Original article

Effect of extrusion welding locations on the corrosion of AM30 alloy extrudate

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A B S T R A C T

The effect of extrusion welding at three different locations on the corrosion of a magnesium alloy (AM30) extrudate after being immersed in 3.5% NaCl solutions for 1 h, 12 h, and 24 h has been investigated. Different electrochemical methods namely, cyclic polarization, open-circuit potential, electrochemical impedance spectroscopy, and current–time measurements were employed. The corroded surfaces were characterized using various spectroscopic analyses. All electrochemical measurements confirmed that the corrosion of the Mg alloy extrudate changes depending on the location of the extrusion welding, which affects the values of the obtained corrosion current, corrosion rate, and corrosion resistance. The severity of corrosion was found to decrease with prolonging the exposure periods of time in the chloride solutions for all taken samples at the different locations of the extrusion welding. This was further confirmed by the scanning electron microscopy micrographs and the energy dispersive X-ray profiles taken for the corroded surfaces of the different extruded AM30 samples.

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1. Introductions

Magnesium and its alloys have been extensively used in various applications [1–3]. This is because of the good characteristics of these materials, which includes their low density and being the lightest of all structural metallic materials, excellent damping properties, etc. [2–6]. The fact that Mg is very reactive metal with high electron negative potential makes it covered with a thin film of its oxide, which in turn is non compacted and dense and does not protect against environmental exposure [7]. An active corrosion of Mg takes place in chloride solutions, due to the penetration of chloride ions to the magnesium oxide film and reacting with Mg itself causing its rapid dissolution [5–9]. The low corrosion resistance of Mg and some of its alloys, particularly in chloride containing
media, is related to many factors such as their microstructure, alloying elements, grain size, and the presence of the precipitates [8,9]. The high corrosion susceptibility of Mg alloys can be also increased through the presence of impurities and second phases within the alloy causing a local galvanic corrosion of the alloy matrix [6].

Several attempts have been implemented to increase the poor corrosion resistance of Mg alloys. Among those approaches is the surface treatment through the use of chemical conversion coatings, which has proven a limited stand-alone protection in selected applications [10–16]. Some coatings, such as the porous anodized ones are not suitable in harsh environments, particularly if they are not sealed with a resin or paint. Moreover, the metallic coatings can be used only under some conditions due to their high costs [12]. Modifying the corrosive environment via the use of corrosion inhibitors have been also proposed to eliminate the corrosion of Mg and its alloys [17,18]. These inhibitors mitigate the corrosion of materials via numerous mechanisms such as adsorption onto the surface to form a protective layer that isolates it from being attacked by the surrounding environments [19]. The addition of alloying elements can be also employed to enhance the corrosion resistance of Mg. The most known Mg alloys with high corrosion resistances are those containing low percentages of Cu, Ni, and Fe as alloying elements. If these alloying elements are used in high amounts, the dissolution of Mg will rapidly take place via galvanic corrosion and the alloying elements will act as cathodes having small hydrogen overvoltage [5,8,9].

It is well known that the extrusion process is one of the most promising among metal forming processes. It has been reported [20] that the extrusion process applies the hydrostatic compression state of stress in the deformation zone, which improves the workability of metallic materials. Due to the high specific mechanical characteristics and the lightest weight among many metallic materials, the extrusion of many magnesium alloys has been recently increasing [20,21]. This is also because of the use of these extruded alloys in the automotive industry lead to reducing the fuel consumption in motor vehicles. AM30 is a relatively new alloy with a single phase (α-phase, which is hexagonal closed packed phases) [22]. The extruded AM30 contains Al–Mn intermetallics that are randomly distributed within the magnesium matrix along with some coarse grains on the extruded surfaces [23]. The corrosion of extruded AM30 Mg alloy under salt spray and immersion environments has been reported by Song et al. [24]. It was found that the alloy suffers general, pitting and filiform corrosion, which were quantified using optical microscopy, laser profilometry, etc., over 60 h of examination. Compared to other alloys such as AM60 and ZE41, the corrosion rate of the AM30 is lower, while the corrosion rate is greater than that recorded for AZ31 and AZ91 alloys, and even greater than the corrosion rate of pure magnesium [25–27].

The aim of this study was to investigate the effect of extrusion welding locations on the corrosion behavior of Mg alloy (AM30) extrude after their exposure for different periods of time (1 h, 12 h, and 24 h) in 3.5% NaCl solutions. It is well known that 3.5% (weight %) NaCl solution is one of the most harsh media for most metals and alloys because it is equivalent to the wt% of the NaCl salt present in the natural seawater. For that choosing that concentration of NaCl was to get a reasonable corrosion rate for the different tested samples. The corrosion of the tested Mg alloys was evaluated using numerous electrochemical and spectroscopic techniques such as polarization, impedance and chronomperometry along with scanning electron microscopy (SEM) and energy dispersive X-ray analyzer (EDX).

### 2. Experimental details

An extrudate made from magnesium alloy (AM30) fabricated as previously reported in literature [20] was used in this study. The nominal chemical composition (wt%) of the AM30 alloy was as following; 3.4% Al, 0.33% Mn, 0.16% Zn, 0.0026% Fe, 0.0006% Ni, 0.0008 Cu, with the remaining balance of Mg. The extrude samples have extrusion welds in three different locations as shown in Fig. 1. Sodium chloride (NaCl) of 99% purity was purchased from Merck and was used as received.

An electrochemical cell with three-electrode configuration that accommodates for 200 mL was employed in performing the electrochemical tests. An Ag/AgCl and a platinum (Pt) sheet were employed as the reference and counter electrodes, respectively. The extrude samples were cut from the three locations (as can be seen from Fig. 1 with the cross-section area of each coupon of 1.0 cm$^2$) to be used as the working electrodes. Preparing the working electrodes for electrochemical measurements were prepared as previously described elsewhere [7].

An Autolab Potentiostat/Galvanostat (purchased from Metrohm, Utrecht, Netherlands) was used to collect the electrochemical data. The cyclic potentiodynamic polarization curves were obtained via scanning the potential from $\sim$1800 mV in the forward direction to $\sim$800 mV vs. Ag/AgCl at a scan rate of 1.66 mV/s. The potential was directly rescanned again in the backward direction till the backward currents intersected with the forward currents at the same...
scan rate. The electrochemical impedance spectroscopy (EIS) measurements were collected at the open-circuit potential values over a change of frequency from 1,00,000 Hz to 0.1 Hz and an AC wave of ±5 mV peak-to-peak overlaid, and the data were obtained using Powersine software. The curves of the chronocoulometric current vs. time were obtained after applying a value of −1200 mV on the extrudate AM30 alloys after their immersions in the sodium chloride solutions for 24 h. All experiments were carried out in triplicate with excellent reproducibility and were collected on a new polished extrudate AM30 surface and in a fresh portion of the test solution. The field emission scanning electron microscopy (FE-SEM) images and the energy dispersive X-ray (EDX) profile analyses were obtained at 15 kV and a secondary electron imaging (SEI) detector for the surface of the extrudate AM30 samples using JOEL FE-SEM Model 7600 with an attached EDX unit. The SEM images and EDX profiles were obtained for the corroded surfaces of the non coated samples after its immersion in the chloride solutions for 24 h followed by applying −1200 mV (Ag/AgCl) for 40 min.

3. Results and discussion

3.1. Cyclic potentiodynamic polarization (CPP)

CPP measurements were carried out to report the effect of extrusion welding at different locations on the corrosion parameters of AM30 alloy. CPP curves obtained for sample 1 (1), sample 2 (2), and sample 3 (3) from the extrudate after its immersion in 3.5% NaCl solutions for 1.0 h are shown in Fig. 2. In order to understand the effect of prolonging the immersion time in the chloride test solutions of the different extruded samples, the CPP curves were obtained after 12 h and 24 h and the curves are depicted in Figs. 3 and 4, respectively. The values of the corrosion parameters obtained from CPP curves are listed in Table 1. Definitions for the parameters of Table can be expressed as: $\beta_c$ refers to the cathodic Tafel slopes, $\beta_a$ is the anodic Tafel slope, $E_{corr}$ is the corrosion potential, $j_{corr}$ is the corrosion current density, $R_p$ is the polarization resistance, and $R_{corr}$ is corrosion rate. The values of all these parameters were obtained as reported in the previous studies [7,17–19].

As it can be seen from Fig. 2, the current decreases in the cathodic branch till it reaches its minimum at the corrosion current value. It is well known that the cathodic reaction for most metals and alloys in the near neutral solutions such as 3.5% NaCl one is the oxygen reduction reaction [17,28–33]. On the other hand, the cathodic reaction for Mg and its base alloys is the evolution of hydrogen, which is due to the electron consumption on Mg that happens by the unloading of hydrogen ions according to the following reaction [17,34]:

$$2\text{H}^+ + 2\text{e}^- \rightleftharpoons \text{H}_2$$  \hspace{1cm} (1)

The current then increases in the anodic side with the increase of the applied potential. This is due to the dissolution of Mg, which occurs once the metal is in contact with the chloride solution according to the following reaction [35]:

$$2\text{Mg} \rightleftharpoons 2\text{Mg}^{2+} + 4\text{e}^-$$  \hspace{1cm} (2)

The resulted magnesium cations (Mg$^{2+}$) from the anodic dissolution of Mg react with the hydroxide ions (OH$^-$) released.

Fig. 2 – CPP curves obtained for the extrudate AM30 alloy, (1) sample 1, (2) sample 2, and (3) sample 3 after 1.0 h immersion in 3.5% NaCl solution.

Fig. 3 – CPP curves obtained for the extrudate AM30 alloy, (1) sample 1, (2) sample 2, and (3) sample 3 after 12 h immersion in 3.5% NaCl solution.

Fig. 4 – CPP curves obtained for the extrudate AM30 alloy, (1) sample 1, (2) sample 2, and (3) sample 3 after 24 h immersion in 3.5% NaCl solution.
from the dissociation of water at the cathodic reaction to form magnesium hydroxide (Mg(OH)$_2$) as follows [36]:

$$\text{Mg}^{2+} + 2\text{OH}^- \rightleftharpoons \text{Mg(OH)}_2$$  \hspace{1cm} (3)

Due to the very active surface for Mg, the formation of magnesium oxide (MgO) will also take place as per the following reaction:

$$\text{Mg} + \text{O} \rightleftharpoons \text{MgO}$$  \hspace{1cm} (4)

The formed MgO does not produce a complete protection to the surface of Mg and the current increases even more with potential, which is in a good agreement with the work done by Pardo et al. [37]. Moreover, the formed Mg(OH)$_2$ will react with NaCl to form magnesium chloride (MgCl$_2$), which could lead to the high dissolution of Mg and therefore the increase of currents in the anodic side. It is also seen from Fig. 2 that the current recorded in the backward direction was higher than that obtained in the forward direction, which causes an aggressive pitting corrosion. This was revealed by the appearance of a big hysteresis loop, which is the area that has resulted from the difference between the current of the forward direction and the current of the backward direction in the anodic side, on the curves of CPP.

Prolonging the exposure time for the samples to 12 h (see Fig. 3) and further to 24 h (see Fig. 4) decreased the obtained current values. This indicates that the increase of exposure period of time before measurements reduces the dissolution of Mg extruded samples in the chloride solution as a result of oxide film thickening and/or the corrosion products on the surface of Mg. It means that the uniform corrosion of Mg decreases with increasing time. On the other hand, the pitting corrosion gets enhanced with increasing time as indicated by the increase of the area of the hysteresis loops, which were created due to the increase of currents in the reverse direction more than the currents obtained for the forward anodic direction. Furthermore, back scanning of potential in the reverse direction shows higher current values and due to that the current does not intersect with anodic branch but with the cathodic one confirming that the extrude alloys at this condition suffer harsh pitting corrosion with its protection potentials are always more negative compared to its corrosion potentials.

It is also seen from Figs. 2–4 as well as Table 1 that the recorded corrosion parameters for sample 3 are the lowest followed by sample 2 and the highest values were recorded for sample 1. This was confirmed by decreasing the values of $j_{\text{Corr}}$ and $R_{\text{Corr}}$ according to the following order; sample 3 < sample 2 < sample 1. The values of $R_p$ increase as opposite to the values of $j_{\text{Corr}}$ and $R_{\text{Corr}}$ and opposite to the aforementioned order. Moreover, the values of $E_{\text{Corr}}$ are shifted to the less negative direction according to this order. Prolonging the exposure period of time was also found to decrease the corrosion of Mg through decreasing its corrosion rate and increasing its polarization resistance. It is reported [20] that the grain size of each sample of the extruded AM30 alloys is affected by its shape. Where, sample 3 has the finest grain size and the grain size of sample 1 is bigger. The polarized LM mosaic images of (A) sample 1, (B) sample 2, and (C) sample 3 of the extrude, are shown respectively in Fig. 5. These images were obtained as per the procedures reported elsewhere [20]. The change of the grain size depicted by the images of Fig. 5 is the reason for the lower corrosion behavior of sample 3 compared to sample 2 and further to sample 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\rho_i$ (V dec$^{-1}$)</th>
<th>$E_{\text{Corr}}$ (V)</th>
<th>$\rho_s$ (V dec$^{-1}$)</th>
<th>$j_{\text{Corr}}$ (µA cm$^{-2}$)</th>
<th>$R_p$ (Ω)</th>
<th>$R_{\text{Corr}}$ (mpy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1 (1 h)</td>
<td>0.157</td>
<td>−1.493</td>
<td>0.145</td>
<td>220</td>
<td>148.97</td>
<td>5.026</td>
</tr>
<tr>
<td>Sample 2 (1 h)</td>
<td>0.160</td>
<td>−1.480</td>
<td>0.141</td>
<td>180</td>
<td>181.04</td>
<td>4.113</td>
</tr>
<tr>
<td>Sample 3 (1 h)</td>
<td>0.140</td>
<td>−1.470</td>
<td>0.138</td>
<td>140</td>
<td>215.83</td>
<td>3.199</td>
</tr>
<tr>
<td>Sample 1 (12 h)</td>
<td>0.150</td>
<td>−1.510</td>
<td>0.100</td>
<td>200</td>
<td>130.43</td>
<td>4.569</td>
</tr>
<tr>
<td>Sample 2 (12 h)</td>
<td>0.155</td>
<td>−1.505</td>
<td>0.110</td>
<td>170</td>
<td>165.55</td>
<td>3.884</td>
</tr>
<tr>
<td>Sample 3 (12 h)</td>
<td>0.156</td>
<td>−1.495</td>
<td>0.112</td>
<td>130</td>
<td>218.04</td>
<td>2.970</td>
</tr>
<tr>
<td>Sample 1 (24 h)</td>
<td>0.120</td>
<td>−1.540</td>
<td>0.105</td>
<td>180</td>
<td>135.27</td>
<td>4.113</td>
</tr>
<tr>
<td>Sample 2 (24 h)</td>
<td>0.112</td>
<td>−1.525</td>
<td>0.095</td>
<td>140</td>
<td>159.63</td>
<td>3.199</td>
</tr>
<tr>
<td>Sample 3 (24 h)</td>
<td>0.103</td>
<td>−1.525</td>
<td>0.090</td>
<td>45</td>
<td>464.07</td>
<td>1.028</td>
</tr>
</tbody>
</table>

3.2. Open-circuit potential (OCP)

OCP measurements were carried out for the different samples of the extruded magnesium alloy in order to show the change of the potential of the extruded AM30 alloy with the increase of immersion time. Fig. 6 depicts the change of OCP versus time for the sample 1 (1), sample 2 (2), and sample 3 (3) from the analyzed extrude in 3.5% NaCl solution. As it can be seen from Fig. 6 the potential increases in the less negative direction with time for all tested extrude samples. This shift of potential increases in the order of sample 1 < sample 2 < sample 3 and proves that the dissolution of the extrude material takes place in an opposite direction to this order. The appearance of potential fluctuations indicates also that the pitting corrosion occurs for all samples. This agrees with the data obtained by CPP measurements, where the pitting potential for all extruded Mg samples are lower than its corrosion potential, $E_{\text{Corr}}$.

3.3. Electrochemical impedance spectroscopy (EIS)

EIS experiments have been widely employed in analyzing the kinetic parameters for the corrosion at the metal/solution
Fig. 5 – Polarized LM mosaic images of (A) sample 1 on its surface the fine and coarse grains are defined, (B) sample 2 showing curved extrusion weld line, and (C) sample 3 showing the extrusion weld line of the extrudate, respectively [20].

interface [38–42]. Here, EIS data were collected after different exposure times at the value of OCP. Fig. 7 shows the Nyquist plots obtained for: (1) sample 1, (2) sample 2, and (3) sample 3 from the extrudate AM30 alloy, respectively after 1 h immersion in 3.5% NaCl solutions. Similar EIS plots were obtained after the immersion in the NaCl solutions for 12 h and 24 h and the spectra are depicted in Figs. 8 and 9, respectively. The impedance data were then best fitted to an equivalent circuit as can be seen in Fig. 10.

The values obtained from the equivalent circuit shown in Fig. 10 are recorded in Table 2. Where, $R_S$ is a solution resistance, $Q_1$ ($Y_{Q_1}$, CPEs) is the first constant phase elements at the interface between the magnesium alloy and chloride solution, $Q_2$ ($Y_{Q_2}$, CPEs) is the second constant phase elements at the interface between a surface layer formed on the surface of AM30 alloy and the solution, $R_{P1}$ represents the polarization resistance at the AM30 alloy/solution interface, and $R_{P2}$ is another polarization resistance at the interface between the formed layer (corrosion product and/or oxide) on the surface of AM30 alloy and the solution; $R_{P2}$ can also be defined as the charge transfer resistance [43]. It is clearly seen from Fig. 7 that sample 1 and sample 2 of the extrudate alloys recorded only one small semicircle. The diameter of the semicircle of sample 2 is slightly wider than the one was for sample 1 indicating that the corrosion resistance of sample 2 is higher. On the other hand, the Nyquist plot recorded for sample 3 shows a
The Nyquist plots obtained after prolonging the exposure time of extruded AM30 samples in the chloride solutions for 12 h and 24 h are shown in Figs. 8 and 9, respectively. The EIS spectra obtained from Figs. 8 and 9 showed almost similar behavior to those ones obtained from Fig. 7. The impedance data depicted in Table 2 also indicated that the values of all resistances, $R_S$, $R_P$, and $R_P$, increase in the order sample 3 > sample 2 > sample 1 for all periods of exposure time. The data obtained from Nyquist plots thus confirm the results obtained from polarization data.

Table 2 also indicates that $Q_1$ values represent a double layer capacitor because the values of $n$ that accompany this constant phase elements are close to 1.0 (the values of $n$ varies exactly between 0.8 at its minimum and 1.0 as maximum). This means that the surface develops corrosion products with some porosity that allows Mg to dissolve underneath the formed layer of corrosion products. Moreover, the values of $Y_Q$ decreases for Mg alloys in the following order sample 1 > sample 2 > sample 3 and also decreases with the increase of exposure period of time from 1 h to 12 h and even lower after 24 h of the electrode immersion. It is worth to mention also that the second constant phase elements can be considered as representation of the double layer capacitors for its $n$ values are also close to unity. The values of $Y_Q$ decrease in the same order like $Y_Q$, which confirms that the film that may form on the surface of the AM30 alloy is not dense enough to act as a protective layer to prevent the corrosion of Mg in the NaCl solution [18,44].
Table 2 – EIS parameters obtained for the extruded AM30 alloys in 3.5% NaCl solutions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$R_0$ (Ω)</th>
<th>$Q_1$</th>
<th>$n$</th>
<th>$R_{p1}$ (Ω)</th>
<th>$Q_2$</th>
<th>$n$</th>
<th>$R_{p2}$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1 (1.0 h)</td>
<td>12.34</td>
<td>0.0007213</td>
<td>0.85</td>
<td>192.3</td>
<td>0.004301</td>
<td>0.95</td>
<td>277.23</td>
</tr>
<tr>
<td>Sample 2 (1.0 h)</td>
<td>13.40</td>
<td>0.0004223</td>
<td>0.80</td>
<td>217.7</td>
<td>0.003852</td>
<td>0.80</td>
<td>339.80</td>
</tr>
<tr>
<td>Sample 3 (1.0 h)</td>
<td>14.51</td>
<td>0.0003291</td>
<td>0.89</td>
<td>565.0</td>
<td>0.000789</td>
<td>0.85</td>
<td>1947.0</td>
</tr>
<tr>
<td>Sample 1 (12 h)</td>
<td>11.54</td>
<td>0.0005125</td>
<td>0.87</td>
<td>137.7</td>
<td>0.001648</td>
<td>0.85</td>
<td>59.493</td>
</tr>
<tr>
<td>Sample 2 (12 h)</td>
<td>12.78</td>
<td>0.0004021</td>
<td>0.91</td>
<td>161.9</td>
<td>0.002873</td>
<td>0.79</td>
<td>284.81</td>
</tr>
<tr>
<td>Sample 3 (12 h)</td>
<td>13.91</td>
<td>0.0000752</td>
<td>1.00</td>
<td>323.6</td>
<td>0.000815</td>
<td>1.00</td>
<td>2368.0</td>
</tr>
<tr>
<td>Sample 1 (24 h)</td>
<td>16.86</td>
<td>0.0003493</td>
<td>0.90</td>
<td>38.02</td>
<td>0.001135</td>
<td>0.80</td>
<td>239.71</td>
</tr>
<tr>
<td>Sample 2 (24 h)</td>
<td>18.24</td>
<td>0.0003262</td>
<td>0.80</td>
<td>54.75</td>
<td>0.002412</td>
<td>0.78</td>
<td>358.82</td>
</tr>
<tr>
<td>Sample 3 (24 h)</td>
<td>27.65</td>
<td>0.0000523</td>
<td>1.00</td>
<td>62.03</td>
<td>0.000754</td>
<td>0.97</td>
<td>2578.1</td>
</tr>
</tbody>
</table>

Fig. 11 – Chronoamperometric current–time curves obtained at $-1.2$ V (Ag/AgCl) for (1) sample 1, (2) sample 2, and (3) sample 3 after their immersion for 24 h in 3.5% NaCl solution.

In order to shed more light on the effect of extrusion welding locations on the corrosion of the AM30 alloy using EIS measurements, the Bode plots were considered. Bode plots (a) impedance of the interface and (b) degree of phase angle obtained for (1) sample 1, (2) sample 2, and (3) sample 3 from the extrudate after 1 h immersion in 3.5% NaCl solution are shown in Fig. 15. Prolonging the immersion time to 12 h and 24 h showed similar Bode plots as depicted in Figs. 25 and 35, respectively. It can be seen that the lowest values for the impedance of the interface [Ω] were recorded for sample 1, which also shows the minimum values of the degree of phase angle [φ]. On the other hand, sample 3 recorded the highest values of $|Z|$ and $\phi$ indicating that sample 3 has the highest corrosion resistance. The Bode plots confirm the Nyquist ones as well as the polarization data that the corrosion resistance for extruded AM30 alloys decreases in the following pattern from most to least corrosion resistant; sample 3 > sample 2 > sample 1.

3.4. Chronoamperometric current–time

The chronoamperometric current–time technique is a powerful method to report the corrosion behavior and whether pitting corrosion occurs for the materials under investigation [17,40–44]. Fig. 11 shows the chronoamperometric current–time curves obtained at $-1200$ mV (Ag/AgCl) for (1) sample 1, (2) sample 2, and (3) sample 3 after their immersion for 24 h in 3.5% NaCl solution. For all samples, the current starts from low values and increases with time accompanied with some fluctuations. The absolute current resulted from sample 1 recorded the highest values. The current recorded due to sample 2 showed almost the same behavior but with slight absolute values. Sample 3 showed the minimum initial current, which gradually increased with the increase of time. The increase of the potentiostatic currents for all samples is due to the higher anodic dissolution of Mg under the corrosiveness attack of the chloride solutions and the applied anodic potential.

The minimum absolute current was also noticed to be for sample 3. It is generally believed that the lower the absolute values of currents refers to the higher the corrosion resistance, which means that the dissolution of AM30 alloy decreases in the following order, sample 3 < sample 2 < sample 1. Moreover, the appearance of current fluctuations confirms the occurrence of pitting corrosion and indicates that all extruded Mg alloy samples suffer pitting corrosion in 3.5% NaCl solution. The current–time experiments at $-1200$ mV thus agree with the polarization and impedance data and all confirm each other.

3.5. Surface morphology investigation

The SEM and EDX investigations were carried out on the surface of the extruded Mg samples after its corrosion in the chloride solution. Fig. 12 shows the micrographs of SEM for (a) sample 1, (b) sample 2, (c) sample 3, and the corresponding EDX profile analyses for (d) sample 1, (e) sample 2, and (f) sample 3, after the current–time measurements shown in Fig. 11 respectively. It can be seen from the SEM micrographs shown in Fig. 12 that the surface of AM30 alloy is deteriorated and fully covered with corrosion products. Although, these corrosion products block the formed pits, the corrosion still takes place and the dissolution of Mg continuous to occur as indicated by the increase of the potentiostatic current with applying a constant active potential value (see Fig. 11). Here, the surface of sample 1 (image (a)) looks more attacked and deteriorated compared to the surface of sample 2 and further
Fig. 12 – SEM/EDX analyses for obtained for (a), (d) sample 1, (b), (e) sample 2, and (c), (f) sample 3 from the extrudate after 24 h of their immersion in 3.5% NaCl solution followed by stepping the potential at −1200 mV (Ag/AgCl) for 30 min.

to sample 3. This agrees with the data obtained from polarization, EIS and chronoamperometric measurements.

The weight percentages (wt%) of the elements found on the surface of sample 1 via EDX profile analysis (Fig. 12(d)) were 50.28% O, 29.92% Mg, 13.76 Cl, 1.58% Na, and traces of Al and Pt. The wt% found of the surface of sample 2 Fig. 12(e)) were 52.12% O, 30.35% Mg, 13.35% Cl, 2.19% Na, and traces of Al and Pt. As well as, the surface of sample 3 (Fig. 12(f)) provided 54.46% O, 34.00% Mg, 2.13% Cl, and 1.83% Na, beside the presence of Al and Pt. The increase of the percentages of O and Mg in sample 3 reveals that the corrosion products are mainly magnesium oxide. The little decrease of O and Mg contents on the surface of sample 2 and further on the surface of sample 1, indicates that the surfaces of sample 2 and sample 1 are less protected compared to the surface of sample 3. The SEM/EDX analyses thus confirm the data obtained by polarization, EIS, and chronoamperometric current–time measurements.
4. Conclusions

The corrosion behavior of three samples (1, 2, and 3) of extrudate AM30 alloy, which were produced at different extrusion welding locations after their immersion for 1 h, 12 h, and 24 h in 3.5% NaCl solution using various electrochemical and spectroscopic techniques was observed, analyzed and reported. CPP measurements indicated that the severity of corrosion varies depending on the location of the extrusion welding and the values of corrosion current and corrosion rate decreased with the increase of immersion time. OCP results proved that the potential of the AM30 alloy shifts toward the less negative values with the increase of time. EIS plots confirmed that the extrudate samples have different corrosion resistances, which increases with increasing the time of immersion. Chronoamperometric current-time at $-1200 \text{ mV vs. Ag/AgCl}$ experiments revealed that all extruded samples suffer severe pitting corrosion but the value of absolute current for each of them was different. SEM/EDX analyses depicted that the surface of the three Mg samples was covered with a corrosion product layer that was mainly a non-protective magnesium oxide. Results together are consistent with each other confirming that the severity of corrosion of AM30 Mg extrudate varies with the change of the location of the extrusion welding and the increase of immersion time in 3.5% NaCl solution decreases the decreases the corrosion of Mg at all locations.

Conflicts of interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jmrt.2019.03.008.

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