



(REVIEW ARTICLE)



## Diversified development of anti-corrosion materials: A review

Yu-Zhao Yang, Rui Zhu, Cheng-Xiang Wang, Huai-Ming Du \* and Hua-Jun Shawn Fan \*

*College of Chemical Engineering, Sichuan University of Science and Engineering, Zigong City, Sichuan Province, 643000, China.*

World Journal of Advanced Research and Reviews, 2024, 22(03), 692–703

Publication history: Received on 01 May 2024; revised on 09 June 2024; accepted on 11 June 2024

Article DOI: <https://doi.org/10.30574/wjarr.2024.22.3.1752>

### Abstract

In recent years, with the development of productivity, the update and iteration of anti-corrosion technology is also advancing rapidly. The innovations of anti-corrosion materials, anti-corrosion technologies, and anti-corrosion mechanisms are emerging in an endless stream. They use different ways to make anti-corrosion stronger, more convenient, and more environmentally friendly. This review summarizes the new discoveries in the field of anti-corrosion in recent years according to different characteristics. These include traditional coatings and corrosion inhibitors that apply new materials; adding nanofillers to the gaps in the coating to prepare new multifunctional coatings; obtaining super-hydrophobic surfaces after special treatment of the coating surface; and discovering the corrosion inhibition effect of bacterial biofilms, and even anti-corrosion coatings suitable for UV preparation. In addition to introducing and analyzing their anti-corrosion methods, the characteristics and application fields of various methods are briefly evaluated. Finally, based on the current development of anti-corrosion, the future development direction of anti-corrosion technology is predicted.

**Keywords:** Overview Of Anti-Corrosion; Corrosion Inhibitor Materials; Coating Filling; Coating Preparation; Anti-Corrosion Development

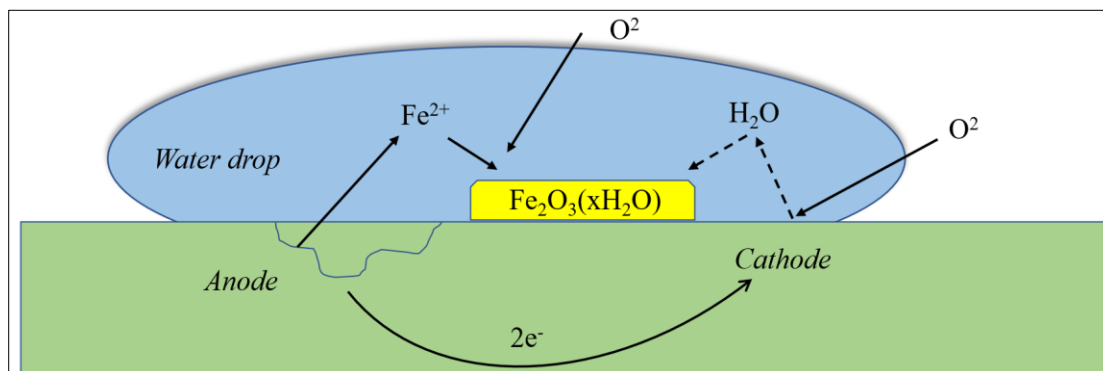
### 1. Introduction

Corrosion is a natural phenomenon that has existed ancient times, as they observed the deterioration of metal objects exposed to the elements. As early as 3000 BC, the ancient Egyptians had discovered that copper and iron would corrode when exposed to air and water [1]. They also discovered some basic anti-corrosion methods, such as using grease or wax to coat the metal surface to prevent the metal from coming into contact with the corrosive medium. Early civilizations used various methods to protect metals, such as applying oils, greases, or coatings to prevent direct contact with corrosive substances, the oxygen in the air. By the 19th century, with the advent of the Industrial Revolution, people's understanding of metal corrosion had improved significantly. British chemist Joseph Faraday first proposed the electrochemical corrosion theory, which is a scientific explanation of corrosion phenomena. His theory explained why metals corrode in certain environments and laid the foundation for the development of anti-corrosion technology.

In the 20th century, with the advancement of science and technology, anti-corrosion technology has also developed greatly. People began to use various high-performance anti-corrosion coatings and anti-corrosion materials, as well as electrochemical anti-corrosion technologies, such as cathodic protection and anodizing [2]. At the same time, people have also begun to research new anti-corrosion technologies, such as self-healing coatings and nanotechnology [3]. In the 21st century, with the improvement of environmental awareness, people began to seek more environmentally friendly and longer-lasting anti-corrosion methods. For example, water-based anti-corrosion coatings have been developed [4], which not only have good anti-corrosion effects, but also have little impact on the environment. In

\* Corresponding author: Huai-Ming Du and Hua-Jun Shawn Fan; Email: [fan27713@yahoo.com](mailto:fan27713@yahoo.com)

addition, people are also studying the use of biotechnology to prevent metal corrosion [5], which is a new development direction of anti-corrosion technology.



**Figure 1** Iron is corroded

The corrosion reaction mechanism of metals occurs when electrons move between the anode and cathode regions of the metal surface through a potential difference (Figure 1 Iron is corroded). The resulting current determines the rate of the dissolution reaction. Therefore, the corrosion reaction is considered an electrochemical reaction [6]. There are different electrochemical methods to evaluate the rate of dissolution reactions, such as linear polarization resistance measurements (LPR) and electrochemical impedance spectroscopy (EIS).

Research has shown that some effective metal anticorrosion techniques include cathodic protection, anodizing, appropriate material selection, and protective coatings [7]. In anti-corrosion coatings, effective protection capabilities mainly come from active and passive anti-corrosion [8]. Active anticorrosion (inhibition) usually refers to adding inhibitors to the metal to reduce the corrosiveness of the electrolyte, or cathodic protection through sacrificial anodes to prevent the formation of metal cations, thereby preventing metal corrosion [9]. For passive anticorrosion (barrier performance), the main method is to form a barrier layer to prevent metal corrosion, including paints, plastics and organic coatings [10].

This article serves as a comprehensive exploration into contemporary anti-corrosion research, delving into the materials and preparation technologies utilized across various anti-corrosion methods and mechanisms. There are six (6) categories of corrosion protection methods reviewed and discussed in this paper. This includes (1) adsorption mechanism, (2) Cathodic protection and anodizing, (3) self-healing, (4) hydrophobic layer mechanism, (5) antibacterial biofilm corrosion Inhibitor, and (6) special techniques. Additionally, it outlines the current challenges within the field, offering insights into the future trajectory of anti-corrosion endeavors. By offering guidance and inspiring ideas, it aims to inform and shape ongoing scientific research in this critical area.

## 2. Results and Discussion

### 2.1. Adsorption mechanism

It is generally accepted that molecular adsorption is required to achieve corrosion inhibition. Bockris succinctly described this premise that a molecule must adsorb to become an inhibitor [11]. The strong adsorption force can inhibit the lateral diffusion of corrosive media at the interface and reduce the easy peeling off of inhibitors.

#### 2.1.1. N-heterocyclic compound corrosion inhibitor system

N-heterocyclic compounds such as imidazole, triazole, pyridine, pyrazole, quinoline, tetrazole, pyrimidine, purine and pyrrole. Nitrogen atoms in nitrogen-based compounds have lone pairs of electrons and  $\pi$  electrons, which can form adsorption interactions with vacant d orbitals on the surface of metals such as iron. This chemical adsorption can prevent the metal surface from contacting the corrosive medium, form a protective layer, and reduce the occurrence of corrosion reactions [12]. All these types of compounds have nitrogen as the main component, and the pi electrons on the corresponding rings have enough tilt to fill the electron defects in the corresponding metals and alloys, thereby preventing corrosion. In addition, the attachment of various electron-withdrawing substituents and electron-donating substituents on the primary heterocycle facilitates adsorption on the mild steel surface to form long-lasting chelate complexes [12].

Other heteroatoms, such as O, P, S, etc., may provide electrons for adsorption. However, heterocyclic organic groups have shortcomings such as solubility, hydrophobicity, non-biodegradability, and toxicity, making N-heterocyclic compounds a better and more effective method.

Quinoline is a nitrogen heterocyclic compound, mainly composed of two rings with the molecular formula  $C_9H_7N$ . Quinoline is electron-rich due to the presence of  $10\pi$  electrons and non-bonding electrons on nitrogen. This is thought to be the most likely reason why it interacts better with metal surfaces. Furthermore, due to their high solubility in aqueous media, quinolines and related derivatives can also be best used to treat aqueous corrosion [13].

As the demand for environmentally friendly and efficient preservatives increases, research on the nitrogen-based compounds is gaining momentum as an alternative to traditional preservatives approaches. Future research can further optimize the structure and performance of nitrogen-based compounds and improve their anti-corrosion effect and stability [12]. In addition, the composite application of nitrogen-based compounds with other anti-corrosion materials can be explored to improve the anti-corrosion effect and extend the service life.

### 2.1.2. Anti-corrosion properties of polyvinyl alcohol

Polyvinyl alcohol (PVA) is a polyhydroxy water-soluble biodegradable corrosion inhibitor [14]. When used alone as a corrosion inhibitor, it shows good application results on aluminum and copper metal substrates. There are abundant hydroxyl groups on the PVA molecular chain, which can improve the solubility of conductive polymers and amino acid corrosion inhibitors in aqueous environments.

Unlike many vinyl polymers, PVA is not prepared by polymerization of the corresponding monomers, but by partial or complete hydrolysis of polyvinyl acetate [15]. According to the degree of hydrolysis of polyvinyl acetate, PVA is divided into partially hydrolyzed (87–89%) and completely hydrolyzed (97–99%). Research has found [16] that various PVA can prevent the corrosion of mild steel in acidic environments to a certain extent, and its corrosion inhibition effect increases with the increase in polymerization degree or PVA concentration. At the same time, partially hydrolyzed PVA has higher corrosion inhibition efficiency [17] because the partially hydrolyzed polyvinyl alcohol molecular chain contains unhydrolyzed ester groups, and at the same concentration, the area of the adsorption film formed on the surface of the metal matrix is bigger.

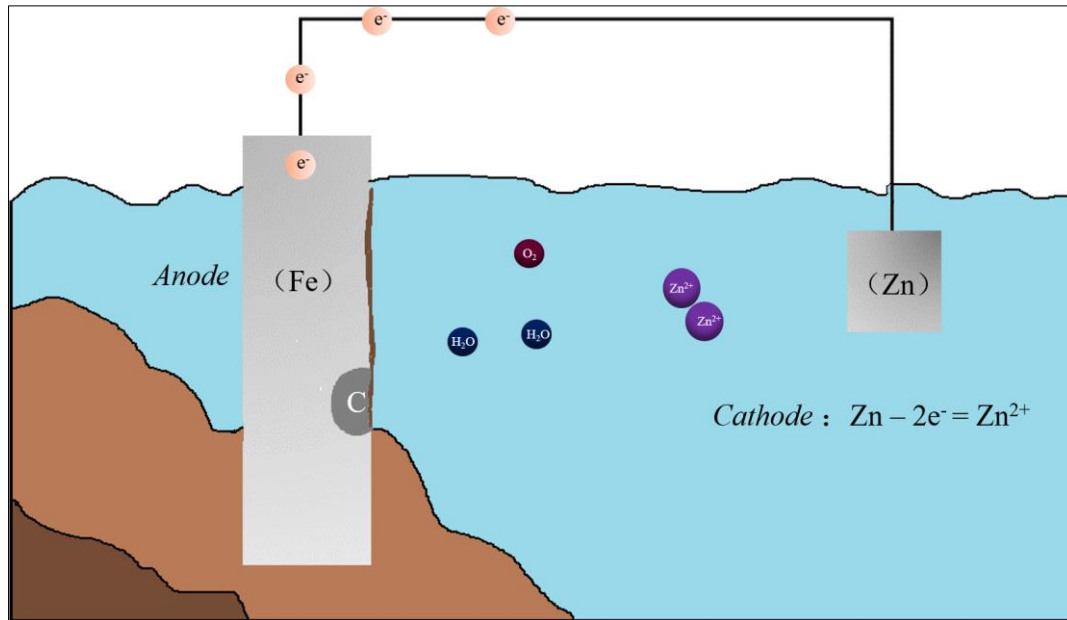
The adsorption behavior of PVA on the surface of mild steel was studied through full chemical calculations at the molecular level [18], and it was found that PVA has the ability to donate and receive electrons in the empty d orbital of Fe atoms, and can be physically adsorbed on the surface of mild steel. Studied the mechanism of PVA inhibiting the pitting corrosion behavior of mild steel in HCl solution [19] and found that PVA competes with the chloride ions in the corrosive medium on the surface of mild steel, and PVA forms an adsorption film on the surface of mild steel to separate the mild steel matrix from the corrosive medium, plays a certain corrosion inhibition role. During the dynamic potential anodic polarization process, as the PVA concentration increases, the pitting corrosion potential of mild steel moves in the positive direction.

In order to solve the problem of low binding strength of some green chemical inhibitors, such as phytic acid [20], to coatings and metal substrates, PVA was added as a green film-forming agent in their chemical conversion precursor solutions [21]-[23]. This is beneficial to improving the micromorphology of the chemical conversion coating, the bonding strength with the metal matrix, and the adhesion of subsequent coatings.

## 2.2. Cathodic protection and anodizing

Cathodic protection, also known as sacrificial metal or electrochemical protection, is an effective technique used to prevent metal corrosion (Figure 2 Cathodic protection of sacrificial anode). It has used to protect a wide range of metallic structures in various environments. This method involves making the metal the cathode in an electrochemical cell by connecting it to a sacrificial anode that is more active and susceptible to oxidation. Cathodic protection works by converting active areas on a metal surface to passive areas, making them the cathode of an electrochemical cell [24]. The sacrificial anode corrodes instead of the protected metal, sacrificing itself to protect the metal from corrosion.

A typical example is the galvanic anodes used as sacrificial anodes in cathodic protection systems. These anodes are made of alloys such as zinc, magnesium, and aluminum, which have a more active voltage than the metal of the target structure. The galvanic anode corrodes preferentially, providing cathodic protection to the metal it is connected to. Common applications of this method include steel water or fuel pipelines, steel storage tanks, ship and boat hulls, offshore oil platforms, and metal reinforcement bars in concrete buildings and structures.



**Figure 2** Cathodic protection of sacrificial anode

### 2.2.1. Cathodic protection nano-magnesium modified silane conversion coating

In order to make the silane conversion film (SCC) have the ability of cathodic protection, nano-Mg particles were used to modify SCC, and nano-Mg modified SCC (nano-Mg@SCC) was prepared on magnesium alloy (MA) AZ91D [25]. SCC hinders the penetration of corrosive electrolyte into the MA matrix and delays the occurrence of cathodic reaction. When the corrosive electrolyte reaches the MA matrix, the anodic reaction occurs and leads to electrochemical corrosion of the MA matrix. However, when the corrosive electrolyte penetrates nano-Mg@SCC, the nano-Mg particles act as sacrificial anodes and preferentially consume the occurrence of anodic reactions, so the anodic reaction occurring on the MA substrate is delayed. Nano-Mg@SCC therefore retains the original physical barrier ability and has a new cathodic protection ability.

## 2.3. Self-healing ability

In recent years, with the increasing demand for long-term protective capabilities, self-healing coatings have become a popular research structure in the field of metal anticorrosion [26]. They enable the coating to self-repair and restore its corrosion resistance after damage, effectively solving the problem of short service life of damaged coatings.

### 2.3.1. Preparation of anti-corrosion coating with self-healing effect through shear thinning.

In order to combine self-healing and waterproofing capabilities and further improve performance, a functional partitioning structure combining a superhydrophobic barrier and a self-healing multilayer membrane was constructed, and a PU barrier coating was constructed on the B-PEA coating. Therefore, the coating consists of three layers, including an epoxy/zinc primer layer (~100  $\mu\text{m}$ ), a B-PEA self-healing layer (~100  $\mu\text{m}$ ), and a superhydrophobic barrier layer (~50  $\mu\text{m}$ ) [27]. The zinc epoxy primer acts as the bottom sacrificial anode. The barrier layer can provide effective protection for the self-healing layer. The air cushion formed on the rough surface of the superhydrophobic coating is beneficial to the formation of a stable barrier/barrier layer to inhibit the intrusion of corrosive substances.

Due to long-term contact with corrosive media, water on the surface of organic coatings inevitably penetrates into the coating through the physical barrier, weakening the isolation effect of the coating, thereby causing metal corrosion [28][29][30].

Shear thinning effect is a fluid property, which means that when certain fluids are subjected to shear force (such as stirring or extrusion), their adsorption degree will decrease as the shear force increases. Small [31][33].

The shear thinning effect was achieved by preparing branched ethyl acrylate-acrylonitrile copolymer (B-PEA) through free radical copolymerization and introducing a small amount of Divinyl benzene [27]. The branched structure produces the shear thinning effect by inhibiting the entanglement of the polymer chains and promoting the orientation of the

polymer chains under shear. Scratching exerts shear forces on the polymer on the surface. As a result, surface polymers undergo a shear thinning effect, resulting in a dramatic decrease in chain mobility or viscosity, followed by a dramatic increase in the self-healing ability of these polymers [34]. In addition to this, due to the stronger adsorption of surface polymers, the interaction between surface polymers and internal polymers must be weakened, thereby inhibiting the scratch expansion and reducing the scratch width [35]. This also helps improve self-healing efficiency. In contrast, there is no shear thinning effect in traditional self-healing coatings, which may exhibit relatively slow repair speeds [36][38].

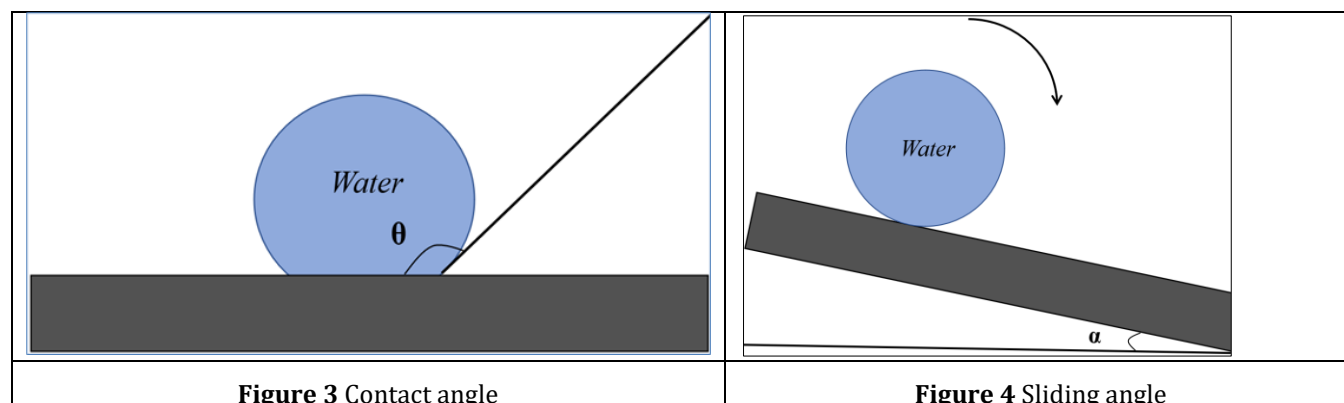
In addition to the shear thinning effect, the self-healing ability of B-PEA is also attributed to the large amount of polar forces. This weak interaction allows for rapid bond exchange, enabling self-healing [27]. The "bond exchange" here refers to the process in which chemical bonds between atoms are broken and re-formed within the molecule. This is a mechanism for self-repair of materials.

Most anti-corrosion coatings need to self-heal under application conditions including heat and light [39], and most self-healing anti-corrosion coatings have low adhesion [40], which hinders their ability to be provided at room temperature without application conditions. Rapid self-healing with high adhesion. The anchoring groups enhance the adhesion mechanism of the coating, which should be attributed to the increase in interchain forces due to the increase in molecular weight and the amount of rigid/polar groups.

The self-healing ability requires the chain segments to have a certain degree of mobility or even chain slippage. The branched structure reduces the entanglement of polymer chains and increases chain mobility. By introducing the synergistic effect of multiple dynamic cross-linked networks of polar, flexible and rigid groups, branched polyacrylates are able to perform at room temperature (~1.5 hours), underwater (1 hour) and in salt solutions (2 hours) Produce rapid self-healing properties [27].

## 2.4. Hydrophobic layer

The surface of lotus leaves is characterized by the combination of micro-nano composite structures and biological wax, which gives lotus leaves unique superhydrophobic properties. This phenomenon is called the "lotus effect" [41]. Superhydrophobic surfaces prepared using the "lotus effect" are widely used in oil-water separation [42] and anti-corrosion fields [43].



As shown in Figure 3 and Figure 4, the water contact angle of superhydrophobic materials is greater than  $150^\circ$  and the sliding angle is less than  $10^\circ$  [44]. The rough structure of the superhydrophobic surface traps air, forming a continuous gas layer at the interface between the matrix and aqueous phase. This gas layer prevents direct contact between water and matrix materials, thus acting as an anti-corrosion agent.

At present, the idea of preparing superhydrophobic surfaces is relatively unified, mainly through the combination of surface micro-nano composite structures and low surface energy materials to obtain this property.

### 2.4.1. HD-SiO<sub>2</sub>/SiO<sub>2</sub> Sol@PDMS superhydrophobic coating

By combining hexadecyl trimethoxy silane (HDTMS) modified SiO<sub>2</sub> nanoparticles and acid-catalyzed silica sol (HD-SiO<sub>2</sub>/SiO<sub>2</sub>-Sol) with polydimethylsiloxane (PDMS) adhesive Mixed, a superhydrophobic coating was prepared on the Al sheet. HD-SiO<sub>2</sub> nanoparticles and acid-catalyzed silica sol (SiO<sub>2</sub> sol) form a binary gradient micro-nano structure, providing excellent superhydrophobicity (water contact angle =  $158.5^\circ$ , sliding angle =  $0^\circ$ ). Superhydrophobic coatings with excellent water-repellent properties have anti-corrosion potential [45].

Experiments show that as the SiO<sub>2</sub> content increases, the micro-rough structure of the coating surface increases significantly, which allows the surface to capture more air and form an air film, preventing direct contact between water and the coating surface, thereby improving the coating surface quality. Hydrophobicity and corrosion resistance [46]. Water droplets roll on the superhydrophobic coating, removing surface impurities and giving the coating good self-cleaning properties.

When the Al sheet coated with the prepared superhydrophobic surface is immersed in a corrosive solution, the hierarchical micro/nanostructures on the superhydrophobic surface form a composite interface with the solution, where air is confined in the valleys between the hierarchical structures. The composite interface results in a reduced contact area between the corrosive solution and the metal layer, thereby acting as a barrier against corrosion and hindering the transfer of electrons and ions between the substrate and the electrolyte [45]. Therefore, the application of superhydrophobic coating can provide an effective barrier coating for aluminum sheets.

It is worth noting that the super hydrophobicity of the coating decreases significantly in an alkaline environment, which may be due to the weak alkali resistance of PDMS [45]. As a result, the coating easily reacts with alkaline substances, causing its hydrophobic structure to be destroyed and reducing its hydrophobicity. Although the coating has certain wear resistance and weather resistance, it may deteriorate after long-term use and requires regular maintenance and repair.

#### 2.4.2. "Slippery Liquid-Infused Porous Surfaces" (SLIPS) surface treatment technology

In practical applications of superhydrophobic surfaces, the continuous gas layer is metastable. The rough structure of the superhydrophobic surface is destroyed and the trapped air is depleted, which will quickly lead to the loss of superhydrophobicity when exposed to a bad environment [47].

The problem of superhydrophobic surfaces has inspired researchers to seek new solutions from nature. They turned their attention from the lotus leaf to another plant, the pitcher plant [48]. Inspired by the structure of the inner wall of a natural pitcher plant pitcher, a smooth liquid-infused porous surface (SLIPS) with a stable continuous lubricant layer was prepared by injecting a low surface energy lubricant into a substrate with a micro/nanoporous structure.

In terms of surface properties, superhydrophobic surfaces and SLIPS exhibit similar hydrophobic properties. However, superhydrophobic surfaces have a relatively single function, and in actual anti-corrosion applications, they are more likely than SLIPS to lose superhydrophobicity due to mechanical or chemical damage to surface features. In contrast, SLIPS, which has low sliding friction, high temperature and high pressure resistance, self-healing, non-adhesion and various excellent properties, is obviously more meaningful for metal anti-corrosion [49][51].

Since the lubricant is injected into the micro/nano structure to form a continuous and uniform dynamic liquid film on the substrate surface, SLIPS exhibits excellent anti-corrosion properties. The dynamic liquid film layer not only prevents direct contact between the substrate surface and the corrosive medium, thereby preventing electron transfer and effectively protecting the metal from corrosion, but also uses low surface energy and low viscosity lubricants to fill the surface micro/nanopore structure, The lubricant layer forming SLIPS makes the surface molecules smooth and cannot provide effective adsorption points for pollutants or bacteria on the surface. It effectively inhibits microbial adhesion when microorganisms come into contact with the substrate and prevents the occurrence of microbial corrosion. In addition, the continuous and uniform characteristics of the dynamic liquid film ensure its durability in the field of anti-corrosion [52].

Compared with superhydrophobic surfaces, SLIPS essentially replaces the air layer with a low surface energy lubricant, forming a continuous and stable lubricant film layer that exhibits excellent water repellency similar to superhydrophobic surfaces. Therefore, the mature development of superhydrophobic surface technology provides a reliable basis for the preparation of SLIPS [53].

Due to the fluidity of the lubricant, when the coating is physically or chemically damaged, SLIPS takes only 150 milliseconds for the lubricant to be released from the base structure and cover the damaged area, allowing the coating to self-heal [54].

With the deepening of research on SLIPS, there are various design and preparation methods of SLIPS. For example, an LDH-carbonate composite coating with a porous top layer and a dense bottom layer was prepared on the surface of magnesium alloy using a one-step hydrothermal method. Further modification of the porous top layer by low surface energy materials and lubricant injection resulted in SLIPS with improved anti-corrosion and anti-icing properties [55].

In addition to water, bacteria are also a possible cause of metal corrosion [56]. Dagger-shaped zeolite imidazolate framework-L layers were prepared on various material surfaces through flexible surface seeding and secondary growth techniques. This layer not only provides the basis for the construction of SLIPS through its inherent porosity and hydrophobicity, but also exhibits mechanical bactericidal activity due to its special dagger-like microstructure. SLIPS based on zeolite-imidazolium salt framework-L effectively prevents bacteria from adhering to the surface and inactivates a small number of adhered residual bacteria through physical puncture, implementing double antibacterial protection on the surface[57].

The preparation process of SLIPS is relatively complex, involving many aspects such as the selection of lubricating liquid, injection method, and construction of the substrate surface, and requires certain technical and equipment support. The film layer may be lost due to the influence of the external environment, resulting in a decrease in the performance of the coating. It is necessary to find a solution to the loss of lubricating fluid. At the same time, the performance of SLIPS may be affected by environmental conditions, such as temperature, pressure, and chemical media, and needs to be optimized and adjusted according to the specific application environment[58][60].

Currently, SLIPS research is still mainly focused on preventing lubricant loss, improving stability and extending service life. However, the problems of cumbersome preparation process and single function of SLIPS are still problems that need to be solved urgently.

## 2.5. Bacterial Biofilm Corrosion Inhibitor

Since traditional anti-corrosion methods may cause pollution to the environment, eco-friendly and effective anti-corrosion methods are needed. Microbiologically influenced corrosion inhibitors (MICI) have been reported as a sustainable corrosion protection method [61]. The anti-corrosion mechanism is attributed to the formation of a biofilm that acts as a barrier against corrosive media.

The mechanism of action of MICI is summarized as [62]: removal of corrosive substances by microorganisms through respiration; formation of extracellular polymeric substances (EPSs) layer to protect metals; mineralization layer produced by microorganisms; competitive microbial corrosion inhibition; and corrosion secreted by bacteria Inhibitors.

Aerobic microorganisms can consume dissolved oxygen through aerobic respiration. Then, as microorganisms consume the oxygen, low- or anoxic zones develop on the metal surface. Since oxygen is the main cause of corrosion, aerobic respiration of microorganisms results in limited oxygen in the environment, preventing metal corrosion by blocking cathodic reactions[62].

The antiseptic effect of strains can be attributed to their biofilm-forming abilities. In fact, EPSs isolated and purified from biofilms have been shown to be a key factor in biofilm corrosion inhibition [63] [64]. EPS is the main component of biological membranes and contains complex components such as polysaccharides, proteins, lipids and nucleic acids[65]. Hydrophobic components in EPS, such as fatty acids, can prevent corrosion by forming an inhibitory barrier[62]. Bacterial cells are embedded in biofilms, and dense and thick biofilms can act as physical barriers. In addition to forming an inhibitory barrier, EPSs can also reduce microbial adhesion to metal surfaces.

Microbial-induced mineralization plays a key role in chemical cycling and deposition in nature [62]. Microbial mineralization layers include phosphate mineralization layers, iron oxide mineralization layers, and carbonate mineralization layers [62]. In addition to protecting the metal from corrosion, the mineralized layer also has the function of repairing damaged coatings.

In fact, selecting appropriate microorganisms for application under different conditions is a critical and yet to be completely resolved issue[66]-[69]. To apply microorganisms as green and effective inhibitors, the corrosion inhibition mechanism of bacteria needs to be studied in depth.

## 2.6. Special Preparation Methods: UV synthesis technology

Hydrogel is a gel material with organic polymer as the skeleton structure and water as the dispersion medium[70]. The hydrogel coating on the surface of the material can make the system have the strength and hardness of the matrix, the hydrophilicity, self-lubricity, and biocompatibility of the hydrogel [71] [72]. The hydrogel coating is composed of lamellae. The three-dimensional network can be used as a carrier of smart corrosion inhibitors [73] [74]. The stimulus-responsive properties of hydrogel materials have been exploited to prepare smart anticorrosion coatings for targeted release of corrosion inhibitors. Currently, hydrogels can be synthesized through chemical cross-linking and physical cross-linking[75] [77].

Currently, UV-induced front-side polymerization prepares polymers in a simple, fast, energy-saving and environmentally friendly way, and breaks through the limitations of light-curing depth. However, the mechanical properties of the prepared methods do not meet the functional requirements of hydrogels. Adding weak hydrogen bonds can make hydrogels stiff, strong, tough, and elastic. Dense dynamic hydrogen bonds between different long chains can be reversibly broken and reconstructed, thereby dissipating large amounts of energy [78][79].

A new UV-initiated frontal polymerization method was proposed to rapidly synthesize bubble-free, self-propagating hydrogel anticorrosive coatings and solve the above problems [80]. First, under the catalysis of ultraviolet light, the photoinitiator is decomposed into free radicals, and the breakage of the C=C bond leads to polymerization within the monomer and long chains. Next, the heat generated by polymerization causes the thermal initiator to pyrolyze into free radicals. Free radicals further induce the cleavage of C=C, which forms a 3D network and simultaneously generates heat. Under the premise of ensuring the balance of heat release and heat generation, the hydrogel polymerizes in a self-propagating manner. The addition of nano-SiO<sub>2</sub> promotes the formation of hydrogen bonds and enhances the stability of the 3D network. This method overcomes the limitations of creating anti-corrosion coatings on wet steel surfaces or even underwater. Front-side polymerization was initiated after the coating solution was exposed to UV light for 20s [80].

PAAc-BAM-DMAA5.6%SiO<sub>2</sub>-triazole was selected as the anti-corrosion coating for research. It was found that the chemical adsorption of hydrogel anti-corrosion coating on steel can effectively prevent the entry of corrosive media. When corrosion first occurs, the released corrosion inhibitor 1,2,4-triazole can form a lower dielectric adsorption on the steel surface. film, which will hinder further corrosion reactions. The addition of nano-SiO<sub>2</sub> forms dense hydrogen bonds and enhances the stability of the 3D network of the hydrogel coating. Under water, the coating physically prevents corrosive media from reaching the steel surface. In addition, results show that 1,2,4-triazole can accumulate on the steel surface, thus playing an active anti-corrosion role [80]. The hydrogel anti-corrosion coating prepared by this new method solves the problems of insufficient mechanical properties and environmental limitations of traditional methods, and demonstrates good anti-corrosion effects.

---

### 3. Conclusions

This article introduces the new materials discovered in recent years in the field of corrosion protection, classified by different adsorption properties and protection methods. In the field of metal protection, compounds containing N, O, P, and S elements are mainly used as corrosion protection materials because their high electron-donating ability makes it easier for them to bond with metals and adsorb.

Cathodic protection can effectively prevent metal corrosion, especially for metal equipment in harsh environments, such as ships in seawater, submarine pipelines, etc. It can also prevent corrosion caused by microbial activity. Cathodic protection requires a "sacrificial metal" as an anode, which requires regular inspection and maintenance to ensure its effectiveness. For some metals that are prone to forming a protective oxide film (such as aluminum, stainless steel, etc.).

Adding fillers to the gaps between the coating molecules to increase the density and adsorption strength of the coating is also a development direction for corrosion protection. However, the process is more complicated. If scratches occur and the coating is damaged, the corrosion protection effect will be lost, and it needs to work together with the self-healing coating. After being corroded or damaged, the self-healing coating can automatically repair and restore its corrosion protection performance. The method of automatic repair can be to release chemicals to form a protective film, or it can be completed through the shear thinning effect and polar force of the coating itself. Superhydrophobic surfaces have a strong repulsion to water and have significant advantages in the corrosion protection of metals. However, it is necessary to pay attention to maintenance and the corrosion protection performance is affected by the acidity and alkalinity of the environment.

MICI uses multiple mechanisms such as biofilm, respiration, mineralization layer and secretion to demonstrate the potential of microorganisms in anticorrosion agents, but its application still needs further research and optimization. Bubble-free, self-propagating hydrogel anticorrosion coatings can be quickly synthesized through ultraviolet irradiation, and anticorrosion coatings can be made even on wet steel surfaces or even underwater, without environmental restrictions.

Today's anti-corrosion coatings do not only have one advantage, but are developing in the direction of integrating multiple functions. They must have excellent anti-corrosion performance, self-healing ability, and simple preparation methods. In addition, the cost of the material and its environmental friendliness are also necessary considerations.



---

## Compliance with ethical standards

### *Acknowledgement*

Partial support was provided by Science Foundation of Sichuan University of Science & Engineering (2020RC06) and Research Collaboration Agreement by Yibin Libao New Materials Ltd Co (HX2021279).

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

---

## References

- [1] Koochaki M S, Khorasani S N, Neisiany R E, et al. A highly responsive healing agent for the autonomous repair of anti-corrosion coatings on wet surfaces. In operando assessment of the self-healing process. *Journal of Materials Science*. 2021; 56: 1794-1813.
- [2] Szabo S, Bakos I. Cathodic protection with sacrificial anodes. *Corrosion Reviews*. 2006; 24(3-4): 231-280.
- [3] Idumah C I, Obele C M, Emmanuel E O, et al. Recently emerging nanotechnological advancements in polymer nanocomposite coatings for anti-corrosion, anti-fouling and self-healing. *Surfaces and Interfaces*. 2020; 21: 100734.
- [4] Pei L, Lin D, Yuan S, et al. A multifunctional and long-term waterborne anti-corrosion coating with excellent 'hexagonal warrior' properties. *Chemical Engineering Journal*. 2023; 457: 141158.
- [5] Marzorati S, Verotta L, Trasatti S P. Green corrosion inhibitors from natural sources and biomass wastes. *Molecules*. 2018; 24(1): 48.
- [6] Yadla S V, Sridevi V, Lakshmi M, et al. A review on corrosion of metals and protection. *International Journal of Engineering Science & Advanced Technology*. 2012; 2(3): 637-644.
- [7] Al-Swaidani A M. Modified zinc phosphate coatings: A promising approach to enhance the anti-corrosion properties of reinforcing steel. *MOJ Civil Eng*. 2017; 3(5): 370-374.
- [8] Chang K, Jia H, Gu S Y. A transparent, highly stretchable, self-healing polyurethane based on disulfide bonds. *European Polymer Journal*. 2019; 112: 822-831.
- [9] Li X, Xue Z, Sun W, et al. Bio-inspired self-healing MXene/polyurethane coating with superior active/passive anticorrosion performance for Mg alloy. *Chemical Engineering Journal*. 2023; 454: 140187.
- [10] Ren H, Li T, Wang H, et al. Two birds with one stone: Superhelical chiral polypyrrole towards high-performance electromagnetic wave absorption and corrosion protection. *Chemical Engineering Journal*. 2022; 427: 131582.
- [11] O'M J. Bockris, AKN Reddy, *Modern Electrochemistry* 2. 1970;
- [12] Sheetal, Batra R, Singh A K, et al. Advancement of corrosion inhibitor system through N-heterocyclic compounds: a review. *Corrosion Engineering, Science and Technology*. 2023; 58(1): 73-101.
- [13] Gao H, Li Q, Dai Y, et al. High efficiency corrosion inhibitor 8-hydroxyquinoline and its synergistic effect with sodium dodecylbenzenesulphonate on AZ91D magnesium alloy. *Corrosion Science*. 2010; 52(5): 1603-1609.
- [14] Asadpour S, Kooravand M, Asfaram A. A review on zinc oxide/poly (vinyl alcohol) nanocomposites: synthesis, characterization and applications. *Journal of Cleaner Production*. 2022; 362: 132297.
- [15] Aruldass S, Mathivanan V, Mohamed A R, et al. Factors affecting hydrolysis of polyvinyl acetate to polyvinyl alcohol. *Journal of Environmental Chemical Engineering*. 2019; 7(5): 103238.
- [16] Umoren S, Gasem Z. Influence of molecular weight on mild steel corrosion inhibition effect by polyvinyl alcohol in hydrochloric acid solution. *Journal of dispersion science and technology*. 2014; 35(8): 1181-1190.
- [17] Umoren S A, Obot I B, Madhankumar A, et al. Effect of degree of hydrolysis of polyvinyl alcohol on the corrosion inhibition of steel: theoretical and experimental studies. *Journal of Adhesion Science and Technology*. 2015; 29(4): 271-295.
- [18] Song W, Zhao X, Jin Z, et al. Poly (vinyl alcohol) for multi-functionalized corrosion protection of metals: A review. *Journal of Cleaner Production*. 2023; 136390.

- [19] Abdallah M, Al-Gorair A S, Fawzy A, et al. Enhancement of adsorption and anticorrosion performance of two polymeric compounds for the corrosion of SABIC carbon steel in hydrochloric acid. *Journal of Adhesion Science and Technology*. 2022; 36(1): 35-53.
- [20] Zhang Z, Liu X, Wang H X, et al. Preparation and characterization of *Enteromorpha prolifera* nanocellulose/polyvinyl alcohol composite films. *Polymer Composites*. 2021; 42(4): 1712-1726.
- [21] Ramezanzadeh B, Vakili H, Amini R. The effects of addition of poly (vinyl) alcohol (PVA) as a green corrosion inhibitor to the phosphate conversion coating on the anticorrosion and adhesion properties of the epoxy coating on the steel substrate. *Applied Surface Science*. 2015; 327: 174-181.
- [22] Saei E, Ramezanzadeh B, Amini R, et al. Effects of combined organic and inorganic corrosion inhibitors on the nanostructure cerium based conversion coating performance on AZ31 magnesium alloy: Morphological and corrosion studies. *Corrosion Science*. 2017; 127: 186-200.
- [23] Lee P J, Ho C C, Hwang C S, et al. Improved physicochemical properties and biocompatibility of stainless steel implants by PVA/ZrO<sub>2</sub>-based composite coatings. *Surface and Coatings Technology*. 2014; 258: 374-380.
- [24] Googan C. The cathodic protection potential criteria: Evaluation of the evidence. *Materials and Corrosion*. 2021; 72(3): 446-464.
- [25] Zhou Y, Zhang P, Yan F. Corrosion resistance of a nano-Mg modified silane conversion coating with cathodic protection on magnesium alloy AZ91D. *Materials Letters*. 2021; 284: 128930.
- [26] Zhao Y, Xu T, Zhou J H, et al. Superhydrophobic nanocontainers for passive and active corrosion protection. *Chemical Engineering Journal*. 2022; 433: 134039.
- [27] Liu Y, Liang H, Zhang Z, et al. Functional partition strategy in assistance by shear thinning/self-healing effect to prepare durable anti-corrosion coating. *Chemical Engineering Journal*. 2023; 473: 145210.
- [28] Emarati S M, Mozammel M. Theoretical, fundamental and experimental study of liquid-repellency and corrosion resistance of fabricated superamphiphobic surface on Al alloy 2024. *Chemical Engineering Journal*. 2020; 387: 124046.
- [29] Cui J, Li X, Pei Z, et al. A long-term stable and environmental friendly self-healing coating with polyaniline/sodium alginate microcapsule structure for corrosion protection of water-delivery pipelines. *Chemical Engineering Journal*. 2019; 358: 379-388.
- [30] Zhu Y, Li H, Zhu M, et al. Dynamic and active antiscaling via scale inhibitor pre-stored superhydrophobic coating. *Chemical Engineering Journal*. 2021; 403: 126467.
- [31] Zhang S, Zhou Y, Libanori A, et al. Biomimetic spinning of soft functional fibres via spontaneous phase separation. *Nature Electronics*. 2023; 1-11.
- [32] Zhang S, Zhou M, Liu M, et al. Ambient-conditions spinning of functional soft fibers via engineering molecular chain networks and phase separation. *Nature Communications*. 2023; 14(1): 3245.
- [33] Yasuda KY, Armstrong R C, Cohen R E. Shear flow properties of concentrated solutions of linear and star branched polystyrenes. *Rheologica Acta*. 1981; 20(2): 163-178.
- [34] Dong Y, Yin Y, Du X, et al. Effect of MXene@ PANI on the self-healing property of shape memory-assisted coating. *Synthetic Metals*. 2022; 291: 117162.
- [35] Wang T, Wang W, Feng H, et al. Photothermal nanofiller-based polydimethylsiloxane anticorrosion coating with multiple cyclic self-healing and long-term self-healing performance. *Chemical Engineering Journal*. 2022; 446: 137077.
- [36] Ma Y, Yang Y, Cao D, et al. Facile Repair of Anti-Corrosion Polymeric Composite Coatings Based on Light Triggered Self-Healing. *Macromolecular Materials and Engineering*. 2021; 306(9): 2100106.
- [37] Zhao X, Wei J, Li B, et al. A self-healing superamphiphobic coating for efficient corrosion protection of magnesium alloy. *Journal of colloid and interface science*. 2020; 575: 140-149.
- [38] Dong Y, Gong M, Huang D, et al. Shape memory, self-healing property, and NIR photothermal effect of epoxy resin coating with polydopamine@ polypyrrole nanoparticles. *Progress in Organic Coatings*. 2019; 136: 105232.
- [39] Zhu Y, Chen M, Wu L. Synthesis of UV-responsive dual-functional microspheres for highly efficient self-healing coatings. *Chemical Engineering Journal*. 2021; 422: 130034.

- [40] Zhou C, Li Z, Li J, et al. Epoxy composite coating with excellent anticorrosion and self-healing performances based on multifunctional zeolitic imidazolate framework derived nanocontainers. *Chemical Engineering Journal*. 2020; 385: 123835.
- [41] Barthlott W, Neinhuis C. Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta*. 1997; 202: 1-8.
- [42] Zhong Q, Shi G, Sun Q, et al. Robust PVA-GO-TiO<sub>2</sub> composite membrane for efficient separation oil-in-water emulsions with stable high flux. *Journal of Membrane Science*. 2021; 640: 119836.
- [43] Li B, Xue S, Mu P, et al. Robust self-healing graphene oxide-based superhydrophobic coatings for efficient corrosion protection of magnesium alloys. *ACS Applied Materials & Interfaces*. 2022; 14(26): 30192-30204.
- [44] Lu Y, Sathasivam S, Song J, et al. Robust self-cleaning surfaces that function when exposed to either air or oil. *Science*. 2015; 347(6226): 1132-1135.
- [45] Xia R, Zhang B, Dong K, et al. HD-SiO<sub>2</sub>/SiO<sub>2</sub> Sol@ PDMS Superhydrophobic Coating with Good Durability and Anti-Corrosion for Protection of Al Sheets. *Materials*. 2023; 16(9): 3532.
- [46] Ouyang Y, Cao Q, Li B, et al. Nanofluid-infused slippery surface: Bioinspired coating on Zn with high corrosion inhibition performance. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2021; 608: 125492.
- [47] Zeng Q, Zhou H, Huang J, et al. Review on the recent development of durable superhydrophobic materials for practical applications. *Nanoscale*. 2021; 13(27): 11734-11764.
- [48] Bohn H F, Federle W. Insect aquaplaning: Nepenthes pitcher plants capture prey with the peristome, a fully wettable water-lubricated anisotropic surface. *Proceedings of the National Academy of Sciences*. 2004; 101(39): 14138-14143.
- [49] Tenjimbayashi M, Togasawa R, Manabe K, et al. Liquid-infused smooth coating with transparency, superdurability, and extraordinary hydrophobicity. *Advanced Functional Materials*. 2016; 26(37): 6693-6702.
- [50] Peppou-Chapman S, Neto C. Depletion of the lubricant from lubricant-infused surfaces due to an air/water interface. *Langmuir*. 2021; 37(10): 3025-3037.
- [51] Kim H N, Kim S J, Choi W, et al. Depletion of lubricant impregnated in a cavity of lubricant-infused surface. *Physics of Fluids*. 2021; 33(2).
- [52] Yan W, Xue S, Xiang B, et al. Recent advances of slippery liquid-infused porous surfaces with anti-corrosion. *Chemical Communications*. 2023; 59(16): 2182-2198.
- [53] Zhang M, Xiao Y, Lian X, et al. Measuring failure pressure of porous superhydrophobic coatings via microfluidic method. *Applied Physics A*. 2018; 124: 1-7.
- [54] Wang J, Kato K, Blois A P, et al. Bioinspired omniphobic coatings with a thermal self-repair function on industrial materials. *ACS applied materials & interfaces*. 2016; 8(12): 8265-8271.
- [55] Zhang J, Gu C, Tu J. Robust slippery coating with superior corrosion resistance and anti-icing performance for AZ31B Mg alloy protection. *ACS applied materials & interfaces*. 2017; 9(12): 11247-11257.
- [56] Zarasvand K A, Rai V R. Microorganisms: induction and inhibition of corrosion in metals. *International Biodeterioration & Biodegradation*. 2014; 87: 66-74.
- [57] Hao L, Jiang R, Gao J, et al. Metal-organic framework (MOF)-based slippery liquid-infused porous surface (SLIPS) for purely physical antibacterial applications. *Applied Materials Today*. 2022; 27: 101430.
- [58] Tenjimbayashi M, Togasawa R, Manabe K, et al. Liquid-infused smooth coating with transparency, superdurability, and extraordinary hydrophobicity. *Advanced Functional Materials*. 2016; 26(37): 6693-6702.
- [59] Kim H N, Kim S J, Choi W, et al. Depletion of lubricant impregnated in a cavity of lubricant-infused surface. *Physics of Fluids*. 2021; 33(2).
- [60] Peppou-Chapman S, Neto C. Depletion of the lubricant from lubricant-infused surfaces due to an air/water interface. *Langmuir*. 2021; 37(10): 3025-3037.
- [61] Iverson W P. Microbial corrosion of metals. *Advances in applied microbiology*. 1987; 32: 1-36.
- [62] Lou Y, Chang W, Cui T, et al. Microbiologically influenced corrosion inhibition mechanisms in corrosion protection: A review. *Bioelectrochemistry*. 2021; 141: 107883.

- [63] Gao Y, Zhang M, Fan Y, et al. Marine *Vibrio* spp. protect carbon steel against corrosion through secreting extracellular polymeric substances. *npj Materials Degradation*. 2022; 6(1): 6.
- [64] Li Z, Zhou J, Yuan X, et al. Marine biofilms with significant corrosion inhibition performance by secreting extracellular polymeric substances. *ACS Applied Materials & Interfaces*. 2021; 13(39): 47272-47282.
- [65] Li Z, Wang X, Wang J, et al. Bacterial biofilms as platforms engineered for diverse applications. *Biotechnology advances*. 2022; 57: 107932.
- [66] Zarasvand K A, Rai V R. Microorganisms: induction and inhibition of corrosion in metals. *International Biodeterioration & Biodegradation*. 2014; 87: 66-74.
- [67] Al-Amiery A A, Mohamad A B, Kadhum A A H, et al. Experimental and theoretical study on the corrosion inhibition of mild steel by nonanedioic acid derivative in hydrochloric acid solution. *Scientific Reports*. 2022; 12(1): 4705.
- [68] Videla H A, Herrera L K. Understanding microbial inhibition of corrosion. A comprehensive overview. *International Biodeterioration & Biodegradation*. 2009; 63(7): 896-900.
- [69] Jayaraman A, Earthman J C, Wood T K. Corrosion inhibition by aerobic biofilms on SAE 1018 steel. *Applied microbiology and biotechnology*. 1997; 47: 62-68.
- [70] Zhang Y S, Khademhosseini A. Advances in engineering hydrogels. *Science*. 2017; 356(6337): eaaf3627.
- [71] Liu J J, Qu S X, Suo Z G, et al. Functional hydrogel coatings. *Natl Sci Rev*. 2021; 8 (2): nwaa254.
- [72] Ma S, Yan C, Cai M, et al. Continuous surface polymerization via Fe (II)-mediated redox reaction for thick hydrogel coatings on versatile substrates. *Advanced Materials*. 2018; 30(50): 1803371.
- [73] Lin B, Wang J, Zhang H, et al. Self-healing performance of ethyl-cellulose based supramolecular gel coating highly loaded with different carbon chain length imidazoline inhibitors in NaCl corrosion medium. *Corrosion Science*. 2022; 197: 110084.
- [74] Wang X, Wang W, Liu A, et al. Self-healing and anti-corrosion performances of 1, 2, 4-triazole modified nano-silica hydrogels. *Colloid and Interface Science Communications*. 2018; 27: 11-17.
- [75] Jiang K, Yan H, Rickert C, et al. Modulating the bioactivity of mucin hydrogels with crosslinking architecture. *Advanced Functional Materials*. 2021; 31(10): 2008428.
- [76] Galperin A, Long T J, Ratner B D. Degradable, thermo-sensitive poly (N-isopropyl acrylamide)-based scaffolds with controlled porosity for tissue engineering applications. *Biomacromolecules*. 2010; 11(10): 2583-2592.
- [77] Zhao Y, Liu W, Yang X, et al. The studies on the stimuli-response of poly (N, N-dimethylamino ethyl methacrylate/acrylic acid-co-acrylamide) complex hydrogel under DC electric field. *Journal of applied polymer science*. 2008; 110(4): 2234-2242.
- [78] Hu X, Vatankhah-Varnoosfaderani M, Zhou J, et al. Weak hydrogen bonding enables hard, strong, tough, and elastic hydrogels. *Advanced materials*. 2015; 27(43): 6899-6905.
- [79] Yu X, Zheng Y, Zhang H, et al. Fast-recoverable, self-healable, and adhesive nanocomposite hydrogel consisting of hybrid nanoparticles for ultrasensitive strain and pressure sensing. *Chemistry of materials*. 2021; 33(15): 6146-6157.
- [80] Sun J, Zhou L, Han P, et al. UV-Initiated Frontal Polymerization for the Fast Synthesis of Bubble-Free, Self-Propagating Hydrogel Anticorrosive Coatings. *ACS Applied Materials & Interfaces*. 2023; 15(23): 28618-28625.