Research Article

Study of the Corrosion Process of AZ91D Magnesium Alloy during the First Hours of Immersion in 3.5 wt.% NaCl Solution

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Received 26 January 2018; Revised 28 March 2018; Accepted 17 April 2018; Published 29 May 2018

Academic Editor: Ramazan Solmaz

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The AZ91D magnesium alloy was immersed in 3.5 wt.% NaCl solution at room temperature for times ranging from 1 minute up to 72 hours. The aim was to investigate the evolution of the corrosion process using confocal laser scanning microscopy (CLSM), electrochemical impedance spectroscopy, and X-ray photoelectron spectroscopy. The microstructure of the as-received alloy was initially characterized by optical microscopy and scanning electron microscopy (SEM). The crystalline phases were identified by X-ray diffractometry. The main phases were primary- α , eutectic- α , and β ($\text{Mg}_{17}\text{Al}_{12}$). Vickers microhardness markings were made on the surface of one etched sample to facilitate the identification of the same region at each different immersion time, thus enabling the observation of the corrosion process evolution. Corrosion initiates at the grain boundaries of the eutectic microconstituent and, then, propagates through primary α -grains. The β -phase was less severely attacked.

1. Introduction

Weight reduction is a serious concern in the automotive and aerospace industries. Magnesium alloys are the state-of-the-art materials when high strength-to-weight ratio is pursued. In this respect, they are gaining increasing interest for structural engineering applications [1–3]. Recyclability and good machinability are additional attributes that make them attractive materials to manufacture low weight parts [4]. In spite of these attractive attributes, the well-known chemical instability in aqueous environments is a core issue for magnesium alloys, limiting their applicability [5–7].

AZ91D is one of the most extensively used magnesium-based alloys with consolidated applications in the automotive industry [8, 9]. It is part of the AZ series, being alloyed with Al and Zn. Typically, its microstructure is comprised of a mixture of magnesium- α , an intermetallic β -phase rich in aluminum ($\text{Mg}_{17}\text{Al}_{12}$), and an eutectic phase consisting of alternating lamellae of the α and β phases [10, 11]. The corrosion behavior of the alloy is markedly affected by its microstructural features. The relative complex mixture of different

phases can give rise to regions with distinct chemical activities, thereby triggering the formation of local electrochemical microgalvanic cells, with preferential dissolution of the least noble phases [12–14]. The β -phase is reported to play a core role in this scenario. Its morphology and distribution within the magnesium matrix are key factors for the corrosion resistance of the AZ91D alloy. Large volume fractions and continuous distribution across the matrix are considered to be beneficial to the general corrosion resistance of the alloy by forming a protective layer of aluminum-rich surface oxide. By contrast, if it is discontinuous and concentrated in small areas due to its relative low volume fraction, it can accelerate galvanic corrosion effects, acting as local cathodes [15–18]. In spite of the knowledge accumulated so far and the consensus on the critical role of the β -phase, several authors have recently highlighted the need for further studies on the corrosion mechanism of Mg-Al alloys in order to expand and consolidate their engineering applications [19–22].

Confocal laser scanning microscopy (CLSM) is a powerful tool for investigating the onset of corrosion processes at

FIGURE 1: CLSM micrograph showing the Vickers impressions on the surface of the etched AZ91D alloy.

either in situ or ex situ conditions [23]. The high magnification and relative short acquisition times can be advantageously exploited in the corrosion field [24]. CLSM was successfully employed to study local corrosion process in aluminum and nickel alloys [25, 26]. Investigations devoted to corrosion of welded joints of high strength steels and pitting corrosion of stainless steels have been reported [27–30]. Notwithstanding, in spite of the increasing interest of magnesium alloys for structural applications, CLSM studies are hardly reported for elucidating the onset of corrosion processes of magnesium alloys in aqueous environments.

In this work, CLSM was employed to investigate the onset of corrosion processes of the AZ91D during short immersion times in 3.5 wt.% NaCl solution at room temperature. The alloy microstructure was initially characterized by optical and scanning electron microscopy (SEM). Corrosion evolution was monitored up to 72 h of immersion.

2. Materials and Methods

2.1. Material and Sample Preparation. A die-cast ingot of the AZ91D magnesium alloy (nominal composition in wt.% 8.3–9.7% Al, 0.35–1.00% Zn, Mn > 0.15%, Si < 0.10%, Fe < 0.005%, Cu < 0.03%, Ni < 0.002%, Mg balance) was kindly provided by Rima Industrial Magnésio S.A. (Brazil). Small square-shaped samples (0.50 cm²) were cut from the as-cast ingot using a conventional metallographic cut-off machine. The samples were embedded in phenolic resin. Next, surface preparation was carried out by sequential grinding with waterproof SiC paper up to grit #1000, followed by polishing with diamond paste (6 μm). After washing with distilled water and ethanol the samples were chemically etched in a solution comprised of a mixture of glacial acetic acid, ethanol, and distilled water for 10 s. Next, the samples were washed with distilled water and dried in a warm air stream provided by a conventional air blowing gun.

Vickers microhardness indentation tester (EQUILAM HVS-1000) was employed to produce surface marking on the etched samples in order to allow for identifying the same region of the microstructure when subjecting the samples to CLSM analysis. Hence, three impressions were made using 1 kg load as shown by a representative micrograph displayed

FIGURE 2: Schematic representation of the different quadrants evaluated around each Vickers impression mark.

in Figure 1. The marked regions were, thereafter, employed as a guide to register micrographs of the same region for the samples subjected to corrosion for different times. For each impression mark four different quadrants were evaluated to investigate the evolution of the corrosion process, as schematically shown in Figure 2. The impression mark is at the center of the figure and the evolution of the corrosion process of the AZ91D alloy was prospected at each one of the four quadrants. Thus, twelve different regions were evaluated for each immersion time.

2.2. Microstructural Characterization. X-ray diffraction (XRD) analysis was carried out to identify the crystalline phases of the AZ91D alloy using a Rigaku diffractometer (Multiflex, 40 kV, 20 mA) operating with Cu- α radiation in the θ - 2θ geometry. The analysis was performed in the range from 20 to 90°. SEM micrographs were obtained to examine to morphology of the different phases (JEOL JMS-6010LA). Elemental composition was determined by energy dispersive X-ray analysis (EDS).

2.3. Immersion Test. Samples prepared as described in Section 2.1 were immersed in 3.5 wt.% NaCl solution at room temperature for the following times: 1 minute, 5 minutes,

FIGURE 3: XRD pattern of the AZ91D magnesium alloy.

10 minutes, 20 minutes, 30 minutes, 50 minutes, 3 hours, 6 hours, 15 hours, 40 hours, and 72 hours. Only the results obtained for the samples immersed for 1 minute, 30 minutes, 3 hours, 6 hours, 15 hours, 40 hours, and 72 hours are presented. The surface morphologies of samples immersed for 5 minutes, 10 minutes, and 20 minutes are very similar to that observed after 1 minute. In the same respect, the surface morphology of the sample immersed for 50 minutes was very similar to that observed after 30 minutes. As consequence, these micrographs of samples immersed for 5 minutes, 10 minutes, 20 minutes, and 50 minutes are not presented throughout the text. After immersion, the sample was removed from the testing solution, washed with distilled water, dried in a warm air stream, and promptly subjected to CLSM analysis (Olympus OLS4100). The evolution of the corrosion process was accompanied by observing the same region of the microstructure at each time, using the hardness impressions as guides to locate the region of interest.

2.4. Electrochemical Impedance Spectroscopy (EIS). EIS measurements were carried out to evaluate the electrochemical behavior of the AZ91D upon immersion in 3.5 wt.% NaCl solution at room temperature. The data were acquired after the same immersion times evaluated during the immersion test (Section 2.3) in order to complement the characterization of the evolution of the AZ91D corrosion process. A conventional three-electrode cell setup was used for the measurements with a platinum wire as the counter-electrode, Ag/AgCl as reference, and the AZ91D alloy as the working electrode. A small sinusoidal perturbation signal was employed with amplitude of ± 10 mV (rms) in the frequency range from 100 kHz to 1 Hz and acquisition of 10 points per frequency decade. The tests were conducted using an Autolab M101 potentiostat/galvanostat.

2.5. X-Ray Photoelectron Spectroscopy (XPS). XPS surface mapping was employed to check the distribution of Mg, Al and O on the surface of the AZ91D alloy after immersion

for different times in 3.5 wt.% NaCl solution at room temperature. The immersion times were the same employed for the immersion test described in Section 3.2. The spectra were obtained using a ThermoFisher Scientific K-alpha+ spectrometer operating with a monochromatic Al- $K\alpha$ radiation source. The spot size was $80\ \mu\text{m}$. The area map was defined with 16×10 points (approximately $3.0\ \text{mm}^2$).

3. Results and Discussion

3.1. Structural Characterization. Figure 3 shows the XRD pattern of the AZ91D alloy. The main crystalline phase is the magnesium matrix α -Mg. The presence of the intermetallic $\text{Mg}_{17}\text{Al}_{12}$ (β -phase) is unequivocally identified. These results are in agreement with the literature [31, 32].

The alloy microstructure is displayed in the CLSM micrographs shown in Figure 4. A general view is shown in Figure 4(a) whereas a more detailed representation is seen in Figure 4(b). The microstructure consists of a mixture of α -Mg, lamellar eutectic microconstituent along the grain boundaries of the magnesium matrix and β - $\text{Mg}_{17}\text{Al}_{12}$ as labeled in Figure 4(b). These features are typical of the AZ91D alloy [33, 34]. Microstructure was further characterized by SEM and EDS analysis. The SEM micrograph shown in Figure 5(a) reveals the different microconstituents of the AZ91D alloy. Their elemental composition was checked by EDS analysis. Mapping analyses for Al and Mg are displayed in Figures 5(b) and 5(c), respectively. It is seen that aluminum is enriched in the eutectic region with respect to the matrix. Yet, it is mainly present in the β -phase whereas the magnesium signal is much more intense in α -Mg. As inferred from the literature, compositional differences between each phase can give rise to regions with distinct chemical activities and, therefore, promote the formation of microgalvanic cells that trigger corrosion process of the alloy [19].

The results presented in this section were allowed to fully characterize the as-cast microstructure of the AZ91D. Next, the evolution of its corrosion process is discussed based on

FIGURE 4: CLSM micrographs of the AZ91D alloy: (a) general view; (b) detailed view.

FIGURE 5: (a) SEM micrograph of the AZ91D alloy; (b) EDS mapping analysis for Al; (c) EDS mapping analysis for Mg.

CLSM analyses carried out in accordance with the immersion test described in Section 2.3.

3.2. Immersion Test. Figure 6 shows CLSM micrographs of the AZ91D alloy immersed for up to 3 h in 3.5 wt.% NaCl solution at room temperature. The Vickers microhardness impression is seen at the bottom right of each micrograph. It is somewhat attacked during the chemical etching procedure

employed to reveal the alloy microstructure. The general microstructure can be perceived in the as-received condition (Figure 6(a)). It was little affected by the NaCl solution up to 3 h of immersion. As shown in Section 3.1, the brighter regions are related to the presence of eutectic-α and β-Mg₁₇Al₁₂. At this time, corrosion spots were formed as indicated by the small stained region at the lower right part of the micrograph (pointed by the red circle in Figure 6(d)).

FIGURE 6: CLSM micrographs of the AZ91D alloy immersed for different times in 3.5 wt.% NaCl solution at room temperature: (a) as-received; (b) 1 min; (c) 30 min; (d) 3 h.

Interestingly, this part of the microstructure presents discontinuous distribution of the β -phase when compared to the upper left part of the micrograph. According to the literature, β -phase morphology is closely related to the onset of corrosion processes of the AZ91D alloy. When it is evenly distributed within the α -Mg matrix, it acts as a barrier against dissolution. If, in turn, it is discontinuous as observed in the region where corrosion spots started to appear, it triggers the formation of microgalvanic cells that drive the localized corrosion attack [15, 16]. Our results point that this mechanism took place for the AZ91D alloy and could be perceived after 3 h of immersion in the electrolyte.

The evolution of the corrosion process was accompanied up to 72 h. Figures 7(a)–7(d) show CLSM micrographs of the same region observed in Figure 6. The micrographs were acquired after 6 h, 15 h, 40 h, and 72 h of immersion in 3.5 wt.% NaCl solution at room temperature. Corrosion spread out slowly. New stained areas are visible after 40 h (Figure 7(c)). Intensively corroded areas were found after 72 h, propagating from right to left (Figure 7(d)). It is noteworthy, though, that some regions remained unaffected by corrosion even after 72 h of immersion. Such regions are mainly the brighter parts of the microstructure, wherein

the β -phase is more evenly distributed. Notwithstanding, corrosion seems to spread even at the β -phase after 72 h (Figure 7(d)).

The morphological features of the corrosion process are not as marked up to 15 h of immersion as they are for 40 h and 72 h. In this respect, in order to give a more clear interpretation of the corrosion spots formed at first hours of immersion, transverse profiles were obtained from the CLSM micrographs as shown in Figure 8 for the as-received condition (Figure 6(a)) and for the specimen immersed for 15 h in 3.5 wt.% NaCl solution at room temperature (Figure 7(b)). These lines were taken from the lower part of the CLSM micrographs shown in Figures 6(a) and 7(b) for the as-received and 15 h conditions, respectively. It is important to mention, though, that the first corrosion spots were observed after 3 h of immersion, as shown in Figure 6(d), and the micrograph from the 15 h condition (Figure 7(b)) was chosen only to exemplify how the transverse profile of the corroded area appears when evaluated using the CLSM measuring tool.

The profiles show the more intense variation of the height for the specimen immersed for 15 h. Moreover, it is clear that a depressive region appear at right for the 15 h condition as indicated by the black circle. Such region was not observed in

FIGURE 7: CLSM micrographs of the AZ91D alloy immersed for different times in 3.5 wt.% NaCl solution at room temperature: (a) 6 h; (b) 15 h; (c) 40 h; (d) 72 h.

the profile obtained for the as-received alloy. At this point, it is important to correlate these profiles with the corresponding microstructures so that the corroded areas can be clearly related to the height variation in the z -axis. Hence, the blue circles shown in Figures 6(a) and 7(b) were inserted to indicate their corresponding regions in the transverse profiles displayed in Figures 8(a) and 8(b), respectively.

By carefully examining the CLSM micrographs for the as-received and 15 h immersed alloy and their corresponding transverse profiles at the regions marked in Figures 6(a) and 7(b), it is noteworthy that the depressive region marked by the black circle in Figure 8(a) corresponds to the region where the corrosion spots firstly appear in the AZ91D microstructure. This corroded region was perceived after 3 h of immersion (Figure 6(d)). CLSM analysis aimed to successfully indicate the onset of corrosion spots by combining their visual identification at the micrograph with the quantitative evaluation of the surface profile.

Notwithstanding, in spite of the interpretation given above, the micrographs shown in Figures 6 and 7 did not allow

one to clearly identify the microstructural features related to the onset of corrosion. Higher magnification micrographs are needed to show the corroded regions in detail, allowing identification of the different phases of the AZ91D alloy. In this regard, higher magnification CLSM micrographs of the AZ91D alloy immersed for 6 h, 15 h, 40 h, and 72 h in 3.5 wt.% NaCl solution at room temperature are shown in Figures 9(a)–9(d). These periods were selected as the initial corrosion spots and their evolution could be promptly examined from their micrographs. Shorter immersion times did not allow an unequivocal visualization of the initial corrosion sites.

Figure 9(a) shows dark points indicating the onset of corrosion mainly at the grain boundaries of the eutectic microconstituent, along with the boundaries of the β -phase. The β -phase, in turn, is not affected. After 15 h of immersion (Figure 9(b)), it remains unaffected, but there were several dark spots indicating corrosion within the α -Mg matrix and also at the eutectic microconstituent. This scenario holds up to 40 h of immersion (Figure 9(c)). Corrosion propagated throughout the whole microstructure after 72 h (Figure 9(d)).

FIGURE 8: Transverse profiles obtained from the CLSM micrographs of the AZ91D alloy: (a) the as-received condition; (b) after immersion for 15 h in 3.5 wt.% NaCl solution at room temperature.

FIGURE 9: CLSM micrographs showing the evolution of the corrosion process of the AZ91D alloy in 3.5 wt.% NaCl solution at room temperature: (a) 6 h; (b) 15 h; (c) 40 h; (d) 72 h.

The β -phase was also dissolved. The eutectic microconstituent was severely attacked as well as the α -Mg matrix.

The evolution of the corrosion process can be checked by examining 3D CLSM micrographs of the AZ91D alloy and the corresponding roughness profile along specific lines. This is exemplified in Figures 10(a)–10(c) for the AZ91D alloy immersed for 6 h, 15 h, and 72 h in NaCl 3.5 wt.% at room temperature.

3.3. Electrochemical Impedance Spectroscopy (EIS). EIS diagrams of the AZ91D alloy immersed in 3.5 wt.% NaCl solution at room temperature for different times are shown in Figure 11.

Nyquist plots (Figure 11(a)) are characterized by capacitive loops whose diameters depend on the immersion time. It is well-known that the capacitive loop diameter is associated with the charge transfer resistance of the electrode surface, being, therefore, related to its corrosion resistance [35, 36]. In this respect, its evolution with the immersion can be an indication of the corrosion reactions taking place on the alloy surface. From Figure 11(a) one can observe that there is a marked decrease of the impedance values from the 1 min condition up to 3 h. The capacitive loops of the 30 min and 3 h conditions are very small compared to the 1 min loop. Thus, in order to more clearly observe them with respect to the other immersion times, the inset of Figure 11(a) shows the Nyquist plots with expanded scales. This would indicate that corrosion reactions are taking place right after immersion in the electrolyte. As a consequence, the alloy surface becomes oxidized. This, in turn, would lead to the formation of a thicker oxide layer, giving rise to an impedance rise which is confirmed by the increase of the capacitive loop diameter for the 6 h and 15 h immersion times. It is noteworthy that the onset of visual corrosion spots were observed for these times, as described in Section 3.2.

Additional evidence for the reasoning derived from the Nyquist plots can be achieved by evaluating the Bode plots shown in Figure 11(b). The phase angles are highly resistive at low frequencies up to 3 h of immersion, being very distant from the ideal capacitive response at -90° which denotes the propensity of the electrode surface to charge transfer reactions [37]. As corrosion proceeds, the phase angles rise up to -40° and -50° for the 6 h and 15 h conditions, leading to a more capacitive response with the development of a more intensively corroded layer. However, as this layer is not compact, it is not protective against corrosion and the phase angles decrease at the low frequencies for the 40 h immersion condition. A new rise toward more capacitive values is found after 72 h as a consequence of the intensified corrosion process. EIS proved to be very sensitive to the evolution of the corrosion process on the AZ91D, allowing one to correlate its results with those obtained from the immersion test (Section 3.2). Further information on the composition of the corroded layer and its correlation with the immersion time was obtained by XPS analysis, as described in the next section.

3.4. X-Ray Photoelectron Spectroscopy (XPS). XPS mapping was used to elucidate the elemental distribution of magnesium, aluminum and oxygen over the AZ91D surface at the

same immersion times evaluated by CLSM and EIS. The results are shown in Figures 12–19. The data are expressed as quantified atomic percentage XPS maps for Mg1s, O1s, and Al2p. Only these signals were detected in significant quantities on the surface of the AZ91D alloy independently of the immersion time. The maps were interpolated up to an equivalent 128×128 pixel density using the Avantage software®.

The maps for the as-received alloy (Figure 12) show that Al2p is present up to 9.0 at% in some areas whereas small regions present a very small amount. For the most part of the area the atomic concentration of Al2p is near the highest value of the scale. Mg1s predominates across the whole surface but it is less intense where the O1s signal is more intense. The O1s signal reaches a maximum of 39.7 at%.

This scenario promptly changes after 1 minute of immersion (Figure 13). The Al2p maximum signal decreased to 6.37 at% whereas that of O1s increased to 56.7 at%. The Mg1s signal became less intense over the upper part of the area where the O1s signal is the most intense. XPS mapping indicates that the surface of the AZ91D alloy became more oxidized right after 1 minute of immersion in 3.5 wt.% NaCl solution at room temperature.

This trend was intensified for the sample immersed for 30 minutes (Figure 14). The area where the Al2p signal is weak increased with respect to the as-received alloy (Figure 14(a)). The O1s signal, in turn, is strong over a bigger part of the probed area (Figure 14(b)) whereas the Mg1s atomic concentration is at the lowest level of the scale in most part of the area (Figure 14(c)).

As corrosion proceeds for longer times the O1s signal remains high over the whole area for 3 h and 6 h of immersion (Figures 15(b) and 16(b)) whereas the signal of Al2p is weak (Figures 15(a) and 16(a)). The Mg1s signal does not follow a clear trend, being less intense at 6 h (Figure 16(c)) than at 3 h (Figure 15(c)). For the sample immersed for 15 h, though, the O1s atomic concentration is relatively high and spreads over almost the whole surface (Figure 17(b)) whereas the signals from Mg1s (Figure 17(c)) and Al2p (Figure 17(a)) are relatively weak over it. The high fraction of the O1s signal for this condition allows one to hypothesize that the impedance increase observed from 6 h to 15 h of immersion (Figure 11(a)) is actually due to the formation of a more spread oxide layer on the surface of the AZ91D alloy after 15 h.

After 40 h of immersion the Al2p signal (Figure 18(a)) seems to be more spread over the whole surface than at 15 h. The Mg1s signal (Figure 18(c)) is more intense than at 15 h whereas the O1s signal presents an opposite trend. For the 72 h condition the Al2p signal decreased with respect to the 40 h condition (Figure 19(a)), the O1s signal increased (Figure 19(b)), and the Mg1s signal decreased (Figure 19(c)).

The more intense Al2p and Mg1s signals observed for the sample immersed for 40 h can be related to the lower impedance values of this condition when compared to the sample immersed for 15 h (Figure 11(a)). In this respect, the charge transfer reactions would take place at the electrode surface due to the incipient protective oxide layer formed during immersion. This layer would be deteriorated from 15 h to 40 h, exposing more aluminum and magnesium to the NaCl solution. As a consequence, the impedance values are

FIGURE 10: CLSM 3D images and corresponding roughness profiles for the AZ91D immersed in 3.5 wt.% NaCl solution for different times: (a) 6 h; (b) 15 h; (c) 72 h.

low at 40 h than at 15 h. Next, as the oxidation process evolves on the surface of the AZ91D alloy, the oxygen signal becomes more intense and the oxide layer formed at 72 h would lead to an increase of the impedance values with respect to the 40 h period, as observed in Figure 11(a).

XPS mapping and EIS measurements gave valuable results, regarding the chemical stability and composition of the oxide layer formed on the surface of the AZ91D alloy upon the first hours of immersion in 3.5 wt.% NaCl solution at room temperature. However, they do not allow identification

FIGURE 11: EIS diagrams of the AZ91D alloy immersed in 3.5 wt.% NaCl solution at room temperature for different times: (a) Nyquist and (b) Bode (phase angle versus $\log f$) plots.

of the microstructural features associated with the first corrosion spots as CLSM does. In this respect, coupling these techniques is an interesting route to understand the corrosion process of the AZ91D alloy.

4. Conclusions

The evolution of the corrosion process of the AZ91D magnesium alloy was examined by CLSM during the first hours of

immersion in 3.5 wt.% NaCl solution at room temperature. This technique proved to be a valuable tool for assessing the onset of corrosion spots in the alloy microstructure. Corrosion started at the interface between the eutectic microconstituent and the β -phase after 6 h of immersion in the electrolyte. Next, it propagated within the eutectic microconstituent and the magnesium matrix. The β -phase remained unaffected by the corrosion process up to 40 h of immersion. After 72 h, the microstructure was severely

FIGURE 12: XPS maps for the atomic percentages of (a) Al₂p; (b) O1s; and (c) Mg1s for the as-received AZ91D alloy.

FIGURE 13: XPS maps for the atomic percentages of (a) Al₂p; (b) O1s; and (c) Mg1s for the AZ91D alloy immersed for 1 minute in 3.5 wt.% NaCl solution at room temperature.

FIGURE 14: XPS maps for the atomic percentages of (a) Al₂p; (b) O1s; and (c) Mg1s for the AZ91D alloy immersed for 30 minutes in 3.5 wt.% NaCl solution at room temperature.

FIGURE 15: XPS maps for the atomic percentages of (a) Al₂p; (b) O1s; and (c) Mg1s for the AZ91D alloy immersed for 3 h in 3.5 wt.% NaCl solution at room temperature.

FIGURE 16: XPS maps for the atomic percentages of (a) Al₂p; (b) O₁s; and (c) Mg₁s for the AZ91D alloy immersed for 6 h in 3.5 wt.% NaCl solution at room temperature.

FIGURE 17: XPS maps for the atomic percentages of (a) Al₂p; (b) O1s; and (c) Mg1s for the AZ91D alloy immersed for 15 h in 3.5 wt.% NaCl solution at room temperature.

FIGURE 18: XPS maps for the atomic percentages of (a) Al₂p; (b) O1s; and (c) Mg1s for the AZ91D alloy immersed for 40 h in 3.5 wt.% NaCl solution at room temperature.

FIGURE 19: XPS maps for the atomic percentages of (a) Al₂p; (b) O1s; and (c) Mg1s for the AZ91D alloy immersed for 72 h in 3.5 wt.% NaCl solution at room temperature.

corroded, even at the β -phase. Corrosion was found to preferentially begin at the regions where the β -phase was discontinuously distributed within the magnesium matrix. XPS mapping revealed that the oxygen atomic concentration was dependent on the immersion time and the composition of the oxide layer was related to the electrochemical behavior observed by EIS.

Data Availability

Data will be made available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

Rima Industrial Magnésio (Brazil) is kindly acknowledged for providing the AZ91D ingot studied in this work. The authors are also thankful to Dr. Nelson Batista de Lima (IPEN/CNEN-SP) for the X-ray diffraction analysis.

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