Statistical Analysis of Corrosion Current Density and Tensile Strength of Al-6061 Alloy by Ageing and Retrogression Heat Treatments

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Abstract In this work, the effect of ageing and retrogression on the polarization resistance of the Al 6061 was assessed, in order to improve the corrosion resistance of the alloy with a negligible effect on the tensile strength. The corrosion resistance behavior was studied by exposing an Al 6061 alloy to a simulated marine environment, and then, the corrosion current density (icorr) was measured. The obtained corrosion results were correlated with tensile strength (TS) reported elsewhere and both measured, the icorr and TS and both were modeled by multiple linear regression. The results showed that the polarization resistance is inversely proportional to the temperature increment of the ageing and retrogression processes. In addition, the samples subjected to 200°C of ageing and 250°C of retrogression temperatures exhibited an enhancement on both corrosion resistance and tensile strength, when compared to the T6 condition and to lower ageing and retrogression temperatures. Furthermore, an empirical equation was proposed to correlate the icorr as a function of heat treatment parameters such as: ageing temperature and retrogression time–temperature for the aluminium alloy.

Keywords Aluminium alloy · Ageing · Retrogression · Corrosion resistance · Tensile strength

1 Introduction

Thermal processes performed on the aluminium 6xxx series accomplish a preferred level of mechanical features, also modifying the corrosion resistance. Polmear [1] was able to demonstrate that all of the attributes of the Al alloys are accomplished by shape, density, and distribution of precipitates [2, 3]. According to Talianker and Cina [4], Cina and Ranish patented a thermal treatment known as retrogression and reageing (RRA), which was applied on 6xxx and 7xxx alloys. Furthermore, Viana et al. [5] studied the optimization of heat treatment (HT) conditions in RRA for refining the formability of 7075-T6 alloy and returning it to its high malleable state as the solution treated quenched form. More recently, Abúndez et al. [6] studied the effect of different ageing and retrogression temperature-times and their correlation with the tensile strength and found that the best mechanical properties are obtained at the highest retrogression temperature and lowest retrogression time, affected by ageing.

Davis [7] found that 6xxx series has fromed moderate to high strength corrosion resistance depending on the precipitates, as a result of the heat treatment. This corrosion behavior can be modified by the HT exposure time, such as ageing, which will affect the type, size, volume fraction and distribution of precipitates in the aluminium matrix [8]. Furthermore, another important factor that affects the ageing response of the aluminium alloy is the cooling rate...
at which the alloy is subjected, which is related to the amount of supersaturation achieved in the alloy [9]. Mariola et al. [10] studied the age hardening process for an Al–Mg-Si alloy 6082 by isothermal ageing at 100, 125, and 150 °C from 0 up to 40 days, and found sizing and density changes of the pre- β′ and β″ phases. The order of the phases begins with the development of independent clusters of Mg and Si atoms, the development of co-clusters that enclose together Si and Mg, the development and growing of β″-needle-shaped second phase particles, the change of β precipitates in β′-lath shaped precipitates, and β′-rod-shaped precipitates after annealing during a long time, and the development of the incoherent stable β, which was reported by Edwards et al. [11]. The above mentioned β″-needle-shaped second phase particle (Mg2Si) has been observed as the predominant intermediate phase in the 6xxx series alloys at the early stages of ageing [9]. When further ageing continues beyond the peak condition, the β′-rod-shaped precipitates are present in moderately overaged conditions [12, 13]. If the ageing process continues, the precipitates coalesce and grow becoming incoherent, leading to a decrease in hardness [8]. The localized corrosion in the heat treatable alloys of aluminium 6xxx series is affected by the chemistry, size, and distribution of the intermetallic second phase particles formed during the heat treatments [14].

Complimentary, the aluminium alloys microstructure is a consequence of the elemental composition and its thermomechanical treatment. From a corrosion point of view, the most relevant microstructural features correspond to grain structure and distribution of second phase particles (intermetallic). It has been thoroughly studied that the electrochemical features of this particles differ from the behavior of the matrix of the alloy, producing susceptibility for localized corrosion [15, 16]. Hence, the critical pitting potential of aluminium alloys strongly depends on the alloying elements, the noble alloying elements tend to raise the potential in the positive direction, in contrast, the pit-alloying elements, the noble alloying elements tend to raise the potential of aluminium alloys strongly depends on the behavior in Al–Mg-Si alloys are: Al3Fe, Al2Cu, Al3Mn, Mg2Al3, Mg2Si, Al7Cu2Fe, Al2CuMg Al20Cu2Mn3, Al12Mn2Si [15, 16].

This work studied the behavior of current corrosion density obtained by the Tafel technique, as a function of combinations from ageing and retrogression temperatures and times. Besides, the icorr was correlated with the tensile strength TS of the material. Finally, an empirical equation was obtained to correlate the icorr, the polarization potential, and the tensile strength as a function of heat treatments performed on Al 6061 alloy.

### 2 Experimental Procedure

#### 2.1 Materials and Heat Treatments

The chemical composition of Al alloy 6061-T6 investigated in this work was provided by the supplier as 0.45–0.90% Mg, 0.20–0.60% Si, 0.10% max of Cu, Mn, Zn, Cr, Ti, and 0.35 max of Fe. Specifications of the alloy are reported elsewhere [6].

#### 2.2 Heat Treatment procedures

The HT performed is reported elsewhere [6]. The parameter conditions are depicted in Table 1. Where A = 10 min, C = 30 min and F = 60 min of retrogression for 150 °C and 200 °C of ageing and retrogression temperature, respectively; the S1 up to S9 corresponds to the sample number. Then A1 up to F1 corresponds to 175° and 225 °C of ageing and retrogression temperature; finally, A2 up to F2 for 200° and 250 °C of ageing and retrogression temperature.

#### 2.3 Electrochemical Measurements

The samples were subjected to electrochemical testing in a conventional open purpose-built naturally aerated cell, which was designed using three electrodes: graphite auxiliary electrode, Ag/AgCl reference electrode, and samples as working electrodes. In addition, the electrochemical cell was attached to a potentiostat Gill AC Serial 1340.

| Sample | Ageing + Retrogression Temperatures | Retrogression Time (min) |
|--------|------------------------------------|--------------------------|
| A51    | 150 + 200 °C                       | 10                       |
| C52    |                                    | 30                       |
| F53    |                                    | 60                       |
| A154   | 175 + 225 °C                       | 10                       |
| C155   |                                    | 40                       |
| F156   |                                    | 60                       |
| A257   | 200 + 250 °C                       | 10                       |
| C258   |                                    | 30                       |
| F259   |                                    | 60                       |

This work studied the behavior of current corrosion density obtained by the Tafel technique, as a function of combinations from ageing and retrogression temperatures on the polarization resistance of the Al 6061. Current corrosion density was obtained by the Tafel technique, as a function of combinations from ageing and retrogression temperatures and times. Besides, the icorr was correlated with the tensile strength TS of the material.
Immersion tests were conducted in quiescent 0.5 M NaCl at room temperature. The open-circuit potential was measured for 10 min prior to polarization testing in order to establish an approximately stable potential. Potentiodynamic polarization was performed using a sweep speed rate of 1 mV/s scan, between the potentials of −1000 to 1000 mV with respect to the open-circuit potential value. Three samples were tested per condition to ensure repeatability, and the polarization curves were averaged. The electrochemical parameters were selected according to [17–19], due to the pitting which could propagate autocatalytically, causing damage to the material. But for initiation, the surface of the alloy had to be polarized more positive than the critical potential of pitting, close to −0.75 V SCE in sea water. Furthermore, in this research work, the reference electrode used was Ag/AgCl. Then the calculated potential against the Ag/AgCl reference electrode used in this research was 0.75 V SCE + 44 mV [17–19]. For more detail on the electrochemical testing results, refer to Appendix A.

2.4 Tensile Properties

The tensile properties used in this research work for correlational purposes were tensile and yield strength, previously reported for the same HT conditions [6], to identify a relationship between mechanical and corrosion properties of the Al alloy 6061-T6.

2.5 Multiple Linear Regression Method

One of the main aims of this work was to develop an empirical model that correlates the corrosion current density, the corrosion potential, and the tensile strength with the HTs performed on the Al 6061 alloy. The equation was developed by Multiple Linear Regression (MLR) modeling since there are more than two independent variables in the experimental conditions [20]. The general model equation used can be consulted in [21, 22].

3 Results and Discussion

3.1 Corrosion Tests

The obtained results considering a potentiodynamic polarization over a potential range about ± 200 mV from the open circuit potential (OCP, E) results in polarization curves that may be further analyzed for corrosion rates. Thus, it is a requirement of all electrochemical assessments of corrosion rate, which represents a uniform active dissolution.

According to, the potentiodynamic polarization curves for A5S1, C5S2, F5S3, A1S4, C1S5, F1S6, A2S7, C2S8, and F2S9 specimens are depicted in Fig. 1, and their respective electrochemical parameters are given in Fig. 2. From the potentiodynamic polarization results, it can observe a spontaneously active character characteristic of aluminium alloys. The polarization curves show a distinct corrosion potential where the current density sharply increases.

All the samples showed an active dissolution with a barely noticeable transition to passivation, exhibiting similar corrosion behavior. In addition, the anodic and cathodic corrosion current densities \(i_{\text{corr}}\) decrease for samples C1S5, A2S7, C2S8, and F2S9, switching to a more negative potential (E\( _{\text{corr}}\) ) when compared to T6 as can be seen in Fig. 1a and 1c. Whereas, the E\( _{\text{corr}}\) of A5S1, C5S2, F5S3, A1S4, and C1S5 exhibit similar corrosion potential values compared with the T6 temper.

Moreover, the observed evidence in the polarization curves show that the A5S1, A1S4, C1S5, and A2S7 samples exhibit lower corrosion current densities due to a shift on the cathodic branches when compared to T6, F5S3, F1S6, C5S2, C2S8, and F2S9 samples in Fig. 1a, b, and c due to the HTs applied. In addition, it is possible to observe the formation of small passivation zone for F1S6 and F2S9 samples where the current decreases on the passive metal until a plateau is reached, characterized by the passive current. These samples were treated with the major retrogression time.

Figure 2 shows the \(i_{\text{corr}}\) of the T6 temper, and the A5S-F5, A1S4-F1S, and A2S-F2S series of Al 6061, which were exposed to 0.5 M NaCl solution. Furthermore, the corrosion current density for sample C2S8 has not been altered by the HTs. Hirth et al. [23] found that some heat treatments improve the resistance proficiency of 6061 alloys in the 0.5 M NaCl medium. The obtained corrosion current densities decrease can be related to the content of Mg and Si as the principal alloying elements in the 6061 alloy, which leads to the development of \(\beta\)-Mg2Si precipitates as it was previously reported by Alexander [24]. It is important to mention that although the main assumption is that Mg and Si are responsible of the observed electrochemical behavior, it is recommended to consider the formation of phases such as (Fe, Mn, Cu)\(_3\)SiAl\(_{12}\) [25] or Al\(_2\)Cu [26], since some Fe, Mn and Cu contents in commercial alloys may be beyond the wt% limits, having an influence in the electrochemical behavior. In addition, considering contents of Fe, Cu and Mn below the upper limits, in solid solution phase, \(\beta\)-Mg2Si has a significant result on the electrode potential and allows to explain an E\( _{\text{corr}}\) of −610 mV value from T6 of aluminium alloy 6061, except for A2S-F2S series, which exhibits Ecorr values close to −800 mV. The susceptibility to intergranular corrosion of 6000 series alloys is mainly dominated by their copper content. It has been reported by Svenningsen et al. [27] that the alloys with lower copper content are resistant to ICG, since this
Fig. 1 Potentiodynamic polarization plots for the heat-treated samples and its comparison with T6 condition

Fig. 2 $i_{corr}$ comparison for all selected HTs
mechanism is related to preferential dissolution of the Cu and Si depleted areas lengthwise to grain borders, which works as cathodes [26]. Furthermore, the precursors of the β-Mg2Si stable phase, which is found in the 6061 aluminium alloys, as well as others of the same series [26]. The above is related to the Si, however, due to the wt% of Cu in this specific alloy, which is below of 0.25%, it seems unlikely to find hardening precipitates related to Cu.

As shown in Fig. 2, the samples A51, A1S4, and A2S7, subjected to the lowest retrogression time, exhibit the relatively minimum \( i_{\text{corr}} \), and it is observed a direct relationship between the retrogression time and \( i_{\text{corr}} \). These results are partially consistent with the findings by Svenningsen et al. [27].

### 3.2 Corrosion Current Density (\( i_{\text{corr}} \)), Tensile Strength (TS) and Heat Treatments Correlation

The effect of ageing and retrogression on the TS for this alloy, for the same temperature and time parameters, has been reported by Abúndez et al. [6] and has been correlated along with its correspondingly \( i_{\text{corr}} \) values in this research work.

### 3.3 Multiple Linear Regression Modelling to Correlate \( i_{\text{corr}} \) and HTs

The multiple linear regression modelling method was applied on the \( i_{\text{corr}} \) data, in order to find a correlation with 3 variables: ageing temperature \( T_a \) in (°C), retrogression temperature \( T_r \) in (°C), and retrogression time \( t_r \) in (min) (see Table 2).

\[
i_{\text{corr}} = \beta_0 + \beta_1 T_a + \beta_2 T_r + \beta_3 T_aT_r + \beta_4 T_r t_r
\]  

As it can be seen in the \( R^2 \) coefficient, the obtained model is acceptable.

Also, as a result of the later applied response-surface Regression to the obtained results using NCSS® statistical analysis software, where a coded hierarchical model has been used as described in Table 3, the response surface plots are obtained.

Where for off-diagonal entries, \( 1 = u1w1, 2 = u1w2, 3 = u2w1, 4 = u2w2, 5 = u1w3, 6 = u3w1, 7 = u2w3, 8 = u3w2, 9 = u3w3; \) then, for diagonal entries, \( 1 = u1, 2 = u2, 3 = u3; \) considering \( u1 = u, u2 = u^2 = u^*u, \) and \( u3 = u^3 = u*u*u.\)

### 3.4 Multiple Linear Regression Modeling to Correlate \( i_{\text{corr}} \) and Tensile Strength TS

Correlation between the reported elsewhere [6] TS and obtained \( i_{\text{corr}} \) in this research work was also studied by multiple linear regression as can be seen in Eq. 19 and Table 4.

### Table 2 β coefficients obtained by MLR

| \( i_{\text{corr}} \) | \( \beta_0 \) | \( \beta_1 \) | \( \beta_2 \) | \( \beta_3 \) | \( \beta_4 \) | \( R^2 \) |
|---------------------|-----|-----|-----|-----|-----|-----|
| \( 1.3000 \times 10^{-3} \) | \( -4.3005 \times 10^{-8} \) | \( -2.4940 \times 10^{-5} \) | \( 1.4210 \times 10^{-5} \) | \( 3.1058 \times 10^{-8} \) | 0.94 |

The \( R^2 \) of the regression analysis for the hierarchical coded model is above 0.97.

According to Fig. 3 \( T_a T_r \) interaction, the obtained \( i_{\text{corr}} \) is statistically significative affected by the ageing temperature \( T_a \), rather than the interaction between \( T_a \) and \( T_r \). Also, the response surface plot accurately describes that at higher ageing temperatures, the \( i_{\text{corr}} \) increases too.

According to Fig. 4 \( T_r t_r \) interaction, the obtained \( i_{\text{corr}} \) is statistically significative affected by both, the retrogression time \( t_r \) and \( T_r \). Furthermore, the lower \( i_{\text{corr}} \) is obtained at an interval of 160–180 °C of ageing temperature \( T_a \) and 15–30 min for retrogression time. Also, in contrast to Fig. 4, at higher ageing temperature and retrogression time \( t_r \), higher \( i_{\text{corr}} \) is obtained.

Finally, in Fig. 5, the interaction between retrogression temperature \( T_r \) and retrogression time \( t_r \) is assessed.

Again, it is observed that the retrogression temperature \( T_r \) has not significant effect on the \( i_{\text{corr}} \) response; however, the retrogression time \( t_r \) does have. A possible explanation of this behavior is related to the fact that when retrogression time increases, the stable \( \beta-Mg_2Si \) phases tend to become coarse [28], hence increasing \( i_{\text{corr}} \) as a result of the formation of larger anodic zones.

The obtained results are quite interesting, because, in practice, the retrogression temperature may be reduced to the minimal tested value, to decrease energy consumption during HTs of aluminium alloys, considering that maximum strength levels are close to 200 °C of ageing temperature for a reduced retrogression time.

### Table 3 Coded Hierarchical model

| A | B | C |
|---|---|---|
| A | \( T_a \) | 2 | 1(11) |
| B | \( T_r \) | 2 | 1(11) |
| C | \( t_r \) | 2 |   |
Fig. 3 Response surface plot of $i_{corr}$ (mA/cm$^2$) vs ageing $T_a$ ($^\circ$C) and retrogression $T_r$ ($^\circ$C) temperature interaction

Fig. 4 Response surface plot of $i_{corr}$ (mA/cm$^2$) vs ageing temperature $T_a$ ($^\circ$C) and retrogression time $t_r$ (minutes) interaction
\[ icorr = \beta_0 + \beta_1 T_a T_r + \beta_2 T_a T_{tr} + \beta_3 T_a T_{tr} + \beta_4 T_a T_{ts} + \beta_5 T_{tr} T_{ts} + \beta_6 T_{tr} T_{ts} \]  

Also, as a result of the later applied response-surface regression to the obtained results, using NCSS® statistical analysis software [29], where a coded hierarchical model has been used, the response surface plots are obtained and can be seen in Fig. 6.

In Fig. 6, three main regions can be identified, a region that goes from 150 to 175 °C of ageing temperature, along with an interval of 100 up to 150 MPa for tensile strength, where high values of \( i_{corr} \) are shown (approximately 0.055 mA/cm²). However, above 150 MPa of tensile strength up to 290 MPa, the second region of importance is observed, where the lower \( i_{corr} \) values can be found. Even at greater values of ageing temperature, \( i_{corr} \) decreases to a minimum value of around 0.0250 mA/cm². Finally, the third region of importance can be found above 290 MPa between an interval of 150 and 180 °C, where maximum corrosion current density is found. These results clearly show that corrosion current density \( i_{corr} \) is affected by the tensile strength, therefore strongly related to the microstructural features as a result of the HT.

### 3.5 Microstructural Features

Apparently, pitting corrosion is not important but pit depth and proliferation speed are enormously detrimental. Pitting is a grave type of localized corrosion from the microstructural point of view, according to Guillaumin and Mankowski [26]. Also Baumgartner and Kaesche [30] have reported the observation of crystallographic shaped pits in different aluminium alloys, presenting a ramified rough profile that grows from a randomly nucleated tunnels depending on the potential and chloride concentration [31]; it happens in passive metals and alloys within hostile mediums. Pitting is regularly seen when chlorides or other halides like NaCl are present. Mainly aluminium pitting...
occurs, as would be expected, because of the high aggressiveness of the studied medium, particularly of rich in chlorides, and due to the very low electrical resistivity that facilitates most electrochemical reactions for aluminium as seen before (Sect. 3.1). Facilitation of ionic conductivity from its salinity and enough dissolved oxygen to act as a cathodic reactant to polarize the aluminium alloys to their pitting potentials is done. The measurements of the penetration of the pitting made at regular intervals show that the pitting corrosion rate is linked to time by a relationship of the type \( V = Kt^{1/3} \) [32]. Pitting, therefore, must tend to slow down over time too [33]. Also, corrosion begins at protective oxide film defects or at discontinuities of the passive film and follow to form a weighty tubercle of hard rust within the pit underneath the original metal. These are usually found in the marine area as in various factories, where harsh corrosive environments occur [32].

When acidity or alkalinity is increased beyond the pH passive range, polarization of potential reaches at least the pitting and corrosion attack become more nearly uniform. Chloride is one of the most frequently encountered in service halide ions which accelerate the anodic reaction while cathodic reaction is oxygen reduction in aerated solutions. In the pH passive region pitting is observed in halides aerated solutions [32].

Normally, aluminum does not pit in aerated media without-halide salts, since the pitting potential is significantly more noble than it is within halide solutions, because aluminum is not polarized to this degree of potential in regular service. At oxide hydroxide aluminum alloy passive film at weak points commences the pitting corrosion [34].

Inside pits attract chloride ions and the positive charge of dissolved cations, facilitating anodic reaction given hydroxides and acids by hydrolysis when aluminium chloride is formed. Helping cathodic sites to shift to acidic pH by hydrolysis [35]:

\[
\text{AlCl}_3 + 3\text{H}_2\text{O} \rightarrow \text{Al(OH)}_3 + 3\text{HCl}
\]

Possible reactions at the cathode are:

\[
3\text{H}^+ + 3e^- \rightarrow \frac{3}{2} \text{H}_2\text{O} + \text{H}_2\text{O} + 2e^- \rightarrow 2\text{OH}^- \quad (4)
\]

Finally, the cathodic locations are often majorly alkaline for the reason of the local formation of hydroxides.

Then, as beforementioned, the SEM micrograph of \( A_{S1}, C_{S2}, F_{S3} \) samples from \( A_{SX}-F_{SX} \) series are shown in Fig. 7a to c, respectively, the SEM micrographs of \( A_{S4}, C_{S5}, F_{S6} \) samples from \( A_{SX}-F_{SX} \) series are shown in Fig. 7d to f, respectively, and finally, the \( A_{S7}, C_{S8}, F_{S9} \) samples from \( A_{SX}-F_{SX} \) series are shown in SEM micrographs in
Fig. 7g to i, respectively. The $A_{SX}$–$F_{SX}$ series, which corresponds to the lowest ageing and retrogression temperatures, shows less clustered dark spots than the other series, as an evidence of pitting corrosion, which indicates the presence of a homogenous corroded surface. $A_{1SX}$–$F_{1SX}$ and $A_{2SX}$–$F_{2SX}$ series show more clustered and large size dark spots.

The author’s thought is that, clustered dark spots shown in the micrographs are due to micro-constituents, which often are sources of electrochemical corrosion, as they contribute to a non-uniform attack at specific Cu rich regions.

4 Conclusions

The results of the assessment of the effect of ageing and retrogression in Al 6061 alloy showed improvement of the polarization resistance and it has been concluded that:

a) Best polarization resistance is achieved at 10 min of retrogression. This retrogression time reduces significantly the negative effect of the overageing temperature. However, the results observed in the response, surface regression, suggest that it is true for higher ageing treatments close to 200 °C.

b) The samples heat-treated by the above procedure exhibits high strength with good corrosion resistance. In contrast, applying ageing without retrogression increases the alloy’s susceptibility to corrosion.
c) By the usage of multiple linear linear regression modeling, an equation that correlates \( i_{corr} \) as a function of T, ageing temperature at constant time, and retrogression temperature at a variable time, is obtained.

By the usage of multiple linear regression modelling, an estimated equation is obtained that correlates \( i_{corr} \) as a function of T, ageing temperature at constant time, and retrogression temperature at a variable time. This equation shows that the temperature regimes have good mechanical properties for practical applications.

Finally, the obtained equation \( i_{corr} = \beta_0 + \beta_1 T_a T_a + \beta_2 T_a T_r + \beta_3 T_a T_s + \beta_4 T_r T_s + \beta_5 T_r T_s \) can be used to estimate the thermal treatment parameters such as ageing temperature and time, as well as, the retrogression temperature and time, balancing tensile strength and corrosion current depending on the application required. Also, the response surface plots can be used to help to visualize the size effect of each of the thermal treatment parameters on corrosion current, to help the designer have a more visual tool. Furthermore, a complimentary equation can be incorporated for design purposes which is more focused on mechanical properties and has been reported previously and is described in subsection 2.4 related to tensile properties.

**Appendix A**

The potentiodynamic polarization over a potential range about \( \pm \ 200 \) mV from the open circuit potential (OCP, \( E \)) results in a polarization curve that can be analyzed for corrosion rate, provided that the rates of other anodic reactions such as associated with redox reactions are small in comparison, which is a requirement of all electrochemical assessments of corrosion rate model system representing uniform active dissolution.

Tafel analysis is a conventional direct current (DC) technique, typically presented in a semi-logarithmic plot. polarization curves provide corrosion rate by extrapolation of the linear cathodic and/or anodic regions that provides the corrosion current at the free corrosion potential. (\( E_{corr} \)) The problems with this approach are that, large potentials can sometimes drive unwanted reactions that obscure the linear portion of the anodic or cathodic branch, making extrapolation inaccurate, and irreversibly altering the electrode surface. This plot is according the following equation:

\[
i_{net} = i_{corr} \left( \exp \left[ \frac{2.3(E - E_{corr})}{b_a} \right] - \exp \left[ -\frac{2.3(E - E_{corr})}{b_c} \right] \right)
\]

This equality is an ideal form of the electrochemical data for the argument of a mixed electrode, where there is only one anodic and one cathodic reaction taking place on the corroding surface. Every of this reaction must be controlled by activation polarization, and \( E_{corr} \) must be separated from both reversible potentials. The Potentiodynamic polarization potentials of wider ranges, produces more data regarding the system than just the corrosion rate, at higher potentials, the current density turns out to be independent of potential due to mass transport constraints and salt film precipitation.

As illustration about the proximity of regions of OCP information is obtained about passivity and susceptibility to localized corrosion. Potentiodynamic polarization does not pretend corrosion rate monitoring, as it includes separation of the potential comparatively far from the steady-state corrosion potential. Corrosion of aluminum alloys are the subject of much studies, and their fundamental reaction in water is aluminum oxidation [9]:

\[
Al \rightarrow Al^{3+} + 3e^-
\]

In oxidation form, aluminum in solution is a trivalent cation \( Al^{3+} \) misplacing three electrons, simultaneously is balanced by ions reduction in the solution catching the three electrons. Furthermore, only two reduction reactions occur in aqueous solutions like fresh water and seawater with pH close to neutral [9]:

1. reduction of \( H^+ \) protons:

\[
3H^+ + 3e^- \rightarrow \frac{3}{2}H_2
\]

\( H^+ \) protons result from the dissociation of water molecules [9]:

\[
H_2 \leftrightarrow H^+ + OH^-
\]

2. Reduction of oxygen dissolved in water [9]:

\[
O_2 + 2H_2O + 4e^- \rightarrow 4OH^-
\]

\( O_2 \) in alkaline or neutral media [9]:

\[
O_2 + 4H^+ + 4e^- \rightarrow 2H_2O
\]

At 20 \( ^\circ \mathrm{C} \) and under atmospheric pressure, the solubility of oxygen in water is 43.4 mg·kg⁻¹. It decreases with increasing temperature and is no more than 30.8 mg·kg⁻¹ at 40 \( ^\circ \mathrm{C} \), and 13.8 mg·kg⁻¹ at 80 \( ^\circ \mathrm{C} \). Globally, the corrosion of aluminum in aqueous media is the sum of two electrochemical reactions, oxidation and reduction [9]:

\[
Al + 3H_2O \rightarrow Al(OH)_3 + \frac{3}{2}H_2
\]

This reaction come with a changeover in the oxidation state of aluminum where transform occurs from the oxidation state 0 in the metal, into the oxidation state of alumina (+ 3), and by an interchange of electrons, since
aluminum drops three electrons that are collected by 3H⁺. The above helps to provide some insight of the global corrosion rate and morphological features of corrosion, like diameter, density, and localization of pits.

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