fire

Article

Development and Evaluation of Steel Component Coatings for Substations/Converter Stations with Both Fire and Corrosion Prevention Functions

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Abstract: There are a large number of steel components in substations/converter stations whose performance is seriously affected by being exposed to environmental corrosion and fire, endangering the operation of the substation/converter station. The current protective measures for steel components in substations/converter stations primarily involve the application of anti-corrosion and fireproof coatings. However, these coatings can easily peel off, resulting in a significant loss of their protective effectiveness. In response to this challenge, a new type of silicone-modified epoxy resin substrate has been synthesized by chemically grafting silicone resin onto epoxy resin segments, which retains the high adhesion of epoxy resin while enhancing its weather resistance. The use of synthesized nano zinc oxide-modified graphene oxide as a fireproof filler significantly improves the physical barrier effect and corrosion resistance of the coating. Additionally, the innovative addition of new metal anti-corrosion active pigments improves the adhesion and impermeability of the coating. Therefore, a steel structure coating for substations/converter stations with both fire and corrosion prevention functions has been developed. Standard tests conducted by national institutions have shown that the coating meets the performance requirements.

Keywords: substations/converter stations; steel components; anti corrosion; fire prevention; coatings

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1. Introduction

Steel equipment, structures, and installations are critical components within substations/converter stations. They are subjected to long-term environmental corrosion factors, leading to material degradation. In the event of a sudden fire, the strength of these steel structures can rapidly decline, resulting in deformation or even catastrophic collapse. Furthermore, the high thermal conductivity of steel materials during fires can cause the formation of cracks and leakage points in valve hall fire prevention systems, leading to severe equipment damage. This not only threatens the integrity of the power grid and personnel safety but can also lead to significant economic losses. Given the dual threats posed by corrosion and fire, there is a critical need for effective anti-corrosion and fireproof measures to ensure the safety and longevity of these essential components.

Current research and applications of fireproof and anti-corrosion coatings for steel structures predominantly focus on single functionalities [1]. For instance, thermal insulation fireproof coatings are specifically developed for fire scenarios and high-temperature operations [2–4], while anti-corrosive coatings are designed to protect against natural corrosive environments [5–9]. In practical engineering applications, to achieve a dual functionality, an anti-corrosion coating is typically applied first, followed by a fireproof coating. However, this layering approach often results in the poor adhesion and peeling of the outer fireproof layer, significantly compromising its protective effectiveness and extending the construction period due to the need for multiple applications. Consequently, there is an urgent need to develop a unified steel structure coating that integrates both fireproof and anti-corrosion properties to address these challenges effectively.

Existing integrated fireproof and anti-corrosion coatings primarily rely on incorporating fireproof and anti-corrosive materials into a resin matrix. Through research, it has been determined that epoxy resin is the preferred choice due to its excellent mechanical and corrosion-resistant properties. However, as an organic polymer resin, epoxy resin exhibits poor high-temperature resistance, is prone to burning, and has poor weather resistance due to its benzene ring structure. The use of silicone modification can improve the heat resistance of this resin [10,11]. In contrast, the migration of silicon chain segments to the surface improves the surface properties of the material. Flame retardants are indispensable for the fire resistance of coatings, and two-dimensional materials are ideal flame retardants [12]. Luo [13] introduced DOPO-modified graphene oxide into an epoxy resin matrix, resulting in a 32% increase in the char yield of the modified graphene oxide, significantly enhancing the fire resistance of the resin matrix. Zhang [14] incorporated magnetic ZF-BNNS nanofiller into an epoxy resin matrix, which retarded the release of thermally decomposed products and promoted the formation of a continuous char layer. The ratio of filler to resin has an impact on the performance of the coating. An excess of resin reduces the material's fire resistance, while an excess of filler has the opposite effect, reducing the film-forming properties of the coating. In order to obtain coatings with both fire and corrosion protection properties, it is necessary to investigate the appropriate filler ratio.

Based on the fire and corrosion prevention requirements for steel structures in substations/converter stations, a novel self-expanding flame-retardant epoxy resin-based fireproof and anti-corrosive coating was developed. This study investigates the impact of various filler ratios on the fireproof and anti-corrosive properties of the coating, using silicone-modified epoxy resin as the substrate. Zinc oxide-modified graphene oxide (GO/ZnO) was synthesized and employed as the coating filler to further enhance the fireproof and anti-corrosive properties of the self-expanding flame-retardant epoxy resin-based coating.

2. Materials and Methods

Materials: E44 Epoxy Resin was purchased from Sinopec (Beijing, China) and KH-550 and PDMS were purchased from Dow Corning (Midland, MI, USA). BYK-110 was purchased from BYK Additives (Shanghai, China). Graphene oxide, pentaerythritol, dibutyltin laurate, melamine, ammonium polyphosphate (DP > 1000), fumed silica, polyamide curing agent (650), and titanium oxide were purchased from Macklin. Zinc phosphate, zinc acetate, and organic solvents were purchased from Sinopharm Chemical Reagent Co. (Shanghai, China)

Testing equipment: A YIKE-360A contact angle meter, an X-ray diffractometer (XRD-6000), an infrared spectrometer (IRAffinity-1S), a Raman spectrometer (DXR3xi).

3. Results and Discussion

3.1. Development of Dual-Function Coating Formula

3.1.1. Substrate

The substrate of the dual-function coating is primarily composed of film-forming resins, which are the most crucial components of the coating [7,8]. Since each type of resin has certain drawbacks, to overcome the limitations of single-resin anti-corrosion coatings, multiple resins can be chemically bonded to combine their strengths, thereby improving the overall performance of composite coatings [8,15–18].

Epoxy resin is favored for its excellent adhesion properties due to its epoxy functional groups, allowing it to form a dense protective film on steel surfaces. However, its weather resistance is poor due to the presence of benzene rings. In contrast, silicone resin has excellent heat and weather resistance but insufficient adhesion, making it unsuitable for large-area application. The complementary advantages of silicone and epoxy resins were utilized in this paper. Through chemical modification, silicone resin was chemically grafted onto epoxy resin segments to synthesize a new type of silicone-modified epoxy resin substrate, which combined the advantages of both resins and compensated for the shortcomings of single-component resins. The silicone resin used was low-molecular-weight hydroxyl silicone oil, while the epoxy resin was E44 epoxy resin (bisphenol A epoxy with an epoxy value in the range of 0.41–0.47), and the silane coupling agent was γ-aminopropyl triethoxysilane.

Epoxy resin, known for its active epoxy functional groups, allows for the introduction of silicone segments through various sophisticated methods, including coupling agent blending, coupling agent grafting, and chemical grafting. Each method achieves specific modifications to enhance resin properties. The coupling agent blending method involves the reaction of the amino groups on the silane coupling agent with the epoxy groups on the epoxy resin, introducing coupling agent fragments at the end to improve the compatibility between the epoxy resin and silicone. Subsequently, the epoxy resin is blended with silicone resin. The coupling agent grafting method entails the reaction of the amino groups on the silane coupling agent with the epoxy groups on the epoxy resin to introduce coupling agent fragments at the end, followed by a reaction with silicone to introduce silicon fragments at the chain end. The chemical grafting method involves a condensation reaction between the silanol groups and the hydroxyl groups on the epoxy resin, introducing silicon fragments into the epoxy resin chain, thereby eliminating compatibility issues between the silicone resin and the epoxy resin. The appearance of the cured coatings obtained using these three methods is depicted in Figure 1.

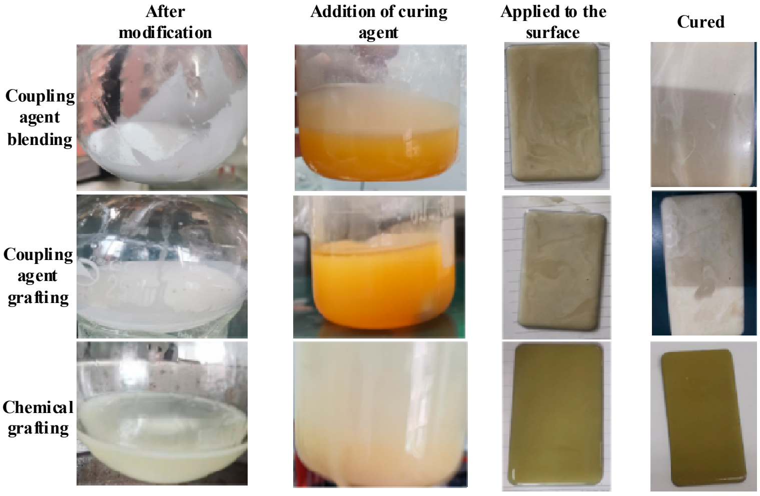


Figure 1. Product status of different modification methods and appearance of cured coatings.

The results indicate that the coating resin synthesized using the chemical grafting method exhibited excellent uniformity after undergoing modification and the addition of a curing agent. When applied to the surface of steel plates and cured, the coatings displayed neither delamination nor fractures, confirming the successful grafting of silicone segments onto the epoxy resin segments. The specific synthesis steps for silicone-modified epoxy resin were as follows: E44 epoxy resin (50 g) and a mixed solution of xylene and cyclohexanone (17 g, 1:1 ratio) were placed into a flask. The mixture was stirred with a magnetic stirrer (at 300 rpm) until the epoxy resin was completely dissolved. The oil bath was heated to 155 °C and 5 g of low-molecular-weight hydroxyl silicone oil (with a viscosity of 30 cs) was placed in a constant-pressure dropping funnel. Gradually, the hydroxyl silicone oil was added dropwise to the epoxy resin solution at a rate of 0.1 mL/s while stirring magnetically at 155 °C for 5 h. The resulting product is the milky white modified epoxy resin. Infrared spectroscopy confirms the successful grafting of silicone onto epoxy resin [19,20] (Figure 2). The final resin used for the coating substrate is the silicone-modified epoxy resin synthesized according to the above steps. The formulations for each epoxy modification method are shown in Table 1. Preliminary tests on the corrosion resistance and related physical properties of the modified resin coatings were conducted using a contact angle meter and salt-water corrosion experiments.

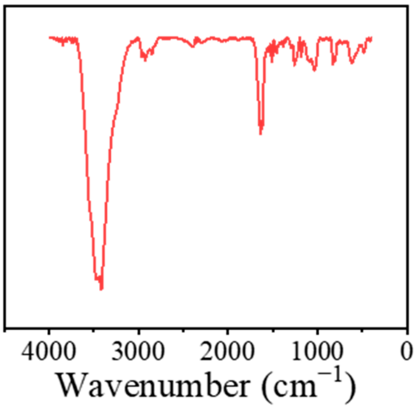


Figure 2. Infrared spectra of polyamide-cured silicone-modified epoxy resin.

Table 1. The formulations for each epoxy modification method.

	E44 (g)	PDMS (g)	KH-550 (g)	Xylene and Cyclohexanone (in a 1:1 Ratio) (g)
Coupling agent blending method	50	7	1.5	17
Coupling agent grafting method	50	7	1.5	17
Chemical grafting method	50	5		17

Figure 3 shows that the water contact angle of the cured epoxy resin substrate after modification (Figure 3a) significantly increased, indicating better hydrophobicity compared to the pre-modified resin (Figure 3b). Figure 4 shows that, after placing the modified and pre-modified coatings in saturated saltwater for two weeks, the surface of the modified resin coatings remained almost unchanged, while the edges of the pre-modified resin coatings were corroded, demonstrating the improved corrosion resistance of the modified resin substrate.

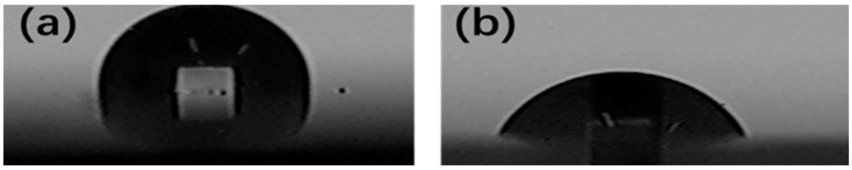


Figure 3. Changes in surface water contact angle after modification (**a**) and before modification (**b**).

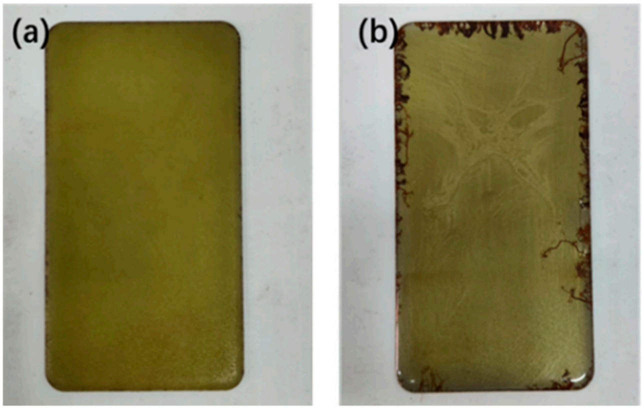


Figure 4. Salt-water corrosion resistance of modified (**a**) and pre modified (**b**) coatings.

3.1.2. Synthesis of Two-Dimensional Material GO/ZnO

Graphite 2D materials are excellent corrosion inhibitors and flame retardants for coatings. However, these materials are prone to self-accumulation, which reduces the dispersibility of the materials in coatings, thus reducing the anti-corrosion and flame-retardant effects of coatings. To address this issue, we synthesized GO/ZnO by modifying graphene oxide with zinc oxide, which improved the dispersibility of the 2D materials in coatings.

Graphene oxide (GO) surfaces feature numerous functional groups such as hydroxyl, carbonyl, and carboxyl groups. GO exhibits physical properties similar to graphene, including a high Young's modulus (approximately 1.0 TPa) [21] and high thermal conductivity (approximately 5000 $Wm^{-1}K^{-1}$) [22]. Therefore, incorporating GO into polymers as a filler is beneficial. The high-strength, two-dimensional lamellar structure of these fillers [23] effectively seals micro-cracks and pores that may form during the curing process of epoxy resins. By acting as a robust physical barrier, these fillers prevent the penetration of corrosive media, thereby significantly enhancing the corrosion resistance of the coating. Additionally, during the film-forming resin decomposition process, GO can form a dense continuous char layer that acts as a physical barrier, slowing down and preventing heat transfer, thereby improving the fire resistance of the coating.

However, GO exhibits poor compatibility with coatings, resulting in unstable film formation and poor dispersion when directly blended with them. Since GO contains numerous oxygen-containing functional groups on its surface, it can be readily functionalized with other functional group structures. Therefore, surface modification techniques can be employed to improve the compatibility of GO with fire retardants and to enhance the stability of the GO's own structure.

Figure 5 shows the process of modifying GO by surface modification with nano zinc oxide via electrostatic self-assembly, reinforcing the char layer structure of GO. The synthesized GO/ZnO composites were characterized by X-ray diffraction (XRD). As shown in Figure 6, the crystal structures of GO, ZnO, and GO/ZnO composites were investigated by analyzing the XRD patterns. The synthesized ZnO shows characteristic peaks corresponding to (002), (100), (101), (102), (103), (110), and (112) crystallographic planes in the hexagonal fibrillated zincite phase of ZnO. The peaks of GO correspond to the characteristic peaks of graphene oxide [24,25]. The XRD patterns of GO/ZnO composites show the characteristic peaks of GO and ZnO, demonstrating the successful synthesis of GO/ZnO composites. Raman spectroscopy can also reflect a nanocomposite structure. Two prominent peaks at 1350 and 1596 cm^{-1} confirm the typical sp2 graphitic structure (G band) and sp3 disordered structure (D band) of GO. In addition, Raman peaks of GO/ZnO in the range of 150–600 cm^{-1} are consistent with the peaks characterizing the hexagonal feldspathic zincite structure of ZnO. This further demonstrated the successful synthesis of GO/ZnO. The introduction of zinc oxide not only strengthens the interaction with the carbon source but also further enhances the material's corrosion resistance and expansion performance under high temperatures. The expansion performance of zinc oxide-modified graphene oxide was significantly increased, as shown in Figure 7.

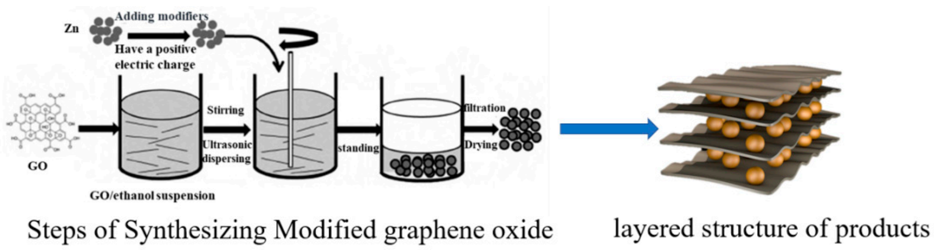


Figure 5. Process diagram of modified graphene oxide.

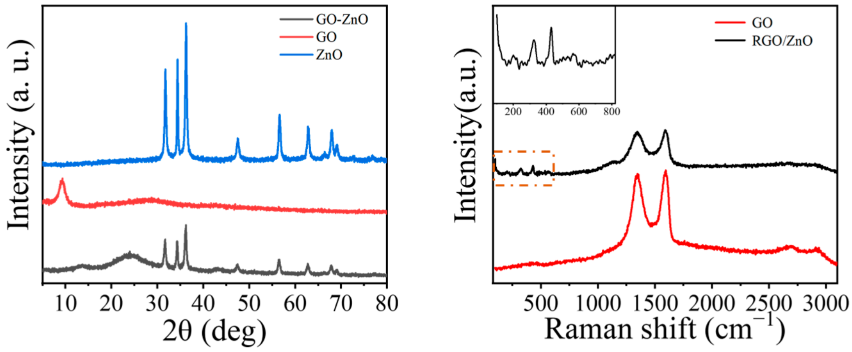


Figure 6. XRD patterns and Raman spectrum of GO, ZnO, and GO/ZnO.

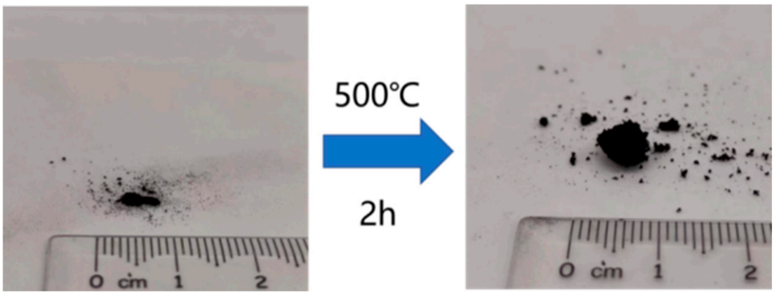


Figure 7. Excellent expansion performance of modified graphene oxide at high temperatures.

3.1.3. Synthesis of Fire-Retardant and Anti-Corrosion Coatings

Currently, to meet fireproof and anti-corrosion requirements, a layer of anti-corrosion primer is typically applied to the surface of materials, followed by a layer of fireproof intermediate paint, and finally a layer of anti-corrosion topcoat on the surface of the fireproof paint. Due to the different components of these two types of coatings, there is a risk of the poor adhesion and peeling of the outer layer. Additionally, the maintenance of the coating in the later period increases economic costs, extends the construction period, and raises construction expenses [16]. In contrast, the fireproof fillers in integrated coatings can further enhance the mechanical and corrosion-resistant properties of the coating, and the synergistic effect of the fillers provides superior fireproof and anti-corrosion performance compared to single-layer coatings [26].

Synthetic integrated anti-corrosive and fire-retardant coatings need to explore the ratio between the fire-retardant system and the anti-corrosive system; a reasonable ratio can make the coatings have better film-forming properties, fire-retardant properties, and anti-corrosive properties.

Intumescent fireproof coatings are widely used for fire protection of steel structures. When the temperature reaches the target level, the carbonization catalyst reacts with the char-forming agent to generate a viscous esterification product [27–29]. Concurrently, the included foaming agent undergoes thermal decomposition, generating inert gasses. These gasses cause the molten film-forming substance to intermix with the viscous esterification product, prompting the mixture to expand and form a dense layer that provides both fireproofing and thermal insulation, as shown in Figure 8. Intumescent fireproof coatings are protective materials that combine both physical and chemical fire protection mechanisms, making them particularly suited for outdoor steel structures.

A classic P-C-N (phosphorus, carbon, nitrogen) intumescent fire-retardant system was selected, using ammonium polyphosphate (APP), pentaerythritol (PER), and melamine (MEL) as fireproof fillers. This fireproof system has been extensively validated and has consistently demonstrated reliable and stable fire-retardant effects [30–32].

The effectiveness of intumescent fireproof coatings is mainly achieved through the isolation of the heat source by the char layer. The fire-retardant effect is closely related to the strength of the char layer. However, a char layer formed solely by fireproof fillers is prone to collapse under high-temperature flames, resulting in a short fire resistance duration. Adding various fireproof pigments and fillers can help form a high-strength expanded char layer, enhancing the flame retardant effect of the coatings.

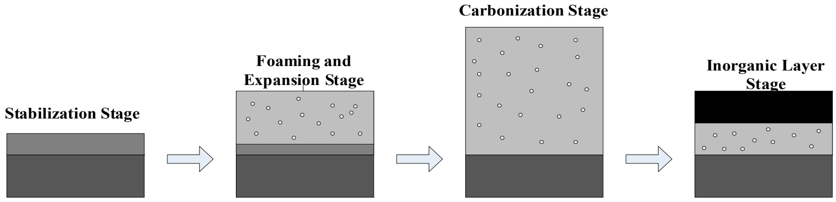


Figure 8. Expansion process of intumescent fireproof coatings.

From among various pigments and fillers, titanium dioxide (TiO_2) was selected due to its strong covering power and chemical stability, which increase the density of the char layer [33–35]. Additionally, it reacts with ammonium polyphosphate in the flame-retardant system during heating to form white TiP_2O_7 [Equation (1)], which prevents the erosion of the char layer by the flame, inhibits heat transfer, and blocks oxygen diffusion to the substrate.

$$2TiO_2 + (NH_4)_4P_4O_{12} \rightarrow 2TiP_2O_7 + 4NH_3 + 2H_2O \quad (1)$$

Under the conditions where the composition of the fireproof filler was determined, the amounts of TiO_2 and graphene oxide added were each set to be 10% of the total filler. The proportions of acid source, carbon source, and gas source were then adjusted.

Fire performance tests were conducted on coatings with varying filler ratios to assess their fire resistance capabilities. Each specimen was secured above an iron frame, positioned with the coating facing downward. An alcohol burner was positioned with its nozzle 6.5 cm directly below the specimen. A layer of insulation cotton covered the back of the steel plate to prevent rapid heat dissipation. Upon igniting the burner, it was moved directly beneath the specimen to uniformly expose the coating to the flame. The temperature of the back plate was measured using a thermocouple. According to China’s national standard GB14907-2018 [36], the time taken for the back plate temperature to reach 500 °C was recorded as the fire resistance limit of the fireproof coating. Changes in the appearance of the coating were observed, and fire resistance limits under different filler ratios were plotted.

After being burned under a high temperature, the coating on the plate rapidly expanded to form a thermal insulation char layer, as shown in Figure 9. It can be seen that the coating expanded 33 times, indicating excellent expansion performance. Additionally, due to the presence of TiO_2 within the coating, white TiP_2O_7 formed on the surface of the char layer at high temperatures, achieving the stabilization of the char layer structure.

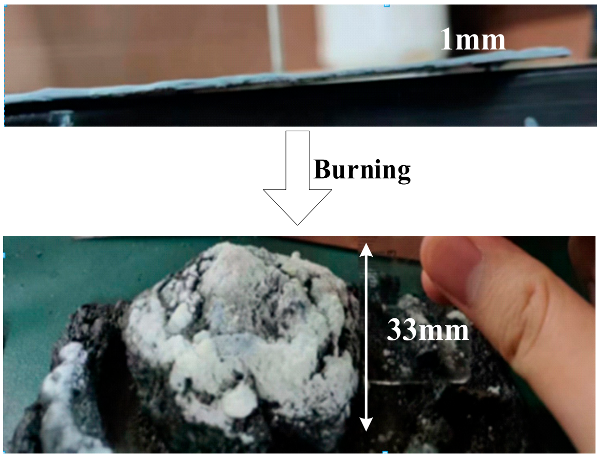


Figure 9. Expansion height map after coating burning.

Figure 10 shows the time–temperature curve of the steel plate back under different filler ratios. When the ratio of MEL to PER is 1.7, and the ratio of APP to PER is 1.9, the fire protection performance of the coating is optimal, with the fire resistance limit reaching the highest value of 2.84 h, meeting the fire protection requirements for dual-function coatings.

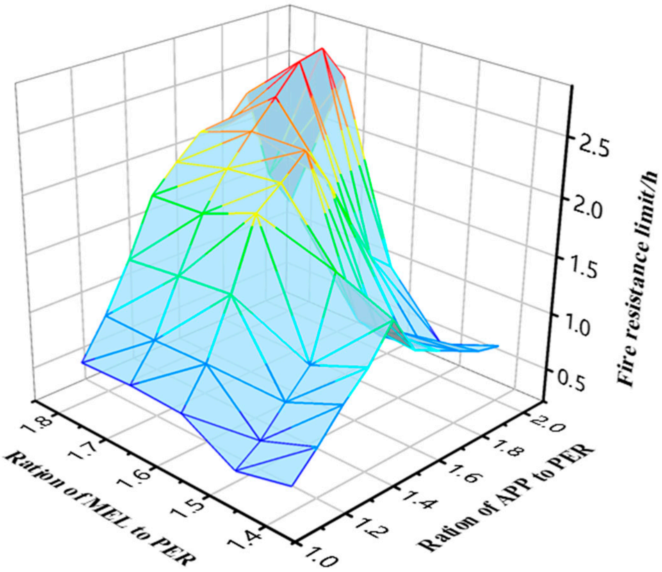


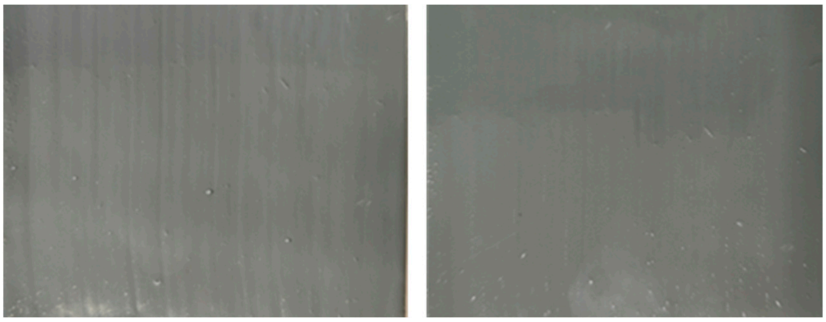
Figure 10. Time–temperature curve of steel plate back.

Anti-corrosive coatings generally consist of film-forming substances, corrosion-resistant fillers, additives, and solvents. Typically, these coatings form a protective layer on the surface of metal materials to isolate corrosive particles from contacting the metal surface, thereby preventing oxidation–reduction reactions that lead to metal corrosion [8]. However, during the film-forming process of the coating, the evaporation of solvents results in the formation of micro-pores within the coating. Prolonged use allows corrosive substances to penetrate through these micro-pores to the metal surface, triggering oxidation–reduction reactions and leading to metal corrosion [37,38]. As the most crucial component in anti-corrosive coatings, corrosion-resistant fillers significantly reduce the rate at which corrosive substances penetrate the coating, thereby substantially extending its service life. Commonly used corrosion-resistant fillers in coatings include lamellar-structure fillers, nanoparticles, and corrosion inhibitors.

Corrosion inhibitors are a crucial component of anti-corrosion systems, with zinc-based inhibitors being commonly used. Inorganic zinc-rich coatings are highly resistant to high temperatures and solvents, possess good electrical conductivity, and are low-toxic. Additionally, their cost-effectiveness makes them a popular choice for anti-corrosion coatings. These properties collectively ensure their widespread use in protecting metal surfaces from corrosion [39]. Therefore, zinc phosphate, an inorganic zinc-rich coating, was chosen as the corrosion-resistant filler. The coated specimen with the corrosion-resistant filler was immersed in saturated salt water for one month, and its surface conditions were observed, as shown in Figure 11. The results indicate that the surface morphology of the anti-corrosion coating remained largely unchanged after salt-water immersion, demonstrating the excellent anti-corrosion performance of the modified coating.

3.1.4. Additives

Although the amount of additives in the coating is relatively small, typically not exceeding 10% of the total coating mass, their impact on the coating is significant. These additives play crucial roles in optimizing the production process, controlling storage stability, rectifying coating defects, managing surface conditions, and enhancing application performance.

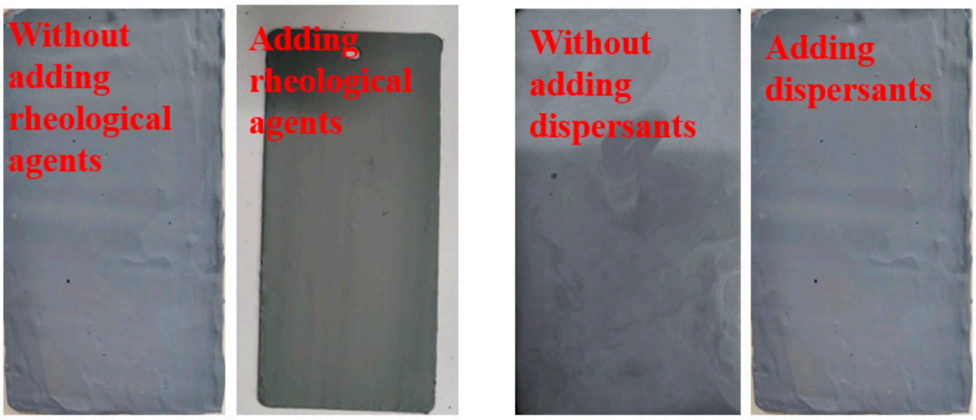


Before immersion After immersion

Figure 11. Surface morphology of coating before and after salt-water resistance test.

Coating additives can be classified in various ways, with one effective method being based on their functional roles within the coating formulation. These roles can be broadly categorized as follows: the first type aids in the manufacturing process of coatings, primarily facilitating wetting, dispersing, defoaming, and stabilizing, ensuring smooth and efficient production processes. The second type functions during storage, preventing issues such as settling, lumping, skinning, and mold growth. This includes anti-settling agents, thickeners, anti-skinning agents, in-can preservatives, in-can sterilizing agents, dispersants, wetting agents, anti-freezing agents, and anti-floating/-flooding agents. The third type acts during application and film formation, providing excellent application properties and ensuring good film-forming effects. The fourth type affects the later performance of the coating, ensuring the durability of the film. This includes adhesion promoters, light stabilizers, anti-graffiti agents, corrosion inhibitors, hand-feel agents, scratch-resistant agents, matting agents, mold inhibitors, and anti-fouling agents.

To improve the leveling properties of the coating during application, various film-forming additives were compounded. BYK-110 was chosen as the wetting and dispersing agent, and fumed silica was used as the rheological agent. Figure 12a illustrates the changes in the coating after the addition of dispersants, while Figure 12b shows the changes in the coating after adding rheological agents. Before adding dispersants, the dispersibility of the TiO_2 in the coating was poor, resulting in color variation on the coated surface. However, after adding the dispersants, the color became uniform, indicating improved pigment dispersion. The addition of the rheological agents resulted in a smoother coating, facilitating application.



(**a**) (**b**)

Figure 12. Changes in coating after adding film-forming agents. (**a**) After adding dispersants. (**b**) After adding rheological agents.

Resin coatings cannot achieve improvements in fire and corrosion resistance solely through the addition of additives. Rather, they must rely on the synergistic effect between additives and fillers to enhance the fire and corrosion resistance of coatings. Adding the rheological additive fumed silica can improve the dispersion ability of fillers in coatings. The better dispersion of the filler can reduce the pores generated during the curing of the coating and ultimately improve the anti-corrosion performance of the coating. At the same time, the dispersion of fillers (ammonium phosphate, melamine, pentaerythritol, titanium dioxide, etc.) in the coating increases the viscosity of the coating, which may reduce the integrity of the coating film after curing. BYK-110 wetting and dispersing agents can improve the coating's surface properties and leveling properties, thereby enhancing its anti-corrosive ability.

The final formulation of the coating includes: silicone-modified epoxy resin as the substrate resin; ammonium polyphosphate, melamine, pentaerythritol, titanium dioxide, zinc phosphate, and modified graphene oxide as the fireproof and anti-corrosion fillers; and the BYK-110 wetting and dispersing agent along with fumed silica (rheological agent) as coating additives. The specific formulation is shown in Table 2.

Table 2. The formulation of integrated fire and anti-corrosion coatings.

Material	**Modified GO**	**Pentaerythritol**	**Melamine**	**TiO_2**	**Ammonium Polyphosphate**
Mass of material (g)	0.3 g	10.2 g	17.2 g	10.2 g	19.4 g
Material	Modified epoxy resin	BYK-110	fumed silica	Zinc phosphate	
Mass of material (g)	20 g	0.05 g	0.5 g	1 g	

3.2. Dual-Function Coating Performance Test

At professional national-level testing institutions, according to the corresponding national standards [39–42], the coatings were subjected to the following tests:

(1) Coatings of various thicknesses were applied to carbon steel substrates (a Q235 steel plate with a thickness of 0.5 mm, a yield strength of 235 MPa, a maximum tensile strength of 460 MPa, an elongation of 26%, and an elastic modulus of 200 GPa), and

their adhesion strength (or pull strength) was repeatedly tested according to standard tensile testing methods. The testing ensured that the adhesion strength of the 3 mm thick coating met or exceeded Grade I standards (pull strength ≥ 0.5 MPa).

The non-heat resistance of steel structures is characterized by the rapid increase in surface temperature during a fire, which leads to a significant reduction in the yield strength, ultimate compressive strength, and elastic modulus of the steel, resulting in the loss of the load-bearing capacity of the structure. Testing the back temperature curves of thin steel members coated with fireproof paint can simulate the temperature changes on the surface of steel structures during actual fires, making it one of the effective measures for evaluating the fire performance of fireproof coatings [43–45]. Coatings of different thicknesses were applied to a carbon steel substrate, and their resistance to hydrocarbon fire was repeatedly tested until the 3 mm thick coating met a hydrocarbon fire resistance limit of no less than 2 h. The fire resistance performance test was conducted in accordance with the heating conditions of the test specified in GB14907-2018 Fire Resistive Coating for Steel Structure, and the specific experimental method was as follows: The test specimen was installed horizontally with its coated surface facing downward on the test furnace, ensuring that the coated surface was approximately level with the lower surface of the furnace cover. The unexposed surface of the specimen was covered with a layer of dry aluminum silicate fiber blanket with a thickness of 50 mm and a bulk density of 128 kg/m^3. The fire-exposed area of the specimen should be no less than 450 mm × 450 mm, and the distance between the edge of the specimen and the inner wall of the furnace should not be less than 250 mm (Figure 13). The temperature on the unexposed surface of each specimen was measured using two thermocouples: one located at the center of the unexposed surface, and the other placed on the centerline of the unexposed surface, 125 mm away from the center. The thermal insulation efficiency of the specimen was expressed by the test time when the average temperature on the unexposed surface reached 538 °C, denoted by Fp.

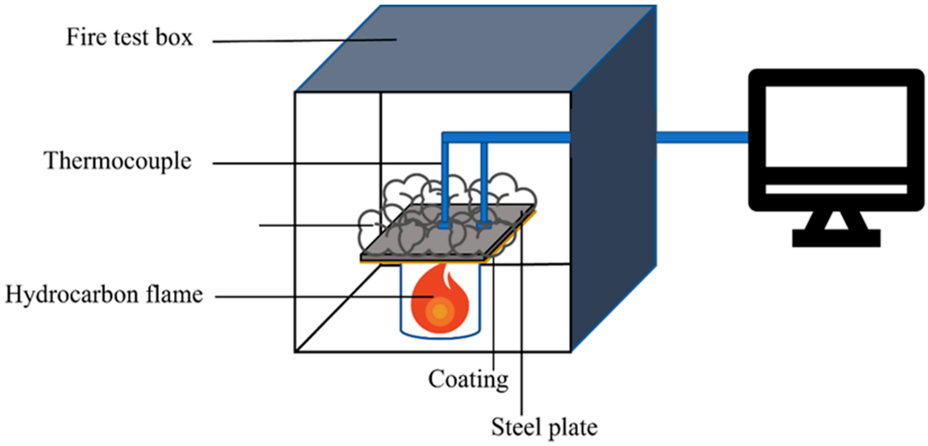


Figure 13. Schematic diagram of the coating fire test device.

(2) Neutral salt spray corrosion resistance tests were conducted until the time to the first appearance of rust was no less than 1000 h.

(3) Coatings were subjected to irradiation aging tests using the filtered xenon-arc lamp light, with continuous exposure for 1000 h. The comprehensive aging performance level of the protective coatings should not be lower than Grade 2.

The test results indicate that the developed dual-function coating meets the standards for fire resistance and corrosion resistance, as shown in Table 3.

Table 3. Standard test results.

No.	Item	Reference Value	Test Results	Conclusion
1	Adhesion strength, MPa	≥0.15	0.63	Pass
2	Fire resistance	FP ≥ 2.00 h; average specimen temperature ≤ 538 °C	FP = 2.00 h; average specimen temperature: 505 °C	Pass
3	Resistance to neutral salt spray	Time to first appearance of rust not less than 1000 h	No rust after 1000 h	Pass
4	Xenon lamp irradiation aging	Continuous exposure for 1000 h, comprehensive aging performance level of coating not lower than Grade 2	Continuous exposure for 1000 h, comprehensive aging performance level of coating not lower than Grade 2	Pass

The standard tests evaluated fire and corrosion resistance separately, without testing the fire resistance of the coating after corrosion. To further verify the effectiveness of the coating in practical applications, comprehensive anti-corrosion and fireproof performance tests of the coating under laboratory conditions are planned.

4. Conclusions

(1) By modifying epoxy resin with silicone, silicone segments were successfully introduced into the epoxy resin. Contact angle tests and salt-water corrosion experiments demonstrated that the modified resin exhibits good anti-corrosion properties.

(2) Zinc oxide-modified graphene oxide was prepared as fireproof filler through electrostatic self-assembly. By adjusting the ratio of coating resin material to fireproof filler, an intumescent fireproof coating was obtained. In the laboratory fire resistance limit test, the coating exhibited excellent intumescent fireproof performance.

(3) In accordance with GB14907-2018 Fire Resistive Coating for Steel Structure, the fireproof performance of the material was evaluated. During the fire-resistance limit test, the average temperature of the specimen remained at 505 °C within 2 h, meeting China's national standards for fireproof coatings.

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