Dean&Francis

ISSN 2959-6157

Applications and Mechanism of Nanotechnology in Metal for Corrosion Protection

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Abstract:

Utilizing the unique properties of nano-scale materials, nanotechnology has emerged as an innovative approach for combating metal corrosion. Based on a meta-analysis of current literature, this article reviews the developmental trajectory of nanotechnology in this field and categorizes its anti-corrosion mechanisms into three primary types: barrier enhancement, active inhibition, and destruction of occurrence conditions. Among these, barrier enhancement relies on physical mechanisms such as the tortuous path effect and pore blocking to passively impede the penetration of corrosive agents and reduce their diffusion rates. In contrast, active inhibition employs chemical strategies, often through stimuli-responsive nanocontainers that release corrosion inhibitors upon damage—enabling self-healing functionality either autonomously or through external control. The most proactive mechanism aims to eliminate the fundamental conditions required for corrosion, with representative examples including superhydrophobic surfaces that repel electrolytes and surface modifications that enhance chemical inertness. Each strategy is evaluated in terms of performance, durability, and practicality, while future prospects highlight the need for multi-functional integrated systems, smarter responsive coatings, improved economic viability, and environmentally sustainable designs.

Keywords: Nanotechnology; metal corrosion prevention; anti-corrosion mechanisms.

1. Introduction

Corrosion prevention of metal products is critically essential for public safety, economic stability and sustainability. Acting as an important issue in infrastructure, energy, transportation and industrial production sector, appropriate methods of prevention are able to extend service time, reduce environmental pollution and even prevent catastrophic failures caused by structural deterioration. Among these

ISSN 2959-6157

methods, nanotechnology with the advantages of materials customization, is widely applied in the field of metal corrosion protection. Thus, this study aims to understand the development trajectory of nanotechnology and its underlying core mechanisms. With meta-analysis of current technologies, core mechanisms of anti-corrosion nanomaterials could be categorized into three types: barrier enhancement, active inhibition and destruction of occurrence conditions.

2. The Development Trajectory of Nanotechnology

Generally, nanotechnology operates at the scale of 1 to 100 nanometers, a realm where materials exhibit enhanced strength, heightened chemical reactivity, and quantum effects. Its core advantage lies in the ability to engineer materials with customized functions, paving the way for revolutionary advancements across chemistry, physics, and a wide range of interdisciplinary fields. [1]

Modern nanotechnology initially inspired by Richard Feynman, the 1965 Nobel Laureate in Physics. At the 1959 American Physical Society meeting at Caltech, Feynman presented a landmark lecture titled „There's Plenty of Room at the Bottom" [1]. In the lecture, the concept of manipulating matter was first introduced at the atomic level, leading a scientific consensus on the viability of this novel idea. Consequently, scientists from diverse research disciplines, have undertaken extensive research and development efforts in nanotechnology, encompassing both experimental trials and theoretical derivations. Theoretically, nearly two decades after Feynman's lecture, Norio Taniguchi, a Japanese scientist, first adopted the term „nanotechnology" to illustrate nanometer-scale semiconductor processes [2]. Theoretically, nearly two decades after Feynman's lecture, Norio Taniguchi, a Japanese scientist, first adopted the term „nanotechnology" to illustrate the manipulation of materials by individual atoms or molecules. He explained that via processing, separation, consolidation, and deformation, materials could be precisely processed at the atomic or molecular scale. La Later, K. Eric Drexler expanded on Taniguchi's concept by creating a framework that placed a central emphasis on the capacity for construction with atomic-level precision in nanotechnology [3]. However, Drexler's theoretical framework was improved by a major experimental breakthrough. The discovery of carbon nanotubes, a tangible and revolutionary material, verified the singular potential inherent in nanotechnology, leading a significantly accelerating progress in the related research field.

At the beginning of the 21st century, a growing enthusiasm spurred significant participation from both individual researchers and national governments. In 2000, the United States is a typical example. In 2000, the federal government established a national nanotechnology program, the National Nanotechnology Initiative (NNI), which aimed to advance fundamental research and foster application development in nanotechnology. Between 2001 to 2010, the federal government invested approximately $12.4 billion in nanoscale science, engineering, and technology [4]. This substantial federal commitment together with billions more in investments from state governments and private companies collectively provides strong support for the development of nanotechnology during this period. The continued prioritization of the field is evidenced by President Obama's FY2011 budget request for an additional $1.8 billion in NNI funding [5]. Inspired by the aforementioned efforts, nations worldwide have significantly increased their research and investment in nanotechnology, leading to rapid growth and flourishing applications across a diverse array of disciplines, including higher-capacity batteries, targeted drug delivery, water purification, stain-resistant fabrics, anti-corrosion coatings and so on.

With the booming development of nanomaterials science, the application of nanotechnology in the field of metal corrosion protection has developed with remarkable speed. Scientists explore the application of the unique properties of nanomaterials (such as small size effect, surface reactivity, high strength, and toughness) into traditional areas, with metal corrosion protection being one of them. By the beginning of the 21st century, as nanotechnology matured, research shifted from simple physical filler applications towards more intelligent and more active protection strategies. Current research in nanotechnology for metal corrosion protection continues to evolve toward greater refinement, practicality, and industrialization by advanced characterization techniques [6]. The developmental process of nanotechnology in metal corrosion protection reflects a trajectory of continuous advancement—from passive protection to active smart protection, from single-function materials to multifunctional integration, and from laboratory-based research to industrial application. It has become one of the key cutting-edge technologies for enhancing material performance, extending equipment lifespan, and conserving resources. It is precisely this evolution that underscores the critical importance of understanding the underlying mechanisms of nanoscale protection, which is essential for developing increasingly efficient, durable, and intelligent anti-corrosion solutions.

3. Mechanisms of Corrosion Protection by Nanomaterials

In the literature, based on the type of corrosive reaction, the mechanisms of metal corrosion have been traditionally classified into three categories: physical, chemical, and electrochemical corrosion [7]. Among them, physical corrosion involves pure physical dissolution processes, either between liquid–solid or solid–solid mixtures, and is relatively uncommon in practical engineering applications. Chemical corrosion, meanwhile, entails direct chemical reactions between metallic materials and non-electrolytes in the environment, resulting in the formation of metallic compounds. In contrast, electrochemical corrosion constitutes the majority of corrosion cases. It occurs in the presence of electrolytes—such as aqueous or humid environments, and involves redox reactions facilitated by electron transfer. This form of corrosion is widely recognized as one of the most destructive forms affecting metallic materials. According to existing literature, this tripartite framework has long provided for understanding metal anti-corrosion strategies. However, with ongoing scientific and technological advancements, the classification has increasingly revealed its limitations, failing to clearly distinguish the overlapping mechanisms in complex cases of corrosion protection and fully capture the interdisciplinary nature of modern corrosion protection mechanisms.

Thus, to further elucidate nanotechnology applications for metallic corrosion protection, the underlying mechanisms of corrosion protection could be categorized into following three types, including barrier-enhanced material, active-inhibition and occurrence condition destruction. This category organizes anticorrosion strategies based on their operational nature, ranging from passive to active interventions, reflecting the degree to which each mechanism engages with the corrosion process.

3.1 Barrier Enhancement

The first category employs a physical barrier enhancement strategy, achieved by incorporating nanomaterials into traditional alloys. Nanomaterials could significantly reduce the diffusion rate of corrosive substances. The following section discusses three representative cases, each demonstrating a distinct mechanism by which this approach extends the service life of metals.

3.1.1 Tortuous Path Effect

The tortuous path effect operates through the deliberate design of a complex internal nanostructure within the material, which significantly prolongs the diffusion pathway of corrosive agents through the protective layers. This mechanism is further amplified when two-dimensional nanomaterials are oriented parallel to the metal substrate, resulting in a highly intricate labyrinth-like architecture that substantially hinders the infiltration of corrosive species. This protective mechanism highly relies on the uniform dispersion of two-dimensional nanomaterials (e.g., graphene, MXene, or hexagonal boron nitride) within the coating matrix. These materials serve as an ideal barrier for constructing a „labyrinth-like" structure due to their exceptionally high aspect ratio [8].

The tortuous path effect is widely applied in metal anti-corrosion, as the automotive industry. For instance, vehicle underbodies are highly susceptible to impact from gravel and erosion by mud and water, leading to corrosion and structural damage. Primer or intermediate coatings containing layered silicates form a tough and highly impermeable barrier, protecting the underlying metal from salt-induced corrosion and preventing the propagation of rust from scratches. Furthermore, high-temperature, humid, and salt-rich environments can cause severe corrosion in automotive braking systems. The application of heat-resistant coatings incorporating MXene or hexagonal boron nitride enhances barrier properties through the tortuous path mechanism, effectively mitigating penetration of corrosive agents and improving durability under demanding conditions [9].

3.1.2 Pore Blocking

Compared to the mechanism of extending the diffusion path, pore blocking aims to reduce the corrosion rate by physically blocking the ingress of corrosive agents. When nanomaterials, such as silica nanoparticles, zinc oxide nanowires, or clay nanosheets, are incorporated into the coating matrix, they physically clog or cover these microscopic pores, thereby preventing corrosive agents, like water, oxygen, and chloride ions, from penetrating through these shortcuts to the metal substrate. This significantly enhances the protective performance of the coating [10].

The fundamental application of nanotechnology based on the pore-blocking mechanism centers on „sealing" functions. This markedly improves performance in sectors where exceptional reliability and long-term durability are critical, such as marine engineering and civil infrastructure. A representative example can be found in marine structures—including ships, offshore platforms, and steel elements of cross-sea bridges—where epoxy resin coatings enhanced with nano-silica (SiO_2), zinc oxide nanoparticles (ZnO), or nanoclay efficiently block pore pathways. This effectively inhibits the infiltration of chloride ions (Cl^-) and water vapor, leading to a considerable

ISSN 2959-6157

prolongation of the structural service life.

3.2 Active Inhibiting

Comparing to the passive approach of barrier enhancement, a more active chemical inhibiting approach is invented for corrosion protection. By releasing corresponding agents, the strategy assists to mitigate the corrosive environment through utilizing stimuli-responsive nanocontainers to achieve active corrosion inhibition. The released inhibitors migrate to the exposed part of the layer, autonomously repairing the coating and preventing further corrosion. The stimulus-response release mechanisms of active-inhibiting smart anticorrosion coatings can be categorized into two major classes based on the source of the trigger, including autonomous response and human control.

3.2.1 Autonomous Response

This mechanism operates entirely on stimuli produced by the corrosion process itself. As metal corrosion begins, the local pH drops at anodic sites or rises at cathodic sites, a behavior commonly observed in metals such as aluminum and magnesium alloys. Pre-embedded smart nanocontainers, such as pH-sensitive microcapsules or ion-exchange materials like layered double hydroxides, detect this shift and release encapsulated corrosion inhibitors via mechanisms including structural swelling, bond cleavage, or ion exchange. The inhibitors then migrate to the damaged zone, forming a protective film that 'autonomously' suppresses further corrosion propagation. This system functions as a self-healing mechanism that operates after corrosion onset, yet responds faster than manual inspection [11].

This technology could be utilized in advanced industrial sectors demanding rigorous corrosion control, extended material service life, and high operational safety, notably in aerospace engineering, energy infrastructure, and microelectronic and precision device encapsulation. More specifically, it could be implemented in critical applications such as aluminum alloy airframes, high-temperature engine parts, and magnesium alloy cabin component. By enabling autonomous and rapid corrosion self-repair, this approach significantly enhances flight safety and prolongs component durability.

3.2.2 Human Control

This mechanism enables users to actively intervene in the protection process. By incorporating nanomaterials that respond to specific external energy sources into the coating, protective actions can be triggered on demand. For instance, incorporating microcapsules (containing healing agents) along with conductive polymers or sacrificial anode nanoparticles (e.g., zinc powder) into the anti-corrosion coating. Besides, applying an alternating magnetic field causes magnetic nanoparticles to produce heat, thereby activating the release of healing agents [12].

This technology offers suitable value for advanced industrial and high-end equipment applications, especially where safety, reliability, and maintenance costs are crucial. For instance, in renewable energy and power infrastructure, the protective function can be triggered on demand using external stimuli before harsh conditions. This is particularly useful ahead of seasonal threats like typhoons or winter de-icing periods. As a result, structural corrosion is slowed down, the service life of critical installations like offshore wind turbine towers is prolonged, and unplanned downtime is significantly decreased.

3.3 Occurrence Conditions Destruction

As the most proactive approach to corrosion prevention, occurrence condition destruction aims at the root causes of corrosion by removing its essential prerequisites. By fundamentally redesigning the interface between metal and environment, the method incorporates functional barriers, actively excluding critical corrosive elements such as water and oxygen.

3.3.1 Protective Layers

This corrosion prevention approach uses engineered barriers which applied through advanced surface treatments to physically isolate the base material from corrosive agents. An example involves coatings designed to be chemically inert. By reducing the material's willingness to react, these coatings significantly strengthen its resistance to environmental breakdown. In detail, this passive mechanism suppresses harmful chemical activity at the surface, providing protection against moisture, oxygen, acids, and other corrosive substances. Owing to the durability, excellent barrier properties, and tunable designs, chemically inert nanocoating has become indispensable in applications demanding extreme reliability.

An innovative application comes from the use of superhydrophobicity, achieved by constructing a micro-nano hierarchical structure on the metal surface—typically fabricated via laser texturing or electrochemical processing combined with low-energy surface modification. This architecture stabilizes a trapped air layer, known as a "plastron," which results in extreme water repellency (contact angles >150°) and minimal adhesion. The barrier function manifests through the formation of a composite air-solid interface that significantly reduces the effective contact area between the electrolyte and the substrate [13]. By minimizing interfacial contact, it effectively prevents electrolyte accumulation and penetration, thereby suppressing the initiation of electrochemical reactions. Furthermore, the same surface characteristics that enable superhydrophobicity provide an ancillary benefit: self-cleaning behavior, whereby rolling water droplets remove surface contaminants that could otherwise compromise the integrity of the protective layer.

However, a significant drawback is the susceptibility of the surface to damage and the difficulty in repairing it, which substantially increases both production and maintenance costs.

3.3.2 Surface Modification

Surface modification techniques enhance inherent material resistance by altering the physicochemical properties of the substrate's outermost layers through microstructural and compositional engineering. The core protective mechanisms are among the most impactful and widely adopted strategies in this discipline. It primarily encompasses three integrated strategies: Firstly, engineered passivation techniques enable the construction of structurally controlled, stable nanoscale oxide layers that act as highly efficient barriers, suppressing the diffusion of corrosive species and significantly reducing ion transport rates [14]. Secondly, advanced surface processing technologies facilitate compositional optimization by precisely introducing corrosion-inhibiting elements into the near-surface region with designed gradients, thereby enhancing the inherent corrosion resistance of the material. A third approach involves refining the material's grains to create a nanocrystalline surface structure. The dense network of grain boundaries that results allows protective elements to spread more quickly, helping to form passive films that are not only more uniform but also capable of rapidly self-repairing.

3.4 Evaluation on the Three Strategies

To sum up, each corrosion protection strategy has its own clear benefits and downsides. Barrier methods are the most economical and mature; condition-disruption strategies are the most fundamental but also the most technically demanding; and active self-healing technologies offer a smart mid-ground option with responsive functionality. Detailed comparisons are listed as followings:

Firstly, by forming a physical shield, barrier method offers durable protection and often improves the overall material properties. This method is widely adopted due to its cost-effectiveness and reliable performance in different settings. While its drawbacks are obvious, including inability to fully stop corrosion once started, lack of self-healing ability, and failure to detect hidden corrosion.

In contrast, active self-healing systems provide intelligent repair functions that react automatically to damage. These are particularly helpful for places that are difficult to access or inspect regularly. However, their complexity and higher costs stop them from wider industrial application.

The most proactive approach involves disrupting the fundamental conditions that cause corrosion. By dealing with corrosion at its source, this strategy not only prevents damage from starting but can also add other benefits, such as improved chemical resistance, environmental adaptability and so on. As a major shift from traditional barrier methods, it targets the root causes of corrosion. However, these systems often face challenges: their coating can be easily broken, production processes can be complicated. They also require a high level of technical expertise and infrastructure, which currently limits their large-scale application.

Overall, these three strategies vary when it comes to how proactive they are, how much they cost, how complex they are, and how practical they are to use.

4. Conclusion

In short, nanotechnology is transforming how we protect metals from corrosion by offering three main strategies—from basic barrier protection to smart self-healing systems. Each has its pros and cons, but future progress will likely come from combining these approaches into multi-functional coatings that are both effective and practical for industrial use. For instance, promoting green and low-cost synthesis processes, developing more durable responsive materials, and utilizing artificial intelligence for corrosion prediction and coating design will be key to achieving large-scale industrial application.

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