The Corrosion Behavior of As-cast Mg–4Al–xEr–0.3Mn Alloys

Yanzhuo LIU, Yongfeng LI, Honggang ZHANG, Jinhui WANG, and Peipeng JIN*

Qinghai Provincial Key Laboratory of New Light Alloys, Qinghai Provincial Engineering Research Center of High Performance Light Metal Alloys and Forming, No. 251, Ningda Road, Qinghai University, Xining, Qinghai Province 810016, China

* Corresponding author: peipeng.jin@qhu.edu.cn

ABSTRACT

Magnesium and magnesium alloys are light-weighting candidates as the structure materials. The microstructure and corrosion behavior of Mg–4Al–xEr–0.3Mn ($x = 2, 4, 6$ all in wt%) alloys were studied. The results showed that the morphology, size and distribution of $Mg_{17}Al_{12}$ phase were gradually improved with the increasing of Er content, and a large number of Al_2Er were observed. The Al_2Er inhibited the hydrogen evolution reaction and promoted the growth of passivation film. Er oxides or hydroxides were found on the surface of the passivation film, and the charge transfer resistance of the film was $4447 \Omega \text{ cm}^2$, while the film resistance was $5852 \Omega \text{ cm}^2$, which reduced the electron transfer efficiency and improved the density and stability of the passivation film, thus greatly improving the corrosion resistance. As Er content reaches 6 wt%, the corrosion rate decreases by nearly 45%.

© The Author(s) 2021. Published by ECSJ. This is an open access article distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 License (CC BY-NC-SA, <http://creativecommons.org/licenses/by-nc-sa/4.0/>), which permits non-commercial reuse, distribution, and reproduction in any medium by share-alike, provided the original work is properly cited. For permission for commercial reuse, please email to the corresponding author. [DOI: [10.5796/electrochemistry.21-00107](https://doi.org/10.5796/electrochemistry.21-00107)].

Keywords : Magnesium Alloys, AE44, Er Element, Corrosion Behavior

1. Introduction

Magnesium and magnesium alloys are green engineering materials in the 21st century due to low density, high specific strength and modulus. However, the application of the magnesium alloys are limited owing to highly active and the lowly standard electrode potential of magnesium, which results in poor corrosion resistance of pure magnesium and magnesium alloys.^{1–3} Meanwhile, MgO and $Mg(OH)_2$ produced on the surface of the magnesium alloys during the corrosion process are destroyed due to the presence of Cl^- and other ions in the aqueous environments, which leads to further corrosion.^{4,5}

Adding alloying element in magnesium alloys can improve the corrosion resistance and promote the mechanical properties of the alloy. During melting process, magnesium alloy melt burns with O_2 and H_2O to form oxidized inclusions.⁶ As beneficial elements for strengthening and toughening magnesium alloys, rare earth (RE) elements also play a role in purifying the melt, which can remove oxidized inclusions in the alloy.^{7,8} Mn can form high-melting point and higher density intermetallic compounds with Fe in the alloy and thus remove the Fe from the melt, which can effectively improve the corrosion resistance of the magnesium alloys. In addition, Mn can reduce the cathode activity of Fe in the alloy through the effect of encapsulating.⁹ Liu et al.¹⁰ found that the addition of rare earth elements improved the corrosion resistance of the Mg–9Al–xRE alloy and the dissolution of anodic magnesium matrix was accelerated by the strip-like Al–RE precipitates. Rosalbino et al.¹¹ found that the improvement of alloy corrosion resistance is attributed to the adding of Ce and Er in Mg–9Al–1RE alloy, which led to the substitution some atoms in $Mg(OH)_2$ with Ce and/or Er atoms and thus reduced the sensitivity of the passivation films to Cl^- . He et al.¹² believed that the finding of Y_2O_3 in Mg–Y alloy occupies a position in the $Mg(OH)_2$ and inhibits the penetration of the detrimental anions on the film, improving the performance of the passivation film.

Table 1. Nominal compositions of the alloys (in wt%).

Alloys	Al	Er	Mn	Mg
AE42	4	2	0.3	Bal.
AE44	4	4	0.3	Bal.
AE46	4	6	0.3	Bal.

Mg–Al alloy has good casting properties, while its corrosion resistance is poor.¹³ According to the previous studies, adding RE elements to the alloy can form the more stable passivation film on the surface.^{1–12} However, there are very few reports about Er effect on the corrosion behavior in Mg–Al system alloys (to the knowledge of the authors). Therefore, in this paper the corrosion behavior of the Mg–4Al–xEr–0.3Mn alloys (denoted as AE4x, E represents rare earth element Er, $x = 2, 4$ and 6) was analyzed and the corrosion mechanism was revealed.

2. Experimental Methods

2.1 Materials preparation

The Mg–4Al–xEr–0.3Mn alloys were prepared from a commercial pure magnesium (>99.99%), pure aluminum (>99.99%), Mg–20 wt% Er intermediate alloy and Mg–5 wt% Mn intermediate alloy, by melting in a crucible resistance furnace under the protection of Ar_2 and SF_6 mixed gas. The molten alloy is cast at 750°C into a steel mold preheated to 300°C and then cooled in air at room temperature. The chemical compositions of the alloys are listed in Table 1.

2.2 Characterization of microstructure and phase

The distribution and morphology of the microstructure were observed by a scanning electron microscope (ZEISS-6035). The phases of the alloys were measured using an X-ray diffractometer (Brook X D8Advance-A25) with a scan rate of $0.02^\circ/\text{s}$ at the range from 15° to 80° . Corrosion products were analyzed using X-ray

Y. Liu orcid.org/0000-0002-7860-4141

photoelectron spectroscopy (XPS Thermo SCIENTIFIC ESCALAB Xi+).

2.3 Electrochemical testing

Electrochemical tests were performed using an AutoLab (Metrohm) electrochemical workstation in 3.5 wt% NaCl solution at room temperature. A traditional three-electrode cell was used with platinum as the counter electrode, a saturated calomel electrode (denoted as SCE) as the reference electrode and the sample as the working electrode. The area of the working electrode was 1 cm^2 , and the samples were ground with SiC paper up to 2000 grit size. The samples were immersed in 120 mL 3.5 wt% NaCl solution for 60 minutes in order to achieve a relatively stable open circuit potential (OCP). The potentiodynamic polarization tests were measured with a scan scope from -500 mV vs. SCE to $+300 \text{ mV}$ vs. SCE at a scan rate of 1 mV/s . The corrosion current was obtained by cathode extrapolation.¹⁴ The electrochemical impedance spectroscopy (EIS) measurements were carried out with an amplitude of 10 mV over the frequency range from 100 kHz to 0.01 Hz at an OCP after 60 minutes stabilization.

2.4 Immersion experiment

The samples volume of immersion experiment were $8 \text{ mm} \times 8 \text{ mm} \times 5 \text{ mm}$ and were ground with SiC paper up to 2000 grit size. The samples were suspended in 250 mL solution with nylon rope and then immersed for 48 h at room temperature. After immersion test, the corrosion products were cleaned using a mixed solution containing 200 g/L CrO_3 and 10 g/L AgNO_3 for 8 minutes in an ultrasonic vibrator. After cleaning, the samples were dried with cold air and then weighed. The corrosion morphology was observed under scanning electron microscope. The weight loss rate W_L ($\text{mg cm}^{-2} \text{ d}^{-1}$) was calculated using the following formula.^{15,16}

$$W_L = \frac{W_b - W_a}{At} \quad (1)$$

where W_b is the quality (mg) of the sample before the immersion test, W_a is the quality (mg) of the sample after the removal of corrosion products after the immersion test, A (cm^2) is the surface area of the sample, and t (day) is the test time.

The corrosion rate P_w (mm y^{-1}) can be calculated by the formula:^{15,16}

$$P_w = 2.10 \times W_L \quad (2)$$

The mosaic approach was used during the sample hydrogen evolution test so that only surface area (1 cm^2) was exposed. The samples were immersed in the solution with a volume of 250 mL at room temperature for 48 h and hydrogen was collected with burette. Each alloy is tested at least three times under the same conditions to ensure the accuracy of the tests.

3. Results

3.1 The phase analysis and microstructure observing

Figure 1 shows the XRD patterns of the as-cast Mg–4Al–xEr–0.3Mn alloys. There are diffraction peaks of α -Mg, $\text{Mg}_{17}\text{Al}_{12}$ and Al_2Er in the all three alloys. In addition, the diffraction peak of Al_7ErMn_5 is also found in the XRD patterns of the AE42 alloy. With the increase of Er content, the diffraction peaks intensity of Al_2Er also increase and the peaks intensities of Al_2Er reached the maximum in the AE46 alloy.

Figure 2 shows the microstructures of as-cast Mg–4Al–xEr–0.3Mn alloys. The lamellar-like $\text{Mg}_{17}\text{Al}_{12}$ precipitated with α -Mg eutectic is very fine and dispersion distribution as shown in Fig. 2a.

Figure 1. XRD patterns of the as-cast Mg–4Al–xEr–0.3Mn alloys.

Figure 2. SEM images of (a) AE42 alloy, (b) AE44 alloy and (c) AE46 alloy.

Figure 3. EDX analyses for the Mg-4Al- x Er-0.3Mn alloys (a) AE42, (b) AE44 and (c) AE46 alloy.

The clump-like Al_7ErMn_5 and bar-like Al_2Er were also found in AE42 alloy (see Fig. 2a), while the particle-like Al_2Er in AE44 and AE46 alloys (as shown in Figs. 2b and 2c). This is consistent with the results in previous literatures.^{17,18} Since the solidification temperature of Al_2Er is much higher than that of the $\text{Mg}_{17}\text{Al}_{12}$ and thus the Al atoms and Er atoms are preferred to form intermetallic compound Al_2Er first during the solidification, which is as nucleation sites of the α -Mg and $\text{Mg}_{17}\text{Al}_{12}$ and further modifies the morphology, size and distribution of the $\text{Mg}_{17}\text{Al}_{12}$ owing to Er as active element inhibiting the growth of the $\text{Mg}_{17}\text{Al}_{12}$.¹⁹ With the increasing of Er content, the volume fraction of the $\text{Mg}_{17}\text{Al}_{12}$ decreased, while the volume fraction Al_2Er increased.

Figure 3 are SEM images and energy spectrum of EDX element surface distribution of the three alloys. The bar-like Al_2Er precipitate and the lamellar-like $\text{Mg}_{17}\text{Al}_{12}$ precipitate are shown in Fig. 3a. With the increasing of Er content, the sizes of the $\text{Mg}_{17}\text{Al}_{12}$ are fined, while the sizes of Al_2Er are coarsen. A few of Al_7ErMn_5 particles are also found in Fig. 3a, while the Al_7ErMn_5 can hardly be seen in Figs. 3b and 3c, which are consistent with XRD results.

3.2 Corrosion behavior

Figure 4 shows the potentiodynamic polarization curve of the alloy after 60 minutes of open circuit potential measurement. The breakdown potentials are marked with arrows. The cathodic polarization curves indicate hydrogen evolution at the cathode and the anodic polarization curve indicates the dissolution of magnesium ions. It is obvious that the current densities of the cathode and anode decrease with the increasing of the Er content. Furthermore, there is an obvious passivation tendency on the anode branches of AE44 and AE46 alloys. It is implied that there is a protective oxide film on the surface of the alloy. The corrosion potentials of AE44 and AE46 alloys are lower than the breakdown potential, while the corrosion potential of AE42 is higher than the breakdown potential.

The cathode hydrogen evolution rate and anode dissolution rate of AE46 alloy are the slowest among the three alloys. When the potential reaches the breakdown potential, the corrosion current increases rapidly, indicating that the ruptured surface film at this critical point is no longer protective and local corrosion occurs. The Tafel fitting^{16,20,21} was used to fit the experimental results as listed in Table 2. E_{corr} , I_{corr} and E_{bp} represent the corrosion potential, corrosion current density and breakdown potential, respectively.

Figure 4. Potentiodynamic polarization curves of the Mg-4Al- x Er-0.3Mn alloys in 3.5 wt% NaCl solution.

Table 2. The electrochemical parameters obtained from Tafel fitted results of the polarization curves.

Alloys	E_{corr} (V)	I_{corr} ($\mu\text{A cm}^{-2}$)	E_{bp} (V)
AE42	-1.545	28.33	-1.55
AE44	-1.533	9.73	-1.48
AE46	-1.574	6.02	-1.43

The film breakdown potential of AE42, AE44 and AE46 alloys are -1.55 V vs. SCE, -1.48 V vs. SCE and -1.43 V vs. SCE, respectively. The results showed that the breakdown potentials increased with the increasing of Er content in the alloys and the passivation films of the samples with higher Er content were more protective. Therefore, the adding of the Er enhances the electrochemical stability of the passivation film, which is consistent with the results in literature.²²

The results of electrochemical measurement are given in Fig. 5. According to the Nyquist curve in Fig. 5a, the Nyquist plots of all alloys consist of three loops including a high-frequency capacitive loop, a medium-frequency capacitive loop, and a low-frequency

Figure 5. The electrochemical measurement of tested specimens in a 3.5 wt% NaCl electrolyte: (a) Nyquist plots, (b) Bode plots, (c) equivalent circuit used to fit the EIS spectra.

Table 3. The fitted EIS data.

Alloys	R_s ($\Omega \text{ cm}^2$)	R_t ($\Omega \text{ cm}^2$)	Y_{dl} ($\Omega^{-1} \text{ cm}^{-2} \text{ s}^n$)	n_{dl}	Y_f ($\Omega^{-1} \text{ cm}^{-2} \text{ s}^n$)	n_f	R_f ($\Omega \text{ cm}^2$)	R_L ($\Omega \text{ cm}^2$)	L (H cm^{-2})
AE42	10.33	463	1.58×10^{-5}	0.93	29.5×10^{-4}	0.05	4396	294	267
AE44	12.34	2055	9.78×10^{-6}	0.57	11.45×10^{-4}	0.50	4820	3581	84800
AE46	5.68	4447	9.27×10^{-6}	0.85	6.83×10^{-4}	0.79	5852	4617	89619

inductive loop. Additionally, there were three-time constants in Fig. 5b. The Nova 2.1 software attached with AutoLab was used to fit the Nyquist curve. The fitting results are listed in Table 3. Figure 5c is the equivalent circuit of the three alloys. R_s , R_t and CPE_{dl} represent the solution resistance, the charge transfer resistance and the double layer capacitance, respectively, which are used to describe the high-frequency capacitive loop. R_f and CPE_f represent film resistance and film capacitance, respectively, which are used to describe the medium-frequency capacitive loop. The induction resistance R_L and inductance L describe the induction loop at low frequencies in Fig. 5c. The constant phase elements (CPE_{dl} and CPE_f) replace the ideal capacitors due to the inhomogeneity of system, and they are defined by two parameters of Y and n . It is found that the $|Z|$ values increase obviously with the increasing of the Er content. When the Er addition to 6 wt%, the $|Z|$ value reaches to 6252 $\Omega \text{ cm}^2$. The higher the R_f value, the better the protection of the passivation film to the alloy matrix is. The occurred inductance at lower frequency is attributed to local corrosion on the surfaces of all three alloys and also possible deposition of corrosion products on the sample surface. The higher the induction resistance, the less tendency of pitting corrosion is.^{23–25}

3.3 Corrosion rate

Figure 6a shows the hydrogen evolution rates curves of the three alloys immersed in 3.5 wt% NaCl solution for 48 h. In the first 12 h, the hydrogen evolution rates of the three alloys are relatively slow.

After 12 h, more and more hydrogen are collected, and the hydrogen evolution rate is obviously accelerated. This indicates that the passivation film formed during the initial immersion process has been damaged with the continuous erosion of Cl^- , resulting in an accelerated corrosion rate. Although EIS results show that there is a tendency to pitting corrosion on the surface. It is surprised to find that AE46 alloy has much less hydrogen evolution from the 0 to 48 h than those of the other alloys. This indicates that the passivation film is produced on the surface of the AE46 alloy, thus the corrosion resistance of the alloy is greatly improved.

Figure 6b shows the weight loss corrosion rates calculated according to Eqs. 1 and 2 for the three alloys after being immersed in 3.5 wt% NaCl solution for 48 h. It is found that the adding Er the Mg alloys has an obviously protective effect on the magnesium alloys in 3.5 wt% NaCl solution. The corrosion rate is only 0.7 mm y^{-1} when the addition of the Er reaches 6 wt%. The corrosion rates of the three alloys are as follows: AE42 > AE44 > AE46.

Figure 7 shows the morphologies of corrosion products on the surfaces of the three alloys immersed in NaCl solution after 48 h (without chromic acid cleaning). It is observed that there is a passivation film of corrosion products on the surface of the sample and it is accompanied by the generation of microcracks. In Fig. 7a, the passivation film are not compact and some deeper corrosion pits can be seen on the surface of the passivation film as shown in inset of the Fig. 7a. The corrosion products are not stable and thus easily

Figure 6. (a) Hydrogen evolution and (b) weight loss rate of as-cast Mg-4Al-xEr-0.3Mn alloys.

Figure 7. SEM images of tested alloys without removing the corrosion products: (a) AE42 alloy, (b) AE44 alloy and (c) AE46 alloy.

fall off from the surface. Figure 7b shows that although the passivation film morphology of the AE44 alloy is similar to that of the AE42 alloy, there are no deeper corrosion pits and the corrosion products are more compact than those of the AE42 alloy. No deep corrosion pits are found on the passivation film of the AE46 as shown in Fig. 7c. It is observed that the passivation film are the most compact among the three alloys and thus it can effectively prevent the alloy from being further corroded.²⁶ The results in literature^{26,27} showed that the initially formed $\text{Mg}(\text{OH})_2$ films did not have microcracks. However, in the high vacuum environment of electron microscopy, $\text{Mg}(\text{OH})_2$ was transformed into MgO , which resulted in microcracks due to changing in molar volume of the passivation film.

4. Discussion

It is well known that the $\text{Mg}(\text{OH})_2$ prevent the magnesium from the corrosion is very limited. It is attributed to the layered structure

of $\text{Mg}(\text{OH})_2$ in the alloy attacked easily by Cl^- , which destroys the integrity of the passivation film and thus the corrosion occurs further. The magnesium atoms dissolve into not only divalent magnesium ions but also monovalent magnesium ions. Namely, magnesium atoms first lose electrons and become monovalent magnesium ions and subsequently monovalent magnesium ions react with water to form more stable divalent magnesium ions and thus release hydrogen (anodic hydrogen evolution).²⁸ As shown in Figs. 7a and 7b, because of the incompleteness of the passivation film and the Cl^- reacts with the magnesium further. Therefore, AE42 and AE44 alloys have more hydrogen evolution. The compact passivation film of the AE46 (see Fig. 7c) is more protective to the magnesium matrix and the hydrogen evolution rate of the AE46 is the lowest one among the three alloys. This is consistent with the results in Fig. 6a. However, the rare earth elements as alloying elements of magnesium are believed to increase the stability of the passivation film.²⁰ The incorporation of Er in the $\text{Mg}(\text{OH})_2$ lattice reduced the corrosion sensitivity of $\text{Mg}(\text{OH})_2$, hence improving the

Figure 8. XPS analysis of AE46 alloy after immersion in 3.5 wt% NaCl solution for 48 h: (a) Mg 1s spectrum, (b) O 1s spectrum, (c) Al 2p spectrum and (d) Er 4d spectrum.

corrosion resistance of the alloy.^{29,30} The research results of He et al. showed that adding Y element to the alloy can introduce Y₂O₃ between the matrix and the corrosion products, which reduces the cathode current density, charge transfer resistance and surface oxide film resistance of the Mg alloys.¹²

Figure 8 is the XPS spectrums of the AE46 alloy immersed in 3.5 wt% NaCl solution for 48 h. It is shown in Fig. 8a that the spectrums of Mg 1s have a peak of Mg(OH)₂ at 1303.67 eV and a peak of MgO at 1304.67 eV. There is a sharp peak at 74.36 eV as shown in Fig. 8c, which indicates that Al element is enriched in the passivation film of the AE46 alloy and hence the passivation film may be consist of Al₂O₃ and/or Al(OH)₃. The compact passivation film of the Al₂O₃ formed on the AE46 alloy can provide a better protective effectiveness of the alloy. The Er³⁺ peaks also appear in the spectrum of Er 4d as observed in Fig. 8d, which indicates that the Er₂O₃ and/or Er(OH)₃ exist in the passivation film. This is consistent with previous electrochemical results as shown in Figs. 4 and 5.

With increasing the content of the Er element, the volume fraction of the Mg₁₇Al₁₂ can be reduced and the Mg₁₇Al₁₂ precipitates change from coarser discontinuous precipitation to finer continuous precipitation. However, it is inevitable to introduce a large amount of Al-RE intermetallic compounds in the alloy, which lead to micro-galvanic corrosion. The cathode current density and hydrogen evolution rate of the AE42 are greater than those of the other two alloys as shown in Fig. 4 and Fig. 6a. Therefore, although the particle-like Al₂Er precipitates serve as the cathodes, which still hinder the hydrogen evolution process surprisingly. The Al₂Er cathodes weaken the tendency of local corrosion and turn into general corrosion. Therefore Al₂Er cathodes accelerate Er-containing passivation film formation and thus the Mg alloy is separated from the corrosive solution by the passivation film.

5. Conclusion

Based on the experimental investigation of the corrosion resistance and corrosion mechanism of as-cast Mg–4Al–xEr–0.3Mn alloy, the following results are obtained:

- (1) With the increasing of Er content, the volume fraction of the effective cathode Mg₁₇Al₁₂ decreases and the grains of Mg₁₇Al₁₂ are fined, while the volume fraction of the Al₂Er increases and the grains of Al₂Er are coarsen.
- (2) AE46 alloy has the best corrosion resistance in 3.5 wt% NaCl solution. The hydrogen evolution rate of cathode and dissolution rate of anode of the AE46 alloy are lowest in all of the three alloys. And the corrosion current density, the charge transfer resistance, the film resistance and the corrosion rate are 6.02 μA cm⁻², 4447 Ω cm², 5852 Ω cm², and 0.7 mm y⁻¹, respectively.
- (3) The high corrosion resistance of AE46 alloy is attributed to the compact passivation film produced on the surface during corrosion. Besides Mg(OH)₂, there may also exist Al₂O₃, and/or Al(OH)₃, and Er₂O₃ and/or Er(OH)₃ in the passivation film, which improve the corrosion resistance of AE46 alloy.
- (4) Although there is a large amount of Al₂Er phase in AE46 alloy, the hydrogen evolution rate is reduced compared with those of the AE42 and AE44 alloys. It is found that the numerous micro-cells are formed on the surface of the alloy to cause overall corrosion and thus accelerate the formation of passivation film.

Acknowledgments

The work was financially supported by the Qinghai Provincial Science and Technology Key Program (No. 2018-GX-A1).

CRediT Authorship Contribution Statement

Yanzhuo Liu: Writing – original draft (Lead)
 Yongfeng Li: Software (Supporting)
 Honggang Zhang: Software (Supporting)
 Jinhui Wang: Project administration (Lead)
 Peipeng Jin: Writing – review & editing (Lead)

Conflict of Interest

The authors declare no conflict of interest in the manuscript.

Funding

Qinghai Provincial Science and Technology Key Program : No. 2018-GX-A1

References

- Y. Yang, X. Xiong, J. Chen, X. Peng, D. Chen, and F. Pan, *J. Magnesium Alloys*, **9**, 705 (2021).
- Z. Zhang, G. Wu, A. Atrens, and W. Ding, *J. Magnesium Alloys*, **8**, 301 (2020).
- X. Li, G. Ma, J. Yin, and W. Liu, *Materials Guide*, **21**, 85 (2017).
- K. Gusieva, C. H. J. Davies, J. R. Scully, and N. Birbilis, *Int. Mater. Rev.*, **60**, 169 (2015).
- L. Yang, S. He, C. Yang, X. Zhou, X. Lu, Y. Huang, G. Qin, and E. Zhang, *J. Magnesium Alloys*, **9**, 676 (2021).
- G. Wu, C. Wang, M. Sun, and W. Ding, *J. Magnesium Alloys*, **9**, 1 (2021).
- J. Xie, J. Zhang, Z. You, S. Liu, K. Guan, R. Wu, J. Wang, and J. Feng, *J. Magnesium Alloys*, **9**, 41 (2021).
- F. Rosalbino, E. Angelini, S. De Negri, A. Saccone, and S. Delfino, *Intermetallics*, **13**, 55 (2005).
- G. Song, *Corrosion Prevention of Magnesium Alloys*, pp. 3–37 (2013).
- Q. Liu, G. Chen, S. Zeng, S. Zhang, F. Long, and Q. Shi, *J. Alloys Compd.*, **851**, 156835 (2021).
- F. Rosalbino, E. Angelini, S. De Negri, A. Saccone, and S. Delfino, *Intermetallics*, **14**, 1487 (2006).
- W. He, E. Zhang, and K. Yang, *Mater. Sci. Eng., C*, **30**, 167 (2010).
- M. S. Dargusch, Z. Shi, H. Zhu, A. Atrens, and G. Song, *J. Magnesium Alloys*, **9**, 950 (2021).
- J. Jayaraj, S. Amruth Raj, A. Srinivasan, S. Ananthakumar, U. T. S. Pillai, N. G. K. Dhaipule, and U. K. Mudali, *Corros. Sci.*, **113**, 104 (2016).
- F. Cao, Z. Shi, G. Song, M. Liu, and A. Atrens, *Corros. Sci.*, **76**, 60 (2013).
- B. Jiang, Q. Xiang, A. Atrens, J. Song, and F. Pan, *Corros. Sci.*, **126**, 374 (2017).
- M. Yang, Y. Liu, J. Liu, Z. Zhang, and C. Jin, *Chinese Rare Earth*, **039(001)** (2018).
- X. Cui, P. Bai, X. Hou, W. Liu, and L. Wang, *Chinese Rare Earth*, **036(004)** (2015).
- D. Xiao and B. Huang, *Chinese Journal of Rare Earth*, **26(001)** (2008).
- Y. Lu, A. R. Bradshaw, Y. L. Chiu, and I. P. Jones, *Mater. Sci. Eng., C*, **48**, 480 (2015).
- Y. Song, E. Han, D. Shan, C. D. Yim, and B. S. You, *Corros. Sci.*, **65**, 322 (2012).
- F. Rosalbino, E. Angelini, S. De Negri, A. Saccone, and S. Delfino, *Intermetallics*, **11**, 435 (2003).
- X. Wang, Z. Chen, E. Guo, X. Liu, H. Kang, and T. Wang, *J. Alloys Compd.*, **863**, 158762 (2021).
- Y. Sun, R. Wang, C. Peng, and Z. Cai, *Corros. Sci.*, **167**, 108487 (2020).
- A. Dobkowska, B. Adamczyk-Cieślak, J. Kubásek, D. Vojtěch, D. Kuc, E. Hadasik, and J. Mizera, *J. Magnesium Alloys*, **9**, 467 (2021).
- S. Yin, W. Duan, W. Liu, L. Wu, J. Yu, Z. Zhao, M. Liu, P. Wang, J. Cui, and Z. Zhang, *Corros. Sci.*, **166**, 108419 (2020).
- G. Song and K. A. Unocic, *Corros. Sci.*, **98**, 758 (2015).
- G. Song, *Corrosion Prevention of Magnesium Alloys*, pp. 51–56 (2006).
- Y. Li, Y. Wei, L. Hou, C. Guo, and P. Han, *J. Rare Earths*, **32**, 1064 (2014).
- F. Rosalbino, E. Angelini, S. De Negri, A. Saccone, and S. Delfino, *Intermetallics*, **13**, 55 (2005).