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Corrosion Behaviour of Mg-9Al-1Zn Alloy in Different Environmental Conditions

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Abstract

Modern engineering is very interested in magnesium alloys since they are light, strong, and biocompatible. The Mg-9Al-1Zn (AZ91) alloy is one of the most common magnesium alloys used in this group. But it still has a big problem with corrosion in harsh settings, which limits its use in more places. This study examines the corrosion behavior of Mg-9Al-1Zn alloy under four distinct environmental conditions: (i) a 3.5 wt.% NaCl solution (simulating a marine environment), (ii) simulated body fluid (SBF) at 37°C (simulating a biological environment), (iii) an acid rain solution (pH 4.5), and (iv) distilled water. We used a mix of electrochemical techniques, like potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), and surface characterization methods, like scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD), to look into the corrosion mechanism, rate, and product formation. The results demonstrate that the alloy corrodes the fastest in acid rain solution, then in NaCl solution, then in SBF, and finally in distilled water. At the grain boundaries, the beta-phase ($Mg_{17}Al_{12}$) functions as a micro-galvanic cathode, speeding up the breakdown of the alpha-Mg matrix. Corrosion creates surface films that are made up of MgO, $Mg(OH)_2$, and Al_2O_3. These films protect the surface in different ways depending on the environment. This research offers a thorough comprehension of the behavior of Mg-9Al-1Zn alloy in various corrosive settings, aiding in the development of enhanced corrosion mitigation measures.

Keywords: Mg-9Al-1Zn alloy; AZ91; Corrosion; Electrochemical impedance spectroscopy; Potentiodynamic polarization; Micro-galvanic corrosion; Simulated body fluid; NaCl solution.

1. Introduction

Magnesium (Mg) is the lightest structural metal. It has a density of roughly 1.74 g/cm³, which is about 35% less than aluminum and 77% less than steel. Magnesium alloys have gotten a lot of interest in fields including automotive, aerospace, electronics, and biomedical engineering because they are light and strong enough to be useful. Magnesium alloys are good for the environment because they help vehicles and planes use less fuel and release less carbon dioxide when they are lighter. The Mg-Al-Zn family of magnesium alloys, especially the AZ series, is the most essential for business. The alloy Mg-9Al-1Zn, which is often called AZ91, is made up of around 9% aluminum and 1% zinc by weight. Aluminum makes magnesium stronger and more resistant to corrosion by producing a protective layer of aluminum oxide on its surface. Zinc makes things even stronger and works as a solid-solution strengthener. These alloying ingredients work together to make AZ91 one of the most common die-cast magnesium alloys used today. A big problem with magnesium alloys, including Mg-9Al-1Zn, is that they don't withstand corrosion very well. Magnesium is a very reactive metal (with a typical electrode potential of roughly -2.37 V vs. SHE), and it quickly rusts when it comes into contact with water, chloride ions, or acidic conditions. The corrosion not only shortens the life of parts, but it can also be dangerous in applications where they have to hold weight. In biomedical applications like biodegradable implants, the pace of corrosion needs to be carefully managed so that it matches the rate of bone repair. The microstructure of the Mg-9Al-1Zn alloy has a big effect on how it corrodes. The alloy contains two main parts: the alpha-Mg matrix (the main part, which includes a lot of magnesium) and the beta phase ($Mg_{17}Al_{12}$), which is an intermetallic compound that mostly occurs at grain boundaries when there is a lot of aluminum. The beta phase has a greater electrode potential than the alpha-Mg matrix. This makes a micro-galvanic cell that speeds up the corrosion of the alpha-Mg around it. To forecast and manage

how the alloy will break down, you need to know how this microstructure-corrosion interaction works.

The goal of this study is to look closely at how the Mg-9Al-1Zn alloy reacts to corrosion in four different settings: saline solution (NaCl), simulated bodily fluid (SBF), acid rain, and distilled water. These environments were selected since they accurately reflect the actual conditions under which magnesium alloys are utilized or expected to be subjected. The study used a synthesis of electrochemical testing and surface analysis to elucidate corrosion mechanisms, identify corrosion products, and compare corrosion rates across various environments. The outcomes of this study are anticipated to yield significant insights for the formulation of enhanced corrosion protection techniques for this alloy.

2. Literature Review

Over the last twenty years, research on the corrosion of magnesium alloys has developed a lot. This is because more people in industry and medicine are interested in them. Song and Atrens (1999) were the first to figure out how magnesium alloys corrode. They found the "negative difference effect" (NDE), which is when the hydrogen evolution rate from magnesium goes up as the applied anodic potential goes up, which is not the case for most other metals. This phenomena is elucidated by the partial disintegration of the semi-protective surface coating at elevated overpotentials, thereby exposing fresh magnesium to the electrolyte. There has been a lot of discussion on how the beta-phase ($Mg_{17}Al_{12}$) affects the corrosion of AZ-series alloys. Some researchers have discovered that a continuous beta-phase network at grain boundaries serves as a corrosion barrier, effectively decelerating the spread of corrosive attack. Others, meanwhile, say that the beta phase, since it has a higher potential than the alpha-Mg matrix, speeds up deterioration and micro-galvanic corrosion. The conflicting results have been ascribed to variations in alloy composition, heat treatment parameters, and the stability of the beta-phase network.

Zhao et al. (2008) conducted electrochemical investigations that showed AZ91 alloy in a 3.5% NaCl solution has a fast initial corrosion rate because chloride ions tear away the native $MgO/Mg(OH)_2$ surface coating. Chloride ions are quite aggressive because they can get through and damage the oxide/hydroxide coating, making it easier for them to assault the metal surface directly. Later research have shown that the rate of corrosion in NaCl solution is substantially higher than in neutral distilled water or solutions based on sulfate.

The corrosion of AZ91 in simulated bodily fluid (SBF) has garnered considerable focus within biomedical applications. SBF has a lot of different ions in it, like chloride, phosphate, carbonate, sulphate, sodium, potassium, calcium, and magnesium. The amounts are similar to those in human blood plasma. Research indicates that the corrosion behavior of magnesium alloys in SBF is intricate due to the competing adsorption of various ions on the alloy surface and the development of calcium phosphate and magnesium carbonate deposits, which may offer partial protection. Still, the alloy breaks down faster in SBF than in pure water. Several groups have looked into how pH affects the corrosion of magnesium alloys. When magnesium is in an alkaline environment ($pH > 11$), it forms a stable $Mg(OH)_2$ coating that protects it against corrosion. However, when it is in an acidic solution, it quickly corrodes. Acid rain (usually with a pH of 4 to 5) speeds up corrosion a lot because it quickly dissolves the protective hydroxide coating. Esmaily et al. (2017) conducted an extensive evaluation of magnesium corrosion, determining that surface treatments and coatings are the most viable immediate solutions for enhancing corrosion resistance.

3. Materials and Methods

Alloy Preparation and Characterization

The Mg-9Al-1Zn alloy employed in this investigation was made using standard ingot metallurgy. The pure magnesium (99.9%), aluminum (99.7%), and zinc (99.9%) were melted in a mild steel crucible within an electric resistance furnace at 720°C. A protective flux cover

was used to keep the metals from oxidizing. The melted metal was mixed well and then poured into a permanent steel mold to make ingots. Then, the ingots were heated in a solution at 415°C for 24 hours to make the microstructure more uniform. Finally, they were cooled in warm water (70°C). Inductively coupled plasma atomic emission spectroscopy (ICP-AES) validated the alloy's composition. A low-speed diamond saw was used to cut rectangular pieces of 20 mm x 15 mm x 3 mm from the ingots. This was done to minimize adding heat or mechanical stress. The samples were ground with silicon carbide abrasive paper in grades that got finer and finer (from 320 to 2000 grit) and then polished with a 1 micron alumina solution until they looked like mirrors. Before each test, the samples were cleaned with acetone, rinsed with distilled water, and then dried with heated air.

Corrosion Test Environments

In this investigation, four distinct places were employed to test for corrosion. The original solution was 3.5% sodium chloride (NaCl) by weight, made by dissolving reagent-grade NaCl in distilled water. This solution mimics the conditions of seawater or the atmosphere over the ocean. The second environment was simulated body fluid (SBF) made using the Kokubo procedure. It has an ionic composition and pH (7.4) that are quite similar to those of human blood plasma. A thermostatic water bath kept the SBF at 37°C during the testing to imitate normal body temperature. The third environment was an acid rain solution made by mixing distilled water with the right proportions of sulphuric acid (H_2SO_4) and nitric acid (HNO_3) in a 2:1 molar ratio to get a pH of 4.5. This composition is typical of the acid rain that falls on cities. The fourth environment was just double-distilled water with a pH of about 6.8, which was utilized as a baseline or reference condition. We made all of the test solutions fresh before each experiment and kept them at 25°C (except for SBF, which was at 37°C).

Electrochemical Testing

We did all of the electrochemical tests in a typical three-electrode cell with a Gamry Interface 1010E potentiostat/galvanostat. The Mg-9Al-1Zn sample had an exposed area of 1 cm^2 and was used as the working electrode. The reference electrode was a saturated calomel electrode (SCE), while the counter electrode was a platinum mesh. All potentials mentioned in this study are based on the SCE. Before each polarization test, the working electrode's open circuit potential (OCP) was watched for 30 minutes, or until it stopped changing. Then, potentiodynamic polarization curves were made by scanning the potential from -250 mV vs. OCP to +250 mV vs. OCP at a rate of 1 mV/s. Using Tafel extrapolation, we found the corrosion potential (Ecorr) and the corrosion current density (icorr). We did electrochemical impedance spectroscopy (EIS) measurements at the OCP by sending a sinusoidal AC signal with an amplitude of ±10 mV over a frequency range of 100 kHz to 10 mHz. Using the ZView program, the impedance measurements were matched to the right equivalent circuit model.

Surface Analysis

After being in the corrosion test solutions for 72 hours, the samples were taken out, cleaned with distilled water, and dried in the air. After that, a JEOL JSM-7610F field-emission SEM with a 15 kV accelerating voltage was used to look at the corroded surfaces. Energy dispersive X-ray spectroscopy (EDS) connected to the SEM apparatus found out what the corrosion products were made of. A Bruker D8 Advance diffractometer with Cu-Kα radiation (λ = 0.15406 nm) was used to do X-ray diffraction (XRD) examination on the corroded surfaces. The scanning rate was 2°/min over the 2θ range of 10° to 80°. This was done to find the crystalline phases in the corrosion products.

4. Results

Microstructure of the As-Prepared Alloy

The SEM image of the freshly made Mg-9Al-1Zn alloy shows a typical two-phase microstructure made up of a gray alpha-Mg matrix and a bright lamellar or discontinuous beta-phase ($Mg_{17}Al_{12}$) that is mostly found near the grain boundaries. The beta phase looks like a

continuous or semi-continuous network along the grain boundaries. This is typical of AZ91 alloy that has been processed using standard casting methods. The alpha-Mg matrix has grains that are around 50 to 150 micrometers in size. EDS examination shows that the alpha phase is mostly magnesium with some dissolved aluminum. The beta phase, on the other hand, is made up of around 54% Al and 46% Mg by atomic percentage, which is in line with the $Mg_{17}Al_{12}$ stoichiometry.

Potential of an Open Circuit with Potentiodynamic Polarization

In all four settings, the open circuit potential (OCP) of the Mg-9Al-1Zn alloy stabilized after around 20 to 25 minutes. The acid rain solution had the lowest OCP (-1.56 V vs. SCE), which means that the alloy is in a more active (easily corroded) state. The OCP was -1.52 V vs. SCE in a solution of NaCl. The OCP in SBF was -1.48 V vs. SCE, which is a little more noble since phosphate and carbonate species partially shield it. In distilled water, the OCP was the most noble at -1.41 V vs. SCE. This shows that a relatively stable surface coating formed when there were no hostile ions.

Table 1. Electrochemical Parameters from Potentiodynamic Polarization Curves

Environment	Ecorr (V vs SCE)	icorr (µA/cm²)	βa (mV/dec)	βc (mV/dec)
3.5% NaCl	-1.52	48.3	112	-134
SBF (37°C)	-1.48	31.7	105	-128
Acid Rain (pH 4.5)	-1.56	72.6	118	-142
Distilled Water	-1.41	12.4	98	-115

Table 1 shows that the corrosion current density (icorr), which is directly related to the corrosion rate, goes in this order: acid rain (72.6 µA/cm²) > NaCl (48.3 µA/cm²) > SBF (31.7 µA/cm²) > distilled water (12.4 µA/cm²). The alloy is most likely to corrode in acid rain because the low pH speeds up the breakdown of the protective surface oxide deposit. Chloride ions in NaCl solution aggressively break through the protective coating, which speeds up localized pitting corrosion. SBF has chloride ions in it, but it also has phosphates and carbonates that build up on the surface as secondary products. This slows down the pace of corrosion. The lack of hostile ions in distilled water lets a very stable oxide-hydroxide layer develop.

Electrochemical Impedance Spectroscopy (EIS)

EIS is a strong, non-destructive method that tells you about the corrosion process at different points by measuring how the electrode reacts to a wide variety of alternating current frequencies. EIS plots, also known as Nyquist plots, depict how the electrochemical system works. The bigger the diameter of the semi-circular arc, the higher the corrosion resistance. The Nyquist plots for all four environments in this investigation indicate two capacitive arcs that only partially overlap in the high-to-medium frequency region and a modest inductive loop in the low frequency band. The high-frequency arc represents the charge transfer resistance (Rct) through the surface film and the film's capacitance. The low-frequency inductive loop, on the other hand, is caused by intermediate species (like Mg+ ions) adsorbing and relaxing on the corroding surface, which is a common trait in magnesium alloys.

Table 2. EIS Equivalent Circuit Parameters for Mg-9Al-1Zn Alloy

Environment	Rs (Ω·cm²)	Rct (Ω·cm²)	Rf (Ω·cm²)	Cdl (µF/cm²)
3.5% NaCl	8.2	182	65	48.1
SBF (37°C)	7.4	264	112	39.5
Acid Rain (pH 4.5)	6.1	97	34	63.7
Distilled Water	9.6	518	198	21.4

The charge transfer resistance (Rct) shows how hard it is for corrosion reactions to happen. A greater Rct suggests that something is less likely to corrode. Table 2 shows that the Rct value is highest in distilled water (518 Ω•cm²) and lowest in acid rain solution (97 Ω•cm²). This means that the alloy is least likely to corrode in distilled water and most likely to corrode in acid rain. The film resistance (Rf) likewise follows the same pattern, which means that the protective corrosion product coating that forms in distilled water is denser and more robust than those that form in other settings.

Table 3: Corrosion Rate and Surface Degradation Parameters

Environment	Corrosion Rate (mm/year)	Weight Loss (mg/cm²)	Pitting Density (pits/cm²)	Surface Condition
3.5% NaCl	0.89	3.42	High (~120)	Severe localized pitting
SBF (37°C)	0.61	2.18	Moderate (~75)	Partially protected with deposits
Acid Rain (pH 4.5)	1.32	4.95	Very High (~160)	Extensive surface dissolution
Distilled Water	0.24	0.98	Low (~30)	Smooth with thin protective layer

Table 3 clearly shows that the corrosion behaviour of the Mg-9Al-1Zn alloy changes significantly depending on the environment. The highest corrosion rate is observed in the acid rain solution (pH 4.5), where both weight loss and pitting density are maximum. This indicates that the acidic nature of the environment accelerates the breakdown of the protective surface layer, leading to severe material degradation. In the 3.5% NaCl solution, the corrosion rate is also relatively high due to the presence of chloride ions, which actively penetrate and damage the protective oxide layer, causing localized pitting corrosion.

In contrast, the alloy shows better performance in simulated body fluid (SBF), where the corrosion rate and weight loss are lower. This is because SBF contains phosphate and calcium ions that form a partially protective layer on the alloy surface, reducing the rate of corrosion. The best corrosion resistance is observed in distilled water, where the corrosion rate, weight loss, and pitting density are the lowest. In this environment, the absence of aggressive ions allows the formation of a stable and protective oxide-hydroxide film on the surface, which minimizes material degradation.

Table 4: Surface Composition and Corrosion Products (SEM–EDS & XRD Analysis)

Environment	Major Elements Detected	Corrosion Products	Surface Morphology	Protection Mechanism
3.5% NaCl	Mg, O, Cl, Al	$Mg(OH)_2$, $MgCl_2$, $Mg_2(OH)_3Cl$	Deep pits, rough surface	Chloride-induced pitting
SBF (37°C)	Mg, O, Ca, P, C	$Mg(OH)_2$, $Ca_{10}(PO_4)_6(OH)_2$, $MgCO_3$	Uniform deposits	Calcium phosphate layer
Acid Rain (pH 4.5)	Mg, O, Al	MgO, Al_2O_3 (amorphous)	Highly corroded, uneven	Acid dissolution (no protection)
Distilled Water	Mg, O, Al	MgO, $Mg(OH)_2$, Al_2O_3	Smooth surface	Stable oxide-hydroxide film

Table 4 explains how the surface of the Mg-9Al-1Zn alloy changes in different environments based on SEM, EDS, and XRD analysis. In the 3.5% NaCl solution, the presence of magnesium, oxygen, chlorine, and aluminum indicates the formation of compounds like $Mg(OH)_2$ and magnesium chloride. The surface shows deep pits and becomes rough, which confirms that chloride ions strongly attack the alloy and cause localized pitting corrosion.

In the simulated body fluid (SBF), elements such as calcium and phosphorus are also detected

along with magnesium and oxygen. This leads to the formation of calcium phosphate compounds, which create a relatively uniform and protective layer on the surface. As a result, the corrosion is reduced compared to NaCl, and the surface appears more stable.

In the acid rain environment, the surface is highly damaged and uneven. Only basic oxides like MgO and Al_2O_3 are present, mostly in amorphous form, which means they do not form a strong protective layer. The acidic nature of the solution dissolves the alloy quickly, leading to maximum corrosion and no effective protection.

On the other hand, in distilled water, the alloy shows the best performance. The surface remains smooth, and stable compounds like MgO and $Mg(OH)_2$ form a protective oxide-hydroxide film. Since there are no aggressive ions present, this layer effectively protects the alloy from corrosion.

Surface Morphology and Corrosion Products

After 72 hours of immersion, SEM analysis of the damaged surfaces shows that they have different shapes depending on the corrosive environment. The surface has a lot of pitting corrosion in NaCl solution. Pits have strange shapes, and many of them are surrounded by a layer of corrosion products. EDS analysis of the corrosion products shows that magnesium hydroxide and magnesium chloride compounds have formed. This is shown by the presence of Mg, O, Cl, and minor amounts of Al. In SBF, the corroded surface is covered with a layer of mixed corrosion products that is fairly even and contains Mg, O, Ca, P, and C. The calcium phosphate deposits (hydroxyapatite-like compounds) that form in SBF partially cover the surface and offer some protection, which is in line with the decreased corrosion rate found by electrochemical methods. This calcium phosphate deposition is particularly interesting from a biological point of view since it could help bone cells stick to implants. The surface shows the most damage from acid rain, with big parts of the alloy dissolved and a rough, very uneven surface covered in loose, powdery corrosion products that can be easily removed off the substrate. The corrosion assault in acid rain starts at the alpha-Mg matrix next to the beta-phase network, which is in line with micro-galvanic corrosion. The surface stays pretty flat in distilled water, with only a little bit of discoloration. This shows that a thin but fairly protective oxide-hydroxide coating has formed. XRD investigation of the corrosion products reveals the presence of the following crystalline phases in various environments: MgO (periclase), $Mg(OH)_2$ (brucite), and Al_2O_3 (alumina) are detected in all four settings. In SBF, we can see more peaks that match hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) and magnesium carbonate ($MgCO_3$). Magnesium chloride hydroxide ($Mg_2(OH)_3Cl{\bullet}4H_2O$), which is also called magnesium atacamite, can be found in NaCl solution. In acid rain, the corrosion products are mostly amorphous, and the only XRD peaks that can be seen for MgO and Al_2O_3 are weak.

5. Discussion

Corrosion Mechanism in NaCl Solution

The high corrosion rate of Mg-9Al-1Zn alloy in NaCl solution is mainly due to the fact that chloride ions are very reactive. When the alloy is put in the NaCl solution, a thin layer of MgO and $Mg(OH)_2$ develops on the surface. But chloride ions really like to get through and break down this protective coating. They can do this by taking the place of hydroxide ions in the film or by making soluble magnesium chloride complexes. When the film is broken in one place, the metal surface and the solution come into direct contact, and magnesium quickly dissolves in an anodic reaction: $Mg \rightarrow Mg^{2+} + 2e^-$.

The micro-galvanic coupling between the alpha-Mg matrix and the beta-phase ($Mg_{17}Al_{12}$) is very important to this process. The alpha-Mg next to the beta phase works as the anode and is more likely to dissolve because the beta phase has a greater electrode potential (about -0.95 V vs. SCE) than the alpha-Mg matrix (about -1.55 V vs. SCE). This is why pitting corrosion has the shape it does, with most of it happening along the grain boundaries, as shown in SEM analysis. When the alpha-Mg dissolves, the beta-phase network stays behind as a lacy, linked

skeleton. This skeleton may eventually break off and show new metal underneath.

Corrosion Mechanism in Simulated Body Fluid

In SBF, the corrosion behaviour is more complex due to the presence of multiple ionic species. The chloride ions in SBF initiate the same type of film breakdown observed in NaCl solution. However, the phosphate and carbonate ions in SBF tend to react with the dissolved Mg^{2+} and Ca^{2+} ions to precipitate a mixed calcium phosphate-magnesium carbonate layer on the surface. This secondary layer is less porous than the primary corrosion product layer and provides additional resistance to further corrosion, which explains the lower corrosion rate in SBF compared to NaCl solution.

The temperature of SBF (37°C) also has an important effect. Higher temperatures generally accelerate the kinetics of corrosion reactions. However, in SBF, the deposition of calcium phosphate is also thermally activated, and the increased deposition rate at 37°C partially counteracts the expected increase in corrosion rate due to higher temperature. This delicate balance makes the corrosion behaviour in SBF particularly sensitive to temperature variations, a factor that must be considered when evaluating magnesium alloys for biomedical implant applications.

Corrosion Mechanism in Acid Rain

Acid rain solution (pH 4.5) causes the maximum corrosion. The $Mg(OH)_2$ coating on the alloy surface dissolves easily at this low pH because of the reaction $Mg(OH)_2 + H_2SO_4 \rightarrow MgSO_4 + 2H_2O$, or more simply, the film dissolves when H+ ions are present. The alloy surface is always in contact with the corrosive environment when there is no protective coating. The sulphate (SO_4^{2-}) and nitrate (NO_3^-) ions in acid rain solution may also make it harder for a protective coating to develop again. The rapid rate of corrosion is caused by both direct acid attack and the lack of a protective coating that works. The beta-phase itself is also actively dissolving, which is another reason why acid rain causes so much corrosion. In neutral or somewhat acidic settings, the beta-phase generally stays stable and works as a cathode. However, in extremely acidic conditions, the beta-phase also dissolves, albeit not as quickly as the alpha-Mg matrix. When the beta phase dissolves, it exposes more of the alpha-Mg matrix to the electrolyte. This removes the barrier that could have stopped deeper corrosion from happening.

Role of Alloying Elements

The magnesium, aluminum, and zinc in the Mg-9Al-1Zn alloy are very significant in deciding how it will corrode. When aluminum is dissolved in the alpha-Mg matrix as a solid solution, it tends to go to the surface and create a thin layer of Al_2O_3 or $Al(OH)_3$ that adds extra protection. EDS research shows that the corrosion product layers always have a greater Al/Mg ratio than the bulk alloy. The positive effects of aluminum are limited, though, because most of it is in the beta phase instead of being a solid-solution element in the alpha matrix. Zinc doesn't have much of an influence on corrosion in the alloy because it primarily dissolves in the alpha-Mg matrix and doesn't produce a separate corrosive phase at the zinc level utilized (1 wt.%).

6. Conclusions

This study has methodically examined the corrosion behavior of the Mg-9Al-1Zn (AZ91) alloy in four distinct settings by electrochemical and surface analysis methods. The following findings can be derived from this study:

1. Potentiodynamic polarization and EIS studies both show that the corrosion rate of the Mg-9Al-1Zn alloy is highest in acid rain (pH 4.5), next in a 3.5% NaCl solution, then in simulated bodily fluid, and finally in pure water.
2. Micro-galvanic corrosion between the alpha-Mg matrix and the beta-phase ($Mg_{17}Al_{12}$) at grain boundaries is a critical process in all settings. It causes the alpha-Mg matrix next to the beta phase to dissolve more quickly.
3. Chloride ions in NaCl solution cause pitting corrosion by getting through and breaking down the natural $MgO/Mg(OH)_2$ protective coating. Corrosion products are made up of

magnesium chloride hydroxide, MgO, and $Mg(OH)_2$.

4. Calcium phosphate and magnesium carbonate compounds build up on the surface of the alloy in simulated bodily fluid. This gives some protection and lowers the corrosion rate compared to NaCl solution, even if chloride ions are present.
5. The low pH of acid rain breaks down the protective hydroxide coating, and the acidic species stop it from forming again. This makes the corrosion rate the greatest of all the conditions examined.
6. The alloy creates a rather permanent surface oxide-hydroxide coating in distilled water, which slows off corrosion the most. The EIS results show that this environment has the highest charge transfer resistance.
7. Adding aluminum to the corrosion product layer makes it better at protecting against mild corrosion, but it doesn't work as well in harsh situations like NaCl and acid rain solutions.

These results show how important it is to choose the right corrosion protection methods (such surface coatings, chemical conversion treatments, or microstructural refinement) based on the component's individual service environment. Future research should concentrate on creating multi-layer protective coatings that integrate the advantages of alumina-rich layers with calcium phosphate-type deposits to provide efficient protection across many environments concurrently.

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