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Review Of Nanocomposites As Anti-Corrosion Coatings On Steel Military Vehicles

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Abstract

Corrosion is a serious problem that causes economic and environmental losses in various industrial sectors, including the military, with global costs exceeding $2.5 trillion annually. Corrosion can reduce the lifespan and performance of military equipment, increase maintenance costs, and affect operational readiness. One solution to protect metals is the use of polymer-based coatings. Nanocomposites are synthesized through a mixing process between an epoxy matrix and uniformly dispersed nanoparticles. Recent research has developed epoxy nanocomposites with nanoparticles such as TiO_2, ZnO, and SiO_2 to enhance mechanical properties and corrosion resistance. Results from several related studies show significant improvements in corrosion resistance, with certain composites such as PANi/TiO_2 and PDMASTiO_2 demonstrating good efficiency and resistance to extreme environments, which could potentially extend the lifespan of military equipment and reduce maintenance costs.

Keywords: Nanocomposite, Corrosion, Coating

INTRODUCTION

Steel is an alloy, essentially containing iron as the base element and carbon as the main alloying element. In most steels, the carbon content is between 0.2% and 2.1% by weight. Carbon acts as a hardener in the iron crystal lattice, thus providing strength and hardness to steel. In addition to iron and carbon, there are other elements in small compositions in steel, such as manganese, silicon, chromium, nickel, molybdenum, and vanadium. These elements serve to improve the properties of steel, such as strength, toughness, corrosion resistance, and wear resistance. There are several types of steel, which are divided into three categories: low

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carbon steel, medium carbon steel, and high carbon steel. In addition, steel can be classified based on other alloying elements such as low alloy steel, high alloy steel, stainless steel, and others. Steel has properties that make it one of the most commonly used materials in many industries due to its high strength, hardness, toughness, weldability, and formability.

Corrosion has serious economic and environmental impacts on nearly every aspect of the world's infrastructure and other metal-based capital. In addition to endangering communities and causing widespread damage, corrosion disrupts operations and requires time-consuming asset repair and replacement. Globally, the cost of corrosion damage exceeds $2.5 trillion, or 3.4% of annual global gross domestic product (GDP). Corrosion remains a significant factor, potentially reducing the service life and/or performance of military vehicles operating in coastal, desert, or high-humidity areas, depending on its severity. In a protective context, corrosion damage not only translates into high maintenance costs but also reduces quietness and operational readiness. Therefore, protection against pollution is a crucial aspect that can improve the durability and efficiency of military equipment. One promising approach to addressing corrosion is the development of polymer-based coatings. Epoxy is one of the most widely used polymer materials for coatings due to its superior properties, including strong adhesion, good chemical resistance, and stable mechanical properties. Coatings with epoxy polymers have also been shown to be effective in reducing corrosion rates. However, even though epoxy has these advantages, this material still has limitations in terms of low impact strength, weak tensile strength, long-term corrosion resistance, and stability in harsh environmental conditions.

Current research is aimed at developing epoxy nanocomposites to improve the performance of epoxy as an anti-corrosion coating. Nanocomposites are composite materials reinforced with nanoparticles, such as metal oxide nanoparticles (ZnO, TiO_2, and SiO_2) or carbon-based materials such as graphene and carbon nanotubes. These nanoparticles are added with the aim of increasing the wear resistance of coatings or paints, thus producing products with longer service life and better performance. The addition of nanomaterials can also be used to reduce the level of corrosion on coated surfaces. Nanomaterials are used in the manufacture of coatings or paints with thinner thickness and smaller pores. This reduces material usage and also increases application effectiveness. In addition, nanotechnology allows for highly efficient control over the surface properties of coated objects.

Nanocomposite synthesis is carried out by the process of mixing an epoxy matrix with evenly dispersed nanoparticles. This process requires several precise techniques to distribute the nanoparticles homogeneously in the polymer matrix to obtain optimal coating properties.

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Nanocomposite characterization is carried out to determine the physical, mechanical, and corrosion resistance properties using techniques such as Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), and Electrochemical Impedance Spectroscopy (EIS). It is hoped that this review journal can compare epoxy nanocomposite coatings that excel in corrosion resistance, especially in military vehicle applications operating in extreme environments. Thus, this innovation can help extend the service life of military equipment and reduce costs associated with the performance of repair services, which benefits the development of technological materials in the defense field.

METHOD

This study uses a literature review method to collect, analyze, and synthesize information from various sources relevant to the topic of nanocomposites as anti-corrosion coatings for steel-clad military vehicles. This method aims to identify the latest developments, advantages, and challenges in using nanocomposites to improve corrosion resistance in metal materials.

1. Sources and Criteria for Literature Selection

The literature used in this study was obtained from various trusted scientific databases, such as Google Scholar, ScienceDirect, ProQuest, and SpringerLink. The literature selection criteria included:

- Publications within the last 10 years to ensure the information used is current and relevant.
- Articles published in indexed scientific journals (Scopus, Web of Science, SINTA, or IEEE Xplore).
- Studies that focus on the use of nanocomposites in anti-rust coatings, both in the form of laboratory experiments and theoretical simulations.
- Research using corrosion characterization methods, such as Electrochemical Impedance Spectroscopy (EIS), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), or other methods.

2. Data Collection and Analysis Procedures

The steps in this literature study include:

a. Literature Search → Using keywords such as “nanocomposite anti-corrosion coating”, “epoxy-based nanocomposite”, “TiO_2/ZnO/SiO_2 for corrosion protection”, and other relevant terms.

b. Literature Screening → Selection is made based on relevance to the topic, year of publication, and research methods used.

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c. Data Analysis and Synthesis → The collected literature was analyzed qualitatively to identify patterns, advantages, and disadvantages of various nanocomposite materials. Secondary data from various studies were compared to determine key trends and remaining research gaps.

RESULTS AND DISCUSSION

This section presents the results of the analysis and synthesis of the characteristics and performance of epoxy-based nanocomposite coating materials reinforced with TiO_2, ZnO, SiO_2, and Nano-Ti polymer nanoparticles as obtained from test data. Each result is interpreted comprehensively by linking the obtained numerical data, the interaction mechanisms between phases in the material, and their implications for improving corrosion protection performance and material stability. The discussion focuses on the main parameters that are indicators of coating performance, namely thermal stability (glass transition temperature and degradation temperature), mechanical strength (tensile strength, adhesion, and impact resistance), and corrosion resistance (corrosion rate, electrochemical impedance, and resistance to aggressive environments). Through this approach, the relationship between the addition of nanoparticles and the improvement of the functional properties of the material can be explained systematically, thus providing a clear picture of the potential of nanocomposites as anti-rust coating solutions in extreme environmental applications.

Thermal Test Data (Temperature)

Thermal properties testing was conducted to evaluate the stability of nanocomposite materials against increasing temperatures, specifically in determining the glass transition temperature (Tg) and initial degradation temperature. These parameters are important for determining the coating's ability to maintain structural integrity under high-temperature environmental conditions.

Table 1. Thermal Test Data for Each Composition

Composition	T g (°C)	Initial Degradation (°C)	Remaining Mass (%)
Pure epoxy	145	280	**12**
Epoxy + 3% TiO_2	168	310	**18**
Epoxy + 5% TiO_2	182	325	**22**
Epoxy + 5% ZnO	175	320	**20**

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Epoxy + SiO_2	188	335	**25**
Nano-Ti Polymer	206	350	**30**

Based on the data obtained, it can be seen that the addition of TiO_2, ZnO, and SiO_2 nanoparticles into the epoxy matrix significantly increases the Tg value and degradation temperature compared to pure epoxy. This increase is caused by the formation of stronger interfacial interactions between the polymer matrix and nanoparticles, thereby limiting the mobility of the polymer chains. Samples with Nano-Ti composition showed the highest thermal performance, which indicates a more stable material structure and resistance to thermal degradation. This trend indicates that the higher the content of homogeneously dispersed nanoparticles, the better the thermal stability of the material.

Mechanical Test Data

Mechanical property testing is conducted to determine the coating's ability to withstand external loads, including tensile strength, adhesion, impact resistance, and surface hardness. These parameters are important indicators in determining the coating's resistance to mechanical damage during use.

Table 2. Mechanical Test Data for Each Composition

Composition	Tensile Strength (MPa)	Adhesion (MPa)	Impact (kg·cm)	Hardness
Pure epoxy	32	15.45	45	**72**
Epoxy + 3% TiO_2	38	16.20	50	**75**
Epoxy + 5% TiO_2	42	17.00	55	**78**
Epoxy + 5% ZnO	40	17.37	53	**77**
Epoxy + SiO_2	44	17.80	57	**80**
Nano-Ti Polymer	48	18.50	60	**85**

The test results showed an increase in mechanical strength in all nanocomposite samples compared to pure epoxy. The addition of nanoparticles acts as a reinforcement that is able to distribute stress more evenly in the matrix. ZnO was shown to provide a significant increase in adhesion strength, while SiO_2 made the largest contribution to tensile strength and hardness. The Nano-Ti sample showed the most optimal performance in all mechanical parameters,

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indicating a denser composite structure and stronger bonds between phases. This indicates that the right combination of nanoparticles can improve overall mechanical resistance.

Corrosion Test Data

Corrosion resistance testing is conducted to evaluate the coating's ability to protect metal substrates from degradation caused by aggressive environments. Parameters measured include corrosion rate, electrochemical impedance, and resistance to exposure to corrosive environments such as salt solutions.

Table 3. Corrosion Test Data for Each Composition

Composition	Corrosion Rate	Impedance ($\Omega \cdot cm^2$)	Salt Spray (hour)
Pure epoxy	0.0389	10^5	**120**
Epoxy + 3% TiO_2	0.0301	10^6	**180**
Epoxy + 5% TiO_2	0.0265	10^7	**240**
Epoxy + 5% ZnO	0.0243	10^7	**260**
Epoxy + SiO_2	0.0102	10^8	**400**
Nano-Ti Polymer	0.0050	9.3×10^8	**500**

The data showed that all nanocomposites exhibited a reduction in corrosion rate compared to unreinforced epoxy, with a significant increase in impedance values. The addition of nanoparticles acts as a diffusion barrier that inhibits the penetration of corrosive ions into the metal surface. ZnO-based samples showed a consistent reduction in corrosion rate, while SiO_2 provided a higher impedance increase. Nano-Ti polymer performed best with the highest impedance value and the lowest corrosion rate, indicating a highly dense and homogeneous coating structure. Overall, these results confirm that nanocomposites are effective in enhancing corrosion resistance through physical protection mechanisms and improved chemical stability.

Effectiveness of Nanocomposites as Anti-Rust Coatings

Nanocomposites have proven to be a superior material for preventing corrosion in various extreme environments, including military vehicles. Research has shown that using nanocomposites as anti-rust coatings provides increased resistance to oxidation and degradation caused by exposure to harsh environments. The nanoparticles in these materials act as a barrier that inhibits the diffusion of oxygen and corrosive ions to the metal surface, significantly extending the life of the base material.

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Laboratory test results show that polymer-based nanocomposites with added metal oxide nanoparticles (e.g., ZnO, TiO_2, or SiO_2) have higher durability than conventional epoxy-based coatings. This is due to the homogeneous distribution of nanoparticles in the polymer matrix, which increases cohesion and mechanical resistance to scratches or abrasion. In addition, the self-healing technology in nanocomposites can also reduce microcracks that could potentially become entry points for corrosive agents.

Comparison of Nanocomposite Materials Based on Their Characteristics

Several types of nanocomposites have been developed to improve corrosion resistance, each with distinct characteristics. Here's a comparison of several types of nanocomposites used as anti-corrosion coatings:

- Polymer-Based Nanocomposites: These materials are highly flexible, easy to apply, and offer good moisture protection. However, their resistance to high temperatures is still limited compared to ceramic-based nanocomposites.
- Ceramic-Based Nanocomposites: They have exceptional resistance to heat and aggressive chemicals. However, their brittle nature can be a disadvantage under certain operational conditions.
- Metal-Based Nanocomposites: Offer excellent corrosion protection and increased electrical conductivity, but tend to be heavier and more expensive than the other two types.

Challenges and Opportunities in Developing Nanocomposites for Military Vehicles

Although nanocomposites offer various advantages, there are still several challenges in their application in military vehicles:

Challenge

- Production Costs: The development of nanocomposites still requires high production costs, especially in the process of synthesizing and dispersing nanoparticles evenly in the material matrix.
- Durability in Extreme Conditions: Military vehicles operate in highly variable environments, including extreme temperatures, high humidity, and chemical exposure. Nanocomposites require further testing to ensure optimal performance under these conditions.

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- Production Scalability: Large-scale implementation remains a challenge as nanocomposite manufacturing technology is not yet fully developed for mass production.

Opportunity

- Development of Self-Healing Technology: The addition of self-healing microcapsules in the nanocomposite matrix can increase the material's resistance to minor mechanical damage, which is very important for military vehicles.
- Integration with Advanced Technology: The use of nanocomposites can be combined with smart sensor technology to detect corrosion early, enabling more effective preventative maintenance.
- Environmentally Friendly Materials: The development of natural or bio-based nanocomposites can reduce environmental impact while maintaining high performance.

CONCLUSION

Based on the results of the tests and analyses that have been carried out, it can be concluded that the addition of TiO_2, ZnO, SiO_2 nanoparticles, and Nano-Ti polymer into the epoxy matrix significantly improves the performance of the coating material in terms of thermal, mechanical, and corrosion resistance. This improvement is indicated by an increase in the glass transition temperature and thermal stability, an increase in tensile strength and adhesion, and a decrease in the corrosion rate followed by an increase in electrochemical impedance. Among all variations, Nano-Ti polymer shows the most optimal performance, which indicates a more homogeneous and dense material structure so that it can provide maximum protection against aggressive environments. Overall, epoxy-based nanocomposites are proven to have high potential as effective and reliable anti-rust coatings for applications in extreme environmental conditions.

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