

A Review Paper on the Research Status and Development Trend of Corrosion Inhibitors

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Abstract: With the widespread use of metals in various industrial sectors, corrosion has become a serious challenge, affecting the life and performance of equipment. As a key technical means, corrosion inhibitors have made significant progress in the past few decades. This paper aims to summarize the research status of corrosion inhibitors and discuss their future development trends. In terms of research status, the research status of corrosion inhibitors at home and abroad was reviewed, and the application of corrosion inhibitors in different application fields was discussed. In addition, we discussed the inhibition mechanism of different types of corrosion inhibitors, such as organic corrosion inhibitors and inorganic corrosion inhibitors.

Keywords: Research Status of Inorganic Corrosion Inhibitors; Organic Corrosion Inhibitors; Compound Corrosion Inhibitors; Corrosion Inhibitors; The Development Trend of Corrosion Inhibitors.

1. Introduction

Corrosion of metals is a widespread and serious issue in various sectors of the national economy and defense construction. It not only weakens equipment strength and functionality but also poses threats to personnel safety through potential leaks or explosions. Additionally, metal corrosion leads to significant economic losses, accounting for 1% to 5% of the global gross national product annually. This exerts a notable impact on national economic development. Therefore, implementing effective anti-corrosion measures, such as the use of slow-release agents, holds great significance in mitigating metal corrosion. In recent years, there has been increased emphasis on the research of corrosion inhibitors due to growing concerns about environmental protection and sustainable resource utilization.

Based on the research status of various corrosion inhibitors in recent years, this paper summarizes the classification, application fields and research progress of corrosion inhibitors at home and abroad, and looks forward to the development trend of corrosion inhibitors in the future.

2. Current Research Status of Corrosion Inhibitors at Home and Abroad

2.1. Research Status of Corrosion Inhibitors Abroad

On a global scale, remarkable strides have been taken in the realm of corrosion inhibitor research. Scholars have delved deeply not only into conventional inhibitors but also yielded innovative outcomes in novel materials and technologies. In recent years, heightened environmental consciousness has spurred interest in eco-friendly corrosion inhibitors, which prioritize attributes like non-toxicity, low toxicity, robust biodegradability, and seamless integration with the environment. These green inhibitors afford substantial corrosion protection while mitigating the negative environmental repercussions associated with their application.

At present, oxygen corrosion inhibitors, corrosion inhibitor polymer coatings, and organic-inorganic composite corrosion

inhibitory materials have received extensive attention. Moreover, some studies involve the synergy of corrosion inhibitors with other corrosion protection technologies to provide a more reliable corrosion protection solution

2.2. Research Status of Corrosion Inhibitors in China

In China, corrosion inhibitor research aligns with global progress. The focus here extends beyond eco-friendly options and new materials to application techniques, especially in marine, petrochemical, and automotive settings. Chinese researchers are also dedicated to creating specialized inhibitors for extreme conditions like high temperatures, pressures, or strong acidity. Additionally, composite corrosion inhibitors, capitalizing on synergistic effects, are widely used for equipment corrosion control.

3. Classification and Mechanism of Corrosion Inhibitors

3.1. Inorganic Corrosion Inhibitors

Inorganic corrosion inhibitors work by creating an insoluble oxide film on the metal surface through ion reactions, which slows down corrosion. They are effective in protecting against metal corrosion in neutral environments, especially at higher concentrations. However, some inorganic corrosion inhibitors, such as nitrite and chromate, have higher toxicity and phosphate can lead to water eutrophication and pollution, leading to their elimination.

Non-toxic, low-toxicity corrosion inhibitors such as silicate, molybdate and tungstate have gradually attracted people's attention. there is still a lack of research on the compounding of three or more inorganic corrosion inhibitors.

The following are two common inorganic corrosion inhibitors:

3.1.1. Molybdate Corrosion Inhibitors

Molybdate corrosion inhibitors, known for low toxicity, good thermal stability, and a wide pH range, gained significant recognition from experts worldwide in 1951. They fall under the category of anodic or passivation film corrosion inhibitors. Currently, compounds like molybdate are primarily used to enhance corrosion inhibitor effectiveness,

reduce costs, and minimize environmental impact. Rui Yulan et al. successfully combined organic phosphonate, gluconate, zinc ion, and molybdate, achieving a scale inhibition rate of over 90% for carbon steel in seawater.

Molybdate corrosion inhibitors are commonly employed in acidic settings like pickling processes and acid solution storage equipment, with a significant impact in diverse industries. They continue to evolve with advancements in science and technology, benefiting from nanotechnology and functional coatings, which expand their performance and application range.

3.1.2. Silicate Corrosion Inhibitors

Silicate corrosion inhibitors, like potassium and sodium silicate, hinder both anode and cathode processes in cold water, making them hybrid inhibitors. The optimal pH range for silicate corrosion inhibition is 7.0~8.5; it's not advisable to use them at extremely high or low pH levels. Temperature affects silicate corrosion inhibitors: at high silicate concentrations, the corrosion inhibition effect remains stable with increasing temperature, but at low silicate concentrations, the effect weakens with rising temperature.

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3.2. Organic Corrosion Inhibitors

Organic corrosion inhibitors are mainly organic compounds with electronegative impurity atoms (O, N, S, etc.) as central polar groups or aromatic rings. Although organic corrosion inhibitors have good corrosion inhibition effect and can be applied to a variety of complex environments, there are still problems of long synthesis time and high production cost. The following are two common organic corrosion inhibitors:

3.2.1. Imidazoline Corrosion Inhibitors

Imidazoline, a five-membered heterocyclic compound with two nitrogen atoms, features hydrophilic groups attached to the nitrogen atoms and hydrophobic carbon chains. The hydrophilic groups enhance solubility, enhancing corrosion inhibition, and form coordination bonds with metal atoms, facilitating chemical adsorption and corrosion reduction. Meanwhile, the hydrophobic branches create a protective film, shielding the metal from corrosive media.

Current research aims to boost imidazoline corrosion inhibitors' efficacy through structural modification and their integration with other corrosion inhibitors. This includes introducing polar functional groups or enhancing their performance via quaternary amination reactions. These modifications result in imidazoline corrosion inhibitors with enhanced stability and water solubility, leading to reduced production costs and improved corrosion inhibition performance.

3.2.2. Amino Acid Corrosion Inhibitors

Amino acid corrosion inhibitors, considered green and highly promising, have garnered significant interest in recent years. They function by creating a protective molecular film through complexation or adsorption on the metal surface, effectively obstructing contact between the corrosive medium and the metal, thus reducing the rate of corrosion.

However, when the amino acid corrosion inhibitor is low,

fewer complexes are formed, which is not enough to form a dense protective film on the metal surface, which may accelerate the corrosion of the metal.

3.3. Compound Corrosion Inhibitor

Compound corrosion inhibitors amplify their effectiveness by blending various corrosion inhibitors in suitable proportions, leveraging the synergy between them. The composition of compound corrosion inhibitors is highly diverse, with common types including organic-inorganic, rare earth-inorganic, and compound inorganic corrosion inhibitors.

However, the design and formulation of compound corrosion inhibitors can be relatively complex, and the interaction between different components needs to be fully considered. Researchers also need to explore more combinations of different types of corrosion inhibitors to achieve superior corrosion protection.

4. Performance Evaluation of Corrosion Inhibitors

4.1. Standards and Methods for Evaluating the Performance of Corrosion Inhibitors

4.1.1. Weightlessness Method

Loss on weight is an experimental method used to evaluate the properties of metal corrosion and corrosion inhibitors, which calculates the corrosion rate by measuring the weight loss of a metal specimen in a corrosive medium. This method is one of the simplest and most intuitive methods for evaluating corrosion.

The corrosion rate is usually expressed as follows:

$$CR = \frac{\Delta W}{AT\rho}$$

thereinto

(ΔW is the mass loss of the specimen, A is the surface area of the specimen

T is the corrosion time, ρ is the density of the metal in grams per cubic centimeter)

However, weight loss has limitations, like its inability to offer detailed electrochemical insights into corrosion and its relatively lengthy experimental duration. Consequently, in practice, weight loss is often combined with other evaluation methods for a more comprehensive assessment.

4.1.2. Electrochemical Polarization

Electrochemical polarization examines the behavior of metal specimens under galvanic corrosion conditions, relying on the electrochemical corrosion process. This method employs electrode potential-current (E-I) curves to investigate corrosion kinetics and inhibition. It commonly utilizes a three-electrode system comprising a reference electrode, a working electrode (metal specimen), and a timing electrode.

Electrochemical polarization provides detailed electrochemical information that provides a deeper understanding of the mechanism of action of corrosion inhibitors. However, it requires professional experimental equipment and technology, and the experimental conditions are relatively demanding.

4.2. Comparative Analysis of the Performance of Different Corrosion Inhibitors

4.2.1. Rate of Corrosion Inhibition

Corrosion rate is an indicator that describes the weight loss

of a metal during corrosion, which indicates the degree of corrosion of the metal surface in a single time. The calculation of corrosion rate is one of the important indicators for evaluating corrosion inhibitor performance and studying corrosion process.

The corrosion rate is calculated as follows:

$$CR = \frac{W_0 - W_1}{A \cdot t}$$

Thereinto:

(CR is the rate of corrosion, W_0 is the initial weight of the specimen

W_1 is the weight of the specimen after a certain exposure time

A is the surface area of the specimen, T is the time of exposure)

In general, temperature, pH of the medium, type and concentration of corrosion inhibitor, type of metal and alloy composition will all affect the corrosion inhibition rate. To analyze the effects of different corrosion inhibitors, we generally use the control variable method to keep other factors affecting the corrosion inhibitor rate consistent, to study the performance of the corrosion inhibitor.

4.2.2. Corrosion Inhibition Efficiency

Corrosion inhibition efficiency is a crucial metric for assessing the performance of corrosion inhibitors, serving as a key reference for practical engineering applications. Comparing the corrosion inhibition efficiency of different inhibitors helps identify the most effective option for specific conditions.

The corrosion inhibition efficiency is calculated as follows:

$$CE\% = \frac{CR_{blank} - CR_{inhibitor}}{CR_{blank}}$$

Thereinto:

CR_{blank} indicates the rate of corrosion inhibition in the absence of a corrosion inhibitor;

$CR_{inhibitor}$ Indicates the rate of corrosion inhibition in the presence of a corrosion inhibitor.

4.2.3. SEM and EDS Analysis

Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) are two analytical techniques commonly used to study the surface and interface properties of materials.

SEM can generate a high-resolution image of surface by detecting electronic signals. In order to study the particle size, grain structure, surface morphology, etc. of the material, the microstructure and morphology of the sample can be observed.

EDS is used to analyze the elemental composition and relative abundance of a sample surface. Major and trace elements in the sample can be analyzed. Used for material analysis, alloy composition analysis, ore mineral analysis, biological sample element analysis, etc.

4.2.4. Polarization Curve

Polarization curve is an experimental data curve commonly used to evaluate the performance of metal corrosion and corrosion inhibitors. Typically, the polarization curve plots the relationship between current density (I) and potential (E).

As can be seen from the polarization curve, corrosion inhibitors can reduce the corrosion current density and become more positive corrosion potential, thereby slowing or stopping metal corrosion. The polarization curve can be monitored in real time during the experiment, and the dynamic process of metal corrosion can be tracked to provide

an in-depth understanding of metal corrosion behavior and corrosion inhibitor performance.

5. Application Areas of Corrosion Inhibitors

As an important material protection technology, corrosion inhibitors are widely used in many industrial fields to slow down the rate of mechanical corrosion and extend the service life of equipment.

During metal processing and manufacturing, metal parts are exposed to moisture, salt water, acidic or alkaline solutions. Adding corrosion inhibitors to lubricating oil, coolant and coating can protect metal parts from corrosion.

In the oil and gas industry, equipment like wells, pipelines, and storage facilities endure prolonged exposure to corrosive environments. Corrosion inhibitors are employed in well water injection, oil and gas pipelines, and equipment lubricating oil to alleviate corrosion damage. In aerospace, where vehicles operate in diverse conditions like high humidity, altitude, and elevated temperatures, corrosion inhibitors safeguard components. Similarly, in the marine sector, metal structures face erosion from salt water and marine organisms. Corrosion inhibitors are applied to offshore platforms, bridges, and port facilities to shield against corrosion.

6. The Development Trend of Corrosion Inhibitors

At present, the concept of environmental protection has been fully accepted and applied to the research and development of corrosion inhibitors, but there are still many problems, such as the relevant theories are still loose in the system, lack of more complete theories to guide R&D, evaluation and production application, research deviation from actual needs, actual efficiency is not high and other problems.

In the future, as interdisciplinary theories gain ground and industries expand, there is a growing need for advanced environmental performance assessment methods. In practical applications, corrosion inhibitor research will increasingly focus on green, environmentally friendly, and efficient solutions. Innovations in nanotechnology, functional coatings, and biotechnology will offer new avenues for enhancing corrosion inhibitor performance.

7. Conclusion

As an important means of corrosion control of metal materials, corrosion inhibitors have been widely studied and applied at home and abroad, and in the future, with the requirements of greening, high efficiency and multi-function, the research of corrosion inhibitors will continue to develop in a more innovative and sustainable direction, providing more choices for metal material protection in different fields.

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