

# Application of Organic Coating in Marine Anticorrosion

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**Abstract.** The development of navigation technology has increased maritime trade and the corrosion problem of ships has received more and more attention. Marine corrosions are mainly electrochemical, mechanical and biological corrosion. Normally, the countermeasures for marine corrosion include sacrificial anode protection, applied current cathodic protection and anti-corrosion coating. However, the first two still have great shortcomings. The sacrificial anode protection is limited by the potential difference between the metal electrodes, and the protection range is small. The applied current cathodic protection requires continuous external batteries, and the cost of detection and maintenance is high. The anticorrosive coating not only has excellent anticorrosive performance, but also has the advantages of simple operation process and low cost. Hence, anticorrosive coatings have been gradually applied to ship anticorrosion. Finally, this paper reviews the application of organic coating method in ship mooring corrosion protection, and introduces three kinds of epoxy anticorrosive coatings, polyurethane anticorrosive coatings and graphene anticorrosive coatings to meet the increasingly stringent development requirements of marine anticorrosive coatings.

**Keywords:** Marine corrosion, organic coating, corrosion protection.

## 1. Introduction

Seawater, due to the high salt concentration, and irregular changes in temperature and humidity, could cause severe marine corrosion. The steel of underwater hull, for instance, corrodes seriously under the influence of salinity of seawater, and the strength of ship structure decreases easily to cause accidents. Corrosion of steel is mainly due to electrochemical corrosion, seawater has more electrolytes, and iron and carbon in steel, the two form a primary cell, which in turn accelerates the corrosion. Traditionally, the measures to deal with ship corrosion are anti-corrosion coatings, sacrificial anode protection, applied current cathodic protection and other technologies [1].

Generally speaking, the sacrificial anode protection method uses the principle of a primary battery. The oxidation reaction occurs using the more reducing metal as the negative electrode, while the metal to be protected as the positive electrode can be protected from corrosion [2]. The applied current cathodic protection method uses an external power source to reduce the potential around the metal, so that the entire metal structure becomes the cathode of a new corrosion cell, which inhibits the migration of metal electrons to weaken the purpose of corrosion in turn [3]. These methods are effective in preventing corrosion, but there are still some improvements to be made. Sacrificial anode protection technology can be limited by the potential difference between the metal electrodes, the protection range is small, while the anode metal needs to be replaced periodically, the cost is high. The applied current cathodic protection method requires a special maintenance system, high detection and maintenance costs, while requiring a continuous external power supply.

Herein, organic coatings have been considered as potential anticorrosion measures, due to their superior anticorrosion properties, strong adhesion, and simplicity of use. Typical organic coatings mainly include epoxy resin anticorrosion coatings, polyurethane anticorrosion coatings, and graphene anti-corrosion coatings. However, their mechanisms still need to be further discussed. Therefore, this paper focuses on several typical organic coatings, and investigates their anticorrosion mechanisms in depth. Finally, these organic coatings can be used in ship anticorrosion, seaside buildings protection, and other related fields.

## 2. Types of ship corrosion

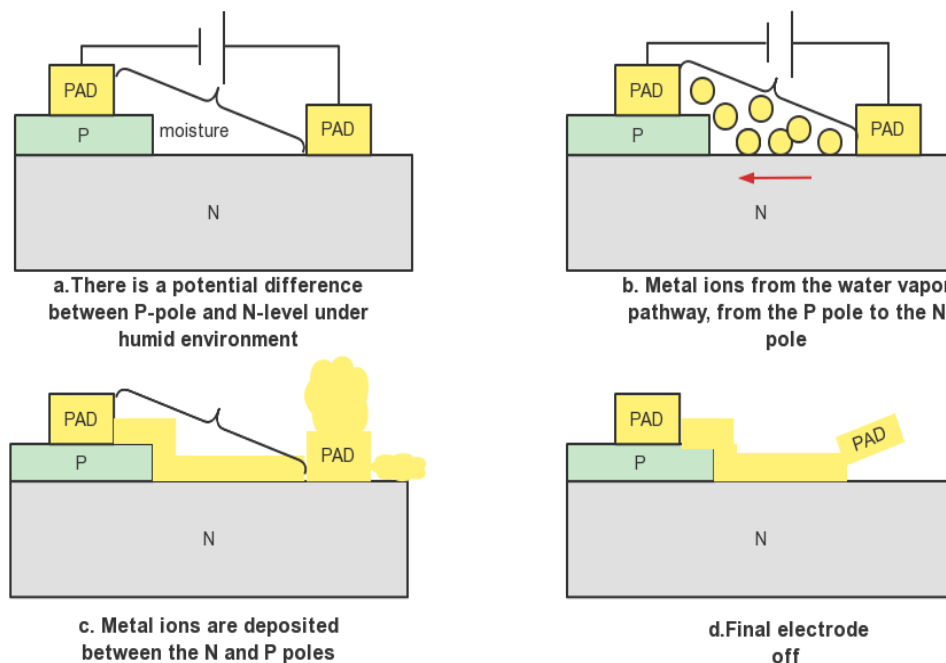
According to different mechanisms, marine corrosion is mainly divided into electrochemical corrosion, mechanical corrosion, biological corrosion and so on. The classification is presented in the form of charts in Table 1.

**Table 1.** Types of ship corrosion

Corrosion type	Corrosion mechanism
Electrochemical corrosion	Corrosion caused by electrodes formed at the interface between metal materials and electrolyte solutions
Mechanical corrosion	Corrosion caused by turbulence or liquid impact.
Biological corrosion	Corrosion caused by acidic metabolites of marine organisms, etc.

### 2.1. Electrochemical corrosion

Electrochemical corrosion is a common type of corrosion. In aqueous solutions and humid environments, a micro battery, also known as a corrosion battery, forms on the metal surface. Oxidation reaction usually occurs in the anode region, resulting in anodic dissolution. The reduction reaction occurs at the cathode and generally only acts as an electron transfer. The main reason for the formation of corrosion batteries is that the metal surface adsorbs the water in the air to form a water film, so that the carbon dioxide, sulfur dioxide and nitrogen dioxide in the air are dissolved in the water film to form an electrolyte solution. The metal immersed in this layer of solution is impure. For example, industrial steel is mostly alloy, that is, in addition to iron, it also contains graphite, cementite and other metals and impurities, most of which are not active iron. This forms the anode of the corrosion cell for iron, and the cathode for impurities, and the close contact between iron and impurities can cause corrosion continuously [4]. The following figure 1 shows the corrosion mechanism of electrochemical corrosion in detail.



**Figure 1.** Electrochemical corrosion mechanism diagram [4]

Wang Yuxin [5] et al. simulated the marine low temperature environment to study the low potential difference trimetallic coupled system composed of 907 A steel, 921 A steel and 980 steel under temperature change of galvanic corrosion. The results showed that the galvanic coupling corrosion coefficient of 907 A steel, the metal used as the anode, increased as the temperature increased. Zhang Zhen [6] et al. heated sodium chloride solutions with a mass fraction of 3.5 % to 20°C and 50°C to simulate the seawater environment, and then put domestic D36, F460 and F690 steels into the

solutions at different temperatures, respectively. It was found that the corrosion resistance of the three test steels was significantly reduced at 50 °C, and the surface film thickness of the test steels decreased with the growth of the immersion time. Yang Zhonggui [7] et al. used finite element simulation method to simulate the electrochemical corrosion characteristics of wind turbine foundation anchors under marine environment, and analyzed and summarized the electrochemical corrosion law of wind turbine foundation anchors under different working conditions. The ocean is extremely corrosive to steel, so the anti-corrosion of ships is extraordinary important.

### 2.1.1. Oxygen concentration difference cell action

The negative charge density on the two pieces of iron metal should have been the same, but due to the different oxygen content in the solution, the following reactions proceed differently when they occur:  $O_2 + 2H_2O + 4e^- = 4OH^-$ . At the iron electrode fed with air, the reduction reaction of oxygen is more rapid, thus the surface electrons are neutralized, and the negative charge density is reduced more for the positive electrode of the primary cell [8]. The mechanism diagram of oxygen concentration cell is shown in figure 2.

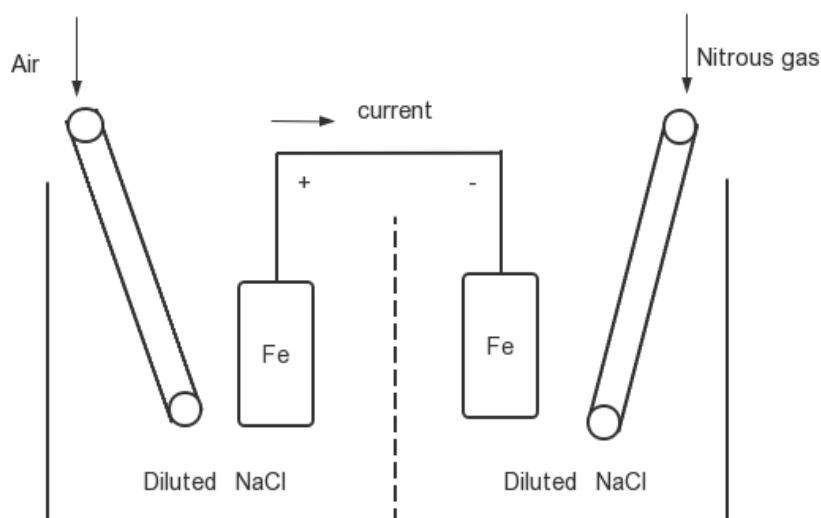


Figure 2. Oxygen concentration difference cell [8]

The oxygen element on the water surface is more than that under water, and oxygen has the ability to hold electrons, so the metal near the surface is facility to get electrons and become a cathode. The metal below the water surface loses electrons and undergoes anodic decay. The bottom has less oxygen than the pores or voids, so the bottom are able to continue to corrode until it finally rusts. Xingpei [9] et al. used E690 steel as the experimental object, and used current measurement, Scanning electron microscopy, and Raman spectroscopy analysis to study its oxygen concentration corrosion behavior in solutions with dissolved oxygen of 0.3-8 mg/L. The results showed that the rust layer could participate in cathodic reaction and thus accelerate metal corrosion under oxygen-rich conditions. And due to the inhomogeneity of the rust layer, it also causes uneven corrosion of the anode metal resulting in corrosion pits.

Under environmental conditions conducive to oxygen supply, such as waves, splashes, flow rates, etc, metal oxygen concentration cells are more active and more likely to cause corrosion.

### 2.1.2. Galvanic corrosion

Galvanic corrosion refers to the corrosion of primary batteries formed by different electrode potentials after two or more different metals contact in conductive media. This corrosion is most common, such as the corrosion formed by centrifugal pump impellers and pump shafts, brass condenser tubes, carbon steel jackets, etc. Xie Hui [10] et al. systematically analyzed the status of electro-couple corrosion of titanium alloys as well as other metals in the marine environment, and found that titanium alloys are very easy to form electro-couple pairs with other metals such as steel

and copper alloys to accelerate corrosion. And the electric insulation coating is the most effective technique to control the electric couple corrosion.

At present, the coating technology to deal with galvanic corrosion is mainly focused on how to effectively isolate metal, but there are still many problems unsolved. In the future study of galvanic corrosion, attention should be paid to the effects of low temperature environment, oxygen concentration and microorganisms on galvanic corrosion.

## 2.2. Mechanical corrosion

Mechanical action corrosion is caused by turbulence or liquid impact, high-speed liquid irregular flow and cavitation phenomenon. The metal under stress is damaged by corrosion, producing cracks along the crystal or through the crystal. This corrosion can continue to damage the organic coating on the surface of the metal, common in the ship's rotor, shaft, etc. Tides and waves in the ocean can produce impact forces on the metal components of mechanical equipment. Lei Hang[11], in order to solve the corrosion problem of the metal of the offshore oil drilling equipment after long-term fluid impact, the study proposed to try to use stainless steel materials and alloy materials. At the same time, anti-corrosion coatings are used on drilling equipment.

## 2.3. Biological corrosion

Biological corrosion includes chemical corrosion and electrochemical corrosion. On the one hand, organisms in the ocean are able to adhere to the bottom of the ship and increase the oxygen content in the water layer, on the other hand, the metabolic process of marine organisms can release CO or the decomposition of the remains of marine organisms can release corrosive gas sulfur, thus acidifying the seawater to accelerate the corrosion of metals [12].

LEILA ABDOLI [13] selected stainless steel 316L and thermal sprayed aluminum-based coatings as raw materials to study the behavior of microorganisms and bacteria adhering to the surface of the coating, and found that the corrosion of marine structural components by bacteria is determined by the nature of the adhering forming biofilm and the physicochemical properties of the material surface interface at the same time. Early biofilm can enhance the corrosion resistance of aluminum-based coatings, but with the extension of time, the biofilm itself has a corrosive effect on steel.

Biological corrosion in marine environment is a complex system. There is an interaction between biochemical molecules produced by their own metabolic processes and electrochemical reactions of corrosion. The future research on biocorrosion can focus on two aspects. Use thick slurry type heavy-duty coating or use corrosion-resistant material for key components.

## 3. Anti-corrosion mechanism of anti-corrosion coatings

The principle of anti-corrosion coatings mainly includes three aspects: physical, electrochemical and chemical principle. The following is a detailed explanation of these three anti-corrosion mechanisms.

### 3.1. Physical Protection

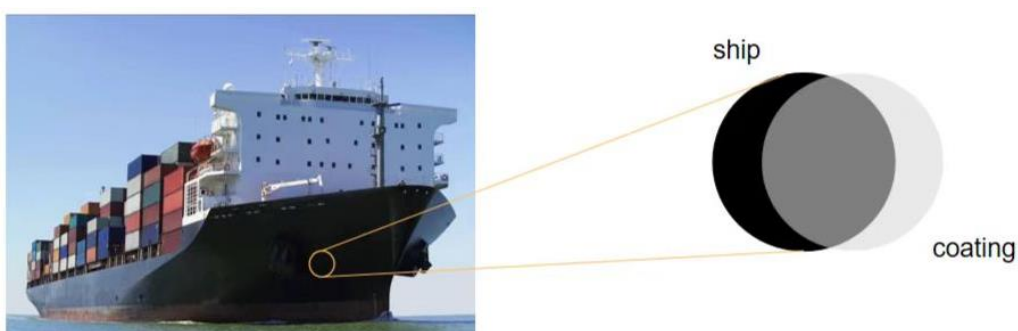


Figure 3. Coating protection principle.[14]

A complete coating film formed on the surface of the metal body isolates the environmental medium (oxygen, water, acid, alkali, salt, etc.) from the metal body, thereby eliminating the "corrosion cell" to form the conditions to protect the metal body from corrosion. This is a physical effect of limited reliability. The main reason is that the organic layer of the film is not completely isolated from the environment, and there are always penetrating media (oxygen, water, etc.) on the metal surface. The penetration capacity depends on the film material and construction process. On the other hand, the insulation of the foil layer from the environment weakens over time, so physical insulation alone cannot effectively protect the metal body.

Studies have shown that the protective effect of organic coatings is not just shielding. The wet adhesion between the coating and the medium surface also plays an important role in anti-corrosion. Wet adhesion ensures that water and oxygen cannot diffuse rapidly on the metal surface to slow down metal corrosion[14]. Zinc phosphate, for example, forms a strong iron complex-zinc phosphate on the surface of steel, which prevents the formation and development of rust and reduces the corrosion of steel [15]. The protection principle of organic coating is shown in Figure 3.

In organic coatings are often used materials that have a certain passivation effect on the metal, such as chromates and redan, etc. When water penetrates into the coating, a small amount of dissolved pigment passivates the substrate and prevents it from continuing to penetrate. The shielding effect of the coating further inhibits the loss of metal ions.

### 3.2. Electrochemical protection

The electrochemical effect of the coating has two main aspects, one is the formation of a passivation layer on the surface of the material, and the other is the oxidation corrosion of some of the more active metals added to the anti-corrosion coating instead of the metal being protected. The electrochemical protection principle of the coating is shown in Figure 4.

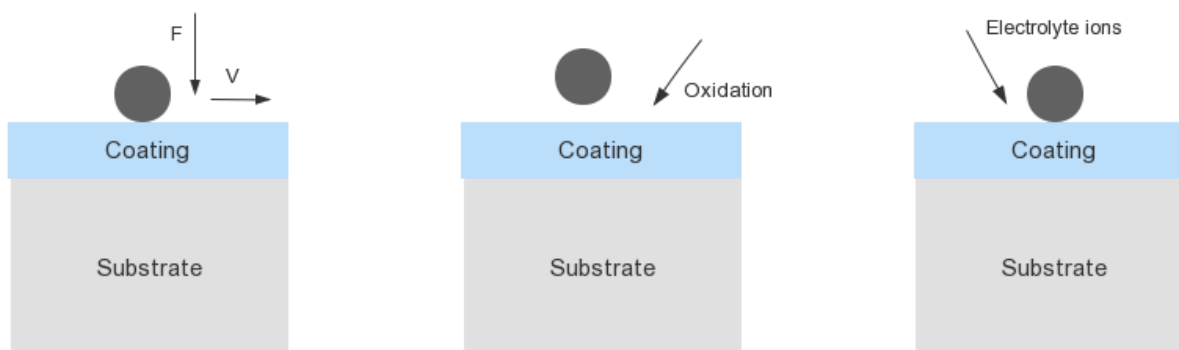


Figure 4. Coating anti-corrosion mechanism diagram [16]

The coatings are mixed with more active metals, which form cathodic protection for steel. One of the most classic examples is zinc-rich coatings, which not only act as a coating and passivation of the bare metal surface, but also reduce the penetration of zinc. However, under acidic or alkaline conditions, zinc oxide is dissolved and the zinc powder is quickly consumed by corrosion [16].

### 3.3. Chemical protection

Reactive fillers, such as zinc oxide, aluminum hydroxide, etc. are added to the anti-corrosion coatings. These fillers achieve the purpose of protecting the metal by reacting with the corrosive substances in the medium. Ma Hongli [17] et al. added a small amount of zinc oxide to the magnesium phosphate cement coating. The protection mechanism and corrosion resistance of the coating were analyzed by Tafel polarization curve and electrochemical impedance spectroscopy. The results show that the addition of zinc oxide increases the compactness of the coating and shifts the self-corrosion potential of the coating positively. The chemical corrosion inhibition and physical shielding of the coating complement each other, and the anticorrosive effect of the coating is further enhanced.

## 4. New organic coating materials for marine use

In solving the problem of corrosion of metal materials, high performance anti-corrosion coating is a simple and effective method. High-performance anti-corrosion coatings for ships have always been a hot topic in material research at home and abroad. The following are several typical high performance anti-corrosion coatings for ships.

### 4.1. Epoxy anti-corrosion coating

The hydroxyl, ether and epoxy groups contained in the epoxy resin molecule are polar structures, which not only have a strong force with the surface of the object to be stuck, but also can diffuse with each other due to the compatibility of its metal oxides.

After the epoxy resin film is cured, the stable benzene ring and ether bond are formed between its molecules, which can endure the erosion of organic solvents and various chemical reagents. Nowadays, most of the epoxy resin coatings for ship anti-corrosion are modified epoxy resin coatings, such as inorganic filler modified epoxy coatings, tar epoxy resin, etc, which are mainly divided into two categories: high solid content and water-based coatings[18].

#### 4.1.1. High solids coatings

High solids coating is a coating system with a solid content greater than 70 % under construction conditions. High solid content coating system has low volatile organic compound (VOC) content, higher coating density after curing, excellent weathering resistance, mechanical strength, etc. Meanwhile, the use of lower VOCs also meets the requirements of the green concept in the field of coatings, and has a broad application prospect.

Li Jiafeng [19] et al. developed a new permanent anticorrosive epoxy coating for the ship splash zone subjected to corrosion. Their team selected bisphenol A liquid epoxy resin and modified resin as the base material of the anticorrosive coating, and the curing agent was selected from modified polyamide and phenalkamine. The test results show that this new permanent anti-corrosion epoxy coating can meet the requirements of anti-corrosion and anti-aging in the splash zone. In addition, it still shows excellent performance under high humidity environment.

For amine-cured epoxy coatings, the extender level is usually increased to avoid sagging of the coating during application. The use of low molecular weight in epoxy high solids coatings is more brittle than conventional coatings [20]. As a result, they are more susceptible to damage from impact, abrasion and grinding. All of these types of damage can impair the barrier properties of the coating. One way to solve this problem is to add a flexibilizer or toughening agent.

#### 4.1.2. Water-based coatings

Another focus of coatings research and development is water-based coatings. Replacing organic solvents with water can further reduce some organic emissions.

The coating system has the following four characteristics[21]. Firstly, the coating has high adhesion to various substrates. Secondly, waterborne coatings have low volatile organic compounds and do not pollute the environment. Thirdly, water-based coatings use water as a dispersion medium, which is less dangerous in storage, transportation and use. Fourth, waterborne coatings have the characteristics of fast drying. When the temperature is 20°C and the relative humidity is 75 %, the surface drying time is generally 2 h.

Ye Changyi [22] et al. prepared waterborne epoxy phosphate coatings with phosphate modified epoxy resin. The results show that the adhesion and hydrophobicity of the coating are significantly improved. The corrosion rate of the metal decreases under the protection of the coating. The waterborne epoxy anticorrosive coating prepared by Tan Weimin [23] et al. solved the problems of easy flash rust, low crosslinking density and poor chemical resistance of waterborne epoxy system. The coating has low VOC content and can be widely used in radiators, steel structures and other fields.

## 4.2. Polyurethane anticorrosive coatings

Polyurethane coatings are characterized by favorable water resistance, good acid solubility, better alkali resistance of most polymers, nice mechanical properties and good weather resistance. They are the results of the reaction of isocyanates ( $R-N=C=O$ ) with reactive water molecules or unstable hydrogen atoms. The crosslinking of polyurethane coatings also depends on the type and structure of isocyanate and curing agent, temperature and the presence of catalyst.

### 4.2.1. High solid polyurethane coatings

The low viscosity, high functionality and high isocyanate content of oligomeric polyisocyanate make polyurethane particularly suitable for high solid content coating. In the development of high solid content polyurethane coatings for epoxy coatings, methods used include reducing resin binders, adding diluents, or reducing the viscosity of polyisocyanate crosslinking agents[24]. According to research, these modifications may reduce the performance of high-solid polyurethane coatings[25].

In the spirit of achieving green chemistry, high-solid polyurethane coatings can also be prepared with plant-based polyols. A novel UV-curable waterborne polyurethane-acrylate (WPUA) was prepared by sequential emulsion polymerization using hydroxyl-terminated natural rubber (HTNR) as raw material[26]. WPUA has good film forming properties, which can provide good wettability and high surface free energy. The mechanical and thermal properties of WPUA film were improved by UV curing.

### 4.2.2. Waterborne polyurethane anticorrosive coatings

The waterborne polyurethane coating is developed by S.S.Pathak[26]. It not only improves the mechanical stress and thermal stability of the product, but also improves the degradation temperature, which is suitable for the marine field.

Xu[27] et al. used poly(propylene carbonate) (PPC) diol as a soft segment to prepare PPC-based waterborne polyurethane emulsion (PPC-PUD). The synthesized PPC-PUD was characterized by Fourier transform infrared spectroscopy (FTIR) and dynamic light scattering (DLS). As a dispersant resin, with dispersant sanding paste, adding waterborne polyurethane emulsion, curing agent and appropriate waterborne additives to prepare baking waterborne coatings. The experimental data show that the waterborne coatings prepared with waterborne polypropylene carbonate resin have excellent salt spray resistance, water resistance and solvent resistance.

At present, there are many modification methods for waterborne polyurethane anticorrosive coatings at home and abroad. It mainly includes epoxy resin modification, silicone copolymerization modification, nano modification and composite modification. After modification, the performance of waterborne polyurethane anticorrosive coatings has been greatly improved, but there are still problems such as poor water resistance and harsh construction conditions.

The development of new modification methods for waterborne polyurethane anticorrosive coatings is the main direction of research on waterborne polyurethane anticorrosive coatings. For example, waterborne polyurethane coatings were prepared by using emulsifiers or introducing hydrophilic groups such as carboxyl and hydroxyl groups into the main chain. The focus of the study is how to improve its water resistance and shorten the curing time.

## 4.3. Graphene anticorrosive coating

Graphene has a two-dimensional lamellar structure, and the carbon-carbon bonds on its planar layer are strongly bonded. Therefore, the chemical properties of graphite are stable and have excellent properties in mechanics, electricity, optics and heat. Through the barrier stacking in the coating, a dense isolation layer is formed by physical methods, which hinders the passage of corrosive media. Herein, graphene is an excellent shielding agent, which separates the metal matrix from the surrounding environment.

For graphene composites, graphene is compounded with polymer. The graphene with smaller particle size is filled into the pores and defects of the polymer coating, which prolongs the diffusion

path of the corrosive medium to a certain extent, thus preventing and delaying the corrosion medium from immersing into the metal matrix. Graphene not only enhances the corrosion resistance of the coating, but also forms good protection for the substrate metal. Meanwhile, the composite coating reacts with the metal substrate to passivate the metal surface or form a protective film to enhance the protective ability of the coating and further improve its corrosion resistance. In addition, graphene has excellent mechanical properties, which can improve the wear resistance of polymer coatings.

#### **4.3.1. Graphene waterborne polyurethane anticorrosive coating**

Waterborne polyurethane is a new type of polyurethane management system that uses water instead of organic solution as a suspending agent, also known as water dispersible polyurethane, water polyurethane or waterborne polyurethane. Waterborne polyurethane is an organic solvent with water, which has the advantages of zero pollution, reliable, high physical performance, good solubility and easy modification of materials. However, due to the volatile matter of water is worse than that of organic solution, the waterborne polyurethane adhesive has a slow drying rate, and the water resistance of raw materials is weak.

Therefore, in order to improve the overall performance, aqueous polyurethane is usually modified by crosslinking, epoxy resin, silicone and inorganic nanomaterials (Si, Ti, CNT). Graphene improves the water resistance, thermal properties and mechanical properties of polyurethane to different levels.

Li [28] et al. added graphene oxide (GO), reduced graphene oxide (RGO) and functionalized graphene derivatives as inorganic nano-fillers to waterborne polyurethane (PU) anticorrosive coatings. Combined with salt spray test, electrochemical impedance spectroscopy (EIS) and other characterization methods, the effects of surface chemical state, dispersion state and graphene content on the corrosion resistance of composite PU coatings were studied. The RGO with a mass fraction of 0.2 % has the most perfect effect on improving the corrosion resistance of the composite PU coating.

#### **4.3.2. Graphene waterborne epoxy anticorrosive coatings**

Wang Yuqiong [29] et al used sodium polyacrylate to uniformly and stably disperse graphene suspension in aqueous solution. After adding graphene, the composite layer showed better watertight barrier properties, the diffusion rate of water molecules in the layer was greatly slowed down, and the corrosion resistance of the layer was significantly improved. The density of the composite ethylene base is greatly reduced, and the coating resistance and load transfer resistance increase.

Zhang[30] et al. synthesized a functionalized silane bridging agent (2-(3,4-epoxycyclohexyl) ethyltrioxysilane) to modify the surface of graphene oxide to overcome the agglomeration of nanomaterials and improve the performance of the coating by functionalization. Corrosion resistance of graphene oxide filled epoxy coating. The functionalized graphene oxide was characterized by Fourier transform infrared spectroscopy, X-ray diffraction, and X-ray photoelectron spectroscopy. The corrosion properties of each coating were tested by electrochemical impedance spectroscopy and salt spray test. It shows that the addition of functionalized graphene oxide improves the corrosion resistance of the epoxy composite layer. When the amount of functionalized graphene oxide is 0.7 % of the weight, the corrosion resistance of the composite layer is the best.

#### **4.3.3. Waterborne graphene acrylic anticorrosive coating**

Waterborne acrylic anticorrosive coatings have low price, simple synthesis, safety and environmental protection, and excellent aging resistance. Lan Xijian[31] et al. used graphene in waterborne acrylic resin anticorrosive coatings, and developed a graphene conductive marine heavy anticorrosive coating. The optimum addition amount of graphene was obtained through experiments, and its anticorrosive mechanism was preliminarily analyzed. The test results show that the marine heavy anti-corrosion coating prepared by graphene has excellent comprehensive performance.

#### **4.3.4. Waterborne inorganic zinc-rich graphene**

Zinc-rich waterborne inorganic primer is a high-strength waterborne anticorrosive primer with silicate solution as an important film-forming material and high content of zinc powder. In order to improve the coating performance, some flake aluminum powder, sericite powder, ferrophosphorus

powder and phosphorus powder can be added to the silicate solution. Yuan Gaobing [32] et al. added graphene as an anti-corrosion additive to the aqueous inorganic zinc-rich liquid silicate system. The results show that the coating without graphene anti-corrosion additives began to appear salt spray test after 1500 hours. There were abnormal changes such as spots, but the coating plate containing trace graphene anticorrosive additives did not change after 2000 hours of salt spray test, indicating that the addition of graphene improved the salt spray performance of the coating.

#### 4.3.5. Summary

The quality of coatings is closely related to the final technical quality. The application of new coatings and the formulation of standards should focus on the efficiency of coating process. For the high solid content coating system, excessive low VOC content can increase the viscosity of the coating, thereby reducing the coating efficiency. Therefore, in the study of high solid content coating standards, in addition to determining the VOC content that the coating should achieve. It should also focus on viscosity, coating curing speed, construction time, etc. For waterborne coating systems, oil-water separation will occur under certain conditions due to the unstable dispersion of oily polymer materials in aqueous solution. Waterborne coatings can be modified by adding fillers.

The dispersion of graphene materials in coatings determines the corrosion resistance of coatings to a large extent. Standardizing the uniform dispersion of various fillers in coatings has important research significance for saving fillers, avoiding energy loss and ensuring coating quality. After graphene modification, the mechanical properties, chemical stability and corrosion resistance of waterborne anticorrosive coatings have been improved. How to establish a comprehensive evaluation method to study the influence of graphene structure, performance, dispersion and dispersion efficiency on the protective performance of coatings, and the relationship between the rapid application growth and development of composite waterborne rust inhibitor graphene-anticorrosive coatings continue to heat up, is expected to further develop.

## 5. Summary and outlook

The development and utilization of the ocean by human beings is deepening, especially the shipping industry and seabed mining industry are developing rapidly. However, the corrosion of ships in marine high salt and high humidity environment is serious, which can easily cause catastrophic accidents. Therefore, ship anti-corrosion work becomes extremely important. Organic coatings have the advantages of strong corrosion resistance, good adhesion and low cost, and have a broader prospect than other types of corrosion protection methods. At the same time, in order to enable the sustainable development of anti-corrosion coatings, we should focus on ecological protection when formulating new standards for ship anti-corrosion protection.

## References

- [1] TAN Longmei. Electrochemical corrosion and protection of metals [J]. China Strategic Emerging Industry, 2019, 0 (24): 0149 - 0149.
- [2] MU Xin, WEI Jie, DONG Junhua, KE Wei. Effect of sacrificial anodic protection on the corrosion behavior of Q235B steel in simulated marine tidal difference intervals [J]. Acta Metallurgica Sinica, 2014, 50 (11): 1294 - 1304.
- [3] ZHANG Jie, JIA Shuai, WANG Xindong, et al. Corrosion and protection in the marine environment [J]. New Technology and New Products in China, 2022 (15): 80 - 82.
- [4] ZHAO Huiping, ZHAO Wenjuan, ZHANG Xiaofang. An analysis of electrochemical corrosion and corrosion protection of metals [J]. Fujian Chemical Industry, 2013, (10): 135 - 136.
- [5] WANG Yuxin, WU Bo, DAI Leyang et al. Study of galvanic corrosion of low-alloy steel in simulated marine cryogenic environment [J]. Chinese Journal of Corrosion and Protection, 2022, 42 (6): 894 - 902.

- [6] ZHANG Zhen, WANG Qi, ZHANG Caiyi, et al. Electrochemical corrosion behavior of D36, F460 and F690 steels for marine engineering in simulated seawater [J]. *Materials for Mechanical Engineering*, 2019, 43 (8): 27 - 34.
- [7] YANG Zhonggui, BAI Jie, WANG Zhimin, et al. The 713 Research Institute of CSIC. Electrochemical corrosion characteristics of wind turbine foundation anchors in marine environment [J]. *Ship Engineering*, 2020, 42 (S1): 620 - 622+626.
- [8] SUN Qi, XIAO Jingxian. Study on local corrosion resistance of low alloy steel for ocean [J]. *Special Steel*, 1992, 13 (4): 16 - 19.
- [9] XING Pei, LU Lin, LI Xiaogang. Study on the corrosion behavior of high-strength steel E690 for marine use with oxygen concentration difference [J]. *Chinese Journal of Materials Research*, 2016, 30 (4): 241 - 247.
- [10] XIE Hui, WU Xingwei, LIU Bin, et al. Advances in the study of galvanic corrosion behavior of titanium alloys/other metals in the marine environment [J]. *Materials Protection*, 2022, 55 (4): 155 - 166.
- [11] LEI Hang. Corrosion factors and prevention technology of offshore oil drilling machinery and equipment [J]. *The Journal of New Industrialization*, 2022, 12 (4): 236 - 240.
- [12] CAO Yuexin. Marine water pipe system corrosion and protection [J]. *Marine Equipment/Materials & Marketing*, 2020, (1): 48 - 49.
- [13] LEILA ABDOLI. Study of biocorrosion behavior of thermal sprayed aluminum-based coatings under marine environment [D]. University of Chinese Academy of Sciences, 2017
- [14] WANG Jingjin, SU Mengxing. Research progress of high-performance anti-corrosion coatings for ships [J]. *Coatings Technology & Abstracts*, 2017, 38 (07): 37 - 48+53.
- [15] ZHANG Feng. Preparation, performance and anti-corrosion mechanism of organic coatings for marine heavy corrosion [D]. Beijing University of Chemical Technology, 2007.
- [16] KONG Fantao. Preparation and application of high anti-corrosion water-based epoxy zinc-rich coating [J]. *Modern Paint and Finishing*, 2021, 24 (08): 13 - 16.
- [17] MA Hongli, WU Qing, YANG Jianming, et al. Effect of zinc oxide on properties of potassium magnesium phosphate based anticorrosive coatings [J]. *Paint & Coatings Industry*, 2022, 52 (3): 71 - 77, 88.
- [18] LIU Xian, SHEN Ting, CHENG Huan. Research progress of epoxy resin anticorrosive coating [J]. *Plastics Science and Technology*, 2021, 49 (09): 96 - 100.
- [19] LI Jiafeng, ZHANG Weiqiang, FANG Jianjun. Development of high solid content epoxy coating for maintenance in splash zone [J]. *Paint & Coatings Industry*, 2020, 50 (04): 58 - 64.
- [20] Heaner W L, Aguirre-Vargas F, Ge S, et al. Tuning Toughness and Flexibility in Liquid Applied High Solids Epoxy Coatings [J]. *Corpus ID*, 2016, 102500379.
- [21] WANG Yingmao, ZHANG Yahao, HUANG Congshu, et al. Research progress and application status of waterborne anticorrosive coatings [J]. *Development and Application of Materials*, 2021, 36 (06): 91 - 96.
- [22] YE Changyi, CHEN Bingyao, YAO Rongmao, et al. Study on preparation and application properties of waterborne epoxy anticorrosive coatings [J]. *Chemistry and Adhesion*, 2020, 42 (04): 272 - 274+303.
- [23] TAN Weimin, WANG Yaxin, SHI Liping, et al. Preparation and properties of high-performance waterborne epoxy anticorrosive coatings [J]. *Coating and Protection*, 2021, 42 (01): 28 - 32+38.
- [24] Pélissier Krystel, Thierry Dominique. Powder and High-Solid Coatings as Anticorrosive Solutions for Marine and Offshore Applications? A Review [J]. *Coatings*, 2020, 10 (10).
- [25] H. Renz, B. Bruchmann. Pathways targeting solvent-free PUR coatings [J]. *Progress in Organic Coatings*, 2001, 43 (1).
- [26] Tsupphayakorn-aek Panchanathan, Suwan Anutida, Tulyapitak Tulyapong, et al. A novel UV-curable waterborne polyurethane-acrylate coating based on green polyol from hydroxyl telechelic natural rubber [J]. *Progress in Organic Coatings*, 2022, 163.
- [27] XU Haiyan, ZHANG Xingyuan, SUN wei, et al. Preparation of Poly (propylene carbonate) waterborne polyurethane and its application in waterborne anticorrosive coatings [J]. *Coatings Technology & Abstracts*, 2015, 36 (02): 3 - 6+43.

- [28] LI Jing, CUI Jincan, YANG Jiayun, et al. Reinforcement of graphene and its derivatives on the anticorrosive properties of waterborne polyurethane coatings [J]. *Composites Science and Technology*, 2016, 129.
- [29] WANG Yuqiong, LIU Shuan, LIU Zhaoping, et al. Waterproof and protective properties of graphene doped waterborne epoxy resin [J]. *Electroplating & Finishing*, 2015, 34 (06): 314 - 319+361.
- [30] Zhang C, Dai X, Wang Y, et al. Preparation and corrosion resistance of ETEO modified graphene oxide/epoxy resin coating [J]. *Coatings*, 2019, 9 (1): 46.
- [31] LAN Xijian, ZHOU Fugen, FENG Weidong. Development of graphene conductive marine heavy anti-corrosion coating [J]. *Shanghai Coatings*, 2014, 52 (12): 17 - 20.
- [32] YUAN Gaobing, LI Shaoxiang, LIU Laiyun. Screening of additives for waterborne inorganic zinc-rich coatings and their effects on coating properties [J]. *China Coatings*, 2014, 29 (11): 46 - 49.