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Research Progress and Outlook on Anti-Corrosion Coatings for Metal Structural Components

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Abstract: ***Metal structural components are widely used in infrastructure sectors such as transportation, construction, and water conservancy. Operating for extended periods under harsh environments characterized by multiple synergistic stressors, these components are prone to defects such as electrochemical corrosion, surface cracking, and coating peeling. These issues significantly shorten the service life of structural components, threaten engineering operational safety, and result in substantial economic losses. As an efficient, economical, and easy-to-apply protective measure, anti-corrosion coatings have become one of the core technologies for enhancing the durability of metal structural components. This paper systematically discusses the types of corrosion affecting metal structural components and categorizes the current mainstream anti-corrosion coatings, summarizing their types, performance characteristics, and research progress. It serves as a reference for the future research, development, and engineering application of high-performance anti-corrosion coatings.***

Keywords: Metal structural components, Anti-corrosion coatings, Research progress.

1. Introduction

Leveraging the excellent mechanical strength, structural toughness, and formability of metallic materials, metal structural components are widely used in numerous critical fields such as architectural bridges, transportation, energy and power, marine engineering, mechanical equipment, and infrastructure construction. However, corrosion is a major factor affecting the service life and functionality of metal structural components. In China, annual economic losses caused by metal corrosion exceed 30 billion yuan, accounting for 4 % of the gross national economy [1]. Currently, one of the most effective methods for metal corrosion protection is the application of anti-corrosion coatings to metal surfaces [2]. To adapt to complex and harsh service environments, coatings must be modified and optimized to enhance their adaptability under various environmental conditions. ased on this, this paper systematically outlines the types of corrosion affecting metal structural components and categorizes the current mainstream anti-corrosion coatings, summarizing their types, performance characteristics, and research progress, with the aim of providing theoretical and practical support for the advancement of metal structural component protection technologies.

2. Types of Corrosion in Metal Structural Components

Metal corrosion, as the result of complex interactions between the metal and its surrounding environment, is a phenomenon involving various physicochemical processes [1]. Table 1 elaborates on several common corrosion types and their own machanisms of metallic structural components.

Table 1: Common Types of Corrosion and Their Mechanisms

Types of Corrosion	Corrosion Mechanisms	Corrosion Characteristics	Influencing Factors
Electrochemical Corrosion	When a metal comes into contact with an electrolyte solution in the environment, a galvanic cell is formed under natural conditions [3]	The corrosion process requires the participation of conductive media such as water and salts, and it often occurs in crevices, pores, and other such areas [3]	It is positively correlated with ambient temperature, humidity, and electrolyte concentration [3]
Chemical Corrosion	Metals undergo direct redox reactions with non-electrolytes [4]	Direct redox reactions occur between the metal and a non-electrolyte, with no current generated [4]	It is directly proportional to environmental humidity [4]
Physical corrosion	The metal undergoes physical dissolution [4]	Metal atoms diffuse into the corrosive medium, or the corrosive medium penetrates into the metal, without the generation of an electric current [4]	It exhibits an exponential relationship with ambient temperature and contact time [5]

3. Anti-corrosion Coatings for Metal Structural Components

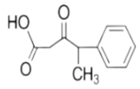
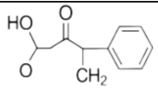
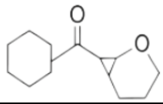
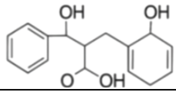
3.1 Organic Anti-Corrosion Coatings

Organic anti-corrosion coatings use organic polymer materials as film-forming substances. They are characterized by good flexibility, strong adhesion, and ease of application, making them one of the most widely used coating types for metal structural components today. Based on the type of resin, organic anti-corrosion coatings can be classified into epoxy resin coatings, polyurethane coatings, and fluorocarbon coatings.

3.1.1 Epoxy Resin Coatings

Epoxy resin coatings offer advantages such as strong corrosion resistance, excellent electrical insulation, and high strength, making them the most widely used type of anti-corrosion coating in both domestic and international markets. For the classification, structural characteristics, and scope of application of epoxy resins, see Table 2 at.

Table 2: Classification, Structural Characteristics, and Scope of Application of Epoxy Resins [5]

Classification	structure	Chemical formula	Characteristics	Application Scenarios
Bisphenol-A type		$(C_{21}H_{24}O_4)_n$	High bonding strength	Crack repair, steel bar anchorage, steel bridge deck paving
Bisphenol-F type		$(C_{19}H_{20}O_4)_n$	High fluidity	Micro-crack repair, mass grouting
Cycloaliphatic type		$(C_8H_{12}O_2)_n$	Excellent weather resistance	Stay cable coating, expansion joint sealing
Novolac type		$(C_{11}H_{15}ClO_3)_n$	High temperature resistance	Fire-resistant coatings, steel bridge deck paving

However, epoxy resin molecules contain two or more epoxy groups. After curing and cross-linking, these epoxy groups form a network structure. This network structure makes the coating highly brittle, prone to cracking after film formation, and insufficiently corrosion-resistant [6]. To address this issue, researchers both domestically and internationally have employed various methods to modify the resin. Shen Xuebing [7] used a silane coupling agent (KH550) to graft-crosslink SiO_2 with graphene oxide (GO), then compounded it with epoxy resin to produce a GO/SiO_2-modified epoxy composite coating. Tests showed that the introduction of the GO/SiO_2 composite filler enhanced the flexibility and corrosion resistance of the epoxy resin; Dai Wazi [8] et al. used polypropylene glycol (PPG) and toluene diisocyanate (TDI) as raw materials, capped with epoxy resin, to prepare epoxy-terminated polyurethane prepolymers (EPPU), which were then used to toughen and modify epoxy resin. The results showed that the modified epoxy resin exhibited increased flexibility.

3.1.2 Polyurethane Coatings

Polyurethane coatings possess excellent flexibility, adhesion, and tunability [9] and have been widely used in construction engineering, transportation, and corrosion protection of metal structural components. Researchers both domestically and internationally have developed various modification methods for polyurethane coatings to enhance their anti-corrosion performance. Li et al. conducted in situ studies on cerium-based bidentate metal-organic frameworks (Ce-MOFs) on GO [10], followed by chemical modification of the GO composite with polydopamine (PDA), ultimately yielding a GO/Ce-MOF@PDA/PU superhydrophobic self-healing anti-corrosion coating. Test results indicate that this composite coating exhibits excellent anti-corrosion performance. Jin [11] modified polyurethane using isophenyl diisocyanate (IPDI), polypropylene glycol (PPG-1000), 2,2-dimethylpropionic acid (DMPA), and epoxy resin. The results indicated that the modified polyurethane coating exhibits high hardness, good heat resistance, and anti-corrosion properties.

3.2 Inorganic Anti-Corrosion Coatings

Inorganic anti-corrosion coatings use inorganic polymers as film-forming agents and offer advantages such as high-temperature resistance, strong anti-corrosion properties, and excellent adhesion. They have become the core materials for long-term anti-corrosion protection of metal structural components in bridges, marine environments, and the power industry. Based on this, the following section primarily introduces research progress on two types of inorganic anti-corrosion coatings.

3.2.1 Inorganic Zinc-Rich Coatings

Inorganic zinc-rich coatings are anti-corrosion coatings that use silicates as the film-forming binder, zinc powder as the pigment and filler, and a small amount of organic substances as additives or auxiliary solvents. They possess excellent electrical conductivity, solvent resistance, heat resistance, and corrosion resistance [12]. The corrosion protection provided by inorganic zinc-rich coatings can be divided into three components: (1) the physical barrier effect of corrosion products; (2) the electrochemical protection provided by the sacrificial anode;(3) the self-healing and passivation effects of the coating [13]. However, traditional inorganic zinc-rich coatings suffer from drawbacks such as poor adhesion, low flexibility, and low impact resistance [14]; therefore, modifying inorganic zinc-rich coatings is of great importance. Liu [15] et al. modified tourmaline powder with vinyl triethoxysilane and, using in-situ polymerization, synthesized a novel silicone-acrylic emulsion as the organic film-forming agent. By adding this to an inorganic potassium silicate solution, they successfully produced a zinc-rich coating with excellent adhesion and corrosion resistance. Jiang [16] et al. used high-modulus potassium silicate solution and fluorocarbon emulsion as film-forming agents, flake zinc powder as the filler, and added an appropriate amount of reduced graphene oxide dispersion as an auxiliary filler to prepare a silicate-based waterborne inorganic zinc-rich coating. The results showed that when the addition of reduced graphene oxide dispersion reached 6%, the mechanical properties and corrosion resistance of the coating were optimal.

3.2.2 Phosphate Coatings

Phosphate coatings are inorganic coatings formed through the chemical reaction between phosphoric acid and alkaline oxides [17]. Inorganic phosphate anti-corrosion coatings are formulated from binders, curing agents, aggregates, filler aggregates, and additives, and possess characteristics such as high adhesion, excellent coatability, corrosion resistance, and being non-toxic and environmentally friendly [18-19]. However, phosphate coatings still suffer from issues such as high curing temperatures, high brittleness, and poor resistance to acids and alkalis [19]. Li [20] et al. synthesized aluminum phosphate binders using $Al(OH)_3$ and H_3PO_4 as raw materials. These binders were used in conjunction with the curing agent MgO and the filler ZrO_2 to prepare coatings. The results showed that as the phosphorus-to-aluminum ratio decreased, aluminum ratio, the viscosity of the aluminum phosphate binder increased while the bond strength of the coating decreased. Therefore, the optimal preparation process for the aluminum phosphate binder is: P/Al = 3:1, with a phosphate concentration of 60%. Kang [21] et al. prepared four different phosphate coatings using Al_2O_3, CaO, SiO_2, and ZnO as curing agents. The results indicated that the phosphate coating using ZnO as the curing agent exhibited the highest corrosion protection efficiency (96.43%) and the best corrosion resistance.

4. Conclusions

Metal structural components are subject to the combined effects of electrochemical, chemical, and physical corrosion, leading to severe corrosion failure. Anti-corrosion coatings, as an efficient and economical protective measure, play a crucial role in enhancing the durability of structural components. This paper systematically reviews the types of corrosion in metal structural components and the research progress on anti-corrosion coatings, drawing the following conclusions:

1) Corrosion of metal structural components can be classified into electrochemical corrosion, chemical corrosion, and physical corrosion based on their mechanisms. Both electrochemical and chemical corrosion involve chemical reactions, but the former generates an electric current while the latter does not; physical corrosion, however, involves only physical dissolution.

2) Currently, anti-corrosion coatings for metal structural components are primarily divided into two major categories: organic coatings and inorganic coatings. Organic anti-corrosion coatings use organic polymer materials as film-forming agents and are characterized by good flexibility, strong adhesion, and ease of application. They are one of the most widely used coating types for metal structural components today. However, they suffer from issues such as high film brittleness, susceptibility to cracking after curing, and insufficient corrosion resistance. Modified high-temperature resistance, strong corrosion resistance, and excellent adhesion, and have become the core materials for long-term corrosion protection of metal structural components in bridges, marine structures, and power facilities. However, they suffer from issues such as poor adhesion, low flexibility, and high curing temperatures. Modification methods primarily involve the blending of film-forming substances, the addition of inorganic nano-fillers, and the use of various additives.

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