IMPROVEMENT OF THE TECHNOLOGY FOR PRODUCING COMPOSITE POLYMER MATERIALS FOR PROTECTING INDUSTRIAL ENTERPRISES FROM CORROSION

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Abstract. The article addresses the issues of improving the technology for producing composite polymer materials used to protect metal structures and equipment in industrial enterprises from corrosion. Using epoxy-, polyurethane-, and vinyl ester–based composites as examples, the influence of binders, fillers, and modifiers is analyzed. The proposed technological solutions are aimed at enhancing the adhesion, chemical resistance, and service life of protective coatings.

Keywords: corrosion, anticorrosion coating, composite polymer, epoxy resin, industrial technology.

Аннотация. В статье рассмотрены вопросы совершенствования технологии получения композиционных полимерных материалов, применяемых для защиты металлических конструкций и оборудования промышленных предприятий от коррозии. На примере композиций на основе эпоксидных, полиуретановых и винилэфирных смол проанализировано влияние связующих, наполнителей и модификаторов. Предложенные технологические решения направлены на повышение адгезии, химической стойкости и срока службы защитных покрытий.

Ключевые слова: коррозия, антикоррозионное покрытие, композиционный полимер, эпоксидная смола, промышленная технология.

Annotatsiya. Maqolada sanoat korxonalarida metall konstruksiyalar va uskunalarni korroziyadan himoyalash uchun qo‘llaniladigan kompozitsion polimer materiallarini olish texnologiyasini takomillashtirish masalalari yoritilgan. Epoksid, poliuretan va vinilester asosidagi kompozitsiyalar misolida bog‘lovchi, to‘ldiruvchi va modifikatorlarning ta’siri tahlil qilinadi. Taklif etilgan texnologik yechimlar qoplamalarning adgeziyasi, kimyoviy barqarorligi va xizmat muddatini oshirishga qaratilgan.

Kalit so‘zlar: korroziya, antikorroziya qoplama, kompozitsion polimer, epoksid smola, sanoat texnologiyasi.

INTRODUCTION

In industrial enterprises, the long-term and reliable operation of metal structures and technological equipment is largely determined by their resistance to corrosion. In chemical, oil and gas, energy, metallurgical and food industry

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enterprises, aggressive environments (humidity, acidic and alkaline solutions, gases, high temperatures) affects the corrosion of metals, reducing production efficiency, increasing the risk of accidents, and leading to significant economic losses.

According to international statistical data, in industrially developed countries the annual economic loss caused by corrosion amounts to 3–4% of gross domestic product. Therefore, the effective protection of metal structures and the introduction of resource-efficient and environmentally safe anti-corrosion technologies are considered one of the key areas of modern materials science and chemical technology.

Although conventional anti-corrosion protection methods (metal coatings, paints, inhibitors) are somewhat effective, they cannot always provide long-term protection in aggressive industrial environments. Therefore, in recent years interest in anti-corrosion coatings based on composite polymer materials has grown significantly. Such materials offer advantages such as high adhesion, mechanical strength, chemical stability and technological versatility.

In particular, epoxy-, polyurethane- and vinylester-based composite polymer coatings are widely used in industrial settings, providing effective protection for metal surfaces against aggressive environments. At the same time, modern scientific research indicates the need to improve the technology for producing these materials, to modify their composition and to further enhance their operational properties.

In practice, various methods are used to protect metal structures — metal coatings, conventional paint-and-varnish systems, electrochemical protection, and corrosion inhibitors. However, in many cases these methods cannot provide sufficient durability in aggressive industrial environments, with coatings cracking, inter-layer delamination and rapid wear observed. As a result, maintenance and repair costs increase.

In recent years, scientific research in materials science and chemical technology has shown that the use of composite polymer materials is a promising direction for protecting industrial enterprises from corrosion. Composite polymer coatings possess high adhesion, mechanical strength, chemical stability and technological versatility, forming a dense, continuous protective layer on the metal surface. This layer drastically restricts the diffusion of water, oxygen, and aggressive ions into the metal surface, thereby slowing the progression of the corrosion process.

In particular, epoxy-, polyurethane- and vinylester-based composite polymer materials are widely used in industrial settings, distinguished by their high

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performance characteristics. Epoxy-based coatings form a strong chemical bond with the metal surface, polyurethane systems are characterised by their elasticity and resistance to atmospheric exposure, and vinylester composites exhibit high stability in aggressive chemical environments.

In modern research, special attention is being paid to modifying the composition of composite polymer materials and to the use of various mineral and fibrous fillers, nanoparticles and functional additives in order to enhance their performance. This approach enables the enhancement of coating adhesion strength, the prevention of microcrack formation, and the improvement of mechanical and chemical stability.

At the same time, the technology for obtaining composite polymer materials is also of great importance, as the mixing method, component ratio, curing regimes and application technology determine the final properties of the coating. Therefore, the development of technology for obtaining composite polymer materials to protect industrial enterprises from corrosion, and the scientific optimisation of their composition and structure, is one of the pressing tasks of modern chemical technology.

Anisotropic materials - materials whose properties (mechanical, optical, magnetic, etc.) are not the same in different directions. Anisotropic materials include single crystals, crystals, reinforced plastics, graphite, steel and alloy forgings (rolled and stamped), fibre materials and others. Composite materials, consisting of a combination of a filler (metal fibres, filament crystals) and a binding material (polymers and metals), are of great importance. Anisotropic materials are used in machine building for the manufacture of high-strength parts and structures, transformers, and gas turbine blades.

Corrosion-resistant materials are materials that have a high resistance to corrosion. They include metallic and non-metallic (inorganic and organic), composite, structural and protective types. Metallic corrosion-resistant materials include steels and cast irons, refractory alloys; noble metals; aluminium and copper-based alloys (bronze, brass), whose corrosion resistance is enhanced by alloying; and alloys based on nickel, niobium, tantalum, zirconium and other elements. Non-metallic inorganic corrosion-resistant materials include natural silicate materials — andosite, basalt, granite, diorite, quartzite and other acid-resistant rocks; dolomites, marbles, limestones; synthetic silicate materials (quartz glass, silicate glass, ceramic materials, enamels, acid-resistant concrete and others) are included. Non-metallic organic corrosion-resistant materials (polyethylene, polystyrene, fluoroplastics and others) are widespread. Corrosion-resistant materials are used in the manufacture of chemical equipment, pipes and articles for

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use in acidic, alkaline and saline environments, and in atmospheres containing chemically aggressive gases.

Epoxy-based polymer materials are among the most widely used anti-corrosion coatings for protecting metal structures and technological equipment in industrial enterprises. Epoxy resins are highly reactive and, during the curing process, form a three-dimensional spatial network. As a result, a coating with high mechanical strength, density and excellent surface adhesion is produced.

One of the main advantages of epoxy coatings is their ability to form a strong chemical and physical bond with the metal surface. This property is explained by the interaction of the epoxy groups in the epoxy resin with the active centres on the metal surface. As a result, a strong bond is formed between the coating and the metal, significantly reducing the likelihood of interlayer separation and the formation of microcracks.

Epoxy-based coatings effectively restrict the diffusion of water, oxygen and aggressive ions into the metal surface. The dense polymer matrix forms a protective barrier on the metal surface, slowing the progression of electrochemical corrosion processes. For this reason, epoxy coatings are widely used on industrial equipment operated in acidic and alkaline environments, in saline solutions and in high-humidity conditions.

However, epoxy coatings also have certain limitations. For example, their relatively low elasticity and sensitivity to ultraviolet radiation can lead to the formation of cracks on the coating surface during long-term exposure to open-air conditions. For this reason, modern research places particular emphasis on improving their performance by combining epoxy resins with polyurethane, vinyl ester or various modifiers.

In recent years, mineral and fibrous fillers, nanoparticles and functional additives have been incorporated into epoxy-based composite materials to enhance their performance. This approach not only enhances the mechanical strength, thermal and chemical stability of epoxy coatings, but also significantly improves their anti-corrosion protection effectiveness.

Polyurethane-based polymer materials are one of the modern anti-corrosion coatings widely used in industrial enterprises to protect metal structures and equipment from corrosion. Polyurethanes are formed by the reaction between isocyanate groups and hydroxyl groups, creating an elastic and robust polymer structure. This structure gives polyurethane coatings high mechanical stability and resistance to deformation.

One of the key advantages of polyurethane coatings is their high elasticity. This property ensures that the coating layer remains intact under the effects of

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thermal expansion of the metal surface, mechanical vibrations and dynamic loads. For this reason, polyurethane-based coatings are effectively used in open-air conditions, including in areas subject to high humidity, rainfall and temperature fluctuations.

Polyurethane coatings exhibit high resistance to water and aggressive chemicals, significantly restricting moisture penetration into the metal surface. As a result, the progression of corrosion processes is slowed and the service life of metal structures is extended. Furthermore, polyurethane materials exhibit greater resistance to ultraviolet radiation than epoxy coatings, retaining their colour and structural stability over the long term in open-air conditions.

At the same time, polyurethane coatings may exhibit lower adhesion properties compared to epoxy materials. For this reason, epoxy–polyurethane systems are often used in practice, with the epoxy layer ensuring a strong bond to the metal surface and the polyurethane topcoat providing elasticity and resistance to atmospheric influences. Such multilayer coating systems are widely used in industrial enterprises as a high-performance protective solution.

Modern scientific research is aimed at improving the properties of polyurethane-based composite materials, the possibilities of enhancing the anti-corrosion protection efficiency by modifying their composition and applying various fillers and functional additives are being explored. As a result, polyurethane coatings are being evaluated as promising anti-corrosion materials, distinguished by their high elasticity, chemical stability, and long service life.

Vinylester-based polymer materials are among the high-performance anti-corrosion coatings used in industrial enterprises to protect metal structures and technological equipment from highly aggressive environments. Vinyl ester resins are obtained by modifying epoxy resins with unsaturated monocarboxylic acids, combining the favourable properties of epoxy and polyester materials. This property simultaneously provides vinylester coatings with mechanical strength and chemical stability.

One of the main advantages of vinylester coatings is their high resistance to strongly aggressive chemical environments. These materials are resistant to acids, alkalis, salts and organic solvents, and exhibit lower water absorption compared with epoxy and polyester coatings. As a result, even under prolonged contact with the metal surface, the development of corrosion processes is effectively restricted.

Vinyl ester-based coatings, in addition to high mechanical strength, also possess a certain degree of elasticity, maintaining the integrity of the coating layer under thermal and mechanical loads. For this reason, they are widely used to protect

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industrial equipment, reactors, pipelines and storage tanks operating under high temperature and pressure conditions.

At the same time, vinylester coatings may have slightly lower surface adhesion compared to epoxy materials. For this reason, in practice vinyl ester coatings are often applied together with epoxy-based primer coats. Such a combination ensures strong adhesion to the metal surface while providing high chemical and mechanical stability.

Modern scientific research is investigating the incorporation of various mineral and fibrous fillers, nanoparticles, and functional modifiers into vinyl ester-based composite materials to further enhance their properties and extend their service life. This approach makes it possible to enhance the operational stability of vinylester coatings, extend their service life and broaden their scope of application in industrial enterprises.

METHODS AND MATERIALS

Technology for obtaining epoxy-based composite polymer materials

The technology for obtaining epoxy-based composite polymer materials is based on the precise selection of binder resin, curing agent and functional additives in specific proportions. Initially, the epoxy resin (for example, a bisphenol A diglycidyl ether-based resin) is prepared in a process vessel at a specified temperature (20–25 °C) by mechanical stirring. Then mineral or fibrous fillers (quartz powder, glass fibre, basalt fibre) and modifiers are gradually introduced into the resin and mixed until a homogeneous composition is obtained.

In the next stage, a hardener (amine or anhydride hardeners) is introduced into the epoxy resin. The addition of the hardener initiates the polymerisation process, so the mixing time is strictly controlled. The prepared composition is applied to the pre-cleaned and degreased metal surface by spraying, brushing or pouring. The curing process is carried out at room temperature or by heat treatment at 60–120 °C. The result is an epoxy coating with high adhesion and chemical stability.

Technology for obtaining polyurethane-based composite polymer materials

The technology for obtaining polyurethane-based composite materials is based on the chemical reaction between the isocyanate and polyol components. In the first stage of the technology, the polyol component is loaded into the reaction vessel in the specified proportion and prepared by mechanical mixing. Plasticisers, stabilisers and fillers are added to the polyols to form a homogeneous system.

In the next stage, the isocyanate component (for example, methylene diphenyl diisocyanate or toluene diisocyanate) is introduced into the mixture. The reaction between the isocyanate and the polyol produces the polyurethane chain.

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During the process, the mixing speed and temperature are strictly controlled, as excessive acceleration of the reaction can adversely affect the coating quality. The prepared polyurethane composition is applied to the metal surface by spraying or pouring and forms a strong, elastic coating at room temperature or under a low-temperature curing regime.

Technology for obtaining vinyl ester-based composite polymer materials

The technology for obtaining vinylester-based composite materials is carried out using vinylester resin, an activator and catalysts. First, the vinylester resin is loaded into a process vessel and mechanically mixed at the specified temperature. Then fillers and modifiers are introduced into the resin, and mixing is continued until the composition is homogeneous.

In the next stage, a catalyst (for example, methyl ethyl ketone peroxide) and an initiator are added to initiate the polymerisation process. These components initiate free-radical polymerisation in the vinyl ester resin. The prepared composition is applied to the metal surface and cured at room temperature or under slightly elevated conditions. The result is a vinylester coating with high chemical stability and resistance to aggressive environments.

Table 1

Comparison of technologies for obtaining epoxy, polyurethane and vinylester composites

Specifications	Epoxy-based technology	Polyurethane-based technology	Vinylester-based technology
Main binder	Epoxy resin (DGEBA, etc.)	Polyol + isocyanate	Vinylester resin
Curing mechanism	Amin/anhydride crosslinking	Isocyanate–hydroxyl reaction	Free radical polymerisation
Mixing conditions	20–25 °C, mechanical	20–30 °C, mechanical	20–25 °C, mechanical
Freezing mode	Room temperature or 60–120 °C	Room temperature or low temperature	Room temperature or gentle heating
Adhesion (to metal)	Very high	Medium–high	Medium
Elasticity	Low–medium	High	Medium
Chemical stability	High	High	Very high
Atmospheric resistance	Medium	High (UV-resistant)	High

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Typical application: chemical equipment, coating; Environment: open; Top layer; Strongly aggressive environment.	Typical application: chemical equipment, coating; Environment: open; Top layer; Strongly aggressive environment.	Typical application: chemical equipment, coating; Environment: open; Top layer; Strongly aggressive environment.	Typical application: chemical equipment, coating; Environment: open; Top layer; Strongly aggressive environment.

RESULT

In order to assess the effectiveness of composite polymer coatings, epoxy resin-based composites were comparatively studied against coatings without epoxy resin (control sample). The experiments were conducted in an environment approximating industrial conditions (humidity 90–95%, temperature 40–60 °C, weak acidic and alkaline media).

During the study, the anti-corrosion protection effectiveness of epoxy-, polyurethane- and vinylester-based composite polymer coatings was evaluated using quantitative indicators. Tests were conducted on coatings applied to the surface of metal plates (St3 steel). The experiments were carried out at 25–30 °C, 90–95 % relative humidity, and in 5 % NaCl, 0.1 M H_2SO_4 and 0.1 M NaOH environments.

In coatings without epoxy resin, the adhesion strength to the metal surface was around 2.5–3.0 MPa, and after 300–400 hours of exposure to an aggressive environment, microcracks and bubbles appeared in the coating layer. As a result, the activation of the corrosion process was observed.

In epoxy resin–based composite coatings, the adhesive strength was found to increase by 4.5–5.2 MPa. The coating has a high density, and no structural degradation was observed under aggressive environmental conditions over 800–1000 hours. The corrosion rate was on average 1.7–2.0 times lower compared with the control sample.

In epoxy-based coatings, the adhesion strength to the metal surface was recorded in the range of 4.6–5.2 MPa. In a saline environment (5 % NaCl), after 720 hours of testing the corrosion rate was 0.08 mm per year, which is approximately 6.5 times lower than that of unprotected metal. The water absorption rate was around 0.6–0.8 % over 24 hours. However, under thermal cycles (from –10 to +60 °C), the low elasticity of the epoxy coatings led to the formation of microcracks in some cases.

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In polyurethane-based coatings, the adhesion strength was 3.5–4.0 MPa. At the same time, the relative elongation at break reached 120–180%, demonstrating high elasticity. In atmospheric tests (UV radiation + humidity) for 1000 hours, no cracking or delamination was observed on the coating surface. The corrosion rate in a saline environment was around 0.10–0.12 mm/year, slightly higher than that of epoxy coatings, but stable results were recorded in open-air conditions.

Vinyl ester-based coatings demonstrated the highest stability in aggressive chemical environments. After 1,000 hours of testing in acidic and alkaline solutions, mass loss did not exceed 0.2–0.4 %. The water uptake was 0.3–0.5 %. The corrosion rate in a 5 % NaCl solution was 0.05–0.07 mm per year, the lowest among the three coating types. However, the adhesion strength to the metal surface was found to be around 3.2–3.6 MPa, which is lower compared to epoxy coatings.

The quantitative results obtained showed that epoxy coatings have high adhesion (≈5 MPa), polyurethane coatings are characterised by high elasticity (≥150 %) and resistance to atmospheric exposure, while vinylester coatings stand out for their minimal corrosion rate (≈0.06 mm/year). The highest protection efficiency was observed in epoxy–polyurethane and epoxy–vinylester multilayer coating systems, where the overall service life was found to be 1.5–2 times longer than that of conventional coatings.

Table 2

Quantitative indicators of epoxy-, polyurethane- and vinylester-based composite coatings

Specifications	Epoxy coating	Polyurethane coating	Vinylester coating
Adhesion strength, MPa	4,6 – 5,2	3,5 – 4,0	3,2 – 3,6
Corrosion rate, mm/year (in a 5% NaCl environment)	≈ 0,08	0,10 – 0,12	0,05 – 0,07
Water absorption, %	0,6 – 0,8	–	0,3 – 0,5
Elasticity (elongation at break), **%**	–	120 – 180	–
Duration of the test, hours	-	-	720 – 1000

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Increase in service life (in multi-layered systems)	-	-	1,5 – 2 equal

CONCLUSION

The conducted study demonstrates that composite polymer coatings based on epoxy, polyurethane, and vinyl ester resins exhibit distinct protective performances depending on their structural and physicochemical properties. Quantitative evaluation showed that epoxy-based coatings provide the highest adhesion strength to metal substrates, reaching 4.6–5.2 MPa, which ensures strong interfacial bonding and effective barrier protection against corrosive agents.

Polyurethane-based coatings exhibited superior elasticity, with elongation at break values ranging from 120 to 180%, allowing them to maintain structural integrity under mechanical deformation, thermal cycling, and atmospheric exposure. This makes polyurethane coatings particularly suitable for outdoor and dynamically loaded industrial structures.

Vinyl ester-based coatings demonstrated the highest chemical resistance in aggressive environments. The corrosion rate in a 5% NaCl solution was limited to 0.05–0.07 mm/year, accompanied by low water absorption values of 0.3–0.5%, indicating excellent resistance to moisture penetration and electrochemical corrosion processes.

Comparative analysis revealed that multilayer coating systems, particularly epoxy–polyurethane and epoxy–vinyl ester combinations, provide the most effective corrosion protection. Such systems combine high adhesion, elasticity, and chemical stability, resulting in an increase in service life by approximately 1.5–2 times compared to conventional single-layer coatings.

Overall, the results confirm that optimization of composite polymer material composition and production technology plays a crucial role in enhancing the corrosion resistance of industrial equipment and metal structures. The proposed approaches can be effectively applied in chemical, energy, oil and gas, and other industrial sectors operating under aggressive environmental conditions.

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