried out starting from $-1.3$ V towards the positive potentials with a scan rate of 5 mVs$^{-1}$ at 25°C. It is observed that the presence of Cl$^-$ ions break down the passive layer at a definite potential known as pitting potential ($E_{\text{pit}}$) at which the...
current increases sharply ($j_{\text{pit}}$) indicating initiation and propagation of pitting corrosion. In a solution containing Cl$^-$ ions, the breakdown of the passive layer and nucleation of pitting is due to the adsorption of Cl$^-$ ions on the passive layer. The adsorbed Cl$^-$ ions can perforate through the passive film particularly at its defect points and imperfection under the influence of a high electric field to reach the base steel surface. Following this, pit growth occurs sooner as a result of increasing concentration of Cl$^-$ ions, result from its migration inside pits and increasing the acidity as a result of hydrolysis of Fe$^{2+}$ ions produced inside pits. Plotting $E_{\text{pit}}$ versus log $C_{\text{NaCl}}$ is given in the inset of Figure 3. It was shown that $E_{\text{pit}}$ shifts toward more negative (active) potentials with an increase in Cl$^-$ ion concentrations. This is due to a decrease in the pitting corrosion resistance by increasing the aggressive ion concentration. On the other hand, from Table 3 it is obvious that as the potential difference ($E_{\text{corr}} - E_{\text{pit}}$) increases the steel possesses high corrosion resistance towards the tested environments. For example, this value is 0.39 V in 0.3 M NaCl while it reaches 0.23 V in 1 M NaCl.

The influence of the scan rate ($\nu$) on the PPC’s of LRBS specimen in 0.5 M NaCl solution was studied and the results are given in Figure 4. The increase in $\nu$ shifts $E_{\text{pit}}$ dramatically to more active potentials. Plotting $E_{\text{pit}}$ vs. log $C_{\text{NaCl}}$ gave straight line as illustrated in the inset of Figure 4 according to the following equation:

$$E_{\text{pit}} = a + b \log \nu$$

where $a$ and $b$ are constants. These results could be described in terms of incubation time (the time needed for Cl$^-$ ions to perforate the passive layer) [9,10]. Therefore, when $\nu$ high, pitting initiation is occurs only at more active potentials, corresponding to enough short incubation time. It is worth noting that the influence of $\nu$ on pitting potential depends on the nature of the metals and alloys. Bond [11] found no significant difference in $E_{\text{pit}}$ for ferritic stainless steel when the scan rate was increased from 200 to 2000 mV h$^{-1}$, while 18Cr-14Ni-Mo austenitic stainless steel showed a pronounced decrease in $E_{\text{pit}}$ as the scan rate was increased [12]. Besides, the effect of the scan rate is found to be more pronounced on the potential difference values ($E_{\text{corr}} - E_{\text{pit}}$) as shown in Table 3. This potential difference is ca. 0.32 V at a scan rate of 5 mV s$^{-1}$ while ca. 0.06 V at a scan rate of 50 mV s$^{-1}$ indicating that as the scan rate increases the steel possesses low corrosion resistance.

Table 3. The difference between $E_{\text{corr}}$ and $E_{\text{pit}}$ at different NaCl concentrations, scan rates and temperatures.

| [NaCl]/M | $E_{\text{corr}}$ mV | $E_{\text{pit}}$ mV | $E_{\text{pit}} - E_{\text{corr}}$ mV |
|----------|----------------------|---------------------|---------------------------|
| 0.3      | 392.5                | 166.4               | 558.9                     |
| 0.5      | 318.1                | 226.6               | 544.7                     |
| 0.7      | 303.6                | 229.1               | 532.7                     |
| 1.0      | 255.9                | 280.1               | 536                       |
| 0.3 a    | 318.1                | 226.6               | 544.7                     |
| 0.5      | 213.1                | 864.9               | 1078                      |
| 100      | 1190                 | 1290                | 20                        |
| 50       | 1382                 | 1443                | 50                        |

$\nu$/mVs$^{-1}$

| Temp./°C | 318.1 | 226.6 | 544.7 |
|----------|-------|-------|-------|
| 25       | 158   | 345.8 | 610.8 |
| 35       | –     | –     | 624.5 |
| 45       | –     | –     | 627.4 |
| 55       | –     | –     | 633.2 |
| 65       | –     | –     | –     |

$^a$The right hand side column should be the left hand side column. After this change, the L.H.S column should contain mV s$^{-1}$ and the temperatures.

Figure 5 illustrates the effect of temperature on the pitting potential of LRBS specimens in 0.5 M NaCl solution at a scan rate of 5 mV s$^{-1}$. The data explore that $E_{\text{pit}}$ shifts to more negative (active) potentials with rising of temperature from 25°C to 35°C, referring that the pitting...
The corrosion resistance of this steel decreases with temperature. This behavior could be assigned to an increase in the adsorption of Cl\(^-\) anions on the passive layer [13] and an increase in the rates of migration and diffusion of reactants and products to and from pits. However, at temperature > 35°C, general corrosion occurs.

### 3.2. Cyclic potentiodynamic polarization (CPP)

The CPP is often used to evaluate the susceptibility of the steel to undergo surface pitting when immersed in a certain corrosion environment. The potential is scanned in a single cycle and the size of the hysteresis loop is examined along with the differences between the values of \(E_{\text{corr}}\) and the crossover repassivation potential \(E_{\text{rep}}\). The \(E_{\text{rep}}\) is measured at the potential where the hysteresis loop closes. Therefore, if these two potentials are the same, there is a small tendency to pitting. If \(E_{\text{rep}}\) is more positive than \(E_{\text{pit}}\), there is no tendency to pitting. On the other hand, if \(E_{\text{rep}}\) is more negative than \(E_{\text{pit}}\), the pitting occurs [14].

A typical example of CPP measurements for LRBS and MS in the tested solutions were carried out as shown in Figure 6. It could be observed that LRBS and MS exhibit pitting corrosion in NaCl solution since the CPP curves are characterized by the presence of \(E_{\text{pit}}\) and \(E_{\text{rep}}\). The pit growth is reduced due to repassivity of the pits. As a result, the current exhibits a sharp decrease attained a zero value at a definite repassivation potential (\(E_{\text{rep}}\)). The repassivation process may be created by the elimination of the stockpile Cl\(^-\) ions from pits by diffusion [15].
On the reverse, CPP curves in the case of NaOH and borate solutions indicate that both LRBS and MS do not exhibit pitting as indicated by the absence of $E_{pit}$, however, they exhibit general corrosion. It would be expected that LRBS should have higher corrosion resistance than MS due to the presence of Cr ($\sim 13\%$) in its composition which is very effective in terms of the thin protective oxide layer formed which stabilizing the passive film in the presence of $\text{Cl}^-$ and increasing the resistance to the initiation of pitting corrosion.

Figure 6. Cyclic polarization curve for LRBS specimens and mild steel electrode in aqueous borate, 1.0 M NaOH and 0.5 M NaCl solutions.
3.3. Electrochemical impedance spectroscopy

Impedance measurements of LRBS specimens in borate (pH 9.0), 0.5 M NaCl and 1.0 M NaOH solutions at 25°C and at its open circuit potential after 30 min of immersion were carried out over the frequency range from 100 kHz to 0.01 Hz (Figure 7(a,b)). The spectra represented in this figure were analyzed by best fitting to the equivalent circuits’ models shown in Figure 8(a–c). To confirm that the used circuit displays the best fit, the EIS Nyquist was plotted for LRBS in borate (pH 9.0), 0.5 M NaCl and 1.0 M NaOH solutions as shown in Figure 9(a–c). In this figure, the symbols represent the experimental data while the solid line represent the best fit by the equivalent circuit model shown in Figure 8(a–c). The EIS parameters obtained by fitting these circuits are listed in Table 4. In Figure 7(a) the Nyquist plot for LRBS in the borate solution has a well-defined tendency to form a semicircle. This behavior is attributed to a charge transfer process, with $|Z|$ (the impedance module) value on the order of 793 ohm. cm$^2$ in the bode plot (Figure 7(b)). The EIS plots show two-time constants and one Warburg impedance. The corresponding fitting results are listed in Table 4. The parameters of the equivalent circuit model shown in Figure 8(a) can be defined according to the usual convention as follows; $R_S$ represents the solution resistance, $CPE_1$ and $CPE_2$ are the constant phase elements, $R_{ct1}$, $R_{ct2}$ are the electrochemical reaction resistances and $Z_w$ Warburg impedance which is obtained at low-frequency range corresponding to a diffusion-controlled process.

On the other hand, the Nyquist plots for the LRBS in NaCl solution exhibit two semicircles, the first capacitive semicircle at low-frequency corresponds to the redox process in the oxide layer [16] while the third capacitive semicircle at lower frequency is correlated to the diffusion of Cl$^-$ ions toward the passive layer to form pitting on the electrode surface. These semicircles show that there is also a charge transfer process, with $|Z|$ value of 4467 ohm. cm$^2$ in the bode plot (Figure 7(b)). The EIS plots show three-time constants and one Warburg impedance. The corresponding fitting results are listed in Table 4. The parameters of the equivalent circuit model shown in Figure 8(b) are inductive resistance ($R_L$), $R_S$, $CPE_1$, $CPE_2$, $CPE_3$, $R_{ct1}$, $R_{ct2}$, $R_{ct3}$, and $Z_w$.

On the other side, the Nyquist plots for the LRBS in NaOH exhibit a high-frequency capacitive semicircle and a low-frequency capacitive semicircle [17]. The capacitive semicircles at high to medium frequency are concerned with the double-layer capacitance and charge transfer resistance of the corrosion process and a low-frequency capacitive semicircle is related to the redox process in the oxides layer. The presence of these two semicircles indicates that there is also a charge transfer process, with $|Z|$ value of 79297 ohm. cm$^2$ in NaOH solution compared to their values in NaCl and the borate solutions indicate that the passive layer for the LRBS in NaOH is less protective and relatively permeable. The EIS plots show two-time constants and one Warburg impedance. The corresponding fitting results are listed in Table 4. The parameters of the equivalent circuit model shown in Figure 8(c) are $R_S$, $CPE_1$ and $CPE_2$, $R_{ct1}$, $R_{ct2}$, and $Z_w$. It is seen from Figure 7(a) that the diameter of the semicircle plotted for the LRBS in borate solution was much larger than that drawn for the LRBS in NaOH and NaCl solutions. The larger
diameter of the semi-circle indicates higher corrosion resistance due to the formation of protective corrosion film. The parameters show that the value of the solution resistance $R_s$ in the borate solution is higher than that in NaCl and NaOH solutions. Also, the values of the charge transfer resistance ($R_{ct1}$, $R_{ct2}$) are higher in borate solution than that in NaCl and NaOH solutions. This means that the capacitance of the double layer should have higher values of $|Z|$ in the borate solution than in NaCl and NaOH solutions. Moreover, the constant phase elements (CPE$_1$, CPE$_2$) recorded lower value with borate solution than that obtained with NaCl and NaOH solutions. The higher values of $R_s$, $R_{ct1}$, $R_{ct2}$ and the lower values of CPE$_1$, CPE$_2$ for the LRBS in borate solution compared to those listed for the LRBS in NaOH and NaCl solutions are due to the increase.

**Figure 8.** Equivalent circuit representing the impedance spectra for the corrosion data of LRBS in (a) Borate (pH 9) (b) 0.5 M NaCl (c) 1.0 M NaOH solutions.
Table 4. EIS parameters obtained by fitting the Nyquist plots shown in Figure 7(a) with the equivalent circuit shown in Figure 8 for LRBS in aqueous borate (pH 9.0), 0.5 M NaCl and 1.0 M NaOH solutions at 25°C.

| Parameter          | Solution     | RS Ω.cm² | CPE₁ Ω.cm² | Rct₁ Ω.cm² | CPE₂ Ω.cm² | Rct₂ Ω.cm² | CPE₃ Ω.cm² | Rct₃ Ω.cm² | Zw (Ω.cm²) | L (Ω) |
|--------------------|--------------|----------|-------------|-------------|-------------|-------------|-------------|-------------|------------|-------|
| Borate (pH 9.0)    | 5.243        | 188.2 × 10⁻⁶ | 266.79      | 102.5 × 10⁻⁶ | 56830       | –           | –           | 121.0 × 10⁻⁶ | –         |
| NaCl 0.5 M         | 4.407        | 172.4 × 10⁻⁶ | 238.4       | 804.44 × 10⁻⁶ | 2566        | 883.3 × 10⁻³| 123.6       | 5.178 × 10⁻³ | 745.1 × 10⁻⁴|
| NaOH 1.0 M         | 2.329        | 151.8 × 10⁻⁶ | 171.9       | 180.7 × 10⁻⁵ | 516.6       | –           | –           | –           | –         |

in the corrosion resistance of the LRBS surface in the borate solution than that in NaCl and NaOH solutions. The EIS measurements confirm that the LRBS surface in the borate solution showed better corrosion resistance and higher passivation than that the LRBS surface in NaCl and NaOH solutions.

Also, it was shown from the Nyquist plot Figure 7(a) that the LRBS specimens have higher corrosion resistance in the tested solutions than MS (data of MS are not included). These results are in good compliance with the measurements of potentiodynamic polarization as shown in section 3.1.

Figure 9. EIS Nyquist plot for LRBS in (a) Borate (pH 9) (b) 0.5 M NaCl (c) 1.0 M NaOH solutions, symbols represent the experimental data and solid line represents the best fit using the equivalent circuits shown in Figure 8.
Figure 10. Free corrosion potential vs time for LRBS specimens in aqueous borate, 1.0 M NaOH and 0.5 M NaCl solutions.

Figure 11. (a) Chronoamperometric current-time curves obtained at different potentials vs. Ag/AgCl for LRBS specimens in 0.5 M NaCl solution, (b) Chronoamperometric current-time curves obtained at $-0.18$ V vs. Ag/AgCl for LRBS specimens in different concentrations of NaCl solution.
3.4. Open circuit potentials

The relationship between the free corrosion potential of LRBS specimens in borate, 1.0M NaOH and 0.5M NaCl solutions in an open circuit condition at 25°C was studied and the results are shown in Figure 10. In the case of LRBS in NaCl solution, the potential increased gradually to reach a steady-state potential in a very short time. The increase in the potential in the first few minutes could be assigned to the increase in the thickening of the passive layer formed. The oscillation in the potential could be due to the passivation-repassivation process.

The OCP measurements for LRBS show that LRBS in borate solution possesses the highest noble potential (highest corrosion resistance) than those in NaOH or NaCl which possess the lowest noble potential (lowest corrosion resistance).

According to PPC’s, CPP, EIS, and OCP measurements, the corrosion resistance of LRBS immersed in the tested solutions decreases in the order: borate > NaCl > NaOH solutions.

3.5. Chronoamperometric measurements

Figure 11(a) shows a series of potentiostatic current–time transients of LRBS specimens in 0.5 M NaCl at different anodic step potentials ($E_{a,s}$) ($−0.25$ to $−0.05$ V) (around $E_{pit}$) at 25°C. The results explore that at $−0.25$ V, a very small passive current is observed $j_{pass}$, which means that under the prevailing conditions, the Cl$^−$...
ions are not able to induce pitting within the duration of the experiment (120 s). However, increasing $E_a$ increases the $i_{\text{pass}}$. As the current established during the oxide film formation process is a measure of the protective ability of the passive film its increase with the increase in $E_a$ is due to the decrease in the thickness of the passive film. Moreover, at higher anodic potentials, Cl$^-$ ions induce pitting corrosion as evidenced by a sharp rise in the passive current density after a certain incubation time $t_i$. Finally, the pit growth current achieves a steady-state value as the incubation time $t_i$ decline and the steady-state current increases with increasing the anodic potential. The same trend was obtained by using different concentrations of Cl$^-$ ions. At low Cl$^-$ ions concentration (0.3M), the observed $i_{\text{pass}}$ obtained is small. However, with increasing the Cl$^-$ ion concentrations, the current increases rapidly as a result of passive layer pitting by Cl$^-$ ions as shown in Figure 11(b).

Figure 12 shows a series of potentiostatic current–time transients of LRBS specimens in borate solution at different $E_a$'s (0.10 V to 0.50 V) at 25°C. It is observed that the current transients traced in the potential range of 0.10 V up to 0.50 V explore tricky characteristics. The current at first declines due to passive layer growth, achieving a minimum value $j_m$ at a time $t_m$, then enhances to attain a maximum value $j_M$ at the time $t_M$, and finally declines once more and achieves an equilibrium state. The ascending part of the current can be ascribed to the partial electrooxidation of Fe$^{2+}$ to Fe$^{3+}$ in the passive layer. It is likely that the current begins to reduce (the final decrease) once more upon the formation of a denser layer. The results show that as $E_a$ becomes more positive, $j_m$ enhances and both $t_m$ and $t_M$ decline.

On the other hand, a series of $j$–$t$ transients for various values of the potentiostatic anodic potentials $E_a$'s were performed for LRBS in NaOH as shown in Figure 13. The transients are characterized by the rapid achievement of the steady-state current at each anodic step potential. The data show that as the potential is made nobler, the steady-state current increased. It is found that the rising parts of the transients fit the linear relation between $j$ vs. $t^{1/2}$ as shown in Figure 14, whereas the final decreasing parts of the transients produced the corresponding graphs shown in Figure 13. These results hold up the suggestion that the growth of the passive layer proceeds under mixed diffusion and kinetic control.

From the above data it could be concluded that the passive film, particularly, the initial stage of passive film formation is strongly depending on the environments as well as on the applied anodic potential [18].

3.6. Surface morphology

The SEM photomicrographs obtained for LRBS specimens before and after potentiodynamic polarization in the tested solutions are shown in Figure 15. Figure 15(a) represents the surface morphology of the as-received LRBS after mechanical polishing. However, Figure 15(b–d) shows the morphology of LRBS after anodic potentiodynamic polarization in NaOH, NaCl and borate solutions respectively. In NaOH solution (Figure 15(b)) the LRBS was strongly corroded and NaOH solution shows a deleterious effect on the steel. However, in 0.5 M NaCl solution, the morphology shows a dramatic change. Although Cl$^-$ ions break down the passive layer formed on the steel surface, a protective
layer is formed on its surface due to the accumulation of corrosion products which leads to the protection of steel to some degree (Figure 15(c)). On the other hand, the borate solution has a mild corrosive effect on the steel surface (Figure 15(d)). The data showed by the SEM is in good consent with the data obtained previously from the PPC’s as well as from the EIS and CPP. This work opened the door for further investigations of the corrosion resistance of some daily-life used articles such as Razor Blade produced by the large companies all over the world i.e. not only from the Lord company but also from other international companies.

4. Conclusions

The corrosion behavior of LRBS and MS in aqueous environments was investigated using potentiodynamic polarization curves (PPC’s), cyclic potentiodynamic polarization (CPP), electrochemical impedance spectroscopy (EIS), Open circuit potential (OCP) and chronoamperometric (%t–t transients) techniques in aqueous borate (pH 9.0), 1.0 M NaOH and 0.5 M NaCl solutions. The results gained can be summed as follows:

(i) The rate of corrosion of LRBS in NaOH is higher than that in NaCl and borate solutions and MS is more corroded in the tested solutions than LRBS specimens.

(ii) The corrosion resistance of LRBS and MS in the tested solutions can be arranged as follows: borate > NaCl > NaOH.

(iii) LRBS and MS exhibit pitting corrosion in NaCl solution and the CPP curves are characterized by the presence of $E_{\text{pit}}$ and $E_{\text{rep}}$.

(iv) The initial stage of passive film formation, detected by chronoamperometric study, is strongly depending on the environments as well as on the applied anodic potential.

(v) All the measurements using PPC’s, CPP, EIS, and OCP are in good consent and support the proposal that the corrosion resistance of LRBS immersed in the tested solutions decreases in the order: borate > NaCl > NaOH solutions.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

**ORCID**

Nobl F. El Boraei [http://orcid.org/0000-0002-2571-5569](http://orcid.org/0000-0002-2571-5569)

**References**

[1] Sherif ESM, Almajid AA, Khalil AK, et al. Electrochemical studies on the corrosion behavior of API X-65 pipeline steel in chloride solutions. Int. J. Electrochem. Sci. 2013;8:9360–9370.

[2] Widder SH, Baechler MC. Impacts of water quality on residential water heating equipment. Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830, Pacific Northwest National Laboratory Richland, Washington 2013.
[3] Yu Y, Shironita S, Souma K, et al. Effect of chromium content on the corrosion resistance of ferritic stainless steels in sulfuric acid solution. Heliyon. 2018;4:1–13. doi:10.1016/j.heliyon.2018.

[4] Amadeh A, Ebadpour R. Effect of cobalt content on wear and corrosion behaviors of electrodeposited Ni–Co/WC nano-composite coatings. J Nanosci Nanotechnol. 2013;13:1360–1363.

[5] Ibrahim MAM, Korablov SF, Yoshimura M. Corrosion of stainless steel coated with TiN, (TiAl)N and CrN in aqueous environments. Corros Sci. 2002;44:815–828.

[6] Freirea L, Nóvoaa XR, Montemorb MF, et al. Study of passive films formed on mild steel in alkaline media by the application of anodic potentials. Mater Chem Phys. 2009;114:962–972.

[7] Abd El Meguid EA, Gouda VK, Mahmoud NA. Pitting corrosion behaviour of type SUS904L and SUS316L stainless steels in chloride solutions. Mater Trans JIM. 1994;35:699–702.

[8] Abd El Meguid EA, Mahmoud NA, Abd El Rehim SS. The effect of some sulphur compounds on the pitting corrosion of type 304 stainless steel. Mater Chem Phys. 2000;63:67–74.

[9] Do Duc H, Tissot P. Anodic behaviour of tin in neutral phosphate solution. Corros Sci. 1979;19:179–190.

[10] Abd El Rehim SS, Foad El-Sherbini EE, Amin MA. Pitting corrosion of zinc in alkaline medium by thiocyanate ions. J Electroanal Chem. 2003;560:175–182.

[11] Bond APJ. Effects of molybdenum on the pitting potentials of ferritic stainless steels at various temperatures. J Electrochem Soc. 1973;120:603–606.

[12] MacDougall B. Effect of Chloride Ion on the localized breakdown of Nickel oxide Films. J Electrochem Soc. 1979;126:919–929.

[13] Augustynski J, Frankenthal RP, Kruger J., editor. Proceedings of the Fourth International Symposium on passivity. Pennington (NJ): The Electrochemical Society; 1978.

[14] Poursae A. Determining the appropriate scan rate to perform cyclic polarization test on the steel bars in concrete. Electrochim Acta. 2010;55:1200–1206.

[15] Assaf FA, Abd El Rehim SS, Zaky AM. Pitting corrosion of zinc in neutral halide solutions, Mat. Chem. Phys. 1999;58:58–63.

[16] Di‘az B, Joiret S, Keddam M, et al. Passivity of iron in red mud’s water solutions. Electrochim Acta. 2004;49:3039–3048.

[17] R Galindo-Luna YR, Torres-Islas A, Romero RJ, et al. Corrosion behavior of AISI 316L stainless steel in a NaOH-H2O mixture. Int J Electrochem Sci. 2018;13:631–641.

[18] Sedriks AJ. Corrosion of stainless steel. 2nd ed. New York (NY): Wiley; 1996.