

Article

Not peer-reviewed version

Long Term Atmospheric Corrosion of Magnesium Alloys: Influence of Aluminium Content

[Dominique Thierry](#) ^{*}, [Dan Persson](#), [Nathalie LeBozec](#)

Posted Date: 22 December 2025

doi: 10.20944/preprints202512.1971.v1

Keywords: atmospheric corrosion; magnesium alloys; field exposures; Al content



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Article

Long Term Atmospheric Corrosion of Magnesium Alloys: Influence of Aluminium Content

Dominique Thierry ^{1,*}, Dan Persson ¹ and Nathalie LeBozec ²

¹ Corrosion Department, Division of Materials and Production, Research Institutes of Sweden (RISE), Isafjordsgatan 28A, 114 28 Stockholm, Sweden

² French Corrosion Institute, 220 Rue Pierre Rivoalon, 29200 Brest, France

* Correspondence: dominique.thierry@ri.se

Abstract

This paper is dedicated to long term atmospheric corrosion behaviour of magnesium alloys. Five different magnesium alloys namely AZ31, AM60, AZ61, AZ80 and AZ91 were exposed for 4 years under harsh conditions at the marine corrosion site of Brest (France). From the results, the corrosion performance increased in the following order: AZ31<AM60<AZ91<AZ61<AZ80. The corrosion was highly localised during the first year of exposure, but more general corrosion prevailed after long term of exposure. All materials followed a power law with rather similar kinetics of corrosion. The observed difference in the corrosion performance of the alloys was explained by the amount of secondary phases as well as that of the Al-content in the α -Mg phase.

Keywords: atmospheric corrosion; magnesium alloys; field exposures; Al content

1. Introduction

Magnesium (Mg) alloys have shown increasing interest due to their low density and good mechanical properties. They are used for a variety of applications in both the aerospace and automotive sectors, as well as for biodegradable implants. The corrosion of Mg alloys in aqueous media, particularly in chloride-containing solutions, has been the subject of several studies throughout the last few decades. Recent reviews provide a summary of the extensive research on the effects of chemical composition, microstructure, surface condition, and solution compositions [1–5]. However, relatively few investigations have been carried out into the atmospheric corrosion of Mg alloys despite the application of these materials in the automotive and aerospace industry. Under atmospheric conditions, a thin electrolyte film is formed which thickness does not exceed a few hundred micrometres. It can be assumed that such a film is always saturated with oxygen, and that diffusion is not hindered. Although the mechanisms of corrosion of Mg alloys could be rather similar under immersion and atmospheric conditions, the contribution of oxygen reduction is much more important for the later. In addition, other gases such as CO₂ and SO₂ (in polluted areas) may play an important role in the kinetics of atmospheric corrosion and the nature of the corrosion products that are built. Other environmental parameters such as temperature, relative humidity (RH) and chloride deposition generally govern the atmospheric corrosion rate of Mg alloys. Based on laboratory exposures, Le Bozec et al found that the corrosion rates of AZ91D and AM50 increased with RH [6]. This was explained by the formation of a thicker electrolyte layer at higher RH leading to the formation of less protective corrosion product layers. The influence of chloride deposition on the corrosion of Mg alloys (mostly on AZ31 and AZ 91) has been highlighted on several occasions based on both laboratory and field exposures. Based on laboratory exposures, Le Bozec et al [6] show a linear increase of the corrosion rate of AZ91 and AM50 with chloride deposition. This was supported by results obtained under atmospheric exposures performed under trailers operating in different countries [7].

Several studies have shown that the corrosion rate of Mg alloys decreased with increasing content of aluminium. Pardo et al have shown that the mass loss of AZ31 was more than 50 times higher than AM80 and AZ91 after 10 days immersion in 3,5 wt.% NaCl [8]. The better corrosion behaviour of AM80 was explained by the formation of a semi-protective Al-rich oxide layer whereas in the case of AZ91, it was attributed to the presence of a network of eutectic aggregates with higher Al content [8]. More recently, Esmaily et al. compared the atmospheric corrosion rate of four different magnesium alloys containing from 2 to 9 wt% of Al. Mass loss and mass gain were obtained on samples contaminated with 70 $\mu\text{g}/\text{cm}^2$ of NaCl and exposed for 504 hours at temperatures ranging from -4 to 22°C [9,10]. A decrease in the corrosion rate was observed with the aluminium content, and this effect was temperature dependent and the highest at the lower temperature of -4°C. The data were explained by the formation an Al³⁺-enriched layer, which was formed in the bottom of the thin surface film [9,10]. Similar results were obtained by Feliu et al for AZ31 and AM60 under continuous condensation conditions [11], by Jönson et al under indoor atmospheric conditions [12] and by Merino et al under salt spray conditions [13]. However, there is a lack of systematic investigations on the influence of Al in Mg alloys upon long terms field exposure in different climatic conditions. In comparison to immersion studies, relatively few investigations have been performed under atmospheric conditions and in particular long terms exposure conditions outdoor. Since atmospheric corrosion is strongly affected by environmental climatic parameters, field tests are of utmost importance for the evaluation of atmospheric corrosion resistance of magnesium alloys. Most of the data published in the literature have been obtained in China under different environmental conditions (industrial, marine and marine tropical) [14–25]. In comparison, relatively few studies have been performed at field sites outside China [18, **Erreur ! Source du renvoi introuvable.**, 27]. The main body of the published data concern AZ91 and AZ31. As summarised by Liu, the corrosion rate of AZ91 after 12 months exposure under different climatic conditions varied from about 1 to 15 μm (at static exposure sites) and about 32 μm at a dynamic exposure site [16]. As shown in a recent review by Wang and co-authors on the corrosion rate of field exposed magnesium alloys, the corrosion rate of AZ31 is generally higher than that of AZ91 under various exposures conditions [20]. The corrosion rate of AM60 was in the same range as that of AZ91 upon exposure to a marine atmosphere in China [25]. However, the exposure duration is rather short (often below 2 years) in most of these works, and generally one or two magnesium alloys were exposed. In addition, information on the corrosivity category according to ISO 9226 is often not provided during the time of exposure when the work was performed. Hence, it is difficult to obtain a direct comparison between different magnesium alloys with respect to the impact of the microstructure or Al content in the long-term corrosion behaviour of Mg alloys.

The aim of this work was to study the influence of Al in Mg alloys under field exposure conditions. For this purpose, five different commercial alloys were exposed for 4 years in a marine atmospheric site. The microstructure of the alloys was studied using FEG-SEM. The corrosion rate was systematically measured after 3, 12, 24 and 48 months of exposures. Corrosion products were also analysed using infrared spectroscopy.

2. Methodology

Materials and Microstructure Analyses

The materials studied were five commercial alloys with different aluminium content namely AZ31, AM60, AZ61, AZ80 and AZ91 with nominal compositions given in Table 1. AZ31 was cast and hot rolled plates. AZ60 and AZ91 were cast and machined plates. AZ61 and AZ80 were extruded bars

Table 1. Nominal compositions of tested materials.

Material	Element in wt%						
	Al	Zn	Mn	Si	Cu	Fe	Ni
AZ31	3.28	0.98	0.29	0.0089	0.0085	0.0024	0.00067
AM60	6.08	0.041	0.362	0.0123	0.0003	0.0005	0.0006
AZ61	6.85	0.98	0.33	0.023	0.0023	0.0025	0.00076
AZ80	8.6	0.51	0.22	0.01	<0.0005	0.005	0.0005
AZ91	8.97	0.82	0.0087	0.008	0.0079	0.0058	0.00067

All materials were grinded to 4000 SiC paper in ethanol and diamond polished to 0.25 µm (for microstructural investigations). A final polishing with BIB (broad ion beam) was performed to avoid alumina and silica suspensions. Scanning Electron Microscopy (SEM) using a Zeiss 300 FEG SEM equipment was used to study the microstructure of the different Mg alloys. The microscope was equipped with Energy Dispersive X-Ray Spectroscopy (EDS) instrument (Oxford). The number of secondary phases in the alloys was studied using Electron Backscatter Diffraction (EBSD). The software for image analyses was image J. Because EDS beams penetrate the material to a certain extent, the quantitative measurements are not highly accurate as the interaction volume may contain matrix or another underlying phase which is different from the one being probed. Due to this, a large number of EDS analyses were conducted and only statistically confirmed data are reported in this work.

Samples were cut to dimensions of 100x 100 mm (for plates) and to the diameter of the bars, grinded to 1200 SiC paper (in ethanol), degreased in acetone and ethanol prior to the exposure at the marine site of Brest

Atmospheric Exposure

Samples were exposed to the marine corrosion site of Brest (France) for 3 months, 1, 2 and 4 years respectively. The sample orientation was 45° facing south (in front of the dominating wind and the seashore. The mean environmental parameters measured at the site of Brest during the 4 years of exposure are provided in Table 2. The site is classified as C5 for the corrosivity of steel and C3 for the corrosivity of zinc according to ISO 9223.

Table 2. Environmental parameters measured at the site of Brest 2017-2020.

Environmental parameter	Unit	Value
Temperature	°C	13
Relative humidity	%	84
Chloride deposition	mg. m ⁻² day ⁻¹	1000
SO ₂	µg.m ⁻³	<1
Precipitation, yearly	mm	1000
Distance from the sea	m	10
Time of wetness	h. year ⁻¹	500

Three replicates of each material have been removed after 3 months,1, 2, and 4 years of exposure. The samples were brushed to remove non-adherent corrosion products, rinsed in flowing water and the corrosion products were removed by chemical pickling according to ISO 8407. The samples were pickled several times at ambient temperature in a solution of 200 g/l. CrO₃, then rinsed with water and ethanol prior to weight loss determination until complete elimination of the corrosion products. Pitting corrosion was also evaluated after pickling using an optical microscope.

Analyses of Corrosion Products

FTIR-spectroscopy was performed using a Bruker Vertex 70 spectrometer (Bruker Optics, Ettlingen, Germany) equipped with a wide band (FM) beamsplitter (Bruker) and a DLATGS detector. The spectra were measured using a single-bounce attenuated total reflectance (ATR) with a diamond internal reflection element (Quest, Specac). The spectra were recorded by adding 256 scans with 8 cm^{-1} spectra resolution, in the spectral region $280\text{--}4000\text{ cm}^{-1}$.

3. Results

Microstructures of the Mg Alloys

The microstructures of the materials studied here are shown in Figure 1 and 2. AZ31 has a heterogeneous grain structure with greater variability in grain size from small equiaxed grains of average diameter $<20\text{ }\mu\text{m}$ to larger grain $>50\text{ }\mu\text{m}$. Bright phases of AlMn intermetallic particles and some particles containing Zn (and Al) can be found mainly at grain boundaries (see Figure 2). The $\text{Al}_{12}\text{Mg}_{17}$ and eutectic phases were not seen in this material. The amount of secondary phase was analysed by EDS data to about 1.5%.

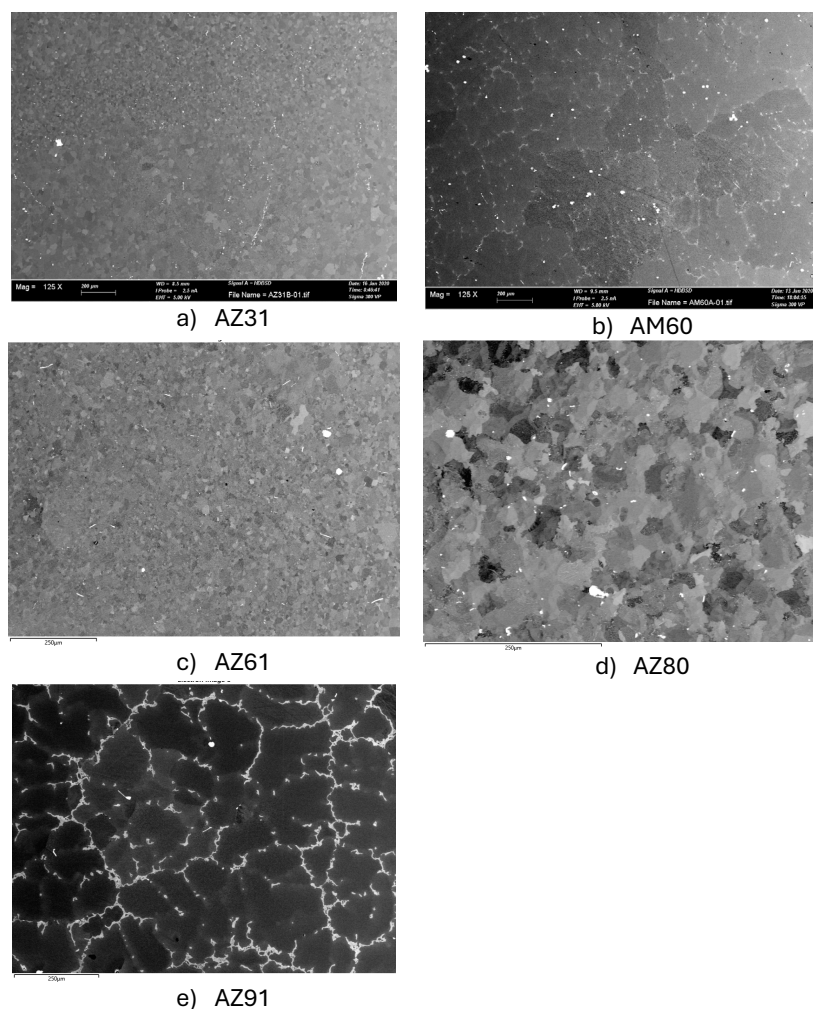


Figure 1. Microstructure of magnesium alloys.

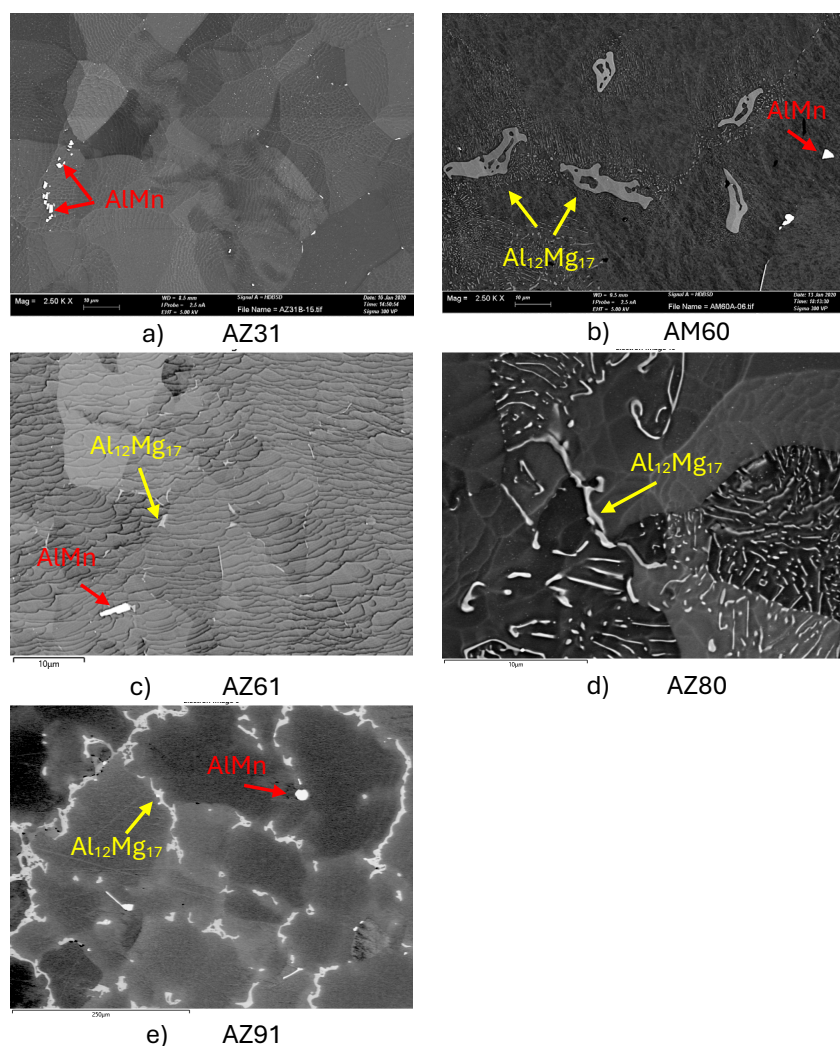


Figure 2. Microstructure of magnesium alloys showing secondary phases.

The microstructure of AM60 revealed very large grains size of several hundred micro-meters in diameter. Aluminum was highly segregated in this alloy. Dendrite arms are seen with secondary phase surrounding them. This phase is rich in aluminum and is identified as $\text{Al}_{12}\text{Mg}_{17}$ (see Figure 3). The very bright second phase contains Mn and Fe. Eutectic is also visible in the material, often in the vicinity of the large $\text{Al}_{12}\text{Mg}_{17}$ phase. According to the EBSD analysis, the $\text{Al}_{12}\text{Mg}_{17}$ was about 2%. The total fraction of secondary phase was about 3%.

The microstructure of AZ61 indicates the presence of $\text{Al}_{12}\text{Mg}_{17}$ and AlMn particles (see Figure 1 and 2). EBSD analysis shows a relatively fine grain structure with equi-axed grains (not dendritic solidification microstructure). The amount of secondary phase was analysed by EDS to 2%.

Small equi-axed grains of average diameter $> 25 \mu\text{m}$ were seen in AZ80, as well as large circular bright phases with Mn, smaller elongated phases and perlite-type lamellas (see Figure 1 and 2). The lamellas in the eutectic have been identified as $\text{Al}_{12}\text{Mg}_{17}$ phase by EBSD. The total fraction of secondary phase was about 2-3%.

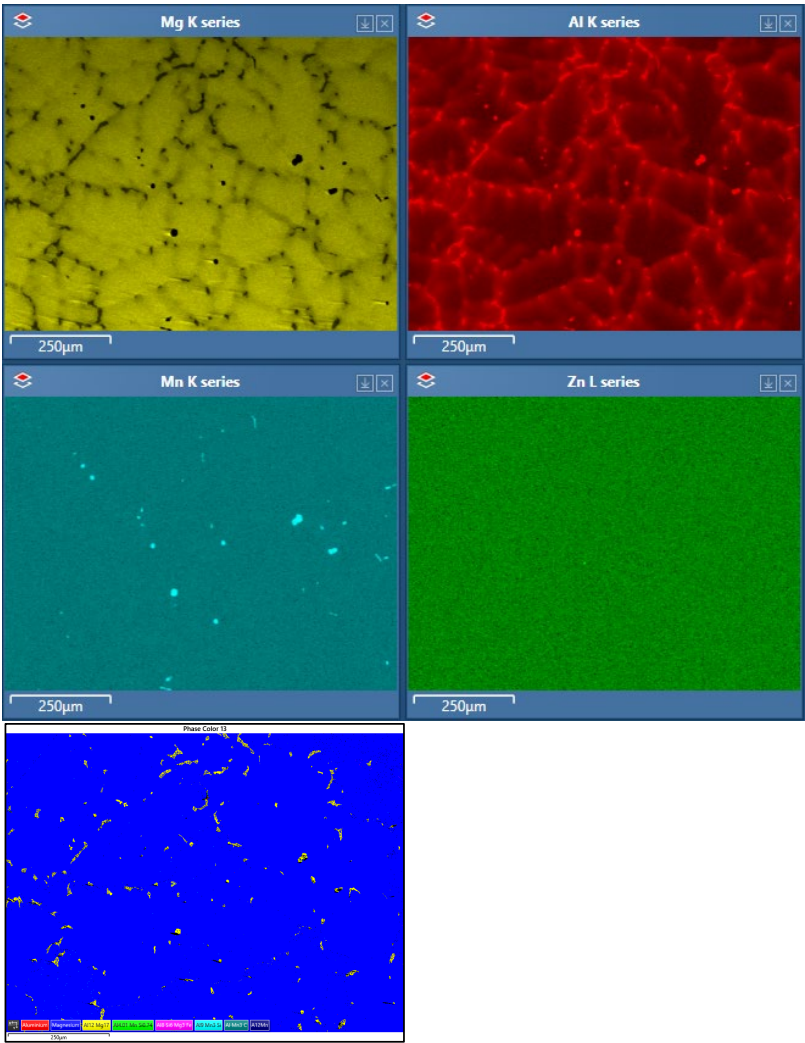


Figure 3. SEM-EDS mapping of AM60 (top, center) and EBSD image (bottom) revealing Al₁₂Mg₁₇ phase.

EBSD analysis of AZ91 shows that this material has dendritic solidification microstructure with very clear dendrites and secondary phases in the inter-dendritic spacings. Grains are very large. EDS mapping shows the strong segregation of Al and Zn. The main secondary phase is the Al₁₂Mg₁₇ phase, but there is also AlMn phase and a Mg₂Si phase present (see Figure 4). Analysis of EDS data gave 12-15% of secondary phase.

The important parameters in the microstructures shown in Figures 1–4 are summarised in Table 2.

Table 2. Microstructural parameters of Mg alloys.

Alloy	Grain size, µm	Secondary phase, %	Main secondary phases
AZ31	<20 and <50	1,5	MnAl
AM60	>100	2	Al ₁₂ Mg ₁₇ and AlMn
AZ61	<20	2	Al ₁₂ Mg ₁₇ and AlMn
AZ80	>25	2-3	Al ₁₂ Mg ₁₇ and AlMn
AZ91	>200	12-15	Al ₁₂ Mg ₁₇ , AlMn and Mg ₂ Si

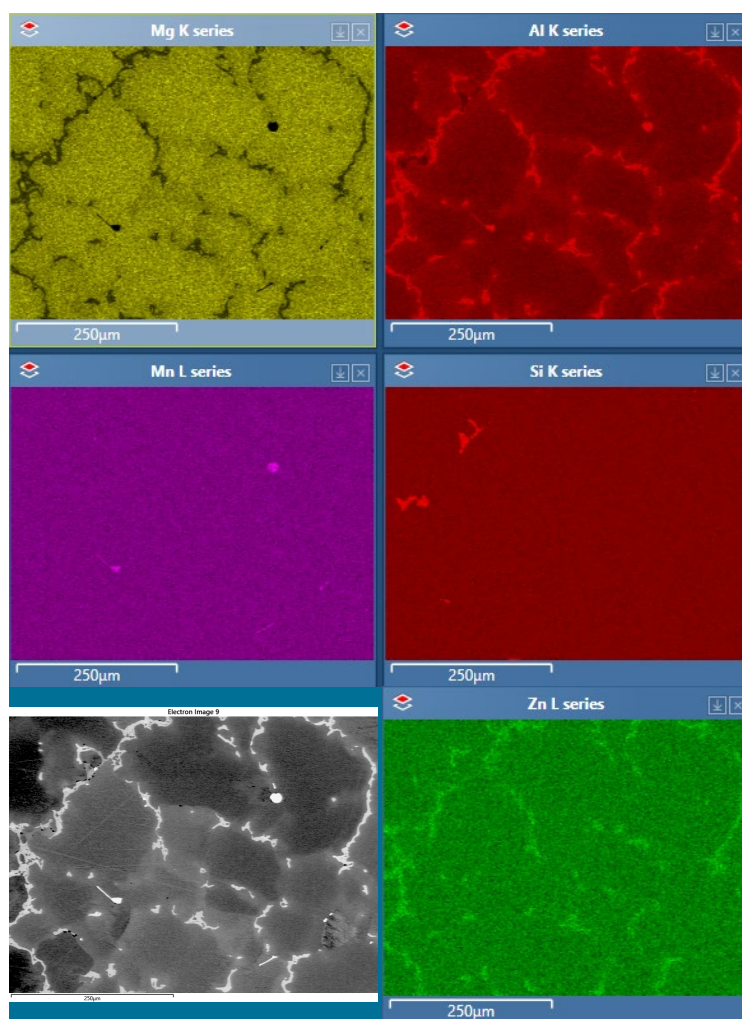


Figure 4. SEML-EDS mapping of AZ91.

Atmospheric Corrosion Rate of the Mg Alloys

The corrosion depth obtained by mass loss of the different Mg alloys is shown in Figure 5 after 3 months, 1-, 2- and 4-years exposure at the marine station of Brest (France). As shown in Figure 5, the corrosion depth over 4 years could be fitted using a power law. This is in line with several studies on long term atmospheric corrosion of different metals and alloys showing that long-term atmospheric corrosion data for outdoor exposure can be expressed as [28–30]:

$$C = At^n \quad (1)$$

where C is the metal loss in μm , t is the exposure time in years, and A and n are constants. A represents the corrosion of the first year and n depends on the protectiveness of the corrosion products. Fits are given in Figure 5 for all Mg alloys. With n values ranging from 0.46 to 0.64, the lower values were found for AZ80 and the highest for AZ31 and AM60. This may be related to a lower protection of the corrosion products for AZ31 and AM60 compared to AZ80 after long term exposure in a marine environment. Rather similar corrosion values have been reported after one year of exposure for AZ31 [17,18], AZ61 [21], and AZ91 [16] after one year exposure in China and the deck of marine scientific research vessel. However, other studies showed lower corrosion rate for AZ91 after one-year exposures in Japan and Sweden [18,26]. In this case, the environmental data, and particularly the chloride deposition were less aggressive as the one of this study. Similarly, the corrosion rate for AZ80 reported in Shenyang (Industrial environment, China) by Song et al. was about 4 time less than the one reported in Figure 5 [22]. Again, values at different field stations are

difficult to compared as the environmental characteristics as well as the microstructure and production route of the alloys could be rather different.

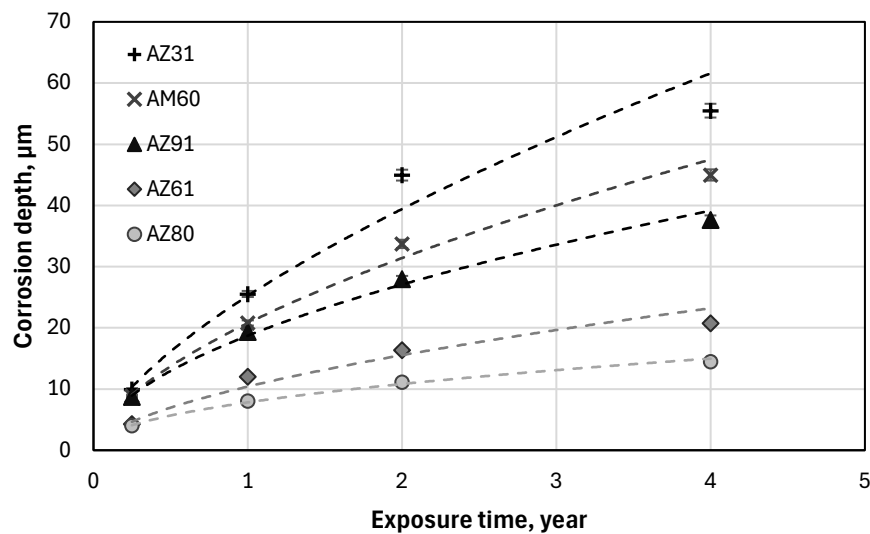


Figure 5. Corrosion depth of magnesium alloys as a function of exposure time at the marine station of Brest.

Corrosion Product Analysis

The morphology and distribution of corrosion products on the surface are different for magnesium alloys after 2 years exposure, see Figure 6. For AZ31, a thick and uniform corrosion product layer is covering the surface. The corrosion products are also relatively uniform on AZ61 and AZ80 but considerably thinner compared to AZ31, which is consistent with the differences in corrosion loss for these alloys. On the other hand, the corrosion product distribution is more inhomogeneous for the AM60 and AZ91 materials, which probably is related to the large grain structure and high Al segregation for these alloys.

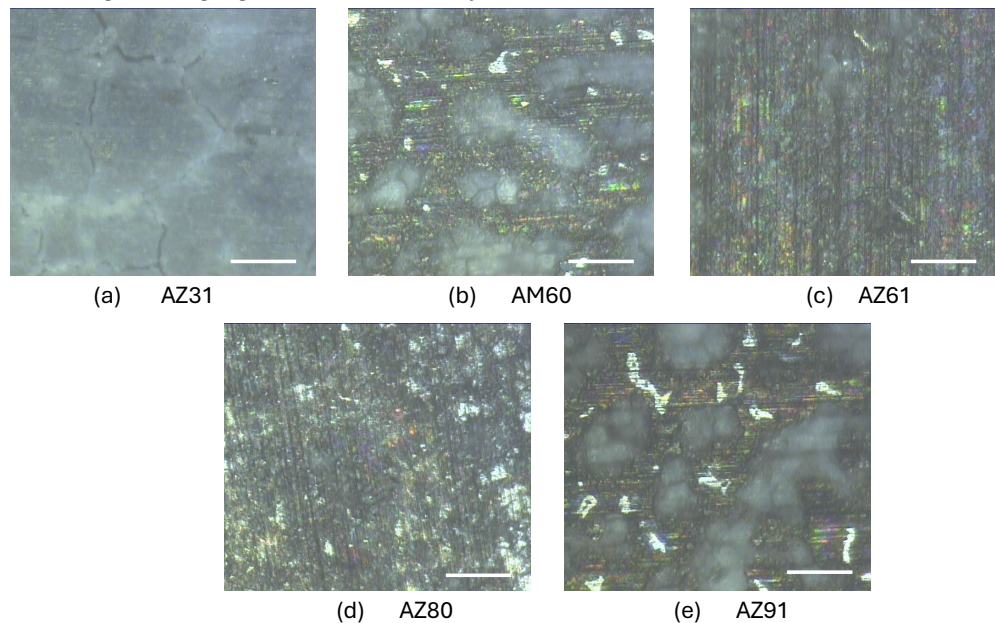


Figure 6. Optical images of magnesium alloys after 2 years exposure. Scale bar = 50 μm.

FTIR-ATR spectra of the different materials after 2 years of exposure are shown in Figure 7. The spectra for AZ31 and AM60 are similar with bands due to magnesium hydroxy carbonate,

Mg₅(CO₃)₄(OH)₂·xH₂O. There are probably also some weak bands due to sulphate, SO₄²⁻, in the spectra. Sulphate was detected on corrosion products in previous studies of field exposed magnesium alloys [12]. For AZ61, AZ80 and AZ91, a characteristic band at 1360-1380 cm⁻¹ due to carbonate is seen. A symmetric carbonate asymmetric stretching band in this region is typical for carbonate containing layered double hydroxide (LDH), for which the carbonate ions are intercalated in the layered brucite structure. The spectra for AZ61, AZ80 and AZ91 are similar to those reported for hydrotalcite, Mg₆Al₂CO₃(OH)₁₆·4H₂O or similar Mg/Al LDH in the literature [31,32]. The corrosion products on these materials have also contributions from sulphate compounds of magesium and/ or aluminium. Hydrotalcite is probably also present in the spectra for AZ31 and AM60 as seen from a shoulder at 1360-1380 cm⁻¹, but these spectra have stronger contributions from magnesium hydroxy carbonate due to higher corrosion rates for these materials. For AZ91, hydrotalcite formation is probably promoted by high Al-content and higher amount of secondary phase. The suggested corrosion products formed on the alloys after 2 years exposure are summarized in Table 3.

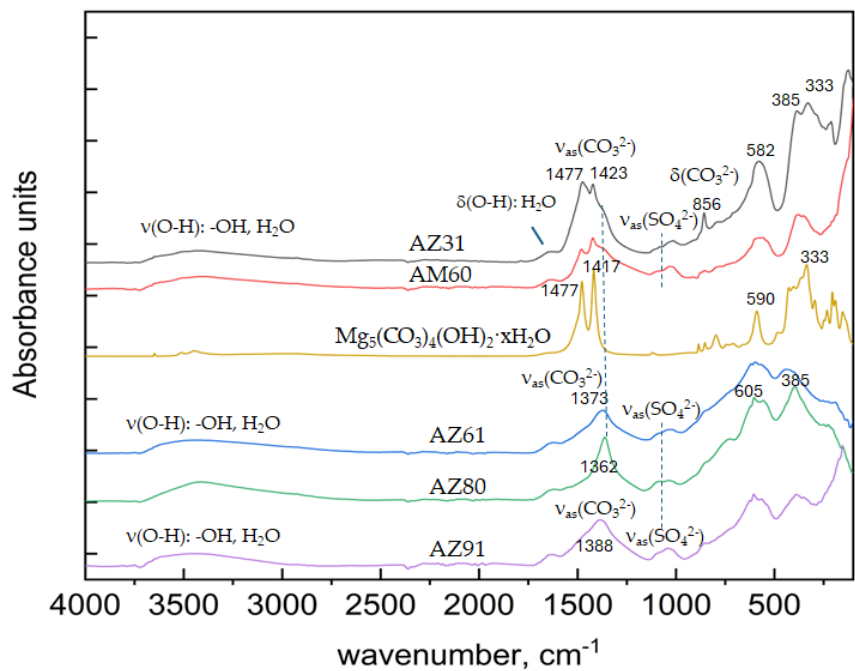


Figure 7. FTIR-ATR spectra of magnesium alloys after 2 years exposure and a reference spectrum of Mg₅(CO₃)₄(OH)₂·xH₂O.

Table 3. Suggested corrosion products after 2 years exposure.

Alloy	Corrosion products
AZ31	Mg ₅ (CO ₃) ₄ (OH) ₂ ·xH ₂ O, Mg ₆ Al ₂ CO ₃ (OH) ₁₆ ·4H ₂ O, Mg/Al-SO ₄ ²⁻
AM60	Mg ₅ (CO ₃) ₄ (OH) ₂ ·xH ₂ O, Mg ₆ Al ₂ CO ₃ (OH) ₁₆ ·4H ₂ O, Mg/Al-SO ₄ ²⁻
AZ61	Mg ₆ Al ₂ CO ₃ (OH) ₁₆ ·4H ₂ O, Mg/Al-SO ₄ ²⁻
AZ80	Mg ₆ Al ₂ CO ₃ (OH) ₁₆ ·4H ₂ O, Mg/Al-SO ₄ ²⁻
AZ91	Mg ₆ Al ₂ CO ₃ (OH) ₁₆ ·4H ₂ O, Mg/Al-SO ₄ ²⁻ (Mg ₅ (CO ₃) ₄ (OH) ₂ ·xH ₂ O)

4. Discussion

Corrosion Rate of Mg Alloys

From the data obtained in Figure 5, it is possible to rank the magnesium alloys as a function of their corrosion properties in a marine atmosphere in temperate harsh environmental conditions in Europe. The following ranking in increasing corrosion protection was obtained: AZ31>AM60>AZ91>AZ61>AZ80.

A rather similar ranking was obtained independently on the time of exposure from 3 to 48 months. In addition, the kinetics of the corrosion rate show rather similar behaviour during the whole exposure time, with somewhat slower kinetics for AZ80 and AZ61 compared to the other magnesium alloys. The corrosion data are in general in good agreement with those reported in the literature. However, a direct comparison is difficult as only few studies indicate precisely the environmental parameters such as for instance chloride and SO₂ deposition. A direct comparison to laboratory exposures is also difficult as it is well known that this type of exposure often fails to mimic the climatic conditions occurring under real outdoor conditions. Nevertheless, the corrosion rates of AZ91 and AZ31 obtained in this work after one year of exposure were close to that reported by Liu et al and Zhang et al in harsh marine environments [16,23]. It should be noted that the mean RH and average rain fall was in the same range for the field station of Brest and that of Nansha (China). However, the temperature was much higher in Nansha (28°C compared to 13°C). On the other hand, the chloride deposition was about 2 times higher in the marine site of Brest compared to Nansha (e.g. 1000 mg m⁻² day⁻¹ and 400 mg m⁻² day⁻¹). Hence, it is likely that the high corrosion rates observed for AZ91 and AZ31 in this work are due to the very high chloride deposition and that this environmental factor is highly dominant in the corrosion of magnesium alloys, in good agreement with the work reported in [6,7,14,16]. This also highlights that more systematic studies under well-defined exposure programs worldwide are needed to systematically identify the impact of different environmental factors on the corrosion rate of magnesium alloys.

As shown in Table 4, the corrosion was highly localised for all alloys, but the kinetics of localised corrosion decreased with time with the formation of corrosion products after one year of exposure. This is in good agreement with the data provided by Liu et al. on AZ91 exposed in harsh marine environments in South China [16]. Indeed, the corrosion starts as pitting corrosion due to the electrochemical potential difference between the Al-Mn phases and β-Mg₁₇Al₁₂ phases distributed along the grain boundaries. Similar results have been obtained by Jonsson et al., indicating that the corrosion attack starts in the α-Mg phase in larger grains at the boundary between the α-Mg phase and the eutectic α-/β-phase. As all studied magnesium alloys present rather similar kinetics for pitting corrosion (only the level of attack is different), it is likely that the mechanism of localised corrosion is also rather similar with attacks in the α grains due to the presence of secondary phases in the alloys (Al-Mn phases, eutectic α, and β-Mg₁₇Al₁₂). With time, as shown in Figure 5 and Table 4, the corrosion rate decreased probably due to the formation of a dense layer of corrosion products hindering the diffusion of oxygen to the metal surface.

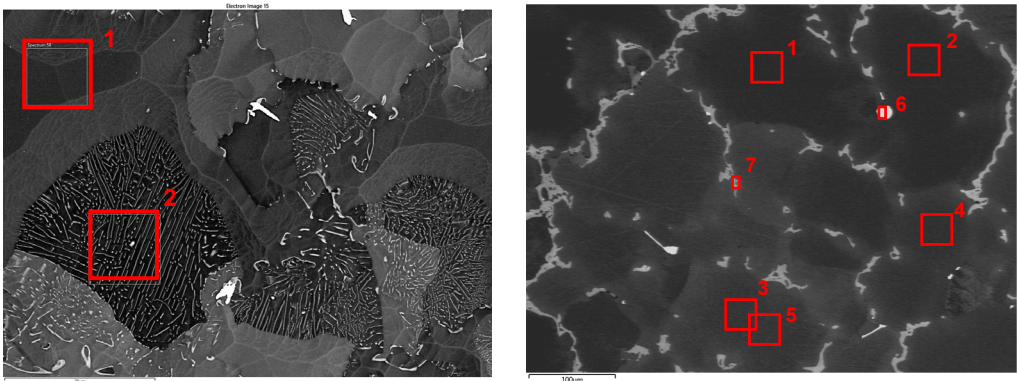
Table 4. Maximum pit depth in µm on magnesium alloys as a function of exposure time at the marine station of Brest.

Alloy	3 months	1 year	2 years	4 years
AZ31	50	120	150	180
AM60	40	100	120	150
AZ61	15	35	45	55
AZ80	10	30	35	45
AZ91	30	90	100	120

Influence of Microstructure

As shown in Figures 1–4 and in Table 2, the magnesium alloys investigated in the present study have different microstructures with reference to grain size and number and nature of secondary phases. Several papers have shown that the corrosion attack starts in the middle of the α-Mg phase. Persson et al. reported that the Volta potential difference between the β-phase and the central regions of the α-Mg grains were in the range from 100 to 150 mV, whereas that between the AlMn and the central regions of the α-Mg grains were slightly higher [33]. Similar data have been also reported by Arrabal et al [34]. Hence from these works, it was shown that the initial corrosion of AZ91 was localised, primarily occurring in the central regions of the α-Mg phase for AZ91 and AZ80. In addition, it was shown that the initiation of corrosion was localised around the Al-Mn inclusions in

the AZ31 alloy. As shown in Table 5, the corrosion rate of the magnesium alloys decreased with the aluminium content in the alloy, except for AZ91 that showed higher corrosion rates compared to AZ61 and AZ80. It should be noted that according to Table 2, the number of secondary phases was much higher for AZ91 compared to the other alloys. As secondary phases act as cathodic sites, this may explain the behaviour of AZ91 observed in this work. Another explanation may be related to the amount of Al in the α -Mg phase as lower amount of Al in this phase will result in less proactive behaviour. EDS analyses at different points of the microstructure of AZ80 and AZ91 are displayed in Figure 8. The content of Al in the α -Mg phase is high in the range of 8 wt% whereas that of AZ91 is low in the range of 3 wt%. The low Al content in the α -Mg phase is due to the high segregation of Al and Zn in this alloy. This may explain the lower corrosion performance of AZ91 compared to AZ80. Similar measurements have been made for the other alloys. Figure 9 shows the thickness loss measured after one year exposure as a function of the Al content in the α -Mg phase. A clear correlation is observed, indicating better corrosion properties as the Al content in the α -Mg phase increases. It is generally agreed that the presence of aluminum is beneficial in improving the corrosion behavior of magnesium. It has been shown by Lunder et al. [35] that 8% of Al is necessary to achieve corrosion protection whereas Warner et al. using TEM studies on Mg-9%Al, found that more than 5% is needed [36]. As the corrosion rate of AZ61 with 5,7 % Al in the α -Mg phase showed only slightly lower performance compared to AZ80, the data presented in the work support the conclusions of Warner et al. [36]. A higher Al-content in the α -Mg phase seems to promote the formation of hydrotalcite and may reduce the formation of pure Mg based corrosion products. This can contribute to the lower corrosion of alloys with higher Al content in the α -phase due the protective properties of the hydrotalcite layer [37]. AZ91 is an exception with relatively lower amount of pure Mg-products probably due much more secondary phases which affect the relative contributions of different products on the surface and negatively impact the corrosion rate.



Alloy	Location	Al, wt%	Zn, wt%	Mn, %
AZ80	1	7,8	0,4	0,0
	2	9,0	0,7	0,0
AZ91	1	3,3	0,0	0,0
	2	3,2	0,2	0,1
	3	2,8	0,0	0,3
	4	3,2	0,1	0,2
	5	3,0	0,1	0,0
	6	37,2	0,0	59,3
	7	38,2	5,1	0,2

Figure 8. Al, Zn and Mn content measured by EDS in α -phase and secondary phases in AZ80 and AZ91.

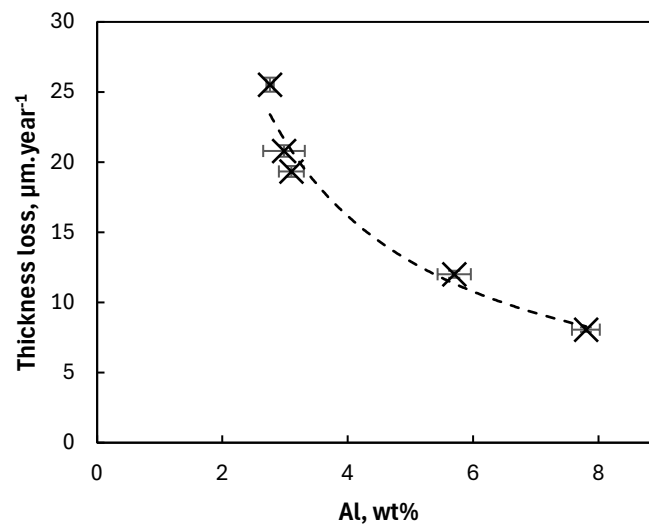


Figure 9. First year thickness loss as a function of aluminum content in α -Mg phase. .

5. Conclusions

From this work, the following main conclusions may be drawn:

- The corrosion performance of the magnesium alloys under harsh marine conditions studied in this work increased in the following order: AZ31<AM60<AZ91<AZ61<AZ80. The ranking was similar at all exposure times ranging from 3 months to 4 years.
- The corrosion was highly localised during the first months of exposure and then became more generalised upon long exposure times.
- The kinetics of corrosion were rather similar for all magnesium alloys, and the corrosion loss followed a power law from which long term corrosion data can be extracted.
- Corrosion products for AZ61, AZ80 and AZ91 contained larger fractions of hydrotalcites whereas AZ31 and AM60 showed more formation of magnesium hydroxy carbonate
- A clear correlation between the Al content in the α -Mg phase and the corrosion loss was observed indicating that this parameter is strongly governing the corrosion rate of magnesium alloys under atmospheric corrosion conditions.

Acknowledgments: Joacim Hagström from SWERIM (Sweden) is thanked for performing the FEG-SEM measurements, and Anne LeGac from French Corrosion Institute (France) for part of weight loss measurements.

References

1. Song, G.-L. Corrosion electrochemistry of magnesium (Mg) and its alloys. In *Corrosion of Magnesium Alloys*; Song, G.L., Ed.; Woodhead: Cambridge, UK, 2011; pp. 3–65.
2. Ghali, E. Activity and passivity of magnesium (Mg) and its alloys. In *Corrosion of Magnesium Alloys*; Song, G.L., Ed.; Woodhead: Cambridge, UK, 2011; pp. 66–109.
3. Atrens, A.; Liu, M.; Zainal Abidin, N.I.; Song, G.-L. Corrosion of magnesium alloys and metallurgical influence alloys. In *Corrosion of Magnesium Alloys*; Song, G.L., Ed.; Woodhead: Cambridge, UK, 2011; 117–161.
4. Huang, J.; Song, G.-L.; Atrens, A.; Dargusch, M. What activates the Mg surface—A comparison of Mg dissolution mechanisms. *J. Mat. Sci. Technol.* 2020, 57, 204–220.
5. Song, G.-L.; Atrens, A. Recently deepened insights regarding Mg corrosion and advanced engineering applications of Mg alloys. *J. Magnes. Alloys* 2023, 11, 3948–3991.
6. LeBozec N.; Jönsson M.; Thierry D., Atmospheric corrosion of magnesium alloys: influence of temperature, relative humidity, and chloride deposition, *Corrosion*, 2004, 60,356-361.

7. Rendahl B, LeBozec N. Assessment of corrosivity of global vehicle environment. Sweden: Research Report Swerea KIMAB Stockholm; 2009.
8. Pardo, M.C. Merino, A.E. Coy, R. Arrabal, F. Viejo, E. Matykina, Corrosion behavior of magnesium/aluminum alloys in 3,5 wt% NaCl, *Corrosion Sci.*, 2008, 50, 823-834.
9. Esmaily, M.; Svensson, J.E.; Fajardo, S.; Biribilis, N.; Frankel, G.S.; Virtanen, S.; Arrabal, R.; Thomas, S.; Johansson, L.G. Fundamentals and advances in magnesium alloy corrosion. *Prog. Mater. Sci.* 2017, 89, 92–193.
10. Esmaily M.; Blucher D.B.; Svensson J.E.; Halvarsson M.; Johansson L.G., New insight in the corrosion of magnesium alloys- The role of aluminum, *Scr. Mater.* 2016, 115, 91–95.
11. Feliu Jr; Maffiotte C.; Galván J.C.; Barranco V., *Corros. Sci.* 2011, 53, 1865–1872.
12. Jönsson M., Persson D., The influence of the microstructure on the atmospheric corrosion behaviour of magnesium alloys AZ91D and AM50, *Corros. Sci.* 2010, 52, 1077–1085.
13. Merino M.C.; Pardo A.; Arrabal S.; Merino S.; Casajús P.; Mohedano M., Influence of chloride ion concentration and temperature on the corrosion of Mg–Al alloys in salt fog, *Corros. Sci.* 2010, 52, 1696–1704.
14. Zhou W.-q.; Shan D.-y.; Han E.-h.; Ke W., Influence of NaCl deposition on atmospheric corrosion behavior of AZ91 magnesium alloy, *Trans. Nonferrous Met. Soc. China*, 2010, 20, 670–673
15. Cui Z.; Li X.; Xiao K.; Dong C., Atmospheric corrosion of field-exposed AZ31 magnesium in a tropical marine environment, *Corrosion Sci.*, 2013, 76, 243–256.
16. Liu H.; Yang L.; Wang M.; Sun C.; Wang X.; Li J.; Li J., Corrosion behavior of AZ91 magnesium alloys in harsh marine atmospheric environment in South China Sea, *Journal of Material Research and Technology*, 2025, 35, 2477-2486
17. Yu, R.H.; Cao, F.Y.; Zhao, C.; Yao, J.H.; Wang, J.J.; Wang, Z.M.; Zou, Z.W.; Zheng, D.J.; Cai, J.L.; Song, G.L. The marine atmospheric corrosion of pure Mg and Mg alloys in field exposure and lab simulation. *Corros. Eng. Sci. Technol.* 2020, 55, 609–621.
18. Liao, J.S.; Hotta, M. Atmospheric corrosion behavior of field-exposed magnesium alloys: Influences of chemical composition and microstructure. *Corros. Sci.* 2015, 100, 353–364.
19. Cui Z.; Li X.; Xiao K.; and Dong C., Atmospheric corrosion of field-exposed AZ31 magnesium in a tropical marine environment, *Corrosion Science*, 2013, 76, 243-256
20. Y. Wang, W. Xu, X. Wang, Q. Jiang, Y. Li, Y. Huang, and L. Yang, Research on Dynamic Marine Atmospheric Corrosion Behavior of AZ31 Magnesium Alloy, *Metals* 2022, 12(11), 1886.
21. Gong, P.; Cao, X.J.; Ning, S.Q.; Zhu, L.P. Influence of Different Environments on Atmospheric Corrosion of AZ61 Magnesium Alloy. *China Surf. Eng.* 2015, 28, 123–128.
22. Song, Y.W.; Dai, J.M.; Sun, S. A comparative study on the corrosion behaviour of AZ80 and EW75 Mg alloys in industrial atmospheric environment. *Mater. Today Commun.* 2024, 38, 108263.
23. Zhang T.; Wu S.; Liu H.; Yang L.; Chen T.; Wang X; and Li Y., Research on Comparative Marine Atmospheric Corrosion Behavior of AZ31 Magnesium Alloy in South China Sea *Materials* 2025, 18(15), 3585.
24. Wang M., Yang L., Liu H., Wang X, Li Y, Huang Y, Recent Progress on Atmospheric Corrosion of Field-Exposed Magnesium Alloys, *Metals* 2024, 14(9), 1000.
25. Yu, R.H.; Cao, F.Y.; Zhao, C.; Yao, J.H.; Wang, J.J.; Wang, Z.M.; Zou, Z.W.; Zheng, D.J.; Cai, J.L.; Song, G.L. The marine atmospheric corrosion of pure Mg and Mg alloys in field exposure and lab simulation. *Corros. Eng. Sci. Technol.* 2020, 55, 609–621.
26. Jönsson M., Persson D., Leygraf C. Atmospheric corrosion of field-exposed magnesium alloys AZ91D. *Corrosion Sci* 2008, 50(5), 1406–13.
27. Southwell, C.R.; Alexander, A.L.; Hummer, C.W. Corrosion of metals in tropical environments-aluminium and magnesium. *Mater. Perform.* 1965, 4, 30–35.
28. Corvo F.; Perez T.; Dzib L.R.; Martin Y.; Castaneda A.; Gonzalez E.; Perez J., Outdoor–indoor corrosion of metals in tropical coastal atmospheres *Corros. Sci.*, 2008, 50, 220-230.
29. DelaFuente D.; Otero-Huerta E.; Morcillo M., Studies of long-term weathering of aluminium in the atmosphere *Corrosion Science*, 2007, 49, 3134-3148.

30. Natesan M.; Venkatachari G.; Palaniswamy N.; Kinetics of atmospheric corrosion of mild steel, zinc galvanized iron and aluminium at 10 exposure stations in India, *Corrosion Science*, 2006, 48, 3584-3608.
31. Lafuente, B., Downs, R. T., Yang, H., & Stone, N. (2015). The power of databases: the **RRUFF** project. Highlights in Mineralogical Crystallography, T Armbruster and R M Danisi, Eds., Berlin, Germany, W. De Gruyter, 1–30.
32. Frost R.L., Spratt H.J., Palmer S.J., Infrared and near-infrared spectroscopic study of synthetic hydrotalcites with variable divalent/trivalent cationic ratios, *Spectrochim. Acta A* 2009, 72, 984–988.
33. Persson D.; Wårnheim A.; Le Bozec N.; Thierry D. Studies of Initial Atmospheric Corrosion of Magnesium Alloys AZ91 and AZ31 with Infrared Spectroscopy Techniques. *Corros. Mater. Degrad.* 2025, 6(4), 59.
34. Arrabal, R.; Pardo, A.; Merino, M.C.; Merino, S.; Mohedano, M.; Casajús, P. Corrosion behaviour of Mg/Al alloys in high humidity atmospheres. *Mater. Corros.* 2011, 62, 326–334.
35. Lunder O; Lein J.E. ; Aune T. Kr.; Nisancioglu K., The rôle of $Mg_{17}Al_{12}$ phase in the corrosion of magnesium alloy AZ91, *Corrosion* 1989, 45, 741.
36. Warner T.J.; Thorne N.A.; Nussbaum G.; Stobbs W.M., A cross-sectional TEM study in corrosion initiation in rapidly solidified Mg-based ribbons, *Surf. Interf. Anal* 1992, 19, 386.
37. Lin J.K., Uan J.Y., Formation of Mg,Al-hydrotalcite conversion coating on Mg alloy in aqueous HCO_3^-/CO_3^{2-} and corresponding protection against corrosion by the coating, *Corrosion Science* 2009, 51, 1181–1188.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.