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Aluminum Alloy as Sacrificial Anode for Corrosion Protection: A Review

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Abstract

Aluminum sacrificial anodes are widely used for cathodic protection in marine, offshore, and energy applications due to their light weight, high current efficiency, and favorable electrochemical potential. Pure aluminum, however, rapidly passivates in seawater, reducing protective performance. Alloying with elements, such as zinc, indium, gallium, tin, and bismuth, improves activation, ensures uniform dissolution, and stabilizes long-term behavior. This review examines the influence of alloying elements on electrochemical performance, microstructure, and mechanical properties, highlighting correlations between intermetallic formation, grain refinement, and anodic efficiency. Experimental studies, including electrochemical testing, weight-loss measurements, and field trials, demonstrate the advantages of optimized aluminum alloys over traditional zinc and magnesium anodes. Applications in ships, offshore platforms, pipelines, storage tanks, and renewable energy systems are discussed, emphasizing the importance of tailored alloy design for reliable and long-lasting protection. Finally, key research gaps are identified, underscoring opportunities for environmentally sustainable alloy development, advanced microstructural engineering, and extended field validation to enhance anode performance in diverse corrosive environments.

Keywords: Sacrificial anode, cathodic protection, corrosion, marine structures, electrochemical performance

INTRODUCTION

Corrosion of metallic structures in marine and offshore environments remains one of the most critical challenges faced by industries such as shipping, oil and gas, and offshore renewable energy. Continuous exposure to saline water, high humidity, and varying temperatures accelerates electrochemical degradation, leading to significant economic losses and safety risks [1]. Among the many corrosion control strategies, cathodic protection (CP) is recognized as one of the most effective approaches for extending the service life of steel structures [2]. CP can be implemented through two primary methods: impressed current cathodic protection (ICCP) and sacrificial anode cathodic protection (SACP). In SACP, a more electrochemically active material is coupled with the protected structure, thereby corroding preferentially and safeguarding the base metal. The choice of sacrificial anode material is critical for ensuring stable performance, long service life, and cost-effectiveness [3].

Traditionally, zinc and magnesium have been used as sacrificial anodes. However, aluminum-based alloys have become the dominant choice in recent decades due to their low density, high theoretical current efficiency, favorable electrochemical potential, and cost advantage over other materials [4]. Despite these benefits, pure aluminum suffers from rapid passivation in seawater, which severely limits its corrosion protection efficiency. To overcome this limitation, various alloying strategies have been developed, incorporating elements such as Zn, In, Ga, Sn, Bi, and rare earths. These additions disrupt the

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passive oxide film, promote uniform dissolution, and enhance electrochemical activity, making aluminum alloys highly effective for long-term cathodic protection applications [5].

This review aims to provide a comprehensive overview of aluminum alloys as sacrificial anodes. It summarizes the historical development, role of alloying elements, performance evaluation techniques, and practical applications in marine and offshore environments. Furthermore, the review highlights the challenges associated with non-uniform dissolution, environmental concerns regarding certain alloying elements, and identifies potential future research directions toward designing environmentally sustainable and high-performance aluminum anodes [6].

FUNDAMENTALS OF SACRIFICIAL ANODE CORROSION PROTECTION

Cathodic protection (CP) is an electrochemical technique widely employed to control corrosion by regulating the reactions occurring at the metal–electrolyte interface. When metallic structures, such as ship hulls, offshore pipelines, or reinforced concrete in splash zones, are exposed to seawater, they function simultaneously as anodic and cathodic sites, resulting in localized corrosion. In such environments, sacrificial anode cathodic protection (SACP) has proven to be particularly effective, especially where conventional anticorrosion coatings or inhibitors exhibit limited performance or durability [7].

In the SACP method, a more electrochemically active metal – typically zinc or aluminum – is intentionally coupled to the structure to act as a sacrificial anode [8]. This anode preferentially corrodes, releasing electrons that flow toward the protected surface, thereby maintaining it in a cathodic state and preventing oxidation. The system creates a galvanic cell in which the sacrificial anode, being more active, corrodes first to protect the base metal [9–11]. This method works well in marine and concrete environments where steel is vulnerable to chloride attack [12]. The anode keeps the steel in a passive potential zone, preventing corrosion from starting or spreading [13]. Reliable performance depends on good electrical contact and adequate electrolyte conductivity.

Principle of Sacrificial Anode Action

The principle of sacrificial anode protection is grounded in the concept of galvanic corrosion, where two dissimilar metals are electrically connected in the presence of an electrolyte, resulting in preferential dissolution of the more active metal [14, 15]. For cathodic protection to be effective, the sacrificial anode must exhibit an electrode potential significantly more negative than that of the metal structure being protected, thereby forcing the latter to act as the cathode within the galvanic couple (Figure 1) [16].

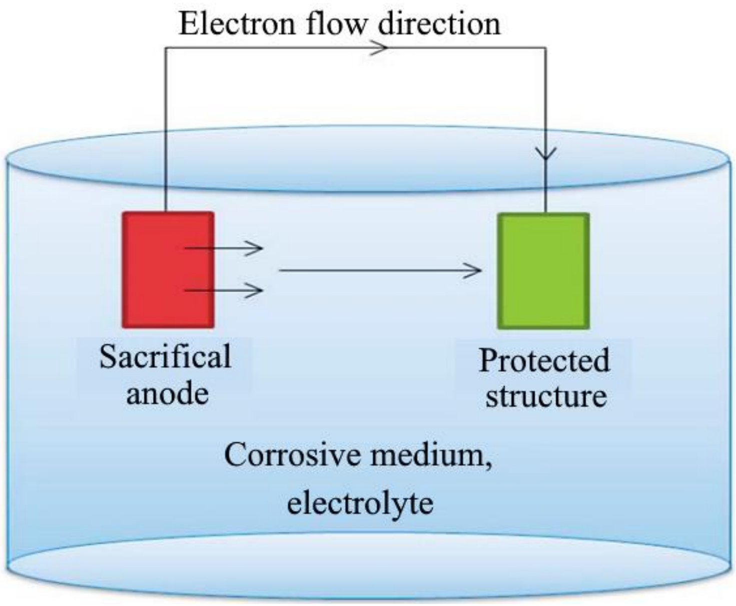

Figure 1. Schematic representation of catholic protection using a sacrificial anode.

When the anode and the structure are electrically coupled in an electrolyte, such as seawater, an electrochemical cell is established. The sacrificial anode undergoes oxidation, releasing metal ions into the solution (Equation (1)), while the protected structure facilitates reduction reactions (Equation (2)), typically involving oxygen or hydrogen species depending on the environment [17, 18].

Anodic Reaction: $M \rightarrow Mn^{+} + ne-$ (1)

Cathodic Reaction: $O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$ (in neutral/alkaline media) (2)

or

$2H^{+} + 2e^{-} \rightarrow H_2$ (in acidic/deaerated media).

The electrons generated at the anode travel through the metallic connection to the structure, maintaining the protected surface at a potential below its corrosion potential and thus suppressing its anodic dissolution [19]. The potential difference between the anode and cathode drives this protective current, which is maintained if the anode continues to corrode.

The rate of anode consumption is influenced by parameters such as the alloy composition, anode efficiency, current density, and the resistivity of the surrounding electrolyte [20, 21]. Commonly employed sacrificial anodes include magnesium, zinc, and aluminum-based alloys, each selected according to their standard electrode potential and the service environment [22]. Aluminum-based anodes are often preferred for marine applications due to their high current efficiency, low density, and favorable electrochemical performance [23].

In essence, the sacrificial anode method transforms the entire surface of the protected metal into a cathode, effectively halting corrosion through the controlled oxidation of a more active alloy. This robust and self-regulating mechanism remains one of the most reliable cathodic protection techniques for marine, offshore, and buried steel structures [24, 25].

Electrode Potentials of Common Anode Materials

The performance of sacrificial anode systems depends primarily on the electrode potential of the anode material relative to the protected metal. Selection of a suitable anode is, therefore, governed by the electrochemical or galvanic series, which ranks metals according to their tendency to corrode in each environment. In seawater applications, the electrode potential is commonly expressed with respect to a silver/silver–chloride (Ag/AgCl) reference electrode. Typical potential for common anode materials is summarized in Table 1.

Table 1. Approximate seawater electrode potentials of common sacrificial anode materials (vs. Ag/AgCl reference electrode).

Material	Electrode Potential (V vs. Ag/AgCl)	Comments
Magnesium alloys	–1.55 to –1.75	High driving potential, risk of overprotection.
Aluminum alloys	–1.05 to –1.20	Balance of activity and stability, widely used.
Zinc alloys	–1.00 to –1.05	Stable, lower efficiency, heavier.

Magnesium-based anodes exhibit the most negative potentials, ranging from approximately –1.55 to –1.75 V vs. Ag/AgCl, providing a high driving voltage for cathodic protection [26]. However, their strong electrochemical activity may cause excessive hydrogen generation and potential overprotection, especially in coated steel or reinforced concrete systems. Zinc alloys, with potentials around –1.00 to –1.05 V, offer excellent stability and uniform dissolution but tend to be heavier and provide lower current efficiency [27]. Aluminum-based alloys occupy an intermediate position, typically between –1.05 and –1.20 V, which delivers a favorable balance between driving potential, efficiency, and stability in marine environments [28]. Due to this balance, aluminum alloys are the most widely used sacrificial anodes for offshore and coastal structures. They offer sufficient potential to protect steel without inducing unwanted side effects, such as coating disbondment or hydrogen embrittlement, that may arise from the more active magnesium anodes [29].

Aluminum alloys occupy a favorable position by providing sufficient driving voltage without the risk of excessive hydrogen evolution associated with magnesium.

Selection Criteria for Anode Materials

The selection of an appropriate sacrificial anode material is a critical factor in ensuring effective and long-term cathodic protection. The anode must possess adequate electrochemical potential, sufficient current capacity, and stable dissolution characteristics under the given environmental conditions [26]. In marine and coastal structures, these factors are further influenced by temperature, salinity, oxygen availability, and flow conditions, which collectively determine the corrosion kinetics and anode efficiency [28].

The most important criterion is the driving potential between the anode and the protected metal. This potential difference must be sufficient to polarize the structure cathodically without causing overprotection or hydrogen evolution [27]. Magnesium alloys, for instance, provide high driving voltage and are preferred for soil or freshwater systems, whereas aluminum and zinc alloys are more suitable for seawater due to their controlled activity and slower consumption rates [29].

Another essential consideration is the current efficiency and consumption rate of the anode. Aluminum-based anodes offer the highest practical efficiency (up to 90%), making them cost-effective for long-term applications [30]. Zinc anodes, while reliable and stable, have lower efficiency and are heavier, resulting in increased installation and replacement costs [31]. Environmental compatibility is also crucial; aluminum and zinc alloys are preferred in marine environments because they produce non-toxic corrosion products and maintain consistent performance even under variable salinity conditions [17].

Finally, the mechanical integrity and uniform dissolution of the anode must be maintained throughout its service life. Irregular dissolution or passive action can reduce protection efficiency and create local corrosion cells on the protected structure. Therefore, the choice of alloy composition, impurity level, and activation elements (such as indium, mercury-free tin, or zinc additions in aluminum anodes) must be optimized to ensure uniform electrochemical behavior and long-term performance [29, 28].

Performance Evaluation of Sacrificial Anodes in Marine Environments

The effectiveness of sacrificial anode systems in marine environments is primarily assessed through their ability to maintain the protected metal within the desired potential range, typically between –0.80 V and –1.10 V versus Ag/AgCl for steel structures [29]. The anode performance depends on several interrelated factors, including alloy composition, environmental conditions, current distribution, and the nature of the electrolyte [28]. Regular monitoring of potential, current output, and anode consumption rate is essential for evaluating system reliability and ensuring sustained protection [27].

In seawater, the performance of anodes is strongly influenced by temperature, oxygen concentration, and chloride ion content. Higher temperatures and salinity generally accelerate anode dissolution and increase current demand [17]. Aluminum-based alloys demonstrate stable electrochemical behavior across a broad range of salinities and temperatures, which explains their wide adoption in offshore and coastal structures [31]. Zinc anodes, though chemically stable, tend to exhibit lower current efficiency in warm or brackish waters due to partial passivation, while magnesium anodes are often avoided in seawater because of their excessive driving potential, which can lead to hydrogen evolution and coating disbondment [1].

The uniformity of anode dissolution is another important performance indicator. Ideally, anodes should corrode uniformly to maintain consistent protection. However, irregular consumption, passivation, or localized attack can cause uneven current distribution, leading to underprotected areas on the structure [30]. Alloying and activation elements, such as indium or tin, are commonly added to aluminum-based anodes to improve dissolution characteristics and prevent surface film formation [29].

Periodic potential mapping and anode mass-loss measurements are standard practices for performance evaluation. These methods help verify the adequacy of protection, detect potential deficiencies, and estimate the remaining service life of the anodes [28]. Overall, aluminum-based anodes continue to offer the best combination of stability, current efficiency, and environmental compatibility for marine applications, provided that electrical continuity and electrolyte conductivity are maintained throughout the service period [27, 29].

DEVELOPMENT OF ALUMINUM ALLOY ANODES

Effect of Alloying Elements on Aluminum Sacrificial Anode Performance

Pure aluminum, although theoretically attractive for sacrificial anode applications because of its low density and high electrochemical capacity, suffers in seawater environments due to rapid formation of a passive oxide (Al_2O_3) film. This film impedes anodic dissolution, lowering current output and reducing reliability. To overcome this, over decades, alloying strategies have been developed to "activate" the aluminum surface, promoting continuous dissolution and improving both driving potential and current efficiency.

Early alloy formulations used toxic activators, like mercury (Hg) and thallium (Tl), to disrupt the oxide film, but environmental and health concerns forced the abandonment of these elements. More benign activators-zinc (Zn) and indium (In)-became standard. Zn in amounts typically around 2–6 wt% helps reduce the stability of the oxide film, shifting the open circuit potential more negative, and increasing driving voltage versus steel. In small amounts (0.01–0.2 wt%), indium is very effective in destabilizing oxide continuity, enhancing uniform dissolution and improving potential stability under service (as shown in recent studies of Al–Zn–In alloys) [32, 33].

Additions of bismuth (Bi) and lead (Pb) in Al–Ga–In systems have been shown to shift potentials further negative and improve activation, but only when their content is carefully controlled to avoid deleterious effects like uneven dissolution and grain shedding. For example, an Al–Ga–In alloy with about 4% Pb + 1% Bi showed very favorable performance in artificial seawater in terms of open circuit potential, working potential, and current efficiency, compared to similar alloys without Bi/Pb [33].

Another modern strategy is incorporating metal oxides (e.g., MnO_2, CeO_2, etc.) and/or heat treatment to improve microstructural uniformity, reduce non-coulombic losses, and promote uniform corrosion rather than localized attack. In an Al–5% Zn–0.1% Sn matrix, adding a low-cost MnO_2 concentrate and applying solution heat treatment at ~550°C significantly boosted current efficiency from ~72% to over 90% under certain test conditions [34].

Impurities also play a subtle but important role: elements, like Fe, Cu, and Si – if uncontrolled – tend to form intermetallic phases that serve as local cathodic sites and cause localized corrosion, reducing anode utilization. Thus, commercial alloys maintain rigorous control over impurity levels.

To optimize the performance of aluminum sacrificial anodes, various deliberate alloying additions have been studied. Elements, such as zinc, indium, bismuth, gallium, tin, and certain metal oxides, can significantly influence anode characteristics, including open-circuit potential, current efficiency, corrosion uniformity, and service life. The combined effects of these alloying elements alongside controlled impurity levels enable the design of alloys tailored for specific marine and industrial applications. Table 2 summarizes commonly used aluminum-based sacrificial anode alloys, their typical compositions, and the observed effects of each addition on anode performance, based on recent studies [6].

The data presented in Table 2 highlight how specific alloying strategies can tailor the electrochemical behavior of aluminum sacrificial anodes. These insights provide a benchmark for comparing the performance of newly developed alloys, guiding decisions on element selection and processing routes to achieve optimal current efficiency, uniform corrosion, and service life. By aligning the composition of experimental alloys with these well-studied formulations, it becomes possible to predict and enhance their protective performance in targeted environments.

Table 2. Composition ranges and effects of various alloying elements on the performance of aluminum-based sacrificial anodes.

Alloy Type/ Additions	**Typical Composition Range (wt%)**	**Effects on Anode Performance**	**Reference(s)**
Al–Zn–In	Zn ~4–6%, In ~0.01–0.05%	More negative open circuit potential; improved activation of surface; high current efficiency; but higher in lowers current capacity and lifetime if above ~0.15–0.20% In	Study of increasing In in Al–Zn–In: noting good balance at ~0.02–0.05% In [32].
Al–Zn–Bi	Zn ~4.2%, Bi ~0.2%	Adding small Bi shifts potential more negative; improves suppression of hydrogen evolution; enhances uniform dissolution	Performance evaluation of Al–Zn–Bi in seawater; ~0.2% Bi study [35].
Al–Ga–In with Pb/Bi	Ga/In minor (<0.1%), Pb ~4%, Bi ~1%	Strong activation, very negative potentials, good current efficiency, but too much Bi or Pb causes uneven surface dissolution and grain shedding	Effect of Bi on Al–Ga–In sacrificial anode; sample with 4% Pb +1% Bi had best performance [33].
Al–Zn–Sn + Metal Oxides	Zn ~5%, Sn ~0.1%, metal oxide (MnO_2, etc.) ~few vol%	With oxide incorporation and proper heat treatment (≈550°C), current efficiency significantly increased, microstructure refined, more uniform corrosion, less self-corrosion	Al–5Zn–0.1Sn with metal oxides and heat treatment work [34].
Impurity Effects (Fe, Cu, Si)	Fe, Cu, Si ≤ small ppm to < ~0.1% levels	Increase in intermetallic cathodic sites → localized attack; raises self-corrosion; lowers current efficiency unless controlled	Impurity effects discussed in reviews and Al–Zn–In studies [6].
Al–Zn–In–Mg–Ga	Zn ~4–5%, In ~0.02%, Mg ~0.1%, Ga ~0.03%	Enhanced discharge performance: gallium addition improves discharge activity and anodic efficiency.	Al–Zn–In–Mg–Ga alloy has best discharge performance [36].
Al–Zn–In–Mg–Ti	Zn ~4–5%, In ~0.02%, Mg ~0.1%, Ti ~0.05%	Enhanced discharge performance: Ti addition improves anodic efficiency.	Effect of Ti discussed and reviews [37].
Al–Zn–Sn–Cu	Zn ~5%, Sn ~0.1%, Cu ~0.1%	Copper addition enhances discharge performance; heat treatment refines microstructure, leading to more uniform corrosion and reduced self-corrosion.	Al–Zn–Sn with Cu and heat treatment work [38].

Microstructural Mechanisms Behind Alloy Activation

The enhanced performance of aluminum sacrificial anodes is not only governed by the presence of activator elements, such as Zn, In, Ga, Bi, etc., but also by the microstructural features these additions induce particularly the formation, distribution, and electrochemical behavior of intermetallic phases, second phases, and grain structure. Understanding these microstructural mechanisms is crucial for designing alloys with stable, uniform dissolution and minimal non-coulombic losses.

One of the key microstructural contributors is the formation of intermetallic particles or second phases resulting from alloying additions or impurities. These particles often possess electrochemical potentials different from the aluminum matrix, creating local galvanic micro-cells. In many Al alloys, intermetallics, such as Al_3Fe, Al_3Cu, Mg_2Si, or phases incorporating Zn and In, may act as either cathodic or anodic sites depending on solution conditions and phase chemistry [39]. If the intermetallic phase is more noble than the matrix, it behaves as a cathode and causes localized corrosion of the aluminium [40]. If it is more active, it dissolves first and reduces uniformity. Controlling the size, shape, and distribution of these particles minimizes micro-galvanic effects and promotes uniform anode dissolution.

Beyond intermetallic, grain size and boundary characteristics also influence dissolution behavior. Fine-grained microstructures typically enhance uniform dissolution by providing more uniform paths for ionic and electronic conduction and reducing large concentration gradients. If grains grow too large or exhibit significant segregation at boundaries (e.g., eutectic zones or segregation of activators), dissolution may become nonuniform, with boundary attack or pitting dominating. Alloying and heat treatments that refine grains and homogenize composition are thus beneficial for maintaining stable current output over time [41].

Another modern tactic is embedding metal oxide or ceramic dispersoids or composite phases within Al–Zn–Sn or Al–Zn matrices to act as micro-scaffolds that disrupt passivating film formation. For example, incorporation of NiO or MnO_2 into Al–Zn base alloys has been shown to improve activation, reduce film impedance, and promote more even dissolution in chloride environments [42]. Similarly, Elsayed et al. demonstrated that incorporating metal oxides in Al–Zn–Sn can boost current efficiency and reduce self-corrosion losses [34]. These dispersed phases can locally stress or destabilize oxide films, facilitating continuous ionic exchange and galvanic activity.

Influence of Alloying Elements on the Mechanical and Microstructural Properties of Aluminum Sacrificial Anodes

The performance of aluminum sacrificial anodes is significantly influenced by the selection and concentration of alloying elements. The data presented in Table 3 demonstrate that alloying elements play a dual role in determining both the microstructural and mechanical properties of aluminum sacrificial anodes. Elements, such as Zn, In, Mg, and Ga, not only enhance anodic activity and current efficiency but also refine the microstructure, promoting uniform corrosion and improved mechanical strength. Conversely, uncontrolled impurities, like Fe and Pb, can lead to brittle intermetallic phases, localized corrosion, and reduced structural integrity (Table 3).

Table 3. Effect of various alloying elements on the microstructure, mechanical properties, and electrochemical performance of aluminum-based alloys for sacrificial anode applications.

Alloying Element	**Typical Composition (wt%)**	**Microstructural Effects**	**Mechanical Properties**	**Electrochemical Performance**	**Ref.**
Zinc (Zn)	4–6	Formation of Zn-rich dendrites; eutectic phases	Increased brittleness with higher Zn content	Enhanced anodic dissolution rate; higher current efficiency.	[43]
Indium (In)	0.01–0.05	Grain refinement; uniform phase distribution	Improved strength and ductility	Enhanced activation and discharge efficiency.	[44]
Magnesium (Mg)	0.05–0.20	Formation of $MgZn_2$ and Mg_2Si phases; grain refinement	Enhanced strength; potential for stress corrosion cracking	Improved electrochemical activity; reduced impurity content.	[45]
Tin (Sn)	0.1	Suppression of plate-like Al3(FeMn) phases; formation of Chinese script α–Fe	Potential decrease in ultimate tensile strength (UTS) and yield strength (YS)	Reduced electrolytic potential; advantageous in sacrificial anodes.	[46]
Bismuth (Bi)	0.2	Enhanced uniform corrosion; suppression of hydrogen evolution	Improved mechanical properties by reducing localized corrosion	Enhanced activation and discharge efficiency.	[47]
Silicon (Si)	0.1	Promotion of Chinese script α–Fe phases; suppression of Al3(FeMn) phases	Increased volume percent of porosity; potential decrease in UTS and YS	Potential reduction in electrolytic potential.	[48]

Gallium (Ga)	0.03	Fine grain structure; uniform phase distribution	Improved strength and ductility	Enhanced discharge activity and anodic efficiency.	[49]
Titanium (Ti)	0.1	Fine grain structure; uniform dissolution	Reduced intergranular corrosion; improved activation performance	Enhanced electrochemical performance.	[50]
Iron (Fe)	Trace amounts	Formation of intermetallic phases; potential for localized corrosion	Reduced mechanical strength; increased brittleness	Increased self-corrosion rate; reduced current efficiency.	[51]

Careful selection and control of these alloying additions are, therefore, essential to optimize anode performance, durability, and reliability in diverse marine and industrial environments.

APPLICATIONS OF ALUMINUM ALLOY ANODES

With the maturation of activated aluminum alloy technology, aluminum sacrificial anodes have become increasingly widespread in applications requiring long-term cathodic protection. Their favorable combination of high theoretical current capacity, lightweight construction, and cost-effectiveness makes them preferred over zinc or magnesium in many large-scale systems. Their adaptability enables use across marine, offshore, and emerging energy infrastructure where structural steel must be safeguarded from corrosion over extended durations (Figure 2).

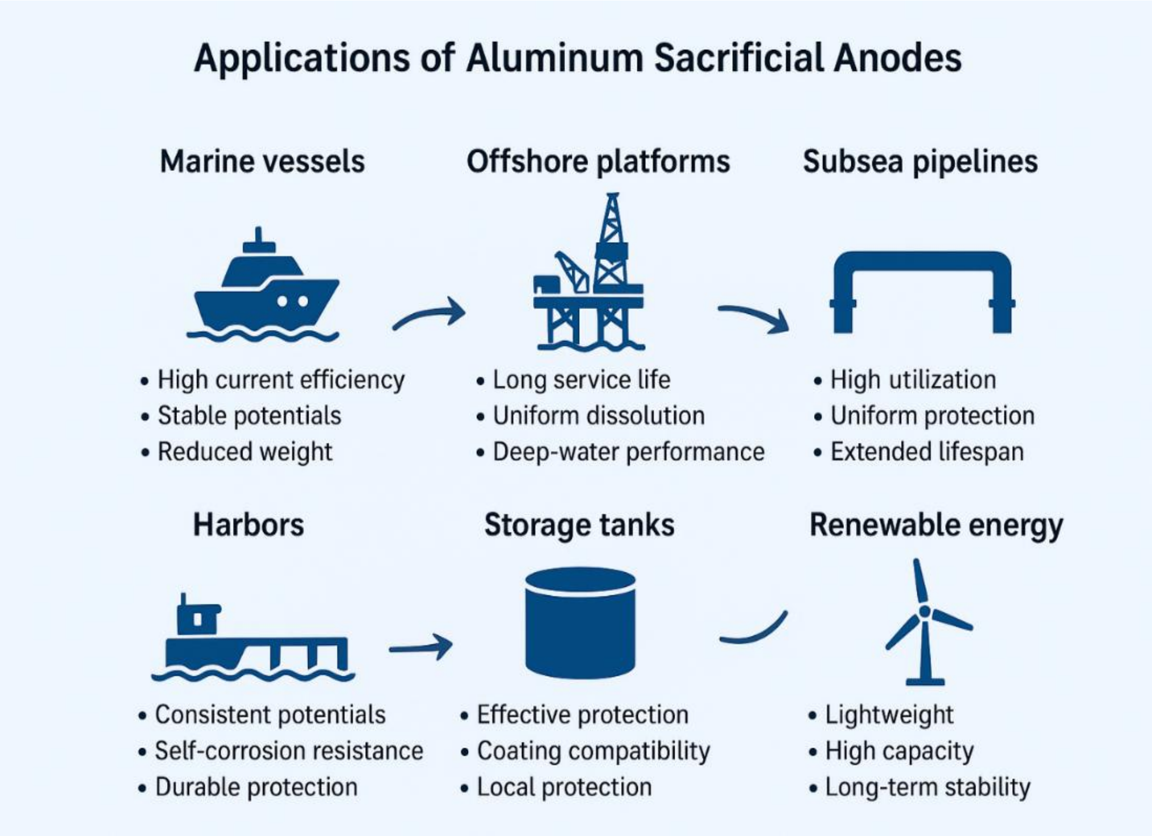

Figure 2. Application of Aluminum sacrificial anodes.

To provide a comprehensive overview of how aluminum sacrificial anodes are employed across various service environments, Table 4 summarizes their principal application domains, operational conditions, and corresponding performance characteristics. Complementing this, Figure 2 schematically illustrates the widespread implementation of aluminum alloy anodes, highlighting their key advantages and versatility in marine, offshore, and renewable energy sectors.

Together, these representations underscore how optimized alloy formulations enable consistent corrosion protection, long service life, and efficient utilization across both conventional and emerging infrastructures.

CHALLENGES AND RESEARCH GAPS

Although aluminum alloy sacrificial anodes have achieved significant success in marine, offshore, and energy infrastructure applications, ongoing research continues to reveal unresolved challenges and new opportunities for performance enhancement. The evolution of design and alloy optimization has expanded their applicability; however, several scientific and practical gaps remain that must be addressed to realize their full potential.

Table 4. Summary of applications, design considerations, and performance factors for Aluminum Sacrificial Anodes.

Application Area	Typical Installation/ Geometry	Key Design & Environmental Considerations	Performance Highlights	Representative References
Marine vessels (hulls, rudders, ballast tanks)	Welded or bolted anode blocks on hull or internal tanks	– Seawater temperature (5–30 °C) – Paint breakdown areas – Flow velocity around hull	– High current efficiency (90–95%) – Stable OCP (≈ –1.1 V vs Ag/AgCl) – Reduced fuel consumption due to weight savings.	[52]
Offshore platforms and subsea structures	Welded anode pods on jackets, risers, manifolds	– Depth > 100 m – Low oxygen & temperature – Inspection difficulty	– Long service life (15–25 yrs) – Uniform dissolution – Reliable deep-water performance.	[53]
Subsea pipelines	Bracelet or ring anodes clamped at intervals	– Coating quality and resistivity – Electrical continuity – Soil vs. seawater exposure	– High utilization > 80 % – Uniform potential distribution – Extended pipeline lifespan.	[54]
Harbors, jetties, and coastal structures	Hung or attached anodes on piles, docks, or quay walls	– Tidal immersion and aeration zones – Variable salinity – Biofouling effects	– Consistent potential across tidal range – Resistant to self-corrosion in stagnant zones.	[55]
Storage tanks and seawater systems	Internal anodes suspended or mounted in tanks and coolers	– Restricted electrolyte circulation – Differential aeration – pH control	– Effective local protection – Compatible with coatings and inhibitors.	[56]
Renewable energy systems (offshore wind, tidal, wave)	Mounted on monopiles, foundations, turbine bases	– Dynamic load and current flow – Sediment movement – Difficult maintenance	– Lightweight, high-capacity anodes – Long-term stability under cyclic immersion – Excellent performance in hybrid CP systems.	[32]

Microstructure–Performance Understanding

One of the most critical gaps lies in the limited understanding of how alloying-induced microstructural variations influence anode efficiency, potential stability, and dissolution morphology. While the roles of elements, such as Zn, In, Sn, and Si, are recognized, their synergistic effects on corrosion kinetics and phase evolution remain only partially understood. Advanced microanalytical tools – such as electron backscatter diffraction (EBSD), in-situ electrochemical microscopy, and 3D tomography – can offer deeper insight into the spatial distribution of active and passive regions, thereby guiding the design of alloys with improved uniform dissolution behavior and reduced passivation tendency [57–58].

Long-Term Field Performance and Environmental Influence

Most existing studies evaluate anode performance under controlled laboratory conditions, whereas real-world marine environments introduce fluctuating salinity, temperature gradients, biofouling, and mechanical stress. These factors can accelerate localized corrosion or alter dissolution patterns, leading to premature anode depletion. Long-term field monitoring and data-driven degradation modeling are required to correlate laboratory electrochemical performance with service-life behavior [21, 59]. Such studies would enhance the predictability of design models and improve reliability for extended offshore operations.

Alloy Development for Renewable and Deep-Sea Applications

The rise of offshore renewable energy systems – such as wind, wave, and tidal power – demands lightweight, durable, and environmentally benign anode materials. Current commercial Al–Zn–In systems may not fully meet these evolving requirements, particularly under dynamic potential cycling and multi-material interfaces. Research should focus on novel alloying additions (e.g., rare earths, Ca, or Ti) and nano-modified aluminum matrices to stabilize the passive film and maintain high efficiency under fluctuating electrical loads [60]. Additionally, understanding anode performance in deep-sea and low-oxygen conditions remains an emerging field.

Sustainability and Environmental Compatibility

As global regulations tighten heavy-metal discharge, the environmental impact of aluminum alloy dissolution products must be re-evaluated. Though aluminum alloys are more eco-friendly than zinc or cadmium-based systems, long-term leaching and sediment accumulation can still pose localized ecological risks. Research into recyclable, low-toxicity alloys and green corrosion inhibitors integrated with anodes could provide sustainable alternatives for future use [61–62].

Integration of Smart Monitoring and Modeling Tools

Future progress also depends on integrating real-time monitoring systems and computational modeling into anode design. The use of digital twins, machine learning algorithms, and electrochemical simulation frameworks can predict potential distribution, anode consumption, and system-level protection efficiency with high accuracy. Such digital tools would enable predictive maintenance and adaptive design of cathodic protection systems, aligning with Industry 4.0 principles [63].

CONCLUSIONS

This study comprehensively reviewed the development, alloying effects, performance evaluation, and applications of aluminum alloy sacrificial anodes, emphasizing their growing importance in corrosion protection systems for marine and offshore infrastructures. The findings reaffirm that activated aluminum alloys, particularly Al–Zn–In-based compositions, offer a balanced combination of high current efficiency, stable potential behavior, and economic advantage over conventional zinc and magnesium anodes.

Alloying additions, such as indium, bismuth, tin, and gallium, play a pivotal role in maintaining activation, suppressing passive film formation, and promoting uniform dissolution morphology. Conversely, impurities, like iron, copper, and silicon, tend to form cathodic intermetallic phases that induce localized corrosion and reduce anode utilization. Therefore, strict control over impurity levels and microstructural refinement is essential to achieve consistent and reliable performance.

A strong microstructure–performance relationship has been established, showing that grain size, phase distribution, and the morphology of intermetallic compounds directly influence dissolution uniformity and electrochemical stability. Properly engineered aluminum alloys thus deliver more predictable potential behavior and enhanced lifetime utilization under real service conditions.

Field and laboratory studies consistently demonstrate that aluminum alloy anodes exhibit 3–4 times higher energy output per unit mass than zinc and maintain effective protection over prolonged immersion periods. Their adaptability to diverse environments – including marine vessels, offshore platforms, subsea pipelines, and renewable energy systems reflects their technological maturity and sustainability.

Despite these advancements, further improvements can be achieved through a deeper understanding of microstructural evolution under variable environmental conditions, long-term field data integration, and computational modeling approaches such as digital twins and machine learning. Additionally, developing environmentally benign alloying systems with reduced heavy-metal content will support compliance with emerging environmental standards.

In summary, aluminum sacrificial anodes represent a cornerstone of modern cathodic protection technology. Continuous innovations in alloy design, manufacturing, and predictive modeling will pave the way for next-generation aluminum anodes-offering higher efficiency, extended service life, and minimal ecological footprint-ultimately contributing to sustainable corrosion management across marine and energy infrastructures.

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