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Review On Corrosion Protection by Conducting Polymers

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Abstract: *Corrosion is a major issue affecting metals and other materials exposed to harsh environmental conditions. The protection of metals from corrosion is vital in various industries, including automotive, aerospace, marine, and construction. Traditional methods of corrosion protection include coatings, sacrificial anodes, and galvanization. However, conducting polymers have recently emerged as an innovative solution due to their unique combination of electrical conductivity and protective properties.This report explores the role of conducting polymers in corrosion protection, their mechanisms, advantages, challenges, and applications. Corrosion is a major issue that leads to substantial economic losses and material degradation in various industries. Traditional corrosion protection methods, such as coatings, galvanization, and cathodic protection, have limitations in terms of cost, effectiveness, and environmental impact. Conducting polymers (CPs) have emerged as a promising alternative for corrosion protection due to their unique electrochemical properties. These polymers, including polyaniline (PANI), polypyrrole (PPy), and polythiophene (PTh), exhibit the ability to conduct electricity and can provide corrosion resistance through both barrier and electrochemical mechanisms. The primary modes of corrosion protection by conducting polymers include forming protective layers that prevent corrosive agents from reaching the metal surface, and actively participating in electrochemical reactions to inhibit corrosion processes. Additionally, conducting polymers possess self-healing properties that enhance long-term durability. Their environmental sustainability, flexibility, and cost-effectiveness make them an attractive solution in corrosion prevention across various sectors, including automotive, aerospace, and marine applications. Ongoing research continues to explore ways to optimize the properties of conducting polymers for more efficient and adaptable corrosion protection systems. This abstract highlights the potential of conducting polymers as a transformative approach to corrosion protection, offering a viable, sustainable, and cost-effective alternative to traditional methods.*

Keywords: *marine industry, Coatings, Sacrificial anodes, Conducting polymers, polyaniline, polypyrrole.*

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I. INTRODUCTION

Corrosion is a widespread and costly problem that affects metals and alloys in various industries, leading to significant economic losses and structure failures [1-4]. Traditional corrosion protection methods, such as coatings, galvanization, and cathodic protection, are affective but often come with limitations such as cost, durability, and environmental impact. Conducting polymers (CPs) have emerged as a promising alternative in the field of corrosion protection5-8]. These polymers possess the unique ability to conduct electricity, making them capable of offering corrosion resistance through both chemical and electrochemical mechanisms. Some of the key conducting polymers include polyaniline (PANI), polypyrrole (PPy), and polythiophene (PTh) [9-12].

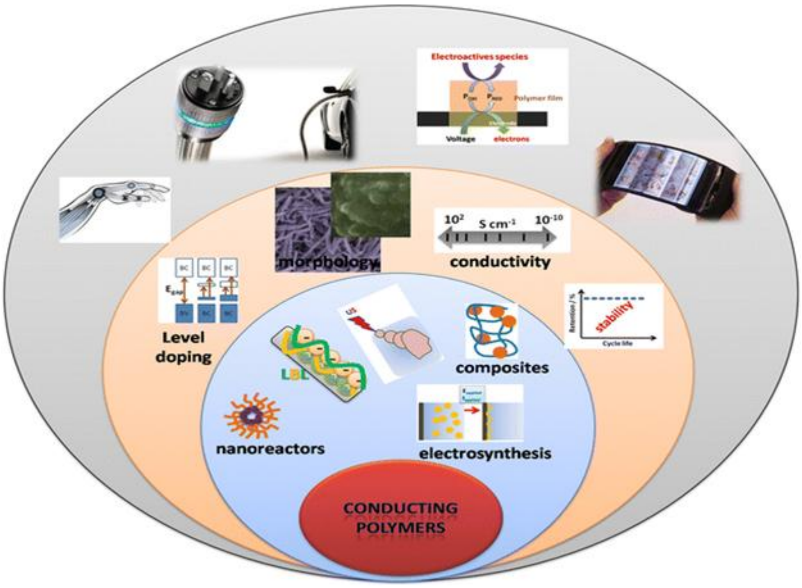

Figure 1: Conducting Polymers

Traditional corrosion protection methods, such as coatings, galvanization, and cathodic protection, have limitations in terms of cost, effectiveness, and environmental impact. Conducting polymers[13-15] (CPs) have emerged as a promising alternative for corrosion protection due to their unique electrochemical properties.[16-18] These polymers, including polyaniline (PANI), polypyrrole (PPy), and polythiophene (PTh), exhibit the ability to conduct electricity and can provide corrosion resistance through both barrier and electrochemical mechanisms.[20-22] The primary modes of corrosion protection by conducting polymers include forming protective layers that prevent corrosive agents from reaching the metal surface, and actively participating in electrochemical reactions to inhibit corrosion processes.[23-26] Additionally, conducting polymers possess self-healing properties that enhance long-term durability. Their environmental sustainability, flexibility, and cost-effectiveness make them an attractive solution in corrosion prevention across various sectors, including automotive, aerospace, and marine applications.[27-32] Ongoing research continues to explore ways to optimize the properties of conducting polymers for more efficient and adaptable corrosion protection systems [33-36]. This abstract highlights the potential of conducting polymers as a transformative approach to corrosion protection, offering a viable, sustainable, and cost-effective alternative to traditional methods.

II. PROPERTIES OF CONDUCTING POLYMERS

Conducting polymers, also known as "synthetic metals," combine the mechanical properties of polymers with the electrical conductivity of metals. The key properties that make conducting polymers suitable for corrosion protection include:

- Electrical Conductivity: Conducting polymers can be doped with various ions or molecules to enhance their conductivity, allowing them to act as a charge carrier and interfere with electrochemical corrosion processes.
- Environmental Stability: Many conducting polymers show resistance to environmental degradation, such as UV radiation, temperature fluctuations, and humidity [37-39].
- Adhesion to Metals: Some conducting polymers have excellent adhesive properties, allowing them to bond effectively with metal surfaces, creating a strong protective layer
- Chemical Resistance: Certain conducting polymers can resist aggressive chemicals, which enhances their ability to protect metals in harsh environments like acids or seawater
- Conducting polymers act as a protective coating that prevents direct contact between metal surfaces and corrosive agents like water, oxygen, chloride ions, and other environmental elements. This helps reduce the rate of corrosion.
- Electrochemical Protection: Unlike traditional non-conductive coatings, conducting polymers can alter the electrochemical reactions at the metal surface by providing an alternative electron flow pathway, thereby reducing the corrosion process
- By creating a robust, long-lasting protective layer on metal surfaces, conducting polymers aim to significantly extend the lifespan of critical infrastructure, machinery, and transportation systems [40-42]. This reduces the need for frequent maintenance, repairs, or replacements.

III. MECHANISM OF CONDUCTING POLYMER

The protective mechanisms of conducting polymers can be broadly classified into two categories: physical barrier protection and electrochemical protection.

- **Physical Barrier Protection:** Conducting polymers, when applied to metal surfaces, form a thin, continuous film that acts as a physical barrier. This layer prevents the penetration of water, oxygen, and other corrosive agents, reducing the likelihood of corrosion. The polymer layer's flexibility and durability help maintain the integrity of the metal surface over time.
- **Electrochemical Protection:** The ability of conducting polymers to conduct electricity allows them to influence the electrochemical reactions that lead to corrosion. When a conducting polymer is applied to a metal, it can alter the metal's electrochemical environment by providing an alternative path for electron flow, preventing the corrosion cells from forming. In some cases, conducting polymers can also act as sacrificial materials, where they undergo oxidation or reduction reactions instead of the metal surface, providing further protection [43-44].
- **Self-Healing Properties:** Some conducting polymers have self-healing capabilities, where they can repair damage to the polymer coating when exposed to external stimuli. This adds an additional layer of longevity to the protection provided.
- **Anodic protection mechanism:** Secures embedded reinforcement against present and potential corrosion utilizing anodes that are embedded in fix patches, and norequirement for wiring or external device.
- **Controlled inhibitor release mechanism (CIR):** The CIR model recommends that the oxidized and doped type of specific ICPs, like Polyaniline (PANI), when applied to a base metal substrate, delivers theanion dopant upon reduction due to coupling to the base metal through defects in the coating
- **An active electronic barrier at the metallic surface:** whenever metallic comes into contact with a doped semiconductor or an electronically carrying out polymer, an electric field is expected to be formed, limiting theflow of electrons from the metallic to an oxidizing species and subsequently avoiding or reducing corrosion
- **Barrier protection mechanism:** CPs coatings form a solid, adhesive, low porosity barrier on a base metal that maintains a basic environment, reducing oxidant access and avoiding oxidation of the metal compactness. Surface. CPs coatings serve active protection in preference to a simple barrier, and the barrier impact improves with an increase in adherence, lesser porosity, and higher compactness.

IV. TYPES OF CONDUCTING POLYMERS FOR CORROSION PROTECTION

Conducting polymers (CPs) are organic materials that possess the ability to conduct electricity, making them useful in various applications, including corrosion protection [45]. These polymers can offer both barrier protection and electrochemical protection against metal corrosion. Several conducting polymers have been developed and researched for their potential to protect metals from degradation in different environments. Below are some of the most widely studied and used conducting polymers for corrosion protection:

4.1Polyaniline (PANI)

Polyaniline (PANI) is one of the most extensively studied conducting polymers due to its easy synthesis, low cost, and good electrochemical properties [46]. It can be synthesized in various forms, such as emeraldine base (EB) and emeraldine salt (ES), which differ in their conductivity.

Corrosion Protection Mechanism

- Electrochemical Protection: PANI can inhibit the electrochemical reactions that lead to corrosion by providing an alternative path for electron transfer, reducing corrosion rates.
- Barrier Protection: PANI forms a dense and stable film on the metal surface, preventing the ingress of moisture, oxygen, and corrosive ions like chloride.

Advantages

- Tunable Conductivity: The conductivity of PANI can be adjusted by varying the dopants or the oxidation state of the polymer.
- Good Environmental Stability: PANI offers good resistance to environmental degradation under moderate conditions.
- Self-Healing Properties: PANI has shown the ability to self-repair minor damage, which is particularly useful for long-term corrosion protection.

Applications:

- Marine coatings, automotive applications, metal pipelines, and storage tanks

4.2 Polypyrrole (PPy)

Polypyrrole (PPy) is another well-known conducting polymer, widely researched for its high conductivity, chemical stability, and environmental resistance [47]. It is typically synthesized by the electrochemical polymerization of pyrrole monomers.

Corrosion Protection Mechanism:

- Electrochemical Protection: PPy can donate or accept electrons, which helps in reducing the corrosion rate of metals. The polymer can also act as a sacrificial anode in certain environments.
- Barrier Protection: PPy forms a thin, continuous, and flexible film that effectively prevents moisture and corrosive ions from reaching the metal surface.

Advantages:

- High Stability: PPy is stable in aqueous and non-aqueous environments, offering reliable protection in a wide range of conditions.
- Ease of Synthesis: PPy can be synthesized easily through electrochemical methods, making it cost-effective for large-scale applications.

Applications:

- Marine environment, automotive coatings, electronic devices, and metal pipes

4.3 Poly(3,4-ethylenedioxythiophene) (PEDOT)

Poly(3,4-ethylenedioxythiophene) (PEDOT) is a widely studied conducting polymer known for its excellent electrochemical stability, high conductivity, and good environmental performance.

Corrosion Protection Mechanism

- Electrochemical Protection: PEDOT works by reducing the electrochemical potential for corrosion to occur and by acting as a barrier against corrosive elements.
- Barrier Protection: The polymer forms a robust and stable coating that resists environmental stressors like humidity, temperature fluctuations, and chemical exposure.

Advantages:

- Superior Stability: PEDOT shows excellent long-term stability in both acidic and neutral environments, making it ideal for harsh conditions.
- Transparency: PEDOT can be used in transparent coatings, allowing its use in applications where aesthetic considerations are important, such as in electronic displays.

Applications:

- Corrosion-resistant coatings for metals, flexible electronics, and transparent conductive films

4.4 Polythiophene (PTh)

Polythiophene (PTh) is another important conducting polymer characterized by high conductivity, good environmental stability, and high corrosion resistance [48]. It is typically synthesized from thiophene monomers.

Corrosion Protection Mechanism:

- Electrochemical Protection: PTh provides an alternative electron pathway, reducing the rate of corrosion. It is particularly effective in protecting metals in acidic and basic conditions.
- Barrier Protection: PTh forms a uniform and protective layer on metal surfaces that resists moisture and ion penetration, preventing corrosion [49].

Advantages:

- Environmental Stability: PTh is stable under a wide range of environmental conditions and provides good protection against corrosion.
- Flexibility: The polymer is flexible and can be applied in thin layers without losing its protective qualities.

Applications:

- Metal protection in harsh environments, marine coatings, and corrosion- resistant paints

4.5Polyacetylene (PAc)

Polyacetylene (PAc) is one of the first conducting polymers discovered. It is synthesized through the polymerization of acetylene monomers and has moderate conductivity compared to other conducting polymers [50].

Corrosion Protection Mechanism

- Electrochemical Protection: PAc has been shown to provide corrosion resistance by modifying the electrochemical environment at the metal surface, preventing oxidation reactions.
- Barrier Protection: As a polymeric coating, PAc forms a protective film that blocks the access of water, oxygen, and corrosive ions to the metal.

Advantages:

- Good Conductivity: While not as high as some other conducting polymers, PAc offers a reasonable conductivity that can be used effectively for corrosion protection in some applications.
- Ease of Synthesis: PAc is relatively simple to synthesize, making it cost- effective for certain applications.

Applications:

- Corrosion protection in controlled environments and research applications

4.6 Poly-para-phenylenediamine (PPD)

Poly-para-phenylenediamine (PPD) is another conducting polymer used for corrosion protection, especially noted for its high chemical stability and electrochemical properties.

Corrosion Protection Mechanism:

- Electrochemical Protection: PPD can act as a charge distributor and provide corrosion inhibition by blocking the electrochemical reaction pathways.
- Barrier Protection: When applied as a coating, it prevents the penetration of water, chloride ions, and other corrosive agents into the underlying metal.

Advantages:

- High Stability: PPD offers excellent resistance against chemical degradation, ensuring long-term protection in various environments.
- Tunability: The properties of PPD can be modified by altering its chemical structure, allowing for tailored corrosion protection.

Applications

Coatings for metal substrates exposed to aggressive chemicals, such as in the chemical processing industry

V. ADVANTAGES OF CONDUCTING POLYMERS

5.1 Enhanced Corrosion Resistance

- Electrochemical Protection: Conducting polymers can form a protective layer on metal surfaces. Their ability to conduct electricity helps them act as an electronic barrier between the metal and the corrosive environment, reducing the electrochemical reactions that lead to corrosion.
- Self-Healing Properties: Some conducting polymers have self-healing capabilities, meaning that they can repair damage to the coating, such as cracks or defects, which helps maintain long-term protection against corrosion.

5.2 Environmentally Friendly

- Low Toxicity: Conducting polymers are often less toxic than traditional corrosion inhibitors, such as chromates, which can be harmful to both human health and the environment.
- Biodegradability: Many conducting polymers are more biodegradable compared to inorganic materials, making them more sustainable and eco- friendly in corrosion protection applications

5.3 Customization and Versatility

- Tunability: The properties of conducting polymers can be tailored by altering their chemical structure, which allows them to be customized for specific corrosion protection needs. This means that they can be designed for use indifferent corrosive environments, such as seawater, acidic, or industrial settings.
- Variety of Forms: Conducting polymers can be applied in various forms, including films, coatings, and composites, allowing for flexibility in their use for corrosion protection in different applications.

5.4 Reduced Maintenance

- Longer Lifespan: Conducting polymers can provide long-term protection with less maintenance, as they tend to be more stable and durable under certain environmental conditions compared to traditional coatings like paints or galvanization.
- Cost-Effectiveness: The durability and self-healing properties can reduce the need for frequent repairs or reapplications, leading to cost savings in the long term.

Improved Mechanical Properties

• Strength and Flexibility: Conducting polymers, when used as coatings, can improve the mechanical properties of surfaces. They are often lightweight yet durable, providing additional resistance to physical damage like scratching and wear.

5.5 Electrochemical Corrosion Control

• Corrosion Inhibition: Some conducting polymers can be doped with corrosion-inhibiting agents, such as corrosion inhibitors or nanoparticles, to enhance their protective capabilities, especially for metals prone to corrosion, like steel and aluminium [51].

• Active Corrosion Protection: Conducting polymers can also be used as part of active corrosion protection systems, where their electrical conductivity allows them to transfer charge and reduce corrosion rates through electrochemical processes.

5.6 Aesthetic Appeal

• Color and Transparency Options: Conducting polymers can be used as coatings that retain color and gloss, providing not just functional protection but also aesthetic value for the surfaces being protected.

5.7 Compatibility with Smart Coatings

• Integration with Sensors: Conducting polymers can be integrated into smart coatings that monitor corrosion in real-time [52]. Their electrical properties can be linked to sensors, enabling early detection of corrosion and the ability to respond dynamically to changing environmental conditions.

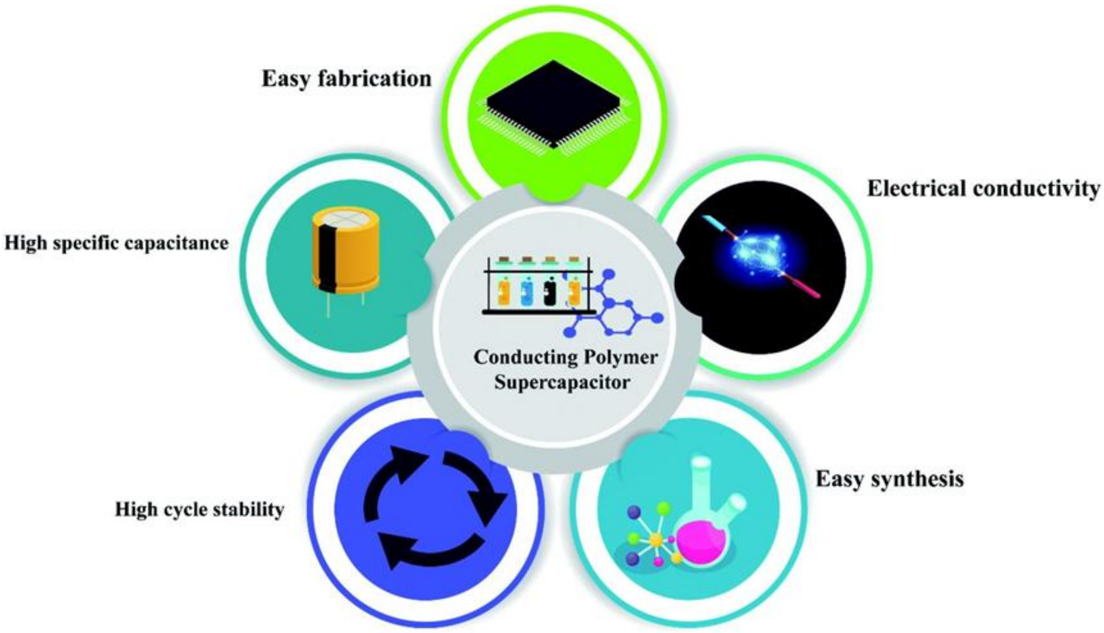

Figure 2: Advantages of CP's

VI. CHALLENGES IN USING CONDUCTING POLYMERS

a) **Durability:** While conducting polymers are stable in many conditions, their long-term durability under extreme conditions, such as high temperatures or continuous exposure to aggressive chemicals, may be limited.

b) **Processing Complexity:** The synthesis and processing of conducting polymers can be more complex compared to traditional coatings, requiring specialized equipment and techniques.

c) **Cost:** Although some conducting polymers are cost-effective, others (such as those requiring specialized dopants or processing) may be expensive.

d) **Adhesion Strength**: In some cases, conducting polymers may not adhere as strongly to certain metal surfaces without additional surface preparation or primers, which could increase the overall cost.

VII. APPLICATIONS OF CONDUCTING POLYMERS

Conducting polymers have found diverse applications in corrosion protection across various industries:

i. Marine Industry: The ability of conducting polymers to resist seawater corrosion makes them ideal for use in marine coatings for ships, offshore platforms, and underwater pipelines.

ii. Automotive and Aerospace: Conducting polymer coatings are used to protect metal components in cars and aircraft, where weight and durability are important considerations.

iii. Construction: Conducting polymers are used to protect infrastructure such as bridges, tunnels, and buildings, particularly in harsh environmental conditions.

iv. Oil and Gas: In the oil and gas industry, conducting polymers are used to protect pipelines and storage tanks from corrosion caused by chemicals and moisture [53].

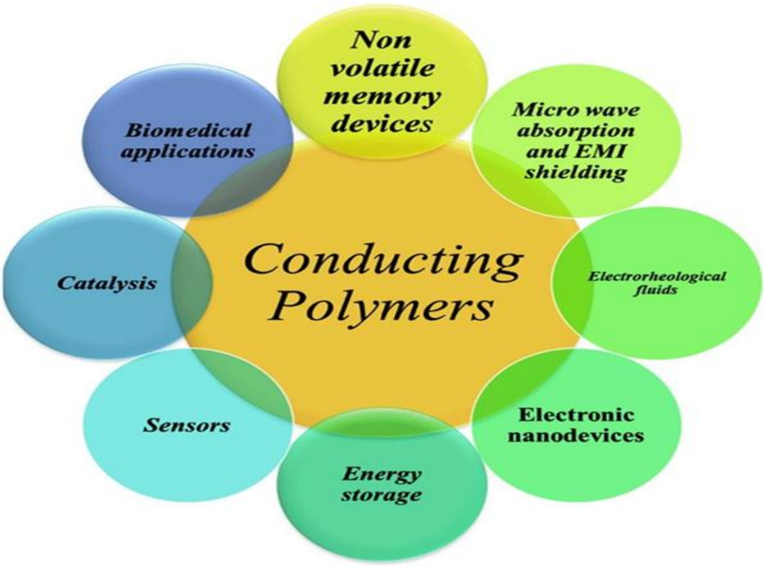

Figure 3: Application

VIII. FUTURE DIRECTIONS

The future of conducting polymers in corrosion protection looks promising, with several emerging trends:

i. Smart Polymers: Researchers are developing "smart" conducting polymers that respond dynamically to environmental changes, such as pH or humidity, to offer more adaptive corrosion protection.

ii. Nanotechnology: The incorporation of nanoparticles into conducting polymers could further enhance their mechanical properties and corrosion resistance.

iii. Eco-friendly Polymers: There is a growing interest in developing bio-based conducting polymers that are environmentally friendly and sustainable.

IX. SUMMARY

Conducting polymers offer a unique and innovative approach to corrosion protection. Their combination of electrical conductivity, environmental stability, and protective properties makes them ideal for a variety of industries. While there are challenges related to durability and processing, ongoing research into the development of new conducting polymers, as well as their applications, holds great potential for improving corrosion protection methods in the future.

DECLARATIONS

Conflict of Interest

The authors declare that they have no Conflict of Interest.

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Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Author's contributionstatement

All authors contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

Cover Letter

This manuscript is the authors' original work and has not been published nor has it been submitted simultaneously elsewhere. All authors have checked the manuscript and have agreed to the submission.

Ethical approval

The paper has been submitted with full responsibility, following due ethical procedure, and there is no duplicate publication, fraud, plagiarism. None of the authors of this paper has a financial or personal relationship with other people or organizations that could inappropriately influence or bias the content of the paper. This article does not contain any studies with human participants or animals performed by any of the authors.

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