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Coating Methods for Magnesium Alloys: Materials, Mechanisms, and Corrosion Behaviors

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Abstract:

Magnesium (Mg) alloys have attracted considerable interest for industrial, structural, and biomedical applications owing to their low density, high specific strength, good thermal conductivity, and recyclability. These advantages make Mg alloys promising candidates for lightweight components in automotive, aerospace, electronics, biomedical, military, and energy-related systems. However, their broader implementation remains limited by inherently poor corrosion resistance, arising from high chemical reactivity, low electrode potential, galvanic interactions, and strong sensitivity to environmental factors such as chloride-containing media, humidity, impurities, and temperature. To overcome these challenges, effective surface protection and coating technologies are essential.

This mini review summarizes recent developments in manufacturing routes, corrosion behavior, and surface coating strategies for Mg-based alloys. Major alloy systems, including Mg–Al, Mg–Zn, Mg–rare earth (RE), and Mg–Ca alloys, are discussed with respect to their microstructural characteristics, dominant corrosion mechanisms, and compatibility with different coating approaches. Emphasis is placed on the principles, performance, and limitations of various coating technologies aimed at improving corrosion resistance and surface durability. By correlating alloy composition with appropriate coating strategies, this work provides practical guidance for the design of tailored surface protection systems for advanced magnesium alloy applications.

Keywords: Mg-based alloys, Alloy composition, Corrosion behavior, Protective coatings, Surface engineering

1. INTRODUCTION

The use of magnesium (Mg) alloys has increased significantly in recent years across industrial, structural, and biomedical fields as a result of ongoing technological advancements. Owing to their unique physical and chemical characteristics, magnesium alloys have become attractive candidates for lightweight engineering applications. During alloy development and processing, the compatibility of magnesium with other technical materials must be carefully considered. Based on processing routes and intended applications, magnesium alloys can be broadly classified into wrought magnesium alloys, cast magnesium alloys, and alloys developed for engineering and research purposes [1].

Magnesium is the lightest structural metal currently in practical use and offers a high strength-to-weight ratio, making it particularly appealing for weight-sensitive industries [2]. In addition, Mg alloys exhibit favorable properties such as high thermal conductivity, excellent electromagnetic shielding capability, and superior recyclability, which make them attractive materials for environmentally sustainable and green engineering applications [3]. As a result, Mg alloys have found widespread use in various sectors, including the automotive industry (e.g., gearboxes, steering wheels, brackets, seat frames, and wheels), where weight reduction improves fuel efficiency and reduces emissions. Other applications include aerospace components, electronics, biomedical devices, sporting goods, military and defense systems, energy technologies, and construction materials [4].

Despite these advantages, the broader application of Mg alloys is severely limited by their inherently poor corrosion resistance. Magnesium exhibits high chemical reactivity and a low standard electrode potential, which makes Mg alloys highly susceptible to corrosion, particularly in aggressive environments. Key corrosion challenges include rapid oxidation, galvanic corrosion, impurity-induced localized corrosion, and strong sensitivity to environmental conditions. Chloride ions, commonly present in marine and industrial environments, aggressively attack Mg alloys, while impurities such as iron, copper, and nickel can form micro-galvanic couples that accelerate localized degradation. Furthermore, elevated temperatures and increased moisture exposure significantly increase corrosion rates [5].

Environmental factors such as relative humidity (RH), temperature, atmospheric gases, electrolyte composition, dust particles, and deposited salt species play a crucial role in the corrosion behavior of Mg alloys. Corrosion severity generally increases with rising humidity levels. For example, little to no surface corrosion is observed on pure magnesium or its alloys after long-term exposure at very low humidity (~9.5%), whereas moderate corrosion may occur at approximately 30% RH. At high humidity levels (~80%), severe surface corrosion is typically observed. Consequently, Mg alloys require effective protection strategies to ensure long-term durability, particularly in marine or salt-rich environments [6].

To address these limitations, extensive research has focused on surface modification and coating technologies as effective approaches to enhance the corrosion resistance of Mg alloys. Among various surface protection techniques, the application of protective coatings has proven to be one of the most efficient and widely adopted strategies [7]. A wide range of coating technologies has been developed to improve corrosion resistance, mechanical integrity, and surface functionality of Mg alloys, as illustrated in Figure 1.

This mini review provides an overview of coating technologies used to enhance the corrosion performance of Mg-based alloys. It also outlines the major classes of magnesium alloys, including commercially important systems such as Mg–Al alloys (e.g., AZ series), Mg–Zn alloys (e.g., ZK series), Mg–rare-earth (RE) alloys, and Mg–Ca alloys. Each alloy system exhibits distinct chemical

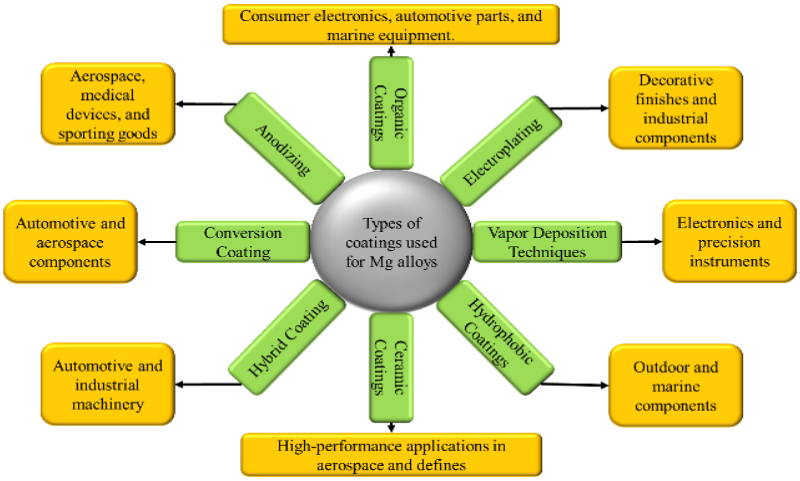

Figure 1 Types of coatings used for Mg alloys and their applications.

compositions and corrosion behaviors, which strongly influence coating selection and effectiveness. Understanding the relationship between alloy composition and coating performance is essential for designing tailored, high-performance corrosion protection systems for advanced magnesium alloy applications.

2. Fabrication and Processing of Magnesium Alloys

2.1. Alloy Design and Composition

The corrosion behavior and mechanical performance of magnesium alloys are strongly influenced by their alloy design and chemical composition. Alloying elements are introduced primarily to improve strength, castability, formability, and corrosion resistance by modifying the microstructure through grain refinement and the formation of secondary phases. The most widely studied and commercially relevant magnesium alloy systems include Mg–Al, Mg–Zn, Mg–rare-earth (RE), and Mg–Ca alloys.

Mg–Al alloys, such as the AZ series, are among the most extensively used magnesium alloys due to their good castability, moderate strength, and cost effectiveness. Aluminum contributes to solid-solution strengthening and promotes the formation of the β-$Mg_{17}Al_{12}$ phase, which can enhance strength but often leads to micro-galvanic corrosion due to its electrochemical potential difference with the α-Mg matrix. Grain refinement in Mg–Al alloys improves corrosion resistance by promoting more uniform corrosion; however, excessive β-phase precipitation along grain boundaries can accelerate localized corrosion[8].

Mg–Zn alloys, including ZK-series alloys, exhibit improved mechanical strength and enhanced grain refinement compared to Mg–Al systems. Zinc contributes to solid solution strengthening and can improve corrosion resistance when present in controlled amounts. However, excessive Zn content may promote the formation of intermetallic phases that act as cathodic sites, increasing localized corrosion susceptibility. The corrosion performance of Mg–Zn alloys is therefore highly dependent on the distribution and stability of Zn-rich second phases[9].

Mg–RE alloys have attracted growing attention due to their superior mechanical properties and relatively improved corrosion resistance. Rare-earth elements such as Y, Nd, Gd, and Ce effectively refine grains and form thermodynamically stable intermetallic phases that are less cathodic than those found in conventional Mg–Al alloys. These characteristics reduce micro-galvanic coupling and promote more homogeneous corrosion behavior, making Mg–RE alloys promising candidates for demanding structural applications[10].

Mg–Ca alloys are of particular interest for biomedical and biodegradable applications due to the biocompatibility of calcium. Calcium acts as a grain refiner and forms Mg_2 Ca intermetallic phases, which can improve mechanical properties at low concentrations. However, Mg_2 Ca is electrochemically more active than the Mg matrix and can significantly increase corrosion rates if present in excessive amounts. Therefore, careful control of Ca content and phase distribution is essential to balance mechanical performance and corrosion resistance[11].

Overall, alloy composition plays a critical role in determining grain size, second-phase morphology, and corrosion susceptibility of magnesium alloys. Understanding these relationships is essential for selecting appropriate surface coating strategies and designing corrosion-resistant Mg alloy systems.

2.2 Primary Fabrication Routes

2.2.1 Casting (die casting, gravity casting)

Casting remains the most widely used fabrication route for magnesium alloys, particularly for large-scale industrial production. In this process, magnesium alloys are melted and poured into molds, where they solidify into the desired shape. Casting alloys are specifically designed to exhibit good fluidity, relatively low melting temperatures, and excellent mold-filling capability, making them suitable for producing components with complex geometries and thin walls.

High-pressure die casting and gravity casting are the two most common techniques. Die casting is extensively employed for high-volume production due to its dimensional accuracy, good surface finish, and short cycle times, whereas gravity casting is typically used for thicker components and lower production volumes. Alloy systems used in casting often contain aluminum and zinc, which improve castability and strength but also promote the formation of secondary phases during solidification.

Common examples of cast magnesium alloys include AZ91, AM60, and AS41, which are widely applied in the automotive and electronics industries. AZ91 offers good strength and castability but suffers from limited ductility and corrosion resistance due to the presence of the β-$Mg_{17}Al_{12}$ phase. AM60 provides improved ductility and impact resistance, making it suitable for safety-related automotive components, while AS41 offers better creep resistance at elevated temperatures[12].

Despite their economic advantages and manufacturing flexibility, cast Mg alloys generally exhibit inferior mechanical properties and corrosion resistance compared to wrought alloys. Solidification-related defects such as porosity, micro-segregation, and non-uniform grain structures are common and can significantly degrade corrosion performance by promoting localized attack. As a result, cast magnesium alloys almost always require post-processing or surface protection, such as conversion coatings, anodizing, or advanced thin-film coatings, to ensure adequate durability in corrosive environments[13].

2.1.2 Wrought Magnesium Alloys

Wrought magnesium alloys are produced through mechanical deformation processes such as extrusion, rolling, and forging, following the initial solidification of the material. These alloys are designed to exhibit good workability, enabling them to undergo substantial plastic deformation without cracking. Compared to casting alloys, wrought Mg alloys possess finer and more uniform microstructures, which contribute to their higher mechanical strength, improved ductility, and superior fatigue resistance. For these reasons, wrought alloys are often employed in applications where enhanced mechanical performance and structural reliability are required[14].

Representative examples include AZ31, ZK60, and WE43, which are commonly used in aerospace components, biomedical devices, and various structural applications. The primary advantages of wrought Mg alloys are their high strength, improved toughness, and microstructural uniformity. However, these benefits come at the cost of more complex and expensive processing routes, limited attainable shapes, and the intrinsic workability challenges associated with the hexagonal close-packed (HCP) crystal structure of magnesium[15].

Figure 2 summarizes the main alloying elements and associated compositions of four commercially available magnesium alloys: AZ81, AE42, AM20, and AM50. The elemental components included in each alloy, the approximate weight percentages of these alloying additions, and the differences between several alloy families (AZ, AE, and AM series) may all be clearly understood thanks to this comparison. Interpreting the material qualities and possible uses related to each type of alloy requires this kind of categorization.

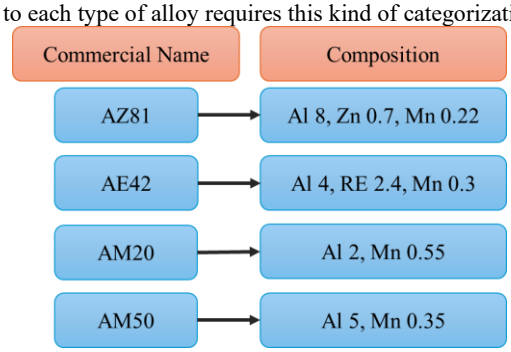

Figure 1 Commercial designations of magnesium alloys along with their typical chemical compositions.

3. Corrosion Types and Mechanism in Mg-Alloys

Magnesium is a highly active metal, and when it meets water, it readily undergoes electrochemical corrosion in both acidic and neutral environments, especially those containing chloride ions. During this process, hydrogen gas is released and a layer of Mg $(OH)_2$ forms on the surface[16].

Corrosion in human body fluids is even more complex than in natural environments because physiological solutions contain various anions, proteins, cells, glucose, and have a dynamic pH. According to widely accepted explanations, two main factors accelerate the degradation of magnesium alloys:

(1) galvanic corrosion caused by impurities and secondary phases

within the alloy.
(2) the instability and porous nature of the oxide and corrosion layers that form on the magnesium surface.

In aqueous environments, magnesium alloys can exhibit several corrosion modes, with general corrosion, pitting corrosion, and localized corrosion being the most common. General corrosion occurs uniformly across the entire metal surface and is typical in pure metals or compositionally uniform alloys; this type is relatively less damaging for implant applications[17]. Localized corrosion, however, is far more destructive because it progresses rapidly in specific regions of the alloy. Common forms of localized attack include intergranular corrosion, filiform corrosion, stress-corrosion cracking, and corrosion fatigue, all of which can severely compromise the integrity of magnesium-based implants[12].

3.1 Pitting corrosion

Pitting is the most frequently observed form of corrosion in magnesium alloys, and its origin is closely tied to the alloy's microstructure. SEM analysis helps reveal this structure, which typically consists of an α-Mg matrix along with β-phase or other secondary intermetallic compounds [18].

In magnesium alloys, pitting usually appears as shallow cavities that form when the protective MgO film on the surface breaks down after exposure to corrosive environments containing ions such as Cl^-. Once this passive layer ruptures, micro-galvanic couples form between the α-Mg matrix and the second-phase particles or impurities. These galvanic interactions accelerate pit growth until corrosion products such as Mg $(OH)_2$ accumulate and partially fill the pits.

Because second-phase particles generally have a higher electrode potential than the α-Mg matrix, pits often initiate in these regions. Research on the rare-earth magnesium alloy GW93 has shown that its pitting corrosion evolves in three stages[19]:
1: The second phase, having a lower potential locally, dissolves first and forms a rare-earth oxide film, becoming more passive.
2: Corrosion then spreads laterally around the dissolved second-phase particles.
3: The pits deepen as the corrosion continues along the dissolved second-phase regions, ultimately producing characteristic pitting damage.

The figure 3 illustrates the initiation of pitting corrosion in a magnesium alloy. A β-phase particle sits exposed on the surface, surrounded by chloride ions (Cl^-). The protective MgO film has broken down around this region, creating an opening where aggressive ions can penetrate. As corrosion progresses, $Mg(OH)_2$ corrosion products accumulate beneath the β-phase particle. The α-Mg matrix on both sides remains intact, while the β-phase acts as a local cathodic site (indicated by the upward arrow), accelerating anodic dissolution in the surrounding magnesium matrix.

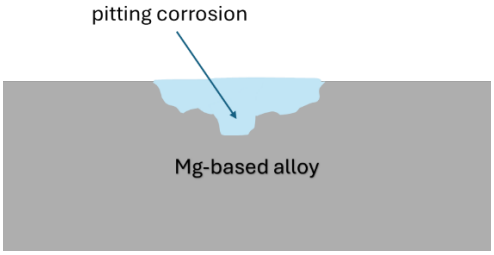

Figure 2 Schematic of pitting corrosion

3.2 Filiform corrosion.

In the early stages of both pitting and filiform corrosion, small, localized pits begin to form within the magnesium matrix. Because they share this initial trigger, these two corrosion modes may appear simultaneously; however, they progress along very different pathways. Pitting corrosion grows deeper into the matrix but affects a relatively small surface area, whereas filiform corrosion spreads laterally across the surface, producing long, thread-like tracks with shallow penetration. Compared with iron- or aluminum-based alloys, magnesium alloys typically exhibit slower filiform growth and produce thinner corrosion filaments[20].

A well-known example of this behavior comes from the work of Williams G. and co-workers, who examined pure magnesium exposed to seawater. They proposed that filiform corrosion originates from the formation of a microscopic galvanic cell within the corrosion filament. The advancing "head" of the filament acts as the anode, while the trailing "tail" serves as the cathode. As the filament grows, the cathodic tail remains electrically connected to the anodic magnesium matrix ahead of it. This connection causes the anodic magnesium to dissolve continuously, breaking down the protective oxide film and enabling the filament to extend.
At the same time, the corrosion product $Mg(OH)_2$ accumulates at the tail of the filament. Once deposited, this product becomes inactive, functioning as an inert cathodic region. This inert zone can then form a new micro-galvanic couple with the adjacent uncorroded magnesium, enabling the filiform corrosion to propagate further along the surface[18].

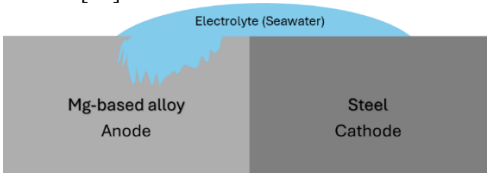

Figure 3 Schematic of Galvanic corrosion

3.3 Galvanic corrosion

Magnesium alloys behave as highly active anodes when placed in contact with other metallic implants such as titanium alloys or stainless steel. In NaCl solutions, their corrosion potential is more than 600 mV lower than that of zinc, the next most active commonly used engineering metal. Even within a single magnesium alloy, galvanic corrosion can occur between the α-Mg matrix and its secondary phases[21].

Because magnesium alloys differ in composition, microstructure, and crystallographic orientation, their electrochemical behavior varies accordingly. These variations create numerous microscopic galvanic couples. When magnesium is used as the anodic component, the corrosion rate increases with the potential difference between it and the coupled metal. For this reason, the potential difference between magnesium and the selected partner metal should ideally remain below 0.25 V to minimize galvanic degradation. Changes in pH also influence galvanic behavior and metal polarity. For example, in an Al–Mg galvanic pair exposed to neutral or slightly acidic dilute NaCl, magnesium initially acts as the anode. However, as Mg dissolves, the local environment becomes alkaline. Once the pH exceeds about 8.5, aluminum becomes the anodic component, effectively reducing the overall corrosion of the alloy under alkaline conditions [22].

Several factors affect galvanic corrosion (Fig.4): the thickness of the electrolyte film covering the metals, the spacing between the galvanic partners, the anode-to-cathode area ratio, and the insulation distance between anodic regions. Magnesium alloys show a limited effective range for galvanic current, with corrosion usually concentrated near the edges of test specimens. Song et al. investigated this by measuring galvanic currents between high-strength steel and AZ91D using a specially designed "sandwich" galvanic corrosion probe under salt-spray conditions. Their results showed that galvanic current decreases exponentially as the distance between anode and cathode increases. The experimental data matched the theoretical prediction closely[23].

4. Deposition methods for Protective Coatings

4.1 Chemical Vapor Deposition (CVD)

Magnesium-based alloys can be coated with protective and useful materials using the flexible Chemical Vapor Deposition (CVD) method. This technique creates a thin, homogeneous layer on the heated magnesium alloy substrate by reacting or breaking down volatile precursor gases. With CVD, a variety of materials, such as metals, polymers, and complex chemicals, may be deposited directly onto magnesium alloys[24]. For instance, polyethylene and crosslinked polyethylene films have been deposited using plasma-enhanced CVD (PECVD), which greatly increases corrosion resistance by forming thick, homogeneous barriers that keep corrosive chemicals out. Furthermore, magnesium alloys may be aluminized via CVD, which creates a coating rich in aluminium to improve oxidation resistance and surface hardness. The thickness and characteristics of the coating may be customized by carefully regulating the process parameters, which include temperature, gas composition, and pressure. For electrical, automotive, and aerospace applications where corrosion prevention and surface functionality are

essential, CVD coatings are especially appealing.

Chemical vapor deposition (CVD) methods, including microwave plasma-assisted CVD and hot filament CVD, have been used to create diamond films. In contrast, a variety of physical vapor deposition (PVD) and CVD techniques, such as ion plating, magnetron sputtering, plasma-enhanced CVD, and the filtered cathodic vacuum arc process (FCVA), may be used to create DLC films. Tetrahedral amorphous carbon (ta–C), the hardest DLC type, may be deposited by the FCVA with a hardness comparable to diamond[25].

4.2 Physical Vapor Deposition (PVD)

A popular method for adding functional and protective coatings to magnesium-based alloys that address their innate vulnerability to surface deterioration and corrosion is physical vapor deposition, or PVD. Metals, alloys, or ceramics are vaporized and subsequently condensed onto the magnesium alloy substrate as a thin layer using a variety of vacuum-based techniques, including arc vapor deposition and magnetron sputtering, which are included in PVD. Depending on the required surface characteristics, the method can deposit pure metals (such as nickel or high-purity magnesium), alloys, or even multicomponent and ceramic coatings[26].

Surface pretreatment, which usually entails grinding, degrading, degreasing, acid pickling, and activation to remove impurities and native oxides and ensure robust coating adherence, is a crucial component of PVD on magnesium alloys. In some procedures, pretreatment may be followed by the application of a temporary anti-corrosion conversion coating to stop oxidation before the PVD process starts[27]. The corrosion resistance, electrical conductivity, and solderability of magnesium alloys are greatly improved by PVD coatings, which qualifies them for direct usage in demanding settings or further surface treatments like electroplating. Hard, wear-resistant ceramic coatings may be created by including ceramic-forming substances (such as hydrogen and nitrogen) during the deposition process according to recent developments. The thin, homogeneous, and firmly bonded PVD films that are produced provide enhanced durability for use in biomedical, electronics, automotive, and aerospace applications.

5. Surface Coating Technologies for Mg-based Alloys

A wide range of coating technologies are researched to protect the surface of Mg-Alloys**,** each with unique advantages in surface functionality, wear resistance, and corrosion resistance. Below are the common coating technologies:

5.1 DLC and Diamond-based coatings.

Previous studies have demonstrated that modifying DLC coatings can improve the corrosion behavior of magnesium alloys. Masami et al. [28] showed that incorporating Si into DLC coatings enhanced the corrosion resistance of AZ91 Mg alloy. Although the addition of a Ti interlayer improved coating adhesion, it negatively affected the overall corrosion protection. In a related study, Si-doped DLC coatings deposited on AZ91 using hollow cathode discharge with DC bias (0 to −300 V) and a ~600 nm Si interlayer promoted the formation of a protective SiC phase, leading to a reduction in corrosion current density by nearly two orders of magnitude compared with the bare alloy [29]. However, the coatings provided only limited long-term protection due to crack formation induced by high residual stresses. Similarly, DLC coatings on Mg–Li alloys showed insufficient durability in both alkaline and acidic environments [30].

Diamond-based coatings are considered promising protective materials owing to their exceptional hardness, chemical stability, low friction, and established biocompatibility [31]. Nevertheless, achieving high-quality diamond films directly on metallic substrates remains difficult. Transition metals such as Fe, Co, and Ni catalyze the formation of sp^2-bonded carbon, which suppresses diamond nucleation [32], while refractory metals (e.g., Ti, Zr, Nb, Hf, and Ta) typically show low nucleation densities and poor film continuity due to lattice mismatch and interfacial stresses with carbide layers [33]. In the case of Mg alloys, their high chemical reactivity and rapid oxide formation further impede diamond nucleation and favour sp^2-rich carbon growth, making interlayer-free diamond deposition particularly challenging and limiting the use of diamond coatings on Mg-based systems[34].

5.2 Micro-Arc Oxidation coatings.

A common surface treatment method for improving the characteristics of alloys based on magnesium is micro-arc oxidation (MAO). By exposing the magnesium alloy to high-voltage plasma discharges in an electrolytic bath, a thick, hard, and ceramic-like oxide layer mostly magnesium oxide is formed on the alloy's surface[35]. The endurance and longevity of magnesium alloy components are greatly increased by this oxide layer, which acts as a strong barrier against corrosion, wear, and abrasion. The smooth, compact surfaces, greater thickness, and enhanced hardness of MAO coatings all contribute to their improved mechanical performance and resistance to corrosion. The thickness and characteristics of the coating may be controlled by adjusting the process parameters, which include voltage, current density, and electrolyte composition. Excellent biocompatibility is another feature of MAO-treated magnesium alloys, which makes this technology very useful for biomedical implants as well as automotive and aerospace applications.

5.3 Polymer coatings.

Magnesium alloy–based bioresorbable scaffolds (BRSs) are being explored as next-generation vascular stents, but their rapid degradation in physiological environments necessitates effective surface protection. Xu et al. [36] investigated biodegradable polymer coatings as corrosion-control layers while also serving as drug reservoirs. Among the polymers examined, PDLLA showed the slowest sirolimus release and favorable reservoir characteristics due to its slow degradation and semi-glassy state. However, PDLLA coatings did not effectively reduce corrosion of AZ31 Mg alloy, as coating defects, cracking, and delamination were observed. In contrast, PCL and PLCL coatings provided improved corrosion resistance. A multilayer design combining a PCL or PLCL interlayer with an outer drug-loaded PDLLA coating successfully integrated the benefits of each polymer, leading to enhanced corrosion protection and demonstrating a promising strategy for magnesium-based coronary scaffold development.

6 Conclusion

As summarized in this mini review, corrosion behavior in Mg alloys is strongly influenced by alloy composition, microstructure, secondary phases, impurities, and exposure conditions. Localized phenomena such as galvanic, pitting, and filiform corrosion further compromise their durability. Surface coatings therefore represent one of the most effective strategies to improve corrosion resistance. Advanced techniques, including DLC and Diamond-based coatings, micro-arc oxidation (MAO) and Polymer coatings on Mg-based Alloys, provide significant enhancements in barrier protection, mechanical stability, and surface functionality, with each method suited to different application needs. Future advancements in coating design, adhesion engineering, and microstructural optimization will be essential for enabling reliable, long-term performance of Mg-based materials in demanding environments.

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