BIOCHEMICAL CORROSION INHIBITION PROCESSES IN DIFFERENT WAYS

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ABSTRACT

Biochemical and microbiologically influenced corrosion inhibition (MICI) uses biological agents, microbial metabolism, or green organic compounds to protect metal surfaces from degradation.

Key Biochemical Inhibition Processes

• Consumption of Corrosive Agents

• Beneficial microorganisms (such as oxygen-reducing or nitrate-reducing bacteria) consume dissolved oxygen or corrosive ions in the environment before they reach the metal.

• Nitrate-reducing bacteria (NRB) outcompete and suppress harmful sulfate-reducing bacteria (SRB), which normally produce corrosive hydrogen sulfide.

KEYWORDS- biochemical, corrosion, inhibition, metal,bacteria

INTRODUCTION

Protective Biofilm and Extracellular Polymeric Substances (EPS) Layers

Controlled or intentionally grown biofilms form a physical barrier on the metal surface.

EPS secreted by bacteria isolate the metal from moisture, oxygen, and aggressive anions.

Biomineralization (Mineralized Layer Formation)

Bacteria such as Bacillus subtilis induce the precipitation of mineral layers (like carbonates or silicates) directly on the metal.

This inorganic-organic hybrid crust blocks the diffusion of chloride ions and oxygen to the substrate.

Secretion of Antimicrobial and Organic Inhibitors

Certain microbes release natural antimicrobial compounds that kill or inhibit aggressive local microflora.

Green inhibitors derived from plant extracts (amino acids, proteins, and biopolymers) utilize heteroatoms like nitrogen, oxygen, and sulfur to chemically or physically adsorb onto metal surfaces.

Quorum Sensing Disruption

Inhibitors target bacterial communication channels (quorum sensing) to prevent pathogenic microbes from organizing into destructive, corrosive colonies.

A chemical compound that can be added to liquids or gases and used to decrease the corrosion rate of a given material (usually a metal) can be referred to as a corrosion inhibitor.[1,2,3]

One method for the inhibition of corrosion would be the addition of a coating on the surface of the metal which acts as a passivation layer and disallows access to the surface of the metal.

Types of Corrosion Inhibitor

Corrosion inhibitors can be classified into four general types based on the method in which they work on the metal to prevent corrosion. These types are:

Cathodic Inhibitor

Cathodic inhibitors can work to slow the cathodic reaction down or they can work to selectively precipitate on the cathodic regions of the metal in order to restrict the diffusion to the metal surface of the elements that are eroded.

Examples for Cathodic Inhibitors include sulfite and bisulfite ions which can react with oxygen to form sulphates. Another example of a cathodic inhibitor is a catalyzed redox reaction by nickel.

Anodic Inhibitor

These types of corrosion inhibitors form a thin preventive oxide layer on the surface of the metal. This reaction leads to a big anodic shift, turning the metallic surface into a passivation area. This passivation area helps in reducing the corrosion of the metal.

Examples for anodic inhibitors include chromates, nitrites, orthophosphates, and molybdates.[4,5,6]

Volatile Corrosion Inhibitor

Volatile corrosion inhibitors can be used to halt the corrosion of condenser tubes in boilers. They are also referred to as vapour phase inhibitors or VPIs.

VPIs work by changing the pH of the exterior atmosphere to less acidic conditions in order to control corrosion. Examples include morpholine and hydrazine which are used to control the corrosion of the condenser pipes in boilers.

Mixed Inhibitors

These types of corrosion inhibitors also form a film on the surface of the metal. They work to reduce cationic reactions as well as anionic reactions. This is done via the formation of a precipitate on the surface of the metal.

Examples for Mixed inhibitors include silicates and phosphates which are used as water softeners to stop the rusting of water.

Uses of Corrosion Inhibitors

Corrosion Inhibitors have a wide range of uses in commercial, process, and industrial environments. Some of these uses are listed below.

Corrosion Inhibitors are used to stop rusting and anodic corrosion of metals. This is generally done via the coating of the metal surface with a chromate layer.
Oxygen scavengers can be used as CIs to react with dissolved oxygen in the environment and can help in preventing cathodic corrosion.
It is very important to prevent rusting and corrosion of fuel pipelines. Therefore, CIs are very important in securing these pipelines and reducing the risk of accidents.
Metal pipes in heating systems are prone to corrosion. CIs play an important role in securing these pipes as well.
Corrosion is the process through which metals return to their original oxide state, creating significant barriers that prevent them from reaching thermodynamic equilibrium. The primary cause of corrosion is a reduction in Gibbs free energy, which causes metals to revert to their reduced oxide state. This complex issue has plagued humanity for years, affecting metals and alloys across various industries and applications worldwide
Mechanical cleaning: This process rapidly removes the exterior layers of a material, including methods such as grinding, blasting, and machining. It is effective regardless of the surface's microstructure or chemical composition.
Chemical pre-treatment: Chemical solutions used for pre-treatment are categorized into alkaline and acidic solutions. These chemicals help can eliminate grease, oil residues, and other contaminants left from manufacturing or mechanical pre-treatment. Organic solvents, such as ethanol and acetone, are commonly used in scientific research for this purpose.[7,8,9]
Laser technology: Due to its high automation, selectivity, efficiency, and environmental friendliness, laser surface texturing has gained popularity in recent years for preparing functional surfaces [61]. Laser processing combines surface texturing with laser chemical modification, making it a popular method for material surface treatment [62]. When a solid surface is irradiated with a laser, it develops nano- and microscale structures, which reduce the surface energy of the substrate or enable specific interactions between the surface and the fouling materials [63]. Additionally, laser surface modification, involving melting and annealing materials, is being explored for improving corrosion resistance in metallic alloys. This process homogenizes microstructures, dissolves intermetallic particles, and extends solid solubility through fast cooling rates, all without altering the surface's chemical composition [64]. Laser cladding is another advanced process where particles are heated using a defocused laser beam, creating a metallurgical bond between the substrate and clad layer. Factors such as laser power, beam size, scanning velocity, cladding geometry, dilution rate, melt pool profile, aspect ratio, and clad layer thickness influence the coating's quality [65]. The technique selective laser melting (SLM) creates metal objects with high surface roughness, which can limit their direct application without further processing [66]. Laser shock peening (LSP) is a new surface treatment method designed to reduce metal corrosion. It involves applying high-energy-density laser pulses to create a cavity on the target surface, inducing deep mechanical residual compressive stresses that enhance corrosion resistance

DISCUSSION

Traditional corrosion protection techniques, despite their limitations, have been used for decades to combat corrosion caused by wear, UV rays, and chemical attacks. These methods require periodic maintenance and reapplication, which can be costly and logistically challenging for industries. One common approach is the use of sacrificial anodes, which are materials designed to corrode preferentially over the metal they protect. However, such methods are often inflexible and not adaptable, making them less suitable for modern industries. As new materials and components are introduced into increasingly demanding environments, advanced corrosion protection techniques are become more pressing necessary

Corrosion inhibitors can be classified as anodic, cathodic, or mixed, depending on their mechanism of action on metal surface reactions and their interactions with ions. They provide optimal protection by simultaneously affecting both cathodic and anodic reactions. Their efficiency depends on factors such as concentration, molecular structure, functional groups, conjugation, and type of bonding atom [78].

They are categorized based on their influence on the anodic, cathodic, or both reactions in the corrosion process.

Anodic Corrosion Inhibitors or Chemical Passivators

When precipitation blocks the anodic sites, the anodic reaction slows down, and the corrosion potential shifts in the cathodic direction. This type of corrosion inhibitor functions by forming a protective oxide layer on the metal surface, leading to a significant anodic shift. As a result, passivation occurs, effectively reducing the corrosion rate [79].

Cathodic Corrosion Inhibitors[10,11,12]

Cathodic inhibitors slow down the cathodic reaction and shift the corrosion potential in the anodic direction by blocking cathodic sites. They facilitate the movement of positive ions toward the cathode, forming a protective layer that reduces or stops the cathodic reaction. This process decreases the diffusion rate of reducing elements to the metal surface, increasing its susceptibility of hydrogen-induced cracking while effectively blocking cathodic reduction processes. As a result, these inhibitors are widely used for corrosion protection [72].

Cathodic inhibitors are frequently used due to their environmental acceptability and ability to prevent hydrogen from diffusing into metal surfaces, thereby reducing environmental harm. Examples include polyphosphates [80], zinc salts [81], and cerium salts [82,83]. However, certain cathodic inhibitors, such as sulfur, can promote hydrogen diffusion into metal surfaces, leading to contamination by forming harmful hydrogen sulfides upon reacting with hydrogen [84,85].

Other variants used as cathodic corrosion inhibitors include ionic liquid monocationic and dicationic compounds [86], as well as hexylmeythylimidazolium tetrafluoroborate ionic liquid [40]. In deaerated HCl solutions, 2-aminomethylbenzimidazole and bis(benzimidazol-2-ylethyl) sulfide can act as cathodic inhibitors in the initial stage for steel [87]. Additionally, 1,12-bis(1,2,4-triazolyl) dodecane is also an excellent choice of cathodic inhibitor for steel in HCl solution [88].

The presence of a protective layer between electrolyte and substrate significantly reduces the average polarization current. This layer acts as a barrier on the metal surface, facilitating the formation of insoluble compounds.

Mixed Corrosion Inhibitors

Substances that form films and produce surface precipitates can obstruct both anodic and cathodic sites. By inhibiting reactions at these sites, mixed-type inhibitors, commonly film-forming compounds, facilitate the establishment of protective processes on the surface. These inhibitors have several advantages, as they control both reactions.

Example include silicates and the phosphate-based corrosion inhibitors [89]. In solution, a combination of imidazoline and phosphate inhibitors forms a lamellar structure [90]. Compounds derived from imidazolium, pyridinium, and dimethyl-ethylbenzylammonium serve as mixed corrosion inhibitors [91]. The corrosion rate decreases when the active anode and cathode areas are reduced.

Inhibitor films can be classified into several types:

(a)Chemisorbed films, where lone pair of electrons is donated to a central adsorption atom in a functional group;

(b)Electrostatic adsorption films, which rely on electrostatic interactions;

(c)Precipitation and/or complex films, which result from reactions between dissolved metal ion and organic inhibitor molecules.[2,3,4]

RESULTS

Many methods have been developed for the restriction of microbial corrosion. The primary challenge has been finding ways to prevent or stop microbial growth without negatively impacting the surrounding environment. The list below provides an overview of some of the tactics that have been used or that are in development.

Using biocide (any chemical that inhibits life) to kill microorganisms. Because biofilms are so resistant, a lot of biocide must be used. This is expensive, has negative effects on the surrounding environment, and can actually cause more corrosion of the surface due to its toxicity. Biocides and other chemical treatments against microbes also tend to be dangerous for the people preparing and applying them.[11]

Rao and Mulky[2] developed an extensive list of methods to limit the growth of microbes and therefore microbial corrosion.

Plant products could aid in restricting microbial growth. These would be biodegradable and safe for the people applying them, but have not yet been widely tested.

Surfactants, specifically ones generated by organisms as secondary metabolites. They're useful because they get between the corrosive liquid and the surface and keep them apart.

Putting a superhydrophobic coating on a surface. This keeps a biofilm from being able to develop, but is sensitive and can easily lose its superhydrophobic qualities.

Using self-healing surfaces can prevent corrosion in cracks or faults. This could be used with a superhydrophobic surface, to mitigate its sensitivity.[3,4,5]

Using hydrophilic surfaces to create a region that deters the development of proteins into a film covering a surface.

Using synthetically-created substances that deter corrosion because of their chemical structures. This may have a smaller negative effect on the environment than other options.

Using biofilms that are grown intentionally to inhibit microbial corrosion. This is done by growing a biofilm on a surface made of a bacteria that can release compounds that kill other microbes and that prevent corrosion.
Using essential oils. The effectiveness of essential oils against microbial corrosion has not been widely tested.
Coating a surface with various nanomaterials or ozone to prevent microbial corrosion.
Microbes acting to inhibit corrosion
Though microorganisms are often responsible for corrosion, they can also protect surfaces from corrosion.[12] For example, oxidization is a common cause of corrosion. If a susceptible surface has a biofilm covering it that takes in and uses oxygen, then that surface will be protected from corrosion due to oxidization. Biofilms can also release antimicrobial compounds, which is helpful if the biofilm is not corrosive and can deter microbes that would be. Biofilms provide a barrier between a surface and the ecosystem surrounding it, so as long as the biofilm has no adverse effects, it can serve as protection from corrosion as well.[11] Because biofilms don't negatively impact the ecosystem, they are potentially one of the best mechanisms for corrosion inhibition. They can also alter the conditions on the surface of a metal so that the metal is less likely to be damaged, preventing corrosion.[6,7,8]

CONCLUSIONS

Metal corrosion poses pervasive challenges across infrastructure, energy and transportation sectors, driving intensive research into methods that can impede or halt metal degradation. Corrosion inhibitors—organic or inorganic compounds added in small concentrations—function by adsorbing onto metal surfaces, forming protective films that block aggressive species such as chloride or sulphate ions. Contemporary approaches extend beyond traditional inhibitors to encompass synergistic combinations, environmentally benign “green” substances and coatings that incorporate self-healing functionalities. Advances in surface analytics, including atomic force microscopy and X-ray photoelectron spectroscopy, have elucidated adsorption mechanisms at the molecular level. Meanwhile, electrochemical techniques such as impedance spectroscopy and potentiodynamic polarisation provide quantitative measures of inhibitor performance. Computational tools, from density functional theory to machine-learning models, now guide the rational design of novel inhibitors by predicting adsorption energies, identifying active functional groups and accelerating discovery through high-throughput virtual screening. Together, these developments are forging robust, cost-effective protection strategies for steels, alloys and other technologically critical metals in diverse environments.[8,9,10]

Research from Nature Portfolio
Recent studies have demonstrated that combining small organic molecules can produce synergistic corrosion inhibition effects on mild steel in acidic environments. Surface analyses by scanning electron microscopy and electrochemical impedance spectroscopy reveal that co-adsorbed mixtures form denser, more uniform barrier films than single compounds, while quantum chemical calculations clarify the key orbital interactions responsible for enhanced adsorption. Another body of work has explored D-glucose-derived polycyclic tetraones as mixed-type inhibitors for steel in hydrochloric acid. Substituent effects on electronic distribution were correlated with inhibition

efficiency, and Monte Carlo simulations mapped the preferred adsorption configurations on Fe surfaces. In addition, investigations into azelaic acid dihydrazide have identified it as an eco-friendly, mixed-type inhibitor achieving over 90% protection at optimal concentrations. Langmuir adsorption behaviour and temperature dependencies were characterised experimentally, and surface imaging confirmed formation of stable inhibitor films that resist acid attack.[12]

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