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CORROSION PROTECTION STRATEGIES FOR METALS USING NANOMATERIALS AND COATINGS

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Abstract

Corrosion poses a significant challenge to the durability and efficiency of renewable energy systems, including solar panels, wind turbines, and geothermal installations, which are often exposed to harsh environmental conditions. To address this issue, advanced nanomaterials and innovative coatings have emerged as promising solutions, offering superior protection through enhanced barrier properties, self-healing mechanisms, and environmental sustainability. Nanomaterials such as graphene, Carbon Nanotubes (CNTs), and nanoceramics reinforce coatings with exceptional mechanical strength and corrosion resistance, while smart coatings with embedded microcapsules or stimuli-responsive polymers enable autonomous damage repair. Furthermore, hybrid nanocomposite coatings combine organic and inorganic components to improve UV resistance, hydrophobicity, and electrochemical stability. The integration of IoT-enabled sensors within these coatings allows for real-time corrosion monitoring, enabling predictive maintenance and minimizing downtime. Sustainable alternatives, including bio-based and chromate-free coatings, are also gaining traction to meet stringent environmental regulations. This review explores the latest advancements in nanomaterial-enhanced corrosion protection strategies, highlighting their potential to extend the lifespan, reduce maintenance costs, and enhance the reliability of renewable energy infrastructure. By leveraging these cutting-edge technologies, the renewable energy sector can achieve greater operational resilience and support the global transition toward sustainable energy systems.

Keywords

Corrosion, nanocomposites, electroplating, inhibition, coatings

1. INTRODUCTION

Mild steels remain the most widely used engineering material for construction and other industrial applications due to their constant availability, low cost and relatively good properties. Low resistance to corrosion and wear is their foremost weakness. These disadvantages have necessitated the adoption of many protection methods, using zinc metal as a barrier in a deteriorating environment to improve their operational performance and service life. Zinc has been widely employed for metallic coatings of mild steel surface either by electrodeposition, hot dipping or through other techniques. Thinner coatings are produced via electro-deposition of zinc compared to hot dipping methods which makes it more suitable for forming processes in the automotive industries (Yazdanian et al., 2022). Electrodeposition of zinc changes the surface characteristics of mild steel by the action of electric current. Advances have been made with regard to the surface finishing and coating of mild steel, however, they remain susceptible to corrosion and other forms of environmental and operational degradation over a period of time (Yu et al., 2021). Although, stainless steel has in some cases been utilized as a replacement for mild steel due to higher resistance they offer against corrosion. However, the high cost of stainless steel compared to mild steel is its set back. Zinc CMS has become a more viable option since stainless steel is not completely impervious to corrosion (Yu et al., 2021).

Composite based coating is widely used for a series of applications in manufacturing industries where protection against wear loss, corrosion, high temperature and improved mechanical properties is required. An effective coating has been achieved by the inclusions of ceramics composites in the matrix of zinc and nickel to form exceptional bond matrices of functional coating particulates such as Ni-SiC, Ni-Al_2O_3, Ni-ZrO_2, $ZnZrO_2$, etc .(Ugla et al., 2021). These particulates are deposited with either direct current (DC) or pulse current (PC). In the DC electroplating process, the current is applied continuously to the coating bath; putting into consideration many other factors like compositions and processing parameters. The current is made to alternate between two values in a PC electrodeposition process, and the pulsating parameters enable the ease of variation of the deposit properties .(Ugla et al., 2021).

Electrodeposition is affected by a series of factors. These factors are temperature, pH, cell voltage, current density and particle distributions, metal ions, concentration, agitation (stirring) of bath and deposition time. Generally, the bath concentration, current density, temperature and voltage should be optimised for optimal deposition at the cathode. Agitation is required for the homogenous dispersion and mass movement of the particles (Udhayakumar et al., 2022). Agitation aids the electrophoresis and consequently minimises particle agglomeration and increases the operating current density during coating. It also limits the gas bubbles which may initiate pits on the substrate's surface. However, minimal agitation is needed in order to avoid electrodes movement, which could result in a low-quality coating. The stirring rate, cell voltage, bath pH and bath temperature are known as the bath operating parameters. Increase in the bath's temperature could partially reduce the deposits grain size. The pH and plating time is greatly dependent on solution type used and required thickness respectively (Suriati, 2022).

However, at a certain value of pH and current density, a surface coating can be irregular and the morphology could change from fine grain size to larger grain size (Song et al.,2025). Coating via electrodeposition can fail prematurely, preventing its functions from being realized. The major reasons for premature coating failures are usually due to poor surface preparation and insufficient coating thickness. There are many other reasons why coating deterioration occurs. Incorrect formulation of coating bath may result in low or no coating at all. An unsuitable coating specified for a given environment and conditions different from that understood by the specifiers could as well result in coating with a short life span. More so, improper or insufficient mixing of the coating at the time of application might also lead to low-quality coating. Nonhomogeneous electrodeposition could lead to an un-even deposited coating that is below the functional and dimensional requirements. However, the key to successful plating lies in the ability to control the non-uniformity of electrodeposition so as to avoid electrochemical heterogeneity of the substrate surface that is under electrodeposition (Patil, 2024). Other reasons for coating deterioration are adverse ambient conditions where the coating system is applied, scratches during drying and/or curing process of the coating, chemical, physical and/or mechanical damage to the coating system during exposure. The formulation or nature of coating bath is also vital in ensuring the longevity of coating because research has shown that some coating fails prematurely in certain environments due to wrong bath formulation or inappropriate coating bath constituents and additives (Udhayakumar et al., 2022; Nhiem et al., 2023).

Therefore, it is imperative to pattern the bath formulation and the main constituent after the environment the material will be applied. A coating bath can be sulphate, chloride, sulphamate or Fluorborate. The sulphate and the chloride bath are the most widely used baths. The coating product of the chloride bath is harder with fewer grains compared to the sulphate bath; however, its structure contains more internal stress (Li et al., 2023). The sulphamate baths have the advantage of a high rate of particle deposition, low inner stress and a large throwback power, although, some impurity might be generated in the sulphamate baths which could result in coatings with low compressive stress and ductility (Lee et al,2021). Fluorborate bath also produces a high-rate deposition; however, high cost and low corrosion inhibition of the coating produced are some of the drawbacks of this bath (Li et al., 2023).

Additives are added to coating baths for specific functions. Boric acid is one of the additives added to sulphate and chloride bath to improve the coating appearance and minimize the brittleness of the coating (Li et al., 2023). A lot of researchers have also reported the use of boric acid as a buffering agent against the increment of pH at the coated surface, while saccharin as an organic additive reduces grain size, coating texture, improves hardness and wear resistance (Kumar et al., 2021). Wear has been responsible for most damage in marine, automotive and other manufacturing industries and it is considered during the bath formulation process. Wear occurs when a component rubs over another repeatedly and results in an unavoidable build-up of heat or thermal stress between the surfaces, leading to the formation of debris and material losses (Ikumapayi et al., 2023). The wear debris generated, if they cannot run off the surfaces, could lead to an increase in pressure and ultimate seizure. In a condition where the debris can successfully escape, the outcome is a loss of fit between the surfaces and a decline in clamping pressure leading to greater vibration. Just like corrosion, uncontrolled wear is one of the foremost reasons for mechanical degradation. However, it can be minimised via composite coating with the right additive that can aid protective thin covering the surface on mild steel. The damaging effect of wear on the mechanical component cannot be overlooked because of the resulting overhead cost, material wastage and shortening of the life span of these components (Fan et al., 2024).

Degradation of mild steel within a short time has become a perpetual challenge of great concern in the marine industries. Improvement of the properties of zinc-coated steel with composite particles is paramount. The cost of replacement of corroded and failed parts is enormous. Therefore, there is an immediate need to reduce the corrosion, mechanical degradation and catastrophic failure of mild steel by addressing the following drawbacks: Structural deformation of marine components due to corrosion that results from exposure to contaminant ions; loss in mechanical properties due to continuous loading which results from the buildup of internal stress; vulnerable to defects such as wear debris and deformations that result from the adhesive and abrasive sliding of one surface over another due to the high frictional forces.

2. CORROSION OF STEEL

Steel corrosion represents a fundamental electrochemical process wherein iron reacts with environmental elements to form various corrosion products, primarily iron oxides and hydroxides. This natural degradation process costs the global economy approximately $2.5 trillion annually, representing 3-4% of the Gross Domestic Product (GDP) of most industrialized nations. The electrochemical nature of steel corrosion involves oxidation reactions at anode sites where iron dissolves into solution as Fe^{2+} ions, and reduction reactions at cathode sites where oxygen is reduced to form hydroxide ions. Understanding the specific types of corrosion that affect steel is crucial for developing effective prevention strategies and maintaining structural integrity across industries including construction, marine, energy, and transportation sectors. Corrosion occurs because metals naturally tend to return to their more stable oxidized states, similar to the ores from which they were originally extracted. This process is both spontaneous and electrochemically favored, with the metal losing electrons (becoming oxidized) while environmental substances gain electrons (becoming reduced) (Odetola et al., 2025). The rate and severity of corrosion depend on multiple factors including environmental conditions, material composition, mechanical stresses, and presence of microorganisms. The following sections provide a detailed examination of the various corrosion types that affect steel, their underlying mechanisms, characteristic appearances, and appropriate prevention strategies. The corrosion process in steel is fundamentally electrochemical in nature, requiring an anode, a cathode, an electrolyte, and a metallic path for electron flow. At the anodic sites, iron oxidizes to ferrous ions ($Fe \rightarrow Fe^{2+} + 2e^-$), releasing electrons that travel through the metal. At the cathodic sites, these electrons are consumed in reduction reactions, typically involving oxygen ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$) in neutral or alkaline environments. The resulting ferrous and hydroxyl ions combine to form ferrous hydroxide, which further oxidizes to form various iron oxides and hydroxides that constitute rust (Zhang et al., 2024).

The presence of electrolytes such as saltwater significantly accelerates corrosion by enhancing ionic conductivity between anodic and cathodic sites. Recent advances in molecular simulations have provided deeper insights into corrosion mechanisms at the atomic level. Density functional theory (DFT) and reactive molecular dynamics studies have revealed how chloride ions disrupt protective oxide layers on steel surfaces, facilitating accelerated corrosion in marine environments. These computational approaches have helped researchers understand precise reaction pathways involved in the initial stages of corrosion, enabling development of more effective prevention strategies (Zhang et al., 2024).

2.1 Uniform Corrosion

As reported by Schmitzhaus, et al. (2024), uniform corrosion, also known as general corrosion, represents the most common form of steel degradation. This type of corrosion is characterized by relatively even material loss across the entire exposed surface. The surface effect produced by most direct chemical attacks (e.g., as by an acid) is a uniform etching of the metal. On a polished surface, this type of corrosion is first seen as a general dulling of the surface, and if allowed to continue, the surface becomes rough and possibly frosted in appearance. Uniform corrosion typically occurs over relatively large areas of a material's surface and is considered the most benign form of corrosion because its effects are predictable and easily quantified. The electrochemical reactions in uniform corrosion occur relatively evenly across the surface, with anodic and cathodic areas shifting position over time (Schmitzhaus, et al. 2024). This results in a gradual thinning of the material until it eventually becomes structurally compromised. While this is the most common form of corrosion, it is generally of little engineering significance because structures will normally become unsightly and attract maintenance long before they become structurally affected. However, if left unchecked, uniform corrosion can progress significantly, as evidenced by facilities that show advanced stages of this corrosion type when control measures are not implemented (Oyewo et al., 2024)

Common examples of uniform corrosion include the rusting of iron exposed to moist air and the deterioration of carbon steel structures in atmospheric conditions. Atmospheric corrosion is considered the most common type of uniform corrosion, and all assets made of carbon steel or other metallic alloys exposed to the atmosphere are prone to this type of degradation. A relatable example mentioned in the search results is the rusting of automobile bodies, specifically Mazda6 models between 2005 and 2008, where wheel wells and hood edges showed brown, brittle flaking metal due to uniform corrosion. Prevention methods for uniform corrosion are summarized in Table 1.

Table 1: Comparison of Major Uniform Corrosion Prevention Methods (Alao et al, 2023; Sekar and Bennet, 2023)

Prevention Method	Mechanism of Action	Applications	Limitations
Protective Coatings	Creates a physical barrier between steel and environment	Structural steel, automotive bodies, industrial equipment	Requires maintenance; can be damaged
Weathering Steels	Forms a stable, protective rust layer that reduces further corrosion	Bridges, outdoor sculptures, architectural elements	Not suitable for highly corrosive environments
Cathodic Protection	Forces the steel to become cathodic using sacrificial anodes or impressed current	Underground pipelines, ship hulls, water tanks	Requires ongoing monitoring and maintenance
Environmental Control	educes corrosivity of environment by controlling humidity or adding inhibitors	Closed systems, storage facilities, industrial processes	Not practical for open atmospheres

2.2 Localized Corrosion

2.2.1 Pitting Corrosion

Nhiem, et al (2023), pitting corrosion is an extremely localized form of attack that results in the formation of small cavities or "pits" on the metal surface. This type of corrosion is particularly insidious and dangerous because it can cause catastrophic failure with minimal overall material loss, making it difficult to detect and predict. Pits typically penetrate from the surface downward in a vertical direction and can take on a variety of different shapes. Early stages of pitting corrosion have pit diameters of ≤20 µm. Pitting initiates at sites where the protective passive film on steel breaks down, often due to the presence of chloride ions combined with depolarizers such as oxygen or oxidizing salts. Once a pit forms, it creates an autocatalytic environment where the pit bottom becomes acidic and depleted in oxygen, while the surrounding surface remains cathodic. This creates an accelerating corrosion cell that drives pit growth (Nhiem et al., 2023). The environment inside pits is almost always higher in chlorides and lower in pH (more acidic) than the overall external environment, leading to concentrated attack. Pitting is especially problematic for passive metals like stainless steels, which otherwise resist corrosive media well. Molybdenum additions to stainless steel (e.g., in 316 stainless) are intended to reduce pitting corrosion susceptibility. Pitting corrosion can lead to unexpected catastrophic system failure, as evidenced by the split tubing shown in the search results caused by pitting corrosion of stainless steel (Dubey and Gangwar, 2021).

2.2.2 Crevice Corrosion

Crevice corrosion occurs in shielded areas where a stagnant solution can accumulate, such as under gaskets, washers, bolt heads, lap joints, or surface deposits. This type of localized attack develops due to oxygen concentration cells that form between the crevice (microenvironment) and the external surface (bulk environment). These restricted areas allow a buildup of corrosive fluids while having only a limited supply of oxygen, which prevents re-passivation (Manjunath et al., 2021). The mechanism involves differential aeration where oxygen becomes depleted within the crevice, causing this area to become anodic relative to the oxygen-rich external surface. As corrosion progresses, the crevice environment becomes increasingly acidic and concentrated in chlorides, accelerating the attack. Crevice corrosion can occur at lower temperatures than pitting and is a significant concern for stainless steels, though molybdenum-containing grades (e.g., 316 and 316L) have increased crevice corrosion resistance. Prevention strategies focus on eliminating crevices through improved design (welded butt joints instead of bolted lap joints), using non-absorbent gaskets, and ensuring complete drainage in vessels and structures. Regular cleaning to remove deposits and proper protective coating application are also effective measures (Odetola et al., 2025).

2.2.3 Intergranular Corrosion

Intergranular corrosion is a selective attack that occurs at or adjacent to the grain boundaries of a metal, while the bulk of the grains remain largely unaffected. This type of corrosion seriously affects the mechanical properties of the metal while the bulk of the metal remains intact. Grain boundaries act as an interface between grains in the material and are considered imperfections in the material's crystal structure, often having a different reactivity compared to the grains themselves (Odetola et al., 2025). The most common cause of intergranular corrosion in stainless steels is sensitization, which occurs when the metal is subjected to temperatures between 800°F and 1650°F (427-899°C), such as during welding or improper heat treatment. At these temperatures, chromium carbides precipitate along grain boundaries, depleting the adjacent areas of chromium below the 11% threshold needed to maintain passivity (Ma et al., 2022). This creates a galvanic couple where the chromium-depleted zones become anodic and susceptible to corrosive attack Stainless steels are particularly susceptible to this phenomenon, often referred to as weld decay when it occurs in the heat-affected zones of welds. Prevention methods include using low-carbon grades (e.g., 304L, 316L) that minimize carbide formation, employing stabilized grades with titanium or niobium that form carbides preferentially to chromium, and implementing appropriate heat treatment procedures after welding to dissolve carbides (Ma et al., 2022).

2.3 Environmentally Assisted Corrosion

2.3.1 Stress Corrosion Cracking

Stress corrosion cracking (SCC) is a particularly dangerous form of corrosion that results from the combined action of tensile stress and a specific corrosive environment. This phenomenon causes the formation of fine cracks that propagate through the metal, often with little visible evidence of general corrosion on the surrounding surface. SCC is considered one of the most disastrous types of corrosion because it is difficult to detect before catastrophic failure occurs. The required tensile stress can be either applied stress (from external loads or pressure) or residual stress (from manufacturing processes like cold forming, welding, machining, or grinding) (Ma et al., 2022). The specific corrosive environment varies depending on the alloy; for stainless steels, chlorides are the primary concern, while carbon steels are susceptible to cracking in alkaline environments or those containing nitrates. The cracks typically have a brittle appearance and form and spread in a direction perpendicular to the location of the stress (Ma et al., 2022).

Common types of SCC in process industries include:

i. Sulfide Stress Corrosion Cracking
ii. Amine Stress Corrosion Cracking
iii. Ammonia Stress Corrosion Cracking
iv. Chloride Stress Corrosion Cracking
v. Carbonate Stress Corrosion Cracking

Prevention strategies include selecting resistant materials for the specific environment, reducing residual stresses through stress relief heat treatment, modifying the environment to eliminate cracking agents, and applying protective coatings to isolate the metal from the corrosive environment (Manjunath et al., 2021).

2.3.2 Corrosion Fatigue

Corrosion fatigue occurs when a metal undergoes cyclic loading in a corrosive environment, leading to premature failure at stress levels below the fatigue limit observed in inert environments. Unlike SCC, which requires specific environmental conditions, corrosion fatigue can occur in any corrosive environment that reduces fatigue resistance (Ma et al., 2022). Udhayakumar, et al. (2022) reported the combination of cyclic stress and corrosion produces cracks that typically lack the branching pattern characteristic of SCC. This type of degradation is particularly problematic for components subject to vibration or repeated thermal cycling, such as turbine blades, propeller shafts, and offshore structures exposed to wave action. Prevention methods include improving surface finish to reduce stress concentrations, applying surface treatments like shot peening to introduce compressive stresses, using corrosion inhibitors, and selecting corrosion-resistant materials.

2.3.3 Microbiologically Influenced Corrosion

As stated by Ma *et al.* (2022), microbiologically influenced corrosion (MIC), also known as microbial corrosion, is caused by the presence and activities of microorganisms on metal surfaces. These microorganisms, which include bacteria, fungi, and algae, can accelerate corrosion processes through various mechanisms. MIC is a significant concern in industries like oil and gas, marine, and wastewater management because it can lead to rapid deterioration of materials. Some common mechanisms of MIC include:

i. Sulfate-reducing bacteria (SRB) that produce hydrogen sulfide, a corrosive agent
ii. Acid-producing bacteria that create localized acidic environments

iii. Microbes that create differential aeration cells or disrupt protective films
iv. Organisms that consume corrosion inhibitors or produce corrosive metabolites

MIC can cause various types of damage, including pitting, crevice corrosion, and stress corrosion cracking. Prevention strategies include regular monitoring of microbial populations, using biocides to control microbial growth, purifying fuels to remove water content, and draining water at regular intervals from fuel tanks after purification (Alao et al., 2023).

2.4 Galvanic and Erosion Corrosion

2.4.1 Galvanic Corrosion

Galvanic corrosion, also known as bimetallic corrosion, occurs when two electrochemically dissimilar metals are in electrical contact while exposed to a common electrolyte. In this scenario, the more active metal (anode) undergoes accelerated corrosion, while the more noble metal (cathode) experiences reduced corrosion rates (Alao et al., 2023) The electrolyte provides a medium for the flow of ions between the two metals, completing the electrical circuit. The severity of galvanic corrosion depends on several factors:

i. Difference in potential between the two metals (further apart in the galvanic series lead to greater driving force)
ii. Surface area ratio of cathode to anode (larger cathode relative to anode leads more severe attack)
iii. Nature of the electrolyte (conductivity, composition, temperature)
iv. Duration of exposure to the electrolyte

Examples of galvanic corrosion include aluminum helicopter blades corroding near steel counterbalances, and scuba tanks suffering corrosion where brass valves contact steel tanks when wetted by condensation. Prevention methods include electrically isolating dissimilar metals using insulating materials, selecting metals close together in the galvanic series, applying protective coatings (carefully—coating the cathode is more effective than coating the anode), and using sacrificial anodes to protect both metals .

2.4.2 Erosion Corrosion

Erosion corrosion results from the combined action of corrosive attack and mechanical abrasion or wear caused by the relative movement between a metal surface and a corrosive fluid. This type of corrosion is characterized by the appearance of grooves, gullies, waves, rounded holes, or other directional patterns on the metal surface (Kumar et al., 2021; Dai et al., 2022). The fluid flow damages protective surface films or prevents their formation, exposing fresh metal to continued corrosive attack. This form of degradation is common in piping systems, valves, pumps, heat exchangers, and other equipment handling moving fluids, particularly when solids are suspended in the fluid. The mechanism involves mechanical removal of surface material that would otherwise form protective corrosion products, continually exposing fresh metal to corrosion (Kumar et al., 2021; Dai et al., 2022).

3. PROTECTION METHODS FOR CORROSION OF STEELS

Corrosion of steel is a major concern in various industries due to its potential to compromise structural integrity, leading to costly repairs and safety hazards. Steel corrodes primarily through electrochemical reactions involving oxygen, water, and electrolytes, forming rust that weakens the material over time (Udhayakumar et al., 2022). Protection methods aim to interrupt this process by creating barriers, altering the electrochemical environment, or modifying the steel itself. These methods can be broadly categorized into coatings, catholic protection, inhibitors, alloying, and design considerations, each offering unique advantages depending on the application environment, such as marine, atmospheric, or buried conditions. Effective implementation often combines multiple approaches for optimal results, with regular maintenance ensuring long-term durability. Table 2 presents the factors influencing corrosion rate and mechanisms

Table 2: Factors Influencing Corrosion Rates and Their Mechanisms (Nhiem et al., 2023; Sekar and Bennet, 2023)

Temperature	Increases rate exponentially Accelerates electrochemical reactions and diffusion processes
Chloride Ions	Dramatically accelerates corrosion Disrupts protective passive films and enhances electrolyte conductivity
pH Level	Acidic environments increase corrosion Low pH dissolves protective films and increase hydrogen evolution

Humidity	Above critical humidity accelerates corrosion Enables formation of electrolyte layer on metal surface
Mechanical Stress	Initiates stress corrosion cracking Synergistic effect of tensile stress and corrosive environment
Microorganisms	Accelerates through metabolic products Bacteria produce corrosive acids and create differential aeration cells

3.1 Barrier Coatings

Barrier coatings are one of the most common and cost-effective methods to protect steel from corrosion by physically isolating the metal surface from corrosive agents like moisture, oxygen, and salts. These coatings include paints, plastics, powders such as epoxy, nylon, and urethane, as well as waxes and sprayed plastics (Omran et al., 2022). A typical modern paint system consists of multiple layers: a primer that inhibits corrosion, intermediate coats for thickness and durability, and a finish coat that resists environmental factors like UV radiation and chemicals. The primer is often applied immediately after surface preparation to prevent initial rusting, while build coats add protective depth, and the topcoat provides aesthetic and additional barrier properties. Application methods vary, with airless spray being preferred in controlled shop environments for uniform coverage, brushes for edges and site touch-ups, and rollers for larger on-site areas. However, improper application can lead to failures such as cracking or peeling, allowing corrosive elements to penetrate and accelerate degradation (Omran et al., 2022). Advantages include ease of application and low cost, but disadvantages encompass the need for periodic reapplication, potential VOC emissions, and environmental hazards during stripping and recoating processes.

In marine environments, barrier coatings like epoxy and polyurethane layers are particularly effective, creating impermeable films that block chloride ions and moisture ingress, which are prevalent in seawater and can cause pitting and crevice corrosion. These organic coatings are often combined with zinc-rich primers to enhance protection, where the zinc provides sacrificial corrosion resistance if the barrier is breached. For buried steel, physical barriers such as tapes, wraps, or extruded polyethylene coatings prevent direct contact with soil electrolytes, reducing the risk of underground corrosion. Surface preparation is crucial for barrier coatings; abrasive blast cleaning to standards like Sa 2½ removes mill scale and rust, creating a rough profile for better adhesion. Without proper preparation, coatings may delaminate, leading to localized corrosion. Advanced formulations, including polyurethane-based products, incorporate self-healing properties or inhibitors that activate upon damage, extending the coating's lifespan in harsh conditions.

3.2 Metallic Coatings

Metallic coatings protect steel by applying a layer of more corrosion-resistant metal, which either acts as a barrier or sacrificially corrodes in place of the steel substrate. Hot-dip galvanizing is a prominent method, where steel is immersed in molten zinc at around 450°C after pickling and fluxing, forming a metallurgically bonded zinc-iron alloy layer topped with pure zinc ((Nhiem et al., 2023). This coating, typically 85µm thick for structural steel, provides cathodic protection to small damaged areas and is highly durable in atmospheric and marine settings, lasting decades with minimal maintenance. However, it cannot be applied on-site for large structures, and zinc fumes pose health risks during the process. Thermal spraying, another metallic coating technique, involves propelling molten zinc, aluminum, or zinc-aluminum alloy particles onto a grit-blasted steel surface using a flame or electric arc, creating a porous layer that is then sealed with an organic topcoat to prevent moisture ingress (Nhiem et al., 2023). This method offers flexibility for on-site application and excellent adhesion through mechanical interlocking, but the porosity requires sealing to avoid under-film corrosion.

As reviewed by Udhayakumar, et al. (2022), alloyed steels, such as stainless steel, incorporate elements like chromium and nickel to form naturally protective passive films—thin oxide layers that self-heal in the presence of oxygen, significantly reducing corrosion rates. These alloys are ideal for oxidized or reduced chemical environments but are expensive, limiting their use to high-value applications. In marine contexts, Zn-Al metallic coatings serve as sacrificial anodes, oxidizing preferentially to shield the steel from aggressive chloride attacks. Galvanizing also protects steel by creating a zinc barrier that corrodes slowly, forming stable compounds like zinc carbonate that further inhibit rust formation. For buried or submerged steel, these coatings must be complemented with additional measures like backfill control to prevent mechanical damage. Overall, metallic coatings excel in providing long-term protection but require careful selection based on environmental exposure and potential for galvanic corrosion if dissimilar metals are in contact.

3.3 Cathodic Protection

Cathodic protection prevents corrosion by making the steel surface the cathode in an electrochemical cell, shifting the potential to favor reduction reactions over oxidation. This is achieved through sacrificial anodes—typically zinc, magnesium, or aluminum—attached to the steel, which corrode instead, supplying electrons to neutralize corrosive charges (Nhiem et al., 2023). In the impressed current systems, an external power source drives the current through inert anodes like high-silicon cast iron, protecting larger structures like pipelines or offshore platforms. The method is highly effective in high-conductivity environments like seawater but less so in high-resistivity soils, and anodes require periodic replacement to maintain efficacy. Advantages include robust protection against uniform and localized corrosion, but drawbacks involve added weight, maintenance costs, and potential overprotection leading to hydrogen embrittlement in high-strength steels.

In marine applications, cathodic protection is often combined with coatings to minimize current demand and extend anode life, as bare steel requires significantly more current. For example, zinc anodes on ship hulls or offshore structures sacrificially corrode, protecting the steel even if coatings are damaged (Oyewo et al., 2023). The NASA fundamentals highlight how connecting dissimilar metals, like zinc to copper, halts corrosion on the nobler metal by accelerating anode dissolution. Proper design ensures uniform current distribution, avoiding shielded areas where corrosion could persist. This method is essential for buried steel pipelines, where backfill and anode placement are critical to prevent external corrosion from soil electrolytes (Oyewo et al., 2025).

3.4 Corrosion Inhibitors

Corrosion inhibitors are chemical compounds added to the environment or applied to the steel surface to reduce corrosion rates by forming protective films or interfering with electrochemical reactions (Yadav et al., 2024). Ecological inhibitors like sodium phosphate chemically interact with steel to create passive layers, achieving up to 91.7% inhibition efficiency in marine settings by adsorbing onto the surface and blocking anodic or cathodic sites. Organic inhibitors, such as amines or phosphonates, are incorporated into coatings or fluids, forming molecular barriers that prevent ion diffusion. Inorganic types, like chromates (though phased out due to toxicity), passivate the surface by promoting oxide film formation. Advantages include low cost and ease of application in closed systems like boilers or cooling towers, but disadvantages involve potential environmental harm and the need for continuous replenishment in open systems.

In marine environments, inhibitors are used in conjunction with coatings; for instance, high-ductility cementitious composites incorporate self-healing agents that deposit calcium carbonate to seal cracks and inhibit chloride penetration. Superhydrophobic surfaces, created through nano-modifications, repel water and inhibit biofilm formation, maintaining effectiveness even after abrasion. These advanced inhibitors offer eco-friendly alternatives, reducing reliance on toxic chemicals while providing robust protection against pitting and crevice corrosion common in saltwater (Yadav et al., 2024).

3.5 Design and Surface Preparation

In the study of Yadav, et al. (2024), effective corrosion protection begins with thoughtful design and thorough surface preparation to minimize vulnerable areas and ensure treatment efficacy. Design considerations include avoiding water traps, crevices, and bimetallic contacts that accelerate galvanic corrosion, using thicker sections in high-exposure areas, and incorporating ventilation to reduce humidity. Selecting corrosion-resistant alloys or galvanized steel from the outset enhances longevity, particularly in coastal or polluted locations where salt spray and pollutants exacerbate degradation Comparison of Advanced Nanomaterial-Based Corrosion Protection Systems (Udhayakumar et al., 2022). Ongoing inspections and environmental monitoring help identify early issues, allowing timely interventions. Surface preparation, such as abrasive blast cleaning, removes contaminants and creates a profile for coating adhesion, with standards like Sa 3 ensuring visually clean steel. Chemical cleaning or pickling dissolves oxides, while testing for salts and roughness verifies readiness. Proper insulation and ventilation prevent condensation, a key corrosion driver, by maintaining dry conditions. Collaborating with experienced fabricators ensures integrated protection strategies, combining design, materials, and maintenance for structural safety. Comparison of advanced nanomaterial-based corrosion protection systems (Lee et al., 2021). A comparison of advanced nanomaterial-based corrosion protection systems.

Table 3: Comparison of Advanced Nanomaterial-Based Corrosion Protection Systems (Lee et al., 2021; Nhiem et al., 2023)

Nanomaterial Type	Protection Mechanisms	Key Advantages	Limitations
Layered Double Hydroxides (LDHs)	Inhibitor release, chloride capture, self-healing	Responsive to corrosion triggers, multifunctional	Complex synthesis, potential inhibitor depletion
Graphene & Derivatives	Barrier protection and electrical conductivity	Exceptional barrier properties, mechanical strength	Dispersion challenges, cost considerations
Polymer Nanocomposites	Enhanced barrier, passive layer formation	Tunable properties, improved mechanical strength	Potential aggregation, interface compatibility issues
Metallic Nanoparticles	Sacrificial protection, barrier enhancement	Multifunctional, electrical conductivity	Potential galvanic coupling concerns
Silica Nanoparticles	Pore blocking, barrier enhancement	Improved coating density, UV resistance	Limited active protection capabilities

4. APPLICATION IN DIFFERENT SECTORS

4.1 Industry and Manufacturing

One of the primary applications of nanomaterials in general industries is the enhanced barrier protection they offer. Unlike conventional polymer coatings that can be permeable to corrosive agents over time, nanocomposite coatings integrate nanoparticles (e.g., titanium dioxide (TiO_2), zinc oxide (ZnO), silicon dioxide (SiO_2), graphene, or carbon nanotubes) into a polymer matrix. The nanoscale fillers create a more tortuous path for corrosive species like water, oxygen, and ions to penetrate the coating. This significantly increases the diffusion resistance and reduces the ingress of corrosive electrolytes to the metal surface, thereby extending the protective life of the coating ((Lee et al., 2021). For instance, studies have shown that the incorporation of TiO_2 nanoparticles can enhance the compactness and crosslink density of epoxy resin coatings, leading to improved corrosion resistance by reducing transport paths for corrosive electrolytes. Similarly, ZnO nanoparticles have been demonstrated to enhance hydrophobicity and maintain impressive corrosion resistance even after extensive exposure, making them suitable for outdoor industrial applications (Kumar et al., 2021; Dai et al., 2022)

According to Saini, et al. (2023), beyond passive barrier properties, nanomaterials also enable active corrosion inhibition. Certain nanoparticles possess inherent corrosion-inhibiting properties or can be engineered to release inhibitors upon sensing the onset of corrosion. For example, cerium oxide nanoparticles can act as effective corrosion inhibitors by forming protective oxide layers on the metal surface. These "smart" coatings can respond to environmental cues, such as changes in pH or localized damage, by releasing encapsulated corrosion inhibitors. This self-healing functionality is a revolutionary concept, allowing the coating to autonomously repair minor defects like scratches or cracks before corrosion can propagate extensively, thereby significantly extending the service life of metallic components and reducing the need for manual inspection and repair. This capability is particularly valuable for complex machinery and large structures where regular maintenance is challenging and costly (Das, 2022).

4.2 Automotive Industries

Cars and other vehicles face a huge challenge from corrosion, which wreaks havoc on how they look, how strong they are, how safe they are, and how long they last. Parts ranging from the outside body and frame to the engine's insides and the exhaust system are constantly exposed to nasty environments like road salt, humidity, acid rain, and blistering heat. While traditional ways to fight rust do help, they often fall short over the long haul. This is where nanomaterials and nanocoating are stepping in as game-changers, offering incredible protection, tougher durability, and even the ability to fix themselves, completely reshaping how the auto industry battles corrosion (Chithra et al., 2022).

As reported by Butler, et al. (2023), exhaust systems are another prime target for severe corrosion because they're hit with hot, corrosive exhaust gases, condensation, and outside factors like road salt. Nanocomposite coatings specifically designed for high-temperature use are proving incredibly effective at protecting these parts. By embedding nanoparticles that resist oxidation and chemical breakdown at high temperatures, these coatings form stable, protective layers on materials like stainless steel, which is common in exhaust systems. The barrier created by these nano-coatings stops aggressive substances in exhaust gases from reaching and corroding the metal, thereby making mufflers, catalytic converters, and exhaust pipes last much longer. Research even suggests these advanced materials can greatly reduce the likelihood of pitting corrosion, even when there's a lot of chloride around (Li et al., 2023).

The exciting field of self-healing nanocoating holds immense promise for the auto industry, tackling the problem of small damage that can compromise corrosion protection. These smart coatings are designed to automatically fix minor scratches, chips, or tiny cracks before corrosion can even get a foothold (Nhiem et al., 2023). They typically have little capsules (either micro or nano-sized) filled with healing agents or corrosion inhibitors hidden within a polymer base. When damage happens, these capsules burst, releasing their contents to fill and seal the flaw, effectively bringing the coating's protective barrier back to life. For example, some self-healing coatings for car surfaces have been developed that can fix scratches in just minutes when exposed to sunlight, using light energy to kickstart a molecular repair process. This technology is incredibly valuable for external body panels, where minor dings and scrapes are common, cutting down on expensive repainting and keeping the vehicle looking pristine while staying protected. Integrating these "smart" materials aligns perfectly with the automotive industry's push for less maintenance, longer service life, and a more sustainable future.

4.3 Aerospace and Aviation

When it comes to the aerospace and aviation industries, materials simply have to perform perfectly, especially in their ability to resist corrosion. That's because aircraft, spacecraft, and their parts are constantly hit with a mix of tough conditions: huge swings in temperature, changing air pressures, lots of humidity, salt spray (particularly near coasts), industrial pollution, and even cosmic radiation. Corrosion in these fields isn't just an annoyance; it can lead to devastating structural failures, endanger safety, balloon maintenance costs, and drastically cut the useful life of incredibly expensive equipment. While older chrome-based coatings did a decent job, they're now under intense pressure from regulations due to their toxicity. This push is forcing the industry to find fresh, eco-friendly alternatives, and nanomaterials and their coatings are leading the charge (Chithra et al., 2022).

For an aircraft's structure and outer skin, mostly made of lightweight aluminum alloys, nanomaterials are bringing a groundbreaking leap in corrosion protection. Aluminum alloys are great because they're strong yet light, which is key for saving fuel, but they're naturally prone to different types of corrosion like pitting, flaking, and corrosion between their grains, especially in wet or salty environments. Nanocomposite coatings, which typically blend nanoparticles like CeO_2, TiO_2, or SiO_2 into polymer or sol-gel bases, form an incredibly dense and impenetrable shield (Kumar et al., 2021). These tiny particles fill in microscopic gaps and flaws in the coating, making it much harder for corrosive agents like water and chloride ions to get through. Research has shown that these coatings stick really well to aluminum and stand up remarkably to salt spray and electrochemical corrosion, even after long periods, outperforming older protective layers. Plus, their thinness and lightness are huge perks for aerospace, adding minimal weight and boosting the aircraft's overall performance and fuel efficiency (Kumaret al., 2021).

In the study of Dhiman and Singla (2024), it was reported that the rise of self-healing nanocoating is particularly transformative for aerospace, where even minor damage can have severe consequences. These smart coatings are designed to automatically fix small cracks or scratches. They typically contain tiny capsules filled with healing agents or corrosion inhibitors. If damage occurs, the capsules burst, releasing their contents to seal the flaw on their own. This automatic repair mechanism stops corrosion from starting and spreading locally, which is vital for keeping large aircraft structures intact—structures that are tough and costly to inspect and repair by hand. The reduction in unexpected maintenance and the ability to space out maintenance checks, thanks to these self-healing abilities, directly translates into huge operational savings and more available aircraft, boosting fleet efficiency and safety. Furthermore, there's a major push to swap out toxic chrome-based primers and coatings for eco-friendly, yet highly effective, nanomaterial solutions, aligning with stricter environmental rules and sustainability goals across the aerospace sector.

4.4 Marine industry

The marine environment poses a significant threat to renewable energy systems due to its inherently corrosive nature, marked by high salt content, dissolved oxygen, fluctuating temperatures, and the presence of marine organisms. These factors accelerate the degradation of materials, especially metallic components found in offshore wind turbines, tidal energy devices, and wave energy converters. This degradation shortens their lifespan, increases maintenance expenses, and can lead to structural failures. Therefore, robust corrosion protection strategies are essential to ensure the longevity and efficiency of marine renewable energy infrastructure (Hussnain et al., 2023; Hussnain et al., 2024).

4.4.1 Effect of Nanomaterials in Preventing Corrosion in Marine Renewable Energy

Nanomaterials offer a promising solution for improving corrosion protection in marine renewable energy systems, thanks to their unique properties such as a large surface area, enhanced strength, and superior barrier capabilities. One key application involves developing corrosion inhibitors based on nanoparticles. For instance, cerium oxide nanoparticles have shown excellent ability to prevent corrosion in aluminium alloys when exposed to marine conditions by forming a protective layer on the metal's surface (Hussnain et al, 20244). These nanoparticles can also be engineered to release protective chemicals in a controlled manner, preventing damage during corrosive attacks. Another important application is the use of nanocoating and nanocomposites. Integrating various nanomaterials like graphene, carbon nanotubes, and metal oxide nanoparticles (e.g., Al_2O_3, TiO_2) into polymer matrices significantly improves their ability to block corrosive agents. These nanocoating create dense, flawless films that act as a physical barrier, stopping water, oxygen, and corrosive ions from reaching the underlying metal. They also boost the mechanical properties of the coatings, such as adhesion, hardness, and wear resistance, which are crucial for withstanding the harsh physical stresses in marine environments. For example, research has shown that nano-composite coatings containing metal oxide nanoparticles and carbon nanotubes on steel substrates dramatically improved corrosion resistance, reducing the corrosion rate by up to 85% compared to traditional coatings.

Furthermore, the concept of self-healing nano-coatings is gaining traction. These intelligent coatings are designed to automatically repair damage, like scratches or cracks, which could otherwise expose the metal to corrosive elements. This is often achieved by embedding nano-capsules filled with corrosion inhibitors or healing agents within the coating material. When damage occurs, these nano-capsules break open, releasing their contents to repair the compromised area and restore the coating's protective barrier. This approach significantly extends the life of coatings and reduces the need for frequent manual repairs, which is particularly advantageous in challenging offshore environments.

4.5 Biomedical applications

Nanomaterials offer revolutionary solutions for improving corrosion protection in medical devices, primarily because of their exceptional surface area, customizable properties, and ability to interact at a cellular level. A key application involves creating nanoparticle-based corrosion inhibitors. For instance, nanoparticles of cerium oxide and graphene quantum dots show promise in safeguarding metallic implants by neutralizing harmful reactive oxygen species and forming protective films, thereby reducing oxidative stress and corrosion (Alao et al., 2023) These nanoparticles can also be designed to be compatible with the body and biodegradable, minimizing concerns about long-term toxicity.

Another critical area is the use of nanocoating and nanocomposites. Incorporating various nanomaterials like titanium dioxide (TiO_2) nanoparticles, hydroxyapatite (Hap) nanocrystals, and graphene into polymer or ceramic bases significantly boosts the corrosion resistance and biocompatibility of implant surfaces (Song et al., 2025).These nanocoating form a dense, strongly adhering barrier that stops corrosive ions from bodily fluids from reaching the underlying metal implant. For example, a TiO_2 nanocoating can enhance the corrosion resistance of surgical stainless steel while also promoting osteointegration (the direct bond between bone and implant) due to its biocompatibility. Similarly, Hap nanocomposites mimic natural bone, reducing adverse reactions and improving long-term stability for orthopaedic implants (Patil et al., 2024).

Additionally, self-healing nanocoating are an emerging innovation for biomedical implants. These smart coatings are designed to automatically repair microscopic damage that could compromise the implant's integrity and lead to corrosion. This often involves embedding tiny capsules containing corrosion inhibitors or beneficial biological agents within the coating material. When damage occurs, these nano capsules burst, releasing their contents to seal the affected area and restore the protective barrier, thereby extending the implant's lifespan and reducing the need for repeat surgeries.

4.5.1 Coatings Prevention in Biomedical Applications

Both traditional and cutting-edge coating systems are crucial for corrosion protection in biomedical uses, forming an essential interface between the implant material and the body's intricate physiological environment. Biocompatible polymer coatings, such as polyethylene glycol (PEG), polylactic-co-glycolic acid (PLGA), and polydimethylsiloxane (PDMS), are widely employed (Fan et al., 2024). These coatings act as inert barriers, preventing direct contact between the metallic implant and bodily fluids, thereby reducing the release of ions and allergic reactions. They can also be engineered to prevent protein buildup and cell adhesion, which helps lessen inflammatory responses and improve compatibility with the body (Dhiman and Singla,2024)].

The incorporation of drug-eluting coatings represents another sophisticated application in biomedicine. These coatings are designed to release specific therapeutic agents, such as anti-inflammatory drugs or antibiotics, in a controlled manner directly at the implant site. This localized drug delivery not only helps prevent infection or reduce inflammation—common issues after implant surgery—but can also contribute to a more stable and corrosion-resistant interface by modulating the biological response around the implant. For example, drug-eluting stents combine corrosion protection with the prevention of restenosis (re-narrowing of blood vessels) by releasing anti-proliferative drugs. The combined strength of robust corrosion protection and targeted biological functions ensures the long-term success and safety of biomedical implants (Li et al, 2023).

4.6 Construction and Infrastructure

The longevity and effectiveness of renewable energy systems are profoundly tied to how their internal makeup and supporting structures are built. These systems, whether they're wind farms, solar arrays, or biomass plants, are intricate combinations of different materials like metals, plastics, ceramics, and composites. Each material has a specific role within the larger operational framework. The "constitution" refers to the fundamental materials used and their arrangement, including their chemical makeup, microscopic structure, and how different components connect. The "infrastructure," on the other hand, includes the larger physical structures and networks that facilitate energy generation, transmission, and distribution, such as wind turbine towers, solar panel frames, pipelines, power lines, and their foundations (Butler et al., 2023). The constitution of renewable energy systems largely determines their natural ability to resist degradation, including corrosion. For example, wind turbine blades are typically crafted from lightweight, high-strength fiberglass or carbon fiber composites, while the tower and internal parts are mostly steel. The gearbox, generator, and bearings often feature various alloys chosen for their specific mechanical properties. In Solar Photovoltaic (PV) systems, the cells themselves are silicon, encased in polymers like EVA, shielded by glass, and framed with aluminum. Electrical connections frequently use copper or silver. Biomass energy facilities utilize a broader array of materials, including various types of steel for boilers, pipes, and structural elements, as well as specialized alloys for components exposed to high temperatures and corrosive gases (Dai et al., 2022).

The inherent challenge lies in the fact that many of these essential materials, particularly metals like steel and aluminum, are prone to corrosion, especially when exposed to harsh environments. This could be salty marine air for offshore wind installations, humid conditions for solar farms, or corrosive chemicals in biomass processes. The points where different metals meet within a system can also create galvanic corrosion cells, accelerating deterioration (Chithra et al., 2022). Therefore, understanding the inherent properties of these materials and how they interact is crucial for effective corrosion protection. Corrosion within this infrastructure can lead to significant structural weakening, operational inefficiencies, and ultimately, catastrophic failures. For example, corrosion of steel towers in wind turbines can jeopardize their structural integrity, while corroded solar panel frames can cause panels to detach. In offshore wind, underwater corrosion of foundations is a major concern, potentially leading to expensive repairs or even structural collapse. Consequently, the application of nanomaterials and advanced coatings is not just an optional extra but a vital part of the design and maintenance strategy for these crucial infrastructure elements, ensuring their longevity and the consistent supply of renewable energy .

5. CONCLUSION

The integration of nanomaterials and advanced coatings represents a transformative approach to corrosion protection in renewable energy systems, addressing the critical need for durability and efficiency in harsh environments. Innovations such as graphene-enhanced barriers, self-healing polymers, and hybrid nanocomposite coatings offer unprecedented resistance to moisture, UV radiation, and chemical degradation, significantly extending the lifespan of solar panels, wind turbines, and geothermal components. Emerging technologies like smart coatings with embedded IoT sensors enable real-time corrosion monitoring, facilitating predictive maintenance and reducing operational costs. Additionally, the shift toward eco-friendly, bio-based nanomaterials ensures compliance with environmental regulations while maintaining high performance. As research and commercialization progress, these cutting-edge solutions will play a pivotal role in enhancing the reliability and sustainability of renewable energy infrastructure, supporting global efforts toward a cleaner and more resilient energy future. By leveraging nanotechnology and smart coatings, the renewable energy sector can mitigate corrosion-related challenges, optimize system performance, and accelerate the transition to sustainable power generation.

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