



Journal of Composites and Compounds

Application of composite conducting polymers for improving the corrosion behavior of various substrates: A Review

Leila Bazli ^{a*}, Mohammad Yusuf ^b, Ali Farahani ^c, Morvarid Kiamarzi ^d, Zahra Seyedhosseini ^e,

Mehran Nezhadmansari ^f, Maryam Aliasghari ^g, Marjan Iranpoor ^h

^a School of Metallurgy and Materials Engineering, Iran University of Science and Technology, Tehran, Iran

^b Department of Chemical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 32610, Malaysia

^c Department of Textile Engineering, Amirkabir University of Technology, Tehran, Iran

^d Department of Polymer Engineering and Color Technology, Amirkabir University of Technology, Tehran, Iran

^e Department of Chemistry, Amirkabir University of Technology, Tehran, Iran

^f Department of Engineering and Materials Science, Sharif University of Technology, Tehran, Iran

^g Department of Chemistry, College of Science, Yadegar-e-Imam Khomeini (RAH) Shahre Rey Branch, Islamic Azad University (IAU), Tehran, Iran

^h Department of Agricultural Machinery Mechanics, University of Tehran, Alborz, Iran

ABSTRACT

One of the most important problems in the manufacturing industry is metal corrosion. Recently, conductive polymers (CPs) have attracted attention due to their economic viability and widespread industrial applications. Upon adsorption, long-chain carbon bonds of polymers provide a blockage for large surface areas of corroding metals. The adsorbed thin films create a barrier between the surrounding environment and the metal substrate. Polypyrrole (PPy), polyaniline (PANI), and polythiophene (PTh) are conducting polymers that are utilized to protect metals and metal alloys against corrosion. A proper selection of synthesis parameters for CPs can improve the anticorrosion behavior of the coatings for metals and metal alloys. This paper has an overview of conducting polymer composite coatings on substrates based on steel, copper, magnesium, aluminum, and their alloys.

©2020 JCC Research Group.

Peer review under responsibility of JCC Research Group

ARTICLE INFORMATION

Article history:

Received 28 July 2020

Received in revised form 07 September 2020

Accepted 13 October 2020

Keywords:

Corrosion resistance

Polyaniline

Polypyrrole

Polythiophene

Metal substrates

Table of contents

1. Introduction	228
2. Conducting polymers	229
3. Corrosion protection mechanisms of CPs	229
3.1. Corrosion inhibitors	230
3.2. Anodic protection	230
4. Composite conducting polymers (CCPs)	230
5. CCPs coatings on metals	231
5.1. CCPs coated on steels	231
5.2. CCPs coated on magnesium and its alloys	233
5.3. CCPs coated on aluminum and its alloys	233
5.4. CCPs coated on copper and its alloys	235
6. Conclusions and future insights	236

1. Introduction

In the electronic and metallurgical industries, corrosion control is a challenge with great importance worldwide [1]. To protect metals from corrosion, various methods have been used. A widely practiced

technique is the application of conducting polymer coatings [2, 3]. An active area of research in electrochemistry in the last decades has been the electrodeposition of CPs on the surfaces of metallic electrodes. In contrast to other coatings, such as paints, CPs do not contain toxic and hazardous constituents for the environment. Additionally, compared to other coatings that only provide physical barriers against corrosive envi-

* Corresponding author: Leila Bazli; E-mail: leilabazli64@gmail.com

DOR: 20.1001.1.26765837.2020.2.5.7.1

<https://doi.org/10.29252/jcc.2.4.7>

This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0>)

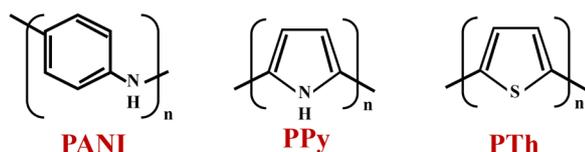


Fig. 1. Chemical composition of PANI, PPy, and PTh.

ronments, CPs provide physical and electronic barrier effects and electromagnetic interference (EMI) shielding which enhances the protection behavior [4-6].

These composite materials are strongly adsorbed onto active sites of the metal substrate leading to suppression of the dissolution process and production of a protective film layer. In fact, corrosion protection of CPs is a kind of anodic protection. According to studies, coating a metal with a conducting polymer places the potential of the electrode in the passive zone in the absence of redox reactions [7]. CPs have been applied on the surface of metals such as zinc [5], copper [6, 7], aluminum [8, 9], iron [10, 11], stainless steel (SS) [12], mild steel (MS) [13], etc. Mostly, polyaniline, polypyrrole, and polythiophene are used for coating metal substrates [8-19]. This review article has an overview of conducting polymers and composites and the state-of-the-art findings in the field of composite conducting polymers coated on various metal substrates are presented.

2.1. Conducting polymers

CPs can be used as a protective coating for the prevention of metal surface corrosion and enhancement of PE values [20]. Intrinsically conducting polymers are organic polymers with electrical conductivity. These compounds can either be semiconductors or show metallic conductivity. Their great advantage is the processability of conductive polymers, mainly by dispersion. Generally, these polymers are not thermoplastics and thereby they are not thermoformable. However, they are organic compounds like insulating polymers. Mechanical properties of conducting polymers are not similar to other commercial polymers, but they exhibit high electrical conductivity [21]. Using organic synthesis methods as well as advanced dispersion techniques, the electrical properties of these polymers can be fine-tuned [22, 23].

Different CPs are commercially available including PANI, PPy, PTh [24-26]. The chemical composition of these polymers is illustrated in Fig. 1. To synthesize CPs, electrochemical or chemical oxidation methods are used [27, 28]. PANI and its derivatives are extensively utilized for anticorrosion coatings due to facile synthesis, enhanced environmental stability, as well as various redox states that allow property regulation. Localized/delocalized polarons and bipolarons may be present in the PANI structure in various proportions, which depends on the methods of synthesis and isolation. PANI is practically applied to protect concrete steel bar reinforcement [28, 29].

Among all known CPs, one can consider PPy as promising material due to its high conductivity, easy and flexible preparation, good mechanical properties, and stability. Potential technological application of PPy include membrane separation [30], electronic and electrochromic devices [31], light-weight batteries [32], chromatographic stationary phases [33], sensors [34], and counterelectrode in electrolytic capacitors [35]. In recent years, it has been reported in several studies that PPy can protect metals and their alloys from corrosion [36-38].

An important class of conjugated polymers is PTh polymers that have a wide range of applications including field-effect transistors, electrochromic, and conducting films [39]. Few reports have demonstrated the use of PTh for the corrosion protection of metals. Among CPs,

some PTh derivatives have shown good performance, which ultimately depends on the environment nature that CPs are in contact with. It is feasible to generate PTh and its derivatives on other CPs such as PPy by applying proper voltage. The combination of these two conducting polymers has led to better corrosion performance [40].

It is possible to formulate CP-based coatings to inhibit corrosion of metals even in damaged areas where the surface of the metal is directly exposed to the corrosive environment. Conducting polymers can be whether in the reduction-nonconductive state or oxidation conductive state. Under appropriate conditions, they can easily switch between the two states. Redox processes occur in CPs; therefore, the expelling/binding of dopants (counterions) is conducted in response to the metal surface potential variation. The potential variation is initiated by local electrochemical reactions resulting from the corrosion. Based on the local corrosive conditions, the dopants can be expelled or inserted by the CP, which often act as inhibitors that prevent the local corrosion reactions upon release [41, 42]. This is considered as a strategy suggested for taking advantage of CP-based corrosion-resistant coatings [43].

3. Corrosion protection mechanisms of CPs

For the provision of electronic conductivity in CPs, oxidative polymerization and anion doping are performed into the polymer. The penetration of aggressive anions into CP coating is prevented by controlling the doping ions. When CP-coated metal substrates are immersed in aggressive environments, such as the sodium chloride solution, the chloride anions present in the medium is exchanged with doped anions in the CP coating. The corrosion protection mechanisms of CPs have not been precisely revealed. Four possible hypotheses have been proposed:

I) Mechanism of controlled inhibitor release: In this mechanism, the anion dopant may be released upon reduction from the oxidized and hence doped CP-based coating on a metallic substrate, which is driven by a coating defect. As far as doped PANI is concerned, the anions are released either through a reduction mechanism or a simple acid-dopant elimination if it is soluble in water [44, 45].

II) Mechanism of anodic protection: according to this mechanism, protective metal oxide layers are formed on the metal surface as a result of CPs providing corrosion protection [46].

III) It is proposed that an electric field is produced when there is a contact between a doped semiconductor or a conducting polymer and a metal resulting in a reduction in the corrosion rate due to the restriction of the electron flow from the metal to an oxidizing species [47].

IV) CPs create an adherent, dense, low porosity film on the metal surface limiting the access of oxidant agents and prevent metal surface oxidation [48] (Fig 2).

A denser CP layer provides a better barrier effect and decreases the rate of H_2O and O_2 transport into the polymer. The reaction site on which O_2 reduction occurs moves from the metal/CP interface to the CP/solution interface by the enhancement of the compactness of the coating and its adherence to the substrate [49]. The change in the O_2 reduction site on the surface of the polymer leads to a decrease in reduction products such as OH across the metal/CP interface, and thereby prevent the coating disbondment and delamination [50]. Furthermore, oxygen reduction requires the local reoxidation of the coating and its active role in the case that local small-size defects or pinholes are generated. Therefore, the improvement of the barrier effect should not inactivate CPs. The open-circuit potential of the metal/CP-based coating/solution system will be in the passive state as far as the conducting polymer is in the conductive form. The site of the O_2 reduction and its kinetics are important factors to determine the prolonged protective properties of the coating. Generally, it has been reported that the barrier effect is improved by

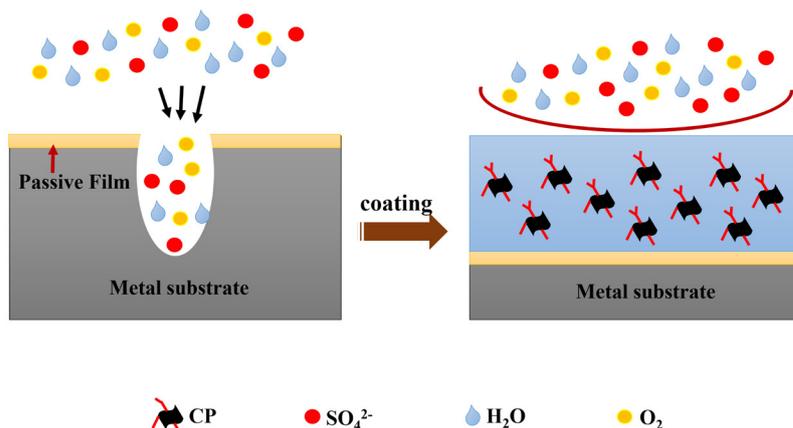


Fig. 2. Barrier effect of CPs for the diffusion of corrosive agents.

the dehydration of CP film electrodeposited on metal surfaces from an aqueous medium [43].

Mechanisms I and II are the most important contributing mechanisms that can rationalize corrosion inhibition by CPs. For a specific metal substrate/CP-based coating/solution system, the other two mechanisms contribute to the corrosion process simultaneously with the controlled inhibitor release or the anodic protection mechanism [10, 43].

3.1. Corrosion inhibitors

Different ways of CP doping can be used for controlling the electrolytic environment near the surface of the metal substrate in case a scratch is formed. In this condition, a galvanic coupling exists between the CP coating and the metal. The anodic reaction involves the metal oxidation, while the cathodic reaction is the CP reduction resulting in the release of the doping anions. However, oxygen is reduced simultaneously on both the metal surfaces and CP coating resulting in the OH production and the CP reoxidation, respectively. Based on the nature of doping anions and the metal, a self-healing process may be triggered. In some metals such as steel, copper, and aluminum, the doping anions such as molybdates and phosphonic acid derivatives act as inhibitors, or oxide formation is initiated [43].

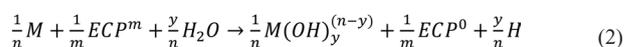
In the inhibition mechanism, a monomolecular barrier is formed by the organic species adsorption onto the surface of the metal. The presence of the adsorbed molecules results in the limitation of the cathodic and/or anodic corrosion reactions such as electron transfer and decreases the rate of corrosion [51, 52]. According to Brycki et al. [53], the inhibitor action involves the replacement of the adsorbed water from the surface of the metal by soluble organic species (Org):



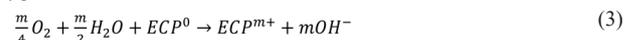
Several investigations have reported that monomeric aniline, as well as functionalized aniline derivatives, act as potential corrosion inhibitors for steel and iron [54-56].

3.2. Anodic protection

The anodic protection activity involved the ways wherein general corrosion of the metal substrates and alloys is prevented by CPs mostly in solutions free of halides [43]. According to Kinlen et al. [57], the electroactive conducting polymer (ECPs) electrochemistry provides anodic protection for the substrate and also prevents cathodic debonding of the polymer coating. In this protection mechanism, the corrosion potential of the metal substrate in the electrolyte of interest moves to the passive region. The proposed reaction between the metal (M) and the oxidized state of the polymer coating (ECP^{m+}) is:



reoxidation of the ECP can occur by dissolved or atmospheric oxygen:



4. Composite conducting polymers (CCPs)

Polymer nanocomposites have found increasing attention in various engineering applications [58-60]. The essential characteristic of this procedure is that CPs make it possible to maintain the substrate surface potential into a passive state wherein a protective oxide film is generated on the surface of metal substrates [43, 61]. As a result, CPs-based coatings are pinhole and defect resistant in such a way as that of the hexavalent chromium coatings. It is due to the replenishing of CP charges consumed by oxidation of metal by O_2 reduction within the CP coating. The corrosion process of metal is prevented by switching the CP-based coating into the oxidation state and thereby changing the potential into the passive region [62].

Expanded studies have focused on the anti-corrosive features of CPs; however, there are still numerous problems to be resolved regarding the fulfillment of mechanical and physico-electrochemical requirements of high performance anticorrosive CP-based coatings exposed to various practical conditions. Anticorrosive CP-based coatings have some limitations such as poor adhesion to the metallic substrate, anion-exchange properties, poor barrier effect due to porous structure, and irreversible consumption of stored charges within the coating, which can oxidize the substrate and form a passive oxide layer. The mentioned drawbacks show their effect more significantly under harsh environments. In case chloride ions are present, these ions can either penetrate through the CP coating or undergo anion-exchange (replacement of chlorides with CP doping anions) and reach the metal-substrate interface. Extended localized corrosion may be induced by chloride ions and during the redox reactions, the charge stored in the CP layer might be irreversibly consumed.

Using CP-based composites consisting of a conducting polymer and different inorganic fillers like metal oxides has been offered as an efficient strategy for the elimination of the disadvantages. In CP-based composites, the CP self-healing properties are combined with qualities of inorganic materials. Therefore, the composite coatings exhibit improved physicochemical and mechanical properties including enhanced hydrophobicity, barrier effect, and adhesion [43, 63-65]. The improvement of these properties leads to the enhancement of corrosion protection. Nano-

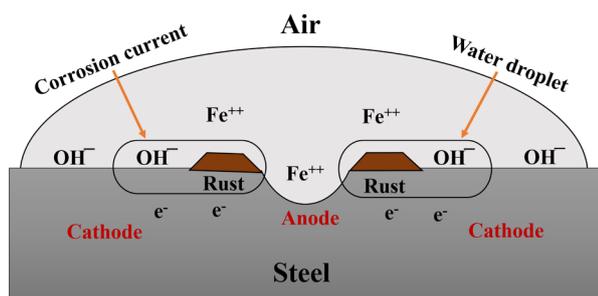


Fig. 3. Corrosion mechanism of steel.

technology has gained dramatic attention in recent years and is expected to make advancements in the design and development of commercially viable CP-based composite coatings [66]. It seems that CP-based nanocomposite can combine the properties of CPs and inorganic materials more effectively compared to microcomposites [67].

5. CCPs coatings on metals

5.1. CCPs coated on steels

Structural steel is corroded through an electrochemical process in the presence of oxygen and moisture. Rust is produced by the oxidation of iron in the steel, which has a volume of six times the original material [68]. The corrosion mechanism is presented in Fig. 3. There are numerous reported focusing on the corrosion protection effect of CP coatings on metals, especially iron and mild steel, and stainless steel and significant advancements have been made [69-76]. Most conducting polymers form conducting films directly on the substrate surface by anodic oxidation [77, 78]. Changing from an insulating state to a conducting state by different doping methods including injection of charge at the interface of a metal and the conducting polymer, photo doping, electrochemical doping, and chemical doping by charge transfer [71]. Due to the capability of these polymers in charge storing and transport, they can anodically protect metals against fast corrosion [79]. The corrosion protection mechanisms of CPs are complex and affected by various parameters [80-85]. Some theories have proposed that a passive oxide film is formed on the metal surface by oxidation-reduction processes, while others have predicted that the barrier mechanism is responsible for provided protection [61, 86, 87].

There are many studies targeting to investigate the corrosion protection of steel by CPs and CCPs. Sathyanarayanan et al. [88] synthesized the PANI-TiO₂ composite coating (PTC) on steel and studied its corrosion protection behavior. To prepare PTC, aniline and TiO₂ were chemically oxidized by ammonium persulfate in a medium containing phosphoric acid. According to the results, the redox property of PTC led to maintaining the steel potential in the passive region. The resistance of the PTC coating in a 3% NaCl solution after 60 days was more than 107 cm² and in the salt spray test for 35 days was 109 cm². However, in both cases, the resistance of the coating was less than 104 cm². It was proposed that the corrosion protection is due to the passivation of steel resulting from the presence of polyaniline. Lenz et al. [73] incorporated TiO₂ pigment into PPy during the electrochemical synthesis of the CP-based coating on AISI 1010 steel. Weight loss and salt spray tests demonstrated that the PPy/TiO₂ composite significantly increased anti-corrosion properties compared to PPy films. The composite coatings were suggested as a primary coating that can be applied on mild steel instead of phosphatized layers.

According to Radhakrishnan et al. [89], composite coatings com-

posed of PANI and nano-TiO₂ prepared by in-situ polymerization on steel plates showed superior corrosion resistance than did PANI coatings in aggressive environments. It was reported that the corrosion resistance improvement for the nanocomposite coating containing 4.18 wt% TiO₂ nanoparticles was beyond 100 times. It was proposed that the improvement is the result of the high surface area accessible for the dopant release due to nano-size additive, redox properties of PANI, charge transport prevention by the TiO₂ nanoparticles, and an increase in diffusion barrier. In a research study by Patil et al. [90], polyvinyl acetate (PVAc)-ZnO-PANI hybrid composite coatings (PVAc as the major matrix) were deposited on steel plates by the dip-coating method. In comparison with the coatings that contained either ZnO or PANI, the coatings that contained both the components exhibited higher corrosion resistance. The PVAc-ZnO-PANI coating showed the I_{corr} value of two-order lower than that of PVAc-ZnO and PVAc coatings. The improvement was reported to be the result of the redox behavior of PANI, enhancement of barrier properties by nanoparticles, as well as the formation of protective oxide layers near the substrate. Hosseini et al. [91] electrodeposited the polypyrrole phosphate (PPy-P) coating by cyclic voltammetry (CV) method on ST12 mild steel. The deposited PPy-P films demonstrated higher corrosion resistance compared to the PPy coating.

To coat 304 stainless steel for bipolar plates used in a proton exchange membrane fuel cell, Ren et al. [92] used galvanostatic deposition to produce an inner layer of PPy with large groups of dodecylsulfate ions, and then a PANI external layer containing small groups of SO₄²⁻ was applied via cyclic voltammetric deposition. According to results, the increase in pitting corrosion potential and corrosion potential of the bare steel for the single PPy and PPy/PANI coatings was more than 500 mV and 400 mV (saturated calomel electrode), respectively. Compared to the single PPy coating, the bilayer composite coating showed more effective corrosion reduction through providing passivity protection as well as a physical barrier with acceptable contact resistance.

Jiang et al. [46] deposited PPy-graphene oxide (GO) composite coatings on 304 stainless steel bipolar plates by in-situ electrodeposition to protect them against aggressive environments. The analysis in the simulated PEMFC environment exhibited that during potentiostatic polarization, the polarization current density of the substrate was significantly reduced by the conductive PPy-GO composite coating. The addition of GO to the PPy matrix led to the enhancement of the adhesion strength and an increase in the diffusion pathway of corrosive agents and therefore, restriction of their inward penetration. The best corrosion resistance was obtained for the composite coating containing 1 mg mL⁻¹ of GO in the electrodeposition electrolyte. The corrosion enhancement in the composites is the result of the improved anodic protection and physical barrier. Jadhav et al. [93] added poly-o-anisidine (POA) and PANI nanoparticles to alkyd paint formulation for protecting the mild steel surface. In comparison with the POA/alkyd coatings, corrosion protection of the PANI/Alkyd coatings was remarkably higher.

Epoxy/graphene composite coatings with hydrophobic surfaces were prepared by Chang et al. [94]. The water droplet's contact angle with the epoxy surface and hydrophobic epoxy/graphene surface were 82° and 127°, respectively. The improvement of the corrosion resistance by applying the composite coating was reported to be due to the physical barrier effect, a decrease in the adsorption of water/corrosive media resulting from the coating hydrophobicity, and high aspect ratio of graphene nanosheets leading to enhancement of the oxygen barrier property. Sumi et al. [95] synthesized PANI-Fe₂O₃ composite by an *In-situ* method and added it to a commercial alkyd resin as an anti-corrosive coating for mild steel. The composite coating was proposed to offer passivation protection and better barrier performance. The complimentary cathodic reaction of the nonconductive leuco-PANI to the conductive emeraldine-PANI was explained to be also responsible for the improved corrosion resistance in the acidic medium. Table 1 summarized research

Table 1.

Research reports on using CCPs for corrosion protection of steel

Authors	CPs	Additive	Coating technique	Medium	Corrosion behavior
Jadhav et al. (2020) [96]	PPy	Fe ₂ O ₃	Electrochemical method	NaCl	Better corrosion resistance was observed by the coating of Fe ₂ O ₃ /PPy.
Sun et al. (2020) [97]	PANI	-	Electrochemical deposition	NaCl	The density of corrosion current decreased 5 times and the coating exhibited effective protection for 140 days.
Deyab et al. (2020) [98]	PANI	Zn-Porphyrin	Electrochemical deposition	H ₂ SO ₄	The composite of PANI/Zn-Pr with 1.0% of Zn-Pr rendered the highest anti-corrosion activity (99.41%).
Chen et al. (2020) [24]	PPy	Polydopamine –functionalized carbon powders	Electropolymerization	H ₂ SO ₄	The PPy/C-PDA coating showed good protection performance for the 304SS bipolar plate in PEMFC.
Rajkumar et al. (2020) [99]	PPy	TiO ₂ , ZnO, and SiO ₂	Incorporation in resin	NaCl	The PPy coating provides the denser passivation film at the interface of PPy and TiO ₂ .
Chen et al. (2019) [100]	PPy	TiO ₂ and V-TiO ₂	Electrochemical method	HCl	comparing V-TiO ₂ /PPy and TiO ₂ /PP composite coatings, the V-TiO ₂ /PPy showed better corrosion resistance performance.
Kong et al. (2019) [101]	PANI	Chitosan	-	HCl	Using the PANI/CTS in 0.5 M HCl solution was effective for corrosion protection of Q235 steel and at high PANI/CTS concentrations, the highest inhibition efficiency was obtained.
Babaei-Sati et al. (2019) [102]	PPy	Al ₂ O ₃	Electrodeposition	H ₂ SO ₄	PPy/Al ₂ O ₃ nanocomposite with declining the density of corrosion current by 18 times, exhibited excellent performance in the protection of MS.
Shi et al. (2019) [26]	PANI	SiO ₂	Drop casting technique	H ₂ SO ₄	The silicone-SiO ₂ @PANI coating with a 4:1 weight ratio of SiO ₂ /PANI exhibited the highest resistance against corrosion (2.24×10 ⁷ Ω cm ²) after immersion in a corrosive medium for about 180 days.
Jaouhari et al. (2019) [103]	PPy	Zinc phosphate	Galvanostatic electrodeposition	NaCl	The ZP/PPy coatings showed excellent corrosion resistance and increased the ZP/PPy coating thickness.
Liu et al. (2019) [104]	PANI	TiO ₂	Electrochemical deposition	NaCl	The epoxy coating with TiO ₂ /PANI particles showed high corrosion protection compared to the blank coating after subjecting to a corrosive environment.
Wang et al. (2019) [38]	PANI	Nb: TiO ₂ nanofibers	galvanostatic method	HCl	The presence of Nb: TiO ₂ nanofibers in the coating of PANI led to the provision of better in-situ anodic protection and physical barrier effect.
Abd El-Lateef et al. (2019) [105]	PANI	Tl ₂ O ₃ -SiO ₂	Electrochemical deposition	HCl	The PANI coating could prevent the carbon steel corrosion and provide maximum yielding of 89% and this amount after the modification with Tl ₂ O ₃ -SiO ₂ nanocomposites was improved and reached 96%.
Ramezanzadeh et al. (2018) [83]	PANI	GO-CeO ₂	Electrodeposition	NaCl	The deposition of CeO ₂ and PANi improved the properties of active and barrier corrosion inhibition of GO nanosheets.
Contri et al. (2018) [106]	PPy	Montmorillonite (Mt)	Electrodeposition	H ₂ SO ₄	The Epoxy/Mt-PPy (5 wt%) could prevent carbon steel corrosion.
Jadhav et al. (2018) [107]	PPy	Mica	Incorporation in resin	NaCl	The pigment-based composite coating of Mo-doped PPy/mica exhibited better protection against corrosion with the steel passivation by the anions of molybdate.
Salem et al. (2018) [108]	PANI	-	Electrochemical deposition	NaCl	The possibility of delamination and blister formations were reduced by composite coatings.
Jiang et al. (2018) [109]	PANI	Ni(OH) ₂	Cyclic voltammetry technique	NaCl	The Ni(OH) ₂ particle deposition in a matrix of PANI prevented access to aggressive media. Also exhibited long-term anti-corrosive behavior.
Arabzadeh et al. (2017) [110]	PPy	-	Cyclic voltammetry method	HCl	The sample synthesized with the scan rate of polymerization equal to 100 mV/s was the best coating.
Ladan et al. (2017) [111]	PPy	TiO ₂	Dip coating	NaCl	Co doping TiO ₂ /PPy decreased the charge transfer across the interface of electrolyte/AISI 1018 steel.
Yan et al. (2017) [112]	PPy	Al ₂ O ₃	Cyclic voltammetry technique	NaCl	The PPy-Al ₂ O ₃ composite coating exhibited good performance in the corrosion protection of 316SS.
Yan et al. (2017) [113]	PPy	SiO ₂	Cyclic voltammetry technique	NaCl	The PPy-SiO ₂ coating exhibited good performance in the corrosion protection of 316SS.
Qiu et al. (2017) [114]	PANI	GO	Pulse-current deposition	Phosphate buffer	The 98.4% corrosion inhibition efficiency and 99.3% protection efficiency was obtained by using the PANI-GO composite coating.

investigation on using CCPs for corrosion protection of steel substrates.

5.2. CCPs coated on magnesium and its alloys

Because of biocompatibility, easy biodegradation, and excellent mechanical properties, Mg alloys have been extensively investigated for biomedical applications. Nevertheless, in a physiological environment, these alloys show a high corrosion rate leading to an increase in the pH value, which adversely affects cell differentiation, proliferation, and viability on the implant surface and thereby induces blood clots together with chronic tissue inflammatory responses [115-119]. Two main strategies for the improvement of the corrosion resistance of Mg and its alloys are surface modification and alloying [120, 121]. CPs and CP-based composites have been developed for the corrosion reduction of Mg-based substrates. The corrosion mechanism of Mg with and without CP coatings is shown in Fig. 4. PANI-TiO₂ composites were deposited on the ZM 21 alloy by Sathiyarayanan et al. [122]. To synthesize the coatings, aniline underwent oxidative polymerization in phosphoric acid with (NH₄)₂S₂O₈ in the presence of TiO₂. Compared to the PANI coating, the composite coating exhibited more effective protection performance as a coating for the ZM 21 alloy. In another research, Guo et al. [123] applied a composite coating of PPy/ZnO to protect biodegradable Mg alloys for orthopedic implant applications. Results indicated the improved corrosion protection, antibacterial property, as well as cytocompatibility of the composite coating suggesting it as proper material for orthopedic implants.

Wang et al. [124] presented the corrosion protection performance of composite coatings based on PANI and coal. PANI/coal powder was synthesized by *in situ* polymerization, the coatings were composed of epoxy, and PANI/coal was deposited on the surfaces of Mg alloys. A significant decrease in the corrosion rate and corrosion current density of the PANI/coal coatings was observed suggesting that the coating is a

Table 2.

Research reports on using CCPs for corrosion protection of Mg and its alloys

Authors	CPs	Additive	Coating technique	Medium	Corrosion behavior
Najibzad et al. (2020) [126]	PANI	Praseodymium	Dip coating	NaCl	The improvement in the performance was observed with applying 2000 ppm concentration compared to other concentrations.
Guo et al. (2020) [123]	PPy	ZnO ₂	Cyclic voltammetry technique	NaCl	An increase in the resistance of the corrosion was observed.
Jothi et al. (2020) [127]	PPy	Gelatin	Electrodeposition	NaCl	The coating exhibited good performance in providing the corrosion resistance of AZ31.
Samadi et al. (2020) [128]	PANI	Praseodymium	Electrochemical methods	NaCl	The composite of PANI/Pr31 that exhibits anti-corrosion behavior can be used as environmentally-friendly and non-toxic corrosion protective coating.
Li et al. (2020) [125]	PPy	V ₂ O ₅	Vapor phase polymerization (VPP)	NaCl	For the synthesis of the protective coating of CPs on reactive metals, the method of mild VPP may be effective.
Maurya et al. (2019) [129]	PANI	Graphene	Incorporation as pigments in epoxy resin	NaCl	The amount of the resistance value >10 ⁶ Ω cm ² was estimated using the composite coatings.
Yufeng Li et al. (2018) [130]	PANI	SiO ₂	Electrochemical methods	NaCl	For the Mg-Li alloy, the good resistance was obtained with the coating and the density of the corrosion current and impedance value was 6.7×10 ⁻⁷ A cm ⁻² and 5×10 ⁴ Ω cm ² , respectively.
Gao et al. (2018) [131]	PANI	-	Electrochemical methods	NaCl	The improvement was observed with the PANI-PhA addition because of the synergistic effect of silane, PhA, and PANI.
Wang et al. (2017) [124]	PANI	Coal	Electrodeposition	NaCl	This sample exhibited excellent resistance to corrosion.
Saremi et al. (2016) [132]	PPy	NaF and polyethylene glycol (PEG)	Cyclic voltammetry technique	NaCl	The observed improvement in the corrosion behavior of the PPy coating with PEG and NaF was due to the inhibition fluoride effect, which is considered a barrier for magnesium alloys.
Chen et al. (2010) [133]	PANI	SiO ₂	Electrochemical methods	NaCl	In the solution of 3.0 wt% NaCl, the coating of PANI-SiO ₂ showed better performance in keeping the potential values in the noble potential compared to the coating of pure epoxy.
Sathiyarayanan. (2007) [122]	PANI	TiO ₂	Electrodeposition	NaCl	For the protection of the Mg ZM 21 alloy, the composite coating was better than Polyaniline coating.

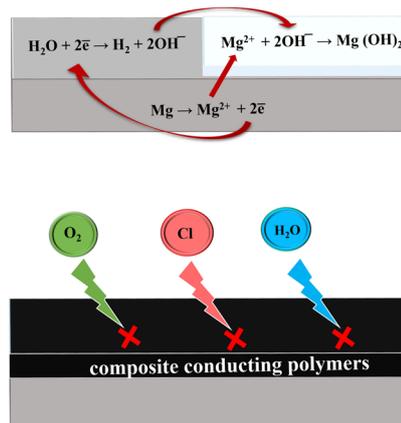


Fig. 4. Corrosion mechanism of bare Mg and CP-coated Mg.

promising candidate for the enhancement of corrosion resistance of Mg alloys in aggressive environments. In a research study by Li et al. [125], a PPy/V₂O₅ composite film was deposited on magnesium by mild vapor phase polymerization (VPP) technique. Corrosion investigations in 3.5 wt% NaCl revealed that the prepared composite film reduced the corrosion rate of Mg. The VPP method was offered as a technique with great potential to synthesize CP-based coating for the protection of reactive metals. Table 2 summarized research investigation on using CCPs for corrosion protection of Mg-based substrates.

5.3. CCPs coated on aluminum and its alloys

Al is an important metal due to its high technological value and its application in the household and aerospace industries [134-137]. Al-

Table 3.

Research reports on using CCPs for corrosion protection of Al and its alloys

Authors	CPs	Additives	Coating technique	Medium	Corrosion behavior
Tomaev et al. (2019) [146]	PPy	Aluminum Oxide	Galvanostatic	H ₂ SO ₄	The improvement in the electrochemical potential was obtained by PP coating, and the incensement in the surface impedance was provided by oxide coating.
Kumar et al. (2017) [147]	PPy	CeO ₂	Galvanostatic	NaCl	For the corrosion protection of the Al in aircraft infrastructures, the nanocomposites of PPy with nanoparticles of CeO ₂ could be effective.
Hosseini et al. (2017) [144]	PPy	TiO ₂ , Mn ₂ O ₃ , and ZnO	Cyclic voltammetry technique	oxalic acid	An excellent improvement in the corrosion protection was observed by applying the synthesized polypyrrole with nanoparticles of TiO ₂ .
Hussein et al. (2016) [143]	PANI / PPy	CNT and Ni ₂ LaO ₄	Cyclic voltammetry technique	oxalic acid	The barrier effect increased with the nanoparticles of NiLa oxide. Also, the reaction of oxygen reduction catalyzed by these particles led to improving the Al passive state.
Ates et al. (2015) [148]	PANI	TiO ₂ , Ag, and Zn	Cyclic voltammetry method	NaCl	The nanocomposite film of PANI/Ag exhibited the highest efficiency of protection (PE = 97.54%).
Ates et al. (2015) [149]	PANI / PPy	TiO ₂	Cyclic voltammetry	oxalic acid	According to the results, the efficiency of corrosion protection of the nanocomposites coated on the electrode of Al1050 was larger compared to PPy (94.9 %), PANI (96.4 %), and uncoated Al1050 electrodes.
Alvi et al. (2015) [150]	PANI	ZnO	Cyclic voltammetry method	HCl	Due to the electronic properties and chain conformation of the ZnO-PANI, it provided excellent protection against corrosion for Al and steel.
Jensen et al. (2014) [151]	PPy	Aluminum flake	Electrochemical methods	KCl	The composite coatings exhibited the reduction of dissolved oxygen over the scribe with no corrosion product concomitant buildup.
Gupta et al. (2013) [152]	PANI	Lignosulfonate	-	NaCl	The low corrosion amount was obtained with the coating of 5 wt% Pani-LGS/epoxy.
Jadhav et al. (2013) [153]	PPy	Aluminum flake	Incorporation in epoxy resin	Electrolyte solution	For the larger defect protection of the AA 2024-T3 substrate, the composite of the wire PPy/Al flake was effective.
Yan et al. (2013) [142]	PPy	Al flake	Incorporation in epoxy resin	DHS solution	The best performance of the protection was obtained by doping the vanadate in the composite coating.
Shabani et al. (2011) [154]	PANI	Montmorillonite	Electrosynthesis	NaCl	Using nanocomposite-coated compared to uncoated Al led to a decrease in the amount of the corrosion current (<i>i_{corr}</i>) from 6.55 μA cm ⁻² to 0.102 μA cm ⁻² .
Hosseini et al. (2011) [134]	PANI	Montmorillonite	Electrochemical methods	NaCl	Epoxy blend with polyaniline and MMT showed the highest corrosion protection for 100h.
Castagno et al. (2010) [155]	PPy	Montmorillonite (MT)	Electrochemical techniques	NaCl	The PPy/MT films with 1% clay provided good performance in the protection of corrosion for Al.
Hosseini et al. (2009) [156]	PPy	Montmorillonite	Electrochemical methods	NaCl	The coating provided good protection of Al corrosion with a combination of epoxyblend with MT and PPy advantages.
Wu et al. (2007) [157]	PANI	Silicate-NiZn ferrite	Electrochemical and salt-spray	NaCl	With the incorporation of the NiZn ferrite/PANI particles, the denser configuration of the ormosil hybrids was obtained which could prevent the Al alloy substrate corrosion.
Shah et al. (2001) [145]	PANI/PPy	-	Galvanostatic and potentiostatic technique	oxalic acid	The low corrosion rates were observed in moderate to high applied electrochemical current densities.

though on the surface of reactive metals such as Al, a thin oxide film is formed protecting them from further corrosion, localized corrosion occurs on the surface of Al when it is exposed to corrosive environments containing complexing agents such as halides [138-141]. There have been several studies regarding the deposition of CP-based coatings on Al-based substrates to enhance their corrosion resistance. In a study by Yan et al. [142], PPy was first deposited on Al flakes in the presence of inhibiting dopants including vanadate, molybdate, or phosphate oxyanions. Then, the modified Al flakes were added to an epoxy primer to protect the AA 2024-T3 alloy. The composite coating showed good protection performance for the Al alloy through the mechanism of oxygen

scavenger protection provided by PPy in the composite coating.

Hussein et al. [143] used the cyclic voltammetry technique to deposit PANI-NiLa and PPy-carbon nanotubes (CNTs) nanocomposite coating on aluminum. The thermal stability of PPy was enhanced by the addition of CNTs, while decreased in the presence of NiLa. The addition of CNTs and NiLa particles improved the protection role and adhesion of the PPy coating for aluminum. Compared to the PPy layer, the nanocomposite coatings had higher protection property for Al in the NaCl solution. PPy-NiLa nanocomposite coating demonstrated the highest corrosion protection. In another study by Hosseini et al. [144], ZnO, Mn₂O₃, and TiO₂, nanoparticles were dispersed in PPy by in-situ electropolymerization to

protect Al electrodes. It was found that the corrosion resistance of the nanocomposites was higher than that of bare PPy in harsh environments. The PPy/TiO₂ composite coating exhibited a remarkable improvement in corrosion protection. The great enhancement of protection properties was reported to be due to the high surface area of nano-additives for the dopant release, charge transport prevention by the TiO₂ nanoparticles, redox properties of PPy together with increased barrier effect to diffusion.

Kunal et al. [145] coated Al-2024-T3 substrate with PPy, PANI, and PPy/PANI composites via potentiostatic and galvanostatic techniques. Results showed that the corrosion rate reduction in the presence of CPs was about three orders of magnitude. Deposition time and applied current density as electrochemical processing variables were found to noticeably affect the corrosion behavior of the coated substrate so that low corrosion rates were achieved by applying moderate to high current densities. Table 3 summarized research investigation on using CCPs for corrosion protection of Al-based substrates.

5.4. CCPs coated on copper and its alloys

Cu is used in industrial and technological applications on a large scale because of its outstanding processability, thermal and electrical conductivity, wear and shock resistance, and ductility. Cu is the best selection for integrates circuits, especially microprocessors due to its improved electromigration performance as well as low resistivity [158-162]. Under neutral pH conditions, protective oxide or hydroxide layers form on the surface of Cu substrates [163-167]. In chloride-containing environments, the copper corrosion process and the protective layer formation are more complex [168, 169]. In oxidative environments, the mechanism of corrosion for copper involves the electrochemical reduc-

tion of water and oxygen at local cathodic zones and the dissolution of Cu at local anodic zones. The rates of reduction and dissolution reactions are slowed down by the formation of the protective film formation, and the diffusion rate of Cu chloride ions into the chloride solution influences the rate of these reactions. However, the diffusion and reduction of corrosive species like oxygen cannot be prohibited by the oxides or hydroxide layers [170, 171].

The enhancement of the corrosion resistance of copper has been an attractive topic for researchers [172, 173]. Applying CPs on copper substrates and their corrosion behaviors have been reported in the literature [174-182]. Beikmohammadi et al. [37] used the in situ electropolymerization technique to deposit PPy/TiO₂ composite coating on copper electrodes. It was proved that the addition of TiO₂ nanoparticles promoted the corrosion protection behavior of the coating compared to bare PPy in a harsh environment. As reported for the similar coatings for other metals, an increment of barrier to diffusion, charge transport prevention by the TiO₂ particles, high surface area of the titanium oxide nanoparticles for the dopant liberation, as well as redox properties of polypyrrole are responsible for the improvement.

Pan et al. [183] used Cu as substrate and electrochemically synthesized the conductive composite coating consisting of an outer PANI layer and an inner PPy layer. They found that the corrosion potential of Cu substrate increased via both the single PPy coating and the bilayered PPy/PANI. In addition, the corrosion current density decreased by an order of magnitude compared to uncoated Cu substrate. They also evaluated the Long-term protection of the coatings. It was shown that the PPy/PANI bilayer coating was better than the single polypyrrole coating that can be an effective physical barrier for inhibiting the penetration of corrosive species.

In another study, Çakmakçı et al. [184] fabricated the poly(pyrrole)/

Table 4.

Research reports on using CCPs for corrosion protection of Cu and its alloys

Authors	CPs	Additive	Coating technique	Medium	Corrosion behavior
Badi et al. (2020) [94]	PANI	Silver nanoparticles	Electrochemical methods	HCl	The coating containing the nanoparticles of PANI-Ag exhibited corrosion protection for 6061 Al alloys used in solar panel frames.
Wan et al (2019) [189]	PPy	Benzotriazole (BTA) or/ and silica	Cyclic voltammetry technique	NaCl	The composite film exhibited good performance in corrosion protection due to the synergetic effect of silica physical barrier and BTA active protection.
Beikmohammadi et al. (2018) [37]	PPy	TiO ₂	Cyclic voltammetry technique	NaCl	Nanoparticles of TiO ₂ exhibited good performance in the improvement of polypyrrole films for the protection of copper.
Jafari et al. (2016) [190]	PPy	Graphene	Cyclic voltammetry technique	H ₂ SO ₄	The number of polymer pores decreased and the nanocomposite morphology after immersion in NaCl solution at a concentration of 5000 ppm for 2 hours, remained constant and unchanged.
Shabani et al. (2015) [191]	PPy	Zeolite	Electrodeposition	NaCl	By using this coating the corrosion current density declined and reached 0.34 $\mu\text{A cm}^{-2}$ and also the potential of corrosion shifted from -0.314 V to -0.141 V.
Pan et al. (2015) [183]	PPy/PANI	-	Cyclic voltammetric and galvanostatic	acidic medium	The PPy/PANI bilayered coating provided better protection for the copper substrate than the PPy coating.
Davoodi et al. (2015) [192]	PPy	Multi-walled carbon nanotubes	Cyclic voltammetry technique	NaCl	Higher protection of corrosion was obtained by using the nanocomposite of PPy/functionalized MWCNT compared to PPy/MWCNT.
Dhibar et al. (2013) [193]	PANI	-	Electrochemical methods	HCl	The promising electrochemical properties were exhibited with doping of 2 wt% PANI.
Ozkazanc et al. (2013) [209]	PPy	Zinc and nickel	Electrodeposited	H ₂ SO ₄	The protection degree for electrodes of copper was enhanced.
K. Wu et al. (2009) [93]	PANI	Silicate/carbon black	Electrochemical methods	NaCl	The resistance of corrosion and barrier properties were enhanced by using the system of PANI/CB.

poly(N methyl pyrrole) bilayer and poly(pyrrole-co-N-methyl pyrrole) copolymer composites via electrochemical synthesis. They applied them on Cu substrate through cyclic voltammetry from an aqueous solution of 0.1 M monomer and 0.3 M oxalic acid. They suggested that the monomer feed ratio strongly affects the performance of coatings, in which the most protective property was illustrated by copolymer fabricated with 8:2 concentration ratio. Electrochemical impedance spectroscopy and anodic polarization using 0.1 M H₂SO₄ solution were employed to evaluate the corrosion behavior of polymer composites. They implied that the bilayer and copolymer coatings had a higher protection effect than that of single PPy coatings.

Branzoi et al. [185] investigated the electropolymerized monolayer poly (N, N' dimethylaniline) (PNDMA), bilayer PNDMA/PANI, polyaniline (PANI), PANI/PNDMA coatings on Cu substrate.

They found that good corrosion protection was obtained by PNDMA-SDS/PANI coatings in aggressive media. In addition, better corrosion inhibition efficiencies were observed for bilayer coatings.

Singh et al. [186] used electrophoretic deposition (EPD), as a less time-consuming, inexpensive, and fairly facile method, to fabricate hydrophobic graphene oxide-polymer composite (GOPC) on copper. The efficacy of the coating under stringent environmental conditions was investigated via EIS and potentiodynamic polarization investigation. They implied that electrochemical degradation of the bare copper substrate was three orders of magnitude higher than GOPC coating. They realized that the GOPC coatings were impermeable to ion diffusion of corrosive liquid solution and oxidizing gas.

In another study, Kim et al. [187] fabricated graphene/polysiloxane (PSX) nanocomposite films possessing superior corrosion protection, high electrical, and dual function. A facile bar coating method using a metering rod was employed for the better in-plane ordering of filler networks in the coating. It was found that PSX-G composite coating films improved the charge transfer resistance dramatically (20,000%), higher electrical conductivity (1700 Sm⁻¹), and decreased rate of corrosion (1/40 th). This was due to complementary effects between the covering agent of graphene defects and inorganic polymer matrix as the anticorrosive layer as well as graphene conductive filler. They implied that the system could be potentially employed in industrial fields including energy storage systems, electromagnetic shielding (EMI), and anti-icing.

Singh et al. [188] applied a cathodic electrophoretic deposition (EPD) technique to fabricate anticorrosive graphene reinforced composite coating. They implied that the Cu substrate became resistant to electrochemical degradation by applying the composite coating. In this regard, the Tafel analysis showed that composite coating reduced the corrosion rate about an order of magnitude lower than that of bare substrate. Table 4 summarizes the studies focusing on the application of CCPs for corrosion protection of steel, Cu, Al, and Mg.

6. Conclusions and future insights

CCPs have been widely investigated for the protection of metal substrates such as steel, Al, Cu, and Mg. PANI, PPy, and PTh are common conducting polymers that have been developed as protective coatings for metals. Composite conducting polymers have been prepared with the incorporation of different components such as ZnO₂, TiO₂, NiLa, Mn₂O₃, etc. Corrosion inhibiting and anodic protection is the most important contributing mechanisms to the reduction of the corrosion rate of metals. It has been demonstrated that CCPs have superior corrosion protection properties than do conducting polymer coatings. This is the result of the high surface area of nano-additives for the dopant release, and the promotion of barrier effect against diffusion. It is expected that in future investigations, a variety of reinforcements will be at the center of attention and more focus will be placed on the application of CCPs on other

metallic substrates and in different fields. Moreover, since the protection against corrosion by CPs is mostly based on the mechanism of anodic protection, the stabilization of the passive oxide film under the polymer coating and inhibition of the aggressive anions from penetration into the polymer film must be carefully considered.

Acknowledgments

The authors received no financial support for the research, authorship and/or publication of this article.

Conflict of interest

The authors declare that there is no conflict of interest.

REFERENCES

- [1] B. Yao, G. Wang, J. Ye, X. Li, Corrosion inhibition of carbon steel by polyaniline nanofibers, *Materials Letters* 62(12-13) (2008) 1775-1778.
- [2] M. Hosseini, M. Sabouri, T. Shahrabi, Corrosion protection of mild steel by polypyrrole phosphate composite coating, *Progress in Organic Coatings* 60(3) (2007) 178-185.
- [3] S. Das, T. Yokozeki, Polyaniline-based multifunctional glass fiber reinforced conductive composite for strain monitoring, *Polymer Testing* 87 (2020) 106547.
- [4] P. Herrasti, F. Recio, P. Ocon, E. Fatás, Effect of the polymer layers and bilayers on the corrosion behaviour of mild steel: Comparison with polymers containing Zn microparticles, *Progress in Organic Coatings* 54(4) (2005) 285-291.
- [5] S. Das, S. Sharma, T. Yokozeki, S. Dhakate, Conductive Layer-based Multifunctional Structural Composites for Electromagnetic Interference Shielding, *Composite Structures* 261 (2020) 113293.
- [6] V. Kumar, S. Das, T. Yokozeki, Frequency independent AC electrical conductivity and dielectric properties of polyaniline-based conductive thermosetting composite, *Journal of Polymer Engineering* 38(10) (2018) 955-961.
- [7] H. Zhu, L. Zhong, S. Xiao, F. Gan, Accelerating effect and mechanism of passivation of polyaniline on ferrous metals, *Electrochimica acta* 49(28) (2004) 5161-5166.
- [8] S. Aeiayach, B. Zaid, P. Lacaze, A one-step electrosynthesis of PPy films on zinc substrates by anodic polymerization of pyrrole in aqueous solution, *Electrochimica acta* 44(17) (1999) 2889-2898.
- [9] T. Zhang, C. Zeng, Corrosion protection of 1Cr18Ni9Ti stainless steel by polypyrrole coatings in HCl aqueous solution, *Electrochimica Acta* 50(24) (2005) 4721-4727.
- [10] G.M. Spinks, A.J. Dominis, G.G. Wallace, D.E. Tallman, Electroactive conducting polymers for corrosion control, *Journal of Solid State Electrochemistry* 6(2) (2002) 85-100.
- [11] N. Ogurtsov, A. Pud, P. Kamarchik, G. Shapoval, Corrosion inhibition of aluminum alloy in chloride mediums by undoped and doped forms of polyaniline, *Synthetic Metals* 143(1) (2004) 43-47.
- [12] K. Shah, J. Iroh, Electrochemical synthesis and corrosion behavior of poly (N-ethyl aniline) coatings on Al-2024 alloy, *Synthetic metals* 132(1) (2002) 35-41.
- [13] A.R. Elkais, M.M. Gvozdenović, B. Jugović, T. Trišović, M. Maksimović, B. Grgur, Electrochemical synthesis and corrosion behavior of thin polyaniline film on mild steel, copper and aluminum, *Hemijaska industrija* 65(1) (2011) 15-21.
- [14] J. Martins, M. Bazzzaoui, T. Reis, E. Bazzzaoui, L. Martins, Electrosynthesis of homogeneous and adherent polypyrrole coatings on iron and steel electrodes by using a new electrochemical procedure, *Synthetic metals* 129(3) (2002) 221-228.
- [15] S. Jafarzadeh, P.M. Claesson, P.-E. Sundell, E. Tyrode, J. Pan, Active corrosion protection by conductive composites of polyaniline in a UV-cured polyester acrylate coating, *Progress in organic coatings* 90 (2016) 154-162.
- [16] A. Ali Fathima Sabirneeza, S. Subhashini, A novel water-soluble, conducting polymer composite for mild steel acid corrosion inhibition, *Journal of applied polymer science* 127(4) (2013) 3084-3092.
- [17] J. Stejskal, M. Trchová, J. Kovářová, J. Prokeš, M. Omastová, Polyaniline-coated cellulose fibers decorated with silver nanoparticles, *Chemical Papers* 62(2) (2008) 181-186.
- [18] S.S. Najjar, A. Kaynak, R.C. Foitzik, Conductive wool yarns by continuous vapour phase polymerization of pyrrole, *Synthetic metals* 157(1) (2007) 1-4.
- [19] S.A. Kumar, K.S. Meenakshi, T. Sankaranarayanan, S. Srikanth, Corrosion resistant behaviour of PANI-metal bilayer coatings, *Progress in Organic Coatings* 62(3) (2008) 285-292.
- [20] T. Li, X. Zeng, J. Xu, Preparation and characterization of conductive polypyrrole/organophilic montmorillonite nanocomposite, *Polymer-Plastics Technology and*

Engineering 46(8) (2007) 751-757.

- [21] S. Das, V. Kumar, T. Yokozeki, Strain sensing behavior of multifunctional polyaniline-based thermoset polymer under static loading conditions, *Polymer Testing* 77 (2019) 105916.
- [22] T. Otero, *Conducting Polymers : Bioinspired Intelligent Materials and Devices*, 2016.
- [23] C. Kvarnström, György Inzelt, Conducting polymers. A new era in electrochemistry, *Journal of Solid State Electrochemistry* 14(5) (2010) 917-917.
- [24] Z. Chen, G. Zhang, W. Yang, B. Xu, Y. Chen, X. Yin, Y. Liu, Superior conducting polypyrrole anti-corrosion coating containing functionalized carbon powders for 304 stainless steel bipolar plates in proton exchange membrane fuel cells, *Chemical Engineering Journal* 393 (2020) 124675.
- [25] M. Bouabdallaoui, Z. Aouzal, A. El Guerraf, S.B. Jadi, M. Bazzouai, R. Wang, E. Bazzouai, Influence of polythiophene overoxidation on its physicochemical properties and corrosion protection performances, *Materials Today: Proceedings* 31 (2020) S69-S74.
- [26] S. Shi, Y. Zhao, Z. Zhang, L. Yu, Corrosion protection of a novel SiO₂@PANI coating for Q235 carbon steel, *Progress in Organic Coatings* 132 (2019) 227-234.
- [27] C. Kvarnström, György Inzelt, Conducting polymers. A new era in electrochemistry, *Journal of Solid State Electrochemistry* 14(5) (2010) 917-917.
- [28] G. Čirić-Marjanović, Recent advances in polyaniline research: Polymerization mechanisms, structural aspects, properties and applications, *Synthetic metals* 177 (2013) 1-47.
- [29] B. Bhanvase, S. Sonawane, New approach for simultaneous enhancement of anticorrosive and mechanical properties of coatings: Application of water repellent nano CaCO₃-PANI emulsion nanocomposite in alkyd resin, *Chemical Engineering Journal* 156(1) (2010) 177-183.
- [30] X. Tan, C. Hu, Z. Zhu, H. Liu, J. Qu, Electrically Pore-Size-Tunable Polypyrrole Membrane for Antifouling and Selective Separation, *Advanced Functional Materials* 29(35) (2019) 1903081.
- [31] V.K. Thakur, G. Ding, J. Ma, P.S. Lee, X. Lu, Hybrid materials and polymer electrolytes for electrochromic device applications, *Advanced materials* 24(30) (2012) 4071-4096.
- [32] I. Sultana, M. Rahman, S. Li, J. Wang, C. Wang, G.G. Wallace, H.-K. Liu, Electrodeposited polypyrrole (PPy)/para (toluene sulfonic acid)(pTS) free-standing film for lithium secondary battery application, *Electrochimica acta* 60 (2012) 201-205.
- [33] J. Wu, Z. Mester, J. Pawluszyn, Speciation of organoarsenic compounds by polypyrrole-coated capillary in-tube solid phase microextraction coupled with liquid chromatography/electrospray ionization mass spectrometry, *Analytica chimica acta* 424(2) (2000) 211-222.
- [34] S. Navale, G. Khuspe, M. Chougule, V. Patil, Camphor sulfonic acid doped PPy/ α -Fe₂O₃ hybrid nanocomposites as NO₂ sensors, *RSC Advances* 4(53) (2014) 27998-28004.
- [35] C. Bu, Q. Tai, Y. Liu, S. Guo, X. Zhao, A transparent and stable polypyrrole counter electrode for dye-sensitized solar cell, *Journal of power sources* 221 (2013) 78-83.
- [36] E. Armelin, R. Pla, F. Liesa, X. Ramis, J.I. Iribarren, C. Alemán, Corrosion protection with polyaniline and polypyrrole as anticorrosive additives for epoxy paint, *Corrosion science* 50(3) (2008) 721-728.
- [37] M. Beikmohammadi, L. Fotouhi, A. Ehsani, M. Naseri, Potentiodynamic and electrochemical impedance spectroscopy study of anticorrosive properties of p-type conductive polymer/TiO₂ nanoparticles, *Solid State Ionics* 324 (2018) 138-143.
- [38] Y. Wang, S. Zhang, P. Wang, S. Chen, Z. Lu, W. Li, Electropolymerization and corrosion protection performance of the Nb:TiO₂ nanofibers/polyaniline composite coating, *Journal of the Taiwan Institute of Chemical Engineers* 103 (2019) 190-198.
- [39] I.F. Perepichka, D.F. Perepichka, H. Meng, F. Wudl, Light-emitting polythiophenes, *Advanced Materials* 17(19) (2005) 2281-2305.
- [40] L. Ai, Y. Liu, X. Zhang, X. Ouyang, Z. Ge, A facile and template-free method for preparation of polythiophene microspheres and their dispersion for waterborne corrosion protection coatings, *Synthetic metals* 191 (2014) 41-46.
- [41] P.J. Kinlen, V. Menon, Y. Ding, A mechanistic investigation of polyaniline corrosion protection using the scanning reference electrode technique, *Journal of the Electrochemical Society* 146(10) (1999) 3690.
- [42] P. Kinlen, Y. Ding, D. Silverman, Corrosion protection of mild steel using sulfonic and phosphonic acid-doped polyanilines, *Corrosion* 58(6) (2002) 490-497.
- [43] P.P. Deshpande, N.G. Jadhav, V.J. Gelling, D. Sazou, Conducting polymers for corrosion protection: a review, *Journal of Coatings Technology and Research* 11(4) (2014) 473-494.
- [44] D. Sazou, P.P. Deshpande, Conducting polyaniline nanocomposite-based paints for corrosion protection of steel, *Chemical Papers* 71(2) (2017) 459-487.
- [45] G. Paliwoda-Porebska, M. Rohwerder, M. Stratmann, U. Rammelt, W. Plieth, Release mechanism of electrodeposited polypyrrole doped with corrosion inhibitor anions, *Journal of Solid State Electrochemistry* 10(9) (2006) 730-736.
- [46] L. Jiang, J.A. Syed, H. Lu, X. Meng, In-situ electrodeposition of conductive polypyrrole-graphene oxide composite coating for corrosion protection of 304SS bipolar plates, *Journal of Alloys and Compounds* 770 (2019) 35-47.
- [47] P. Chandrasekhar, *Conducting polymers, fundamentals and applications*, Springer, New York, 1999.
- [48] R. Hasanov, S. Bilgiç, Monolayer and bilayer conducting polymer coatings for corrosion protection of steel in 1 M H₂SO₄ solution, *Progress in Organic Coatings* 64(4) (2009) 435-445.
- [49] A. Michalik, M. Rohwerder, Conducting polymers for corrosion protection: a critical view, *Zeitschrift für Physikalische Chemie* 219(11) (2005) 1547-1559.
- [50] G. Paliwoda-Porebska, M. Stratmann, M. Rohwerder, K. Potje-Kamloth, Y. Lu, A.Z. Pich, H.-J. Adler, On the development of polypyrrole coatings with self-healing properties for iron corrosion protection, *Corrosion science* 47(12) (2005) 3216-3233.
- [51] Y.I. Kuznetsov, Organic corrosion inhibitors: where are we now? A review. Part IV. Passivation and the role of monoand diphosphonates, *International Journal of Corrosion and Scale Inhibition* 6(4) (2017) 384-427.
- [52] M.A.A. Ali, Inhibition of mild steel corrosion in cooling systems by low-and non-toxic corrosion inhibitors, *The University of Manchester (United Kingdom)*, 2017.
- [53] B. Bogumil Eugeniusz, H.K. Iwona, S. Adrianna, K. Olga, P. Marta, *Organic Corrosion Inhibitors*, in: A. Mahmood (Ed.), *Corrosion Inhibitors, Principles and Recent Applications*, IntechOpen, Rijeka, 2017, p. Ch. 1.
- [54] M. Quraishi, S.K. Shukla, Poly (aniline-formaldehyde): a new and effective corrosion inhibitor for mild steel in hydrochloric acid, *Materials Chemistry and Physics* 113(2-3) (2009) 685-689.
- [55] R. Karthikaiselvi, S. Subhashini, Study of adsorption properties and inhibition of mild steel corrosion in hydrochloric acid media by water soluble composite poly (vinyl alcohol-o-methoxy aniline), *Journal of the Association of Arab Universities for Basic and Applied Sciences* 16 (2014) 74-82.
- [56] D.K. Yadav, D. Chauhan, I. Ahamad, M. Quraishi, Electrochemical behavior of steel/acid interface: adsorption and inhibition effect of oligomeric aniline, *RSC advances* 3(2) (2013) 632-646.
- [57] P. Kinlen, D. Silverman, C. Jeffreys, Corrosion protection using polyaniline coating formulations, *Synthetic Metals* 85(1-3) (1997) 1327-1332.
- [58] L. Bazli, A. Khavandi, M.A. Boutorabi, M. Karrabi, Correlation between viscoelastic behavior and morphology of nanocomposites based on SR/EPDM blends compatibilized by maleic anhydride, *Polymer* 113 (2017) 156-166.
- [59] L. Bazli, A. Khavandi, M.A. Boutorabi, M. Karrabi, Morphology and viscoelastic behavior of silicone rubber/EPDM/Cloisite 15A nanocomposites based on Maxwell model, *Iranian Polymer Journal* 25(11) (2016) 907-918.
- [60] M. Bazli, L. Bazli, R. Rahmani, S. Mansoor, M. Ahmadi, R. Pouriamanesh, Concrete filled FRP-PVC tubular columns used in the construction sector: A review, *Journal of Composites and Compounds* 2(4) (2020) 155-162.
- [61] S.A. Umoren, M.M. Solomon, Protective polymeric films for industrial substrates: A critical review on past and recent applications with conducting polymers and polymer composites/nanocomposites, *Progress in Materials Science* 104 (2019) 380-450.
- [62] M.H. Naveen, N.G. Gurudatt, H.B. Noh, Y.B. Shim, Dealloyed AuNi dendrite anchored on a functionalized conducting polymer for improved catalytic oxygen reduction and hydrogen peroxide sensing in living cells, *Advanced Functional Materials* 26(10) (2016) 1590-1601.
- [63] L. Zhang, W. Du, A. Nautiyal, Z. Liu, X. Zhang, Recent progress on nanostructured conducting polymers and composites: synthesis, application and future aspects, *Science China Materials* 61(3) (2018) 303-352.
- [64] M. Tomczykowa, M.E. Plonska-Brzezinska, *Conducting polymers, hydrogels and their composites: preparation, properties and bioapplications*, *Polymers* 11(2) (2019) 350.
- [65] L. Fu, Q. Qu, R. Holze, V.V. Kondratiev, Y. Wu, Composites of metal oxides and intrinsically conducting polymers as supercapacitor electrode materials: the best of both worlds?, *Journal of Materials Chemistry A* 7(25) (2019) 14937-14970.
- [66] A. Eftekhari, *Front Matter, Nanostructured Conductive Polymers*, John Wiley & Sons, Ltd, Chichester, England, UK, 2010, pp. i-xxiii.
- [67] B. Hema, S.A. Kumar, S.K. Dhawan, *Conducting Polymer Nanocomposites for Anticorrosive and Antistatic Applications*, in: E. Farzad (Ed.), *Nanocomposites*, IntechOpen, Rijeka, 2012, p. Ch. 13.
- [68] C. Cao, M.M. Cheung, Non-uniform rust expansion for chloride-induced pitting corrosion in RC structures, *Construction and Building Materials* 51 (2014)

- 75-81.
- [69] M. Bernard, A. Hugot-Le Goff, S. Joiret, N.N. Dinh, N.N. Toan, Polyaniline layer for iron protection in sulfate medium, *Journal of the Electrochemical Society* 146(3) (1999) 995.
- [70] D.E. Tallman, G. Spinks, A. Dominis, G.G. Wallace, Electroactive conducting polymers for corrosion control, *Journal of Solid State Electrochemistry* 6(2) (2002) 73-84.
- [71] D. Tallman, M. Dewald, C. Vang, G. Wallace, G. Bierwagen, Electrodeposition of conducting polymers on active metals by electron transfer mediation, *Current Applied Physics* 4(2-4) (2004) 137-140.
- [72] D.M. Lenz, M. Delamar, C.A. Ferreira, Improvement of the anticorrosion properties of polypyrrole by zinc phosphate pigment incorporation, *Progress in Organic Coatings* 58(1) (2007) 64-69.
- [73] D.M. Lenz, M. Delamar, C.A. Ferreira, Application of polypyrrole/TiO₂ composite films as corrosion protection of mild steel, *Journal of Electroanalytical Chemistry* 540 (2003) 35-44.
- [74] T. Schauer, A. Joos, L. Dulog, C. Eisenbach, Protection of iron against corrosion with polyaniline primers, *Progress in Organic Coatings* 33(1) (1998) 20-27.
- [75] O. Zubillaga, F. Cano, I. Azkarate, I. Molchan, G. Thompson, A. Cabral, P. Morais, Corrosion performance of anodic films containing polyaniline and TiO₂ nanoparticles on AA3105 aluminium alloy, *Surface and Coatings Technology* 202(24) (2008) 5936-5942.
- [76] K. Thompson, Los Alamos National Laboratory Report LA-UR-92-360; DA Wroblecki, BC Benicewicz, KG. Thompson, and CJ Bryan, *Polymer Preprints* 35 (1994) 265.
- [77] S.P. Sitaram, J.O. Stoffer, T.J. O'Keefe, Application of conducting polymers in corrosion protection, *Journal of Coatings Technology* 69(866) (1997) 65-69.
- [78] A.J. Heeger, *Semiconducting and Metallic Polymers: The Fourth Generation of Polymeric Materials*, *Journal of Physical Chemistry B* 105(36) (2001) 8475-8491.
- [79] M. Qiang, T. Chen, R.-p. Yao, Effect of Preparation Condition of Polyaniline/Monmorillonite Nanocomposite Material on the Anticorrosion Property, *MATERIALS PROTECTION-WUHAN-* 36(7) (2003) 25-27.
- [80] B. Wessling, Dispersion as the link between basic research and commercial applications of conductive polymers (polyaniline), *Synthetic Metals* 93(2) (1998) 143-154.
- [81] O.L. Gribkova, A.A. Nekrasov, V.A. Cabanova, T.V. Krivenko, N.V. Nekrasova, S.A. Yakovlev, E.I. Terukov, A.R. Tameev, Water-processable nanocomposite based on polyaniline and 2D molybdenum disulfide for NIR-transparent ambipolar transport layers, *Chemical Papers* 72(7) (2018) 1741-1752.
- [82] N.N. Taheri, B. Ramezanzadeh, M. Mahdavian, Application of layer-by-layer assembled graphene oxide nanosheets/polyaniline/zinc cations for construction of an effective epoxy coating anti-corrosion system, *Journal of Alloys and Compounds* 800 (2019) 532-549.
- [83] B. Ramezanzadeh, G. Bahlakeh, M. Ramezanzadeh, Polyaniline-cerium oxide (PANI-CeO₂) coated graphene oxide for enhancement of epoxy coating corrosion protection performance on mild steel, *Corrosion Science* 137 (2018) 111-126.
- [84] A. Baldissera, M. Silveira, C. Beraldo, N. Tocchetto, C. Ferreira, Evaluation of the expandable graphite/polyaniline combination in intumescent coatings, *Synthetic Metals* 256 (2019) 116141.
- [85] M.J. Mazumder, L. Goni, S. Ali, M. Nazal, Inhibition of mild steel corrosion in hydrochloric acid medium by polymeric inhibitors containing residues of essential amino acid methionine, *Iranian Polymer Journal* 27(12) (2018) 979-995.
- [86] B. Wessling, From conductive polymers to organic metals, *Chemical innovation* 31(1) (2001) 34-40.
- [87] J. Stenger-Smith, A general review of intrinsically conducting polymers as coatings for corrosion protection, *Proc. US Navy & Industry Corrosion Technology Information Exchange*, Louisville, KY (2000).
- [88] S. Sathiyarayanan, S.S. Azim, G. Venkatachari, A new corrosion protection coating with polyaniline-TiO₂ composite for steel, *Electrochimica Acta* 52(5) (2007) 2068-2074.
- [89] S. Radhakrishnan, C.R. Siju, D. Mahanta, S. Patil, G. Madras, Conducting polyaniline-nano-TiO₂ composites for smart corrosion resistant coatings, *Electrochimica Acta* 54(4) (2009) 1249-1254.
- [90] R.C. Patil, S. Radhakrishnan, Conducting polymer based hybrid nano-composites for enhanced corrosion protective coatings, *Progress in Organic Coatings* 57(4) (2006) 332-336.
- [91] M.G. Hosseini, M. Sabouri, T. Shahrabi, Corrosion protection of mild steel by polypyrrole phosphate composite coating, *Progress in Organic Coatings* 60(3) (2007) 178-185.
- [92] Y.J. Ren, C.L. Zeng, Effect of conducting composite polypyrrole/polyaniline coatings on the corrosion resistance of type 304 stainless steel for bipolar plates of proton-exchange membrane fuel cells, *Journal of Power Sources* 182(2) (2008) 524-530.
- [93] R.S. Jadhav, D.G. Hundiware, P.P. Mahulikar, Synthesis of nano polyaniline and poly-o-anisidine and applications in alkyd paint formulation to enhance the corrosion resistivity of mild steel, *Journal of coatings technology and research* 7(4) (2010) 449-454.
- [94] K.-C. Chang, M.-H. Hsu, H.-I. Lu, M.-C. Lai, P.-J. Liu, C.-H. Hsu, W.-F. Ji, T.-L. Chuang, Y. Wei, J.-M. Yeh, W.-R. Liu, Room-temperature cured hydrophobic epoxy/graphene composites as corrosion inhibitor for cold-rolled steel, *Carbon* 66 (2014) 144-153.
- [95] V.S. Sumi, S.R. Arunima, M.J. Deepa, M. Ameen Sha, A.H. Riyas, M.S. Meera, V.S. Saji, S.M.A. Shibli, PANI-Fe₂O₃ composite for enhancement of active life of alkyd resin coating for corrosion protection of steel, *Materials Chemistry and Physics* 247 (2020) 122881.
- [96] N. Jadhav, S. Kasisomayajula, V. Gelling, Polypyrrole/Metal oxides-based composites/nanocomposites for corrosion protection, *Frontiers in Materials* 7 (2020) 95.
- [97] M. Sun, Z. Ma, G. Zhu, Y. Zhang, Anticorrosive performance of polyaniline/waterborne epoxy/poly (methylhydrosiloxane) composite coatings, *Progress in Organic Coatings* 139 (2020) 105462.
- [98] M. Deyab, G. Mele, Stainless steel bipolar plate coated with polyaniline/Zn-Porphyrin composites coatings for proton exchange membrane fuel cell, *Scientific Reports* 10(1) (2020) 1-8.
- [99] R. Rajkumar, C. Vedhi, Study of the corrosion protection efficiency of polypyrrole/metal oxide nanocomposites as additives in anticorrosion coating, *Anti-Corrosion Methods and Materials* 67(3) (2020) 305-312.
- [100] Z. Chen, W. Yang, B. Xu, Y. Chen, M. Qian, X. Su, Z. Li, X. Yin, Y. Liu, Corrosion protection of carbon steels by electrochemically synthesized V-TiO₂/polypyrrole composite coatings in 0.1 M HCl solution, *Journal of Alloys and Compounds* 771 (2019) 857-868.
- [101] P. Kong, H. Feng, N. Chen, Y. Lu, S. Li, P. Wang, Polyaniline/chitosan as a corrosion inhibitor for mild steel in acidic medium, *RSC advances* 9(16) (2019) 9211-9217.
- [102] R. Babaei-Sati, J.B. Parsa, M. Vakili-Azghandi, Electrodeposition of polypyrrole/metal oxide nanocomposites for corrosion protection of mild steel—A comparative study, *Synthetic Metals* 247 (2019) 183-190.
- [103] A. El Jaouhari, A. Chennah, S.B. Jaddi, H.A. Ahsaine, Z. Anfar, Y.T. Alaoui, Y. Naciri, A. Benlhachemi, M. Bazzou, Electrodeposition of zinc phosphate-polypyrrole coatings for improved corrosion resistance of steel, *Surfaces and Interfaces* 15 (2019) 224-231.
- [104] X. Liu, P. Hou, X. Zhao, X. Ma, B. Hou, The polyaniline-modified TiO₂ composites in water-based epoxy coating for corrosion protection of Q235 steel, *Journal of Coatings Technology and Research* 16(1) (2019) 71-80.
- [105] H.M. Abd El-Lateef, M.M. Khalaf, Novel dispersed Ti2O3-SiO₂/polyaniline nanocomposites: in-situ polymerization, characterization and enforcement as a corrosion protective layer for carbon-steel in acidic chloride medium, *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 573 (2019) 95-111.
- [106] G. Contri, G. Barra, S. Ramoa, C. Merlini, L. Ecco, F. Souza, A. Spinelli, Epoxy coating based on montmorillonite-polypyrrole: Electrical properties and prospective application on corrosion protection of steel, *Progress in Organic Coatings* 114 (2018) 201-207.
- [107] N. Jadhav, T. Matsuda, V. Gelling, Mica/polypyrrole (doped) composite containing coatings for the corrosion protection of cold rolled steel, *Journal of Coatings Technology and Research* 15(2) (2018) 363-374.
- [108] A.A. Salem, B.N. Grgur, The influence of the polyaniline initial oxidation states on the corrosion of steel with composite coatings, *Progress in Organic Coatings* 119 (2018) 138-144.
- [109] L. Jiang, J.A. Syed, Y. Gao, H. Lu, X. Meng, Electrodeposition of Ni(OH)₂ reinforced polyaniline coating for corrosion protection of 304 stainless steel, *Applied Surface Science* 440 (2018) 1011-1021.
- [110] H. Arabzadeh, M. Shahidi, M.M. Foroughi, Electrodeposited polypyrrole coatings on mild steel: Modeling the EIS data with a new equivalent circuit and the influence of scan rate and cycle number on the corrosion protection, *Journal of Electroanalytical Chemistry* 807 (2017) 162-173.
- [111] M. Ladan, W.J. Basirun, S.N. Kazi, F.A. Rahman, Corrosion protection of AISI 1018 steel using Co-doped TiO₂/polypyrrole nanocomposites in 3.5% NaCl solution, *Materials Chemistry and Physics* 192 (2017) 361-373.
- [112] Q. Yan, C. Li, T. Huang, F. Yang, Electrochemical synthesis of polypyrrole-Al₂O₃ composite coating on 316 stainless steel for corrosion protection, *AIP Conference Proceedings*, AIP Publishing LLC, 2017, p. 030005.
- [113] Q. Yan, C. Li, Electrochemical synthesis of polypyrrole-SiO₂ composite coating on 316 stainless steel for corrosion protection, *Anti-Corrosion Methods*

and Materials 64(4) (2017) 452-460.

- [114] C. Qiu, D. Liu, K. Jin, L. Fang, G. Xie, J. Robertson, Electrochemical functionalization of 316 stainless steel with polyaniline-graphene oxide: Corrosion resistance study, *Materials Chemistry and Physics* 198 (2017) 90-98.
- [115] S. Lu, H. Yeh, T. Tian, W. Lee, Degradation of magnesium alloys in biological solutions and reduced phenotypic expression of endothelial cell grown on these alloys, 3rd Kuala Lumpur International Conference on Biomedical Engineering 2006, Springer, 2007, pp. 98-101.
- [116] C. Seal, K. Vince, M. Hodgson, Biodegradable surgical implants based on magnesium alloys—A review of current research, *IOP conference series: materials science and engineering*, IOP Publishing, 2009, p. 012011.
- [117] A.H. Shahbaz, M. Esmailian, R. NasrAzadani, K. Gavanji, The effect of MgF_2 addition on the mechanical properties of hydroxyapatite synthesized via powder metallurgy, *Journal of Composites and Compounds* 1(1) (2019) 18-24.
- [118] F. Sharifianjazi, M. Moradi, A. Abouchenari, A.H. Pakseresht, A. Esmailkhanian, M. Shokouhimehr, M. Shahedi Asl, Effects of Sr and Mg dopants on biological and mechanical properties of SiO_2 -CaO- P_2O_5 bioactive glass, *Ceramics International* 46(14) (2020) 22674-22682.
- [119] M. Rahmati, K. Raieisi, M.R. Toroghinejad, A. Hakimzad, M. Santamaria, Effect of pulse current mode on microstructure, composition and corrosion performance of the coatings produced by plasma electrolytic oxidation on AZ31 Mg alloy, *Coatings* 9(10) (2019) 688.
- [120] M. Rahmati, K. Raieisi, M.R. Toroghinejad, A. Hakimzad, M. Santamaria, The multi-effects of K_2TiF_6 additive on the properties of PEO coatings on AZ31 Mg alloy, *Surface and Coatings Technology* 402 (2020) 126296.
- [121] X.-N. Gu, Y.-F. Zheng, A review on magnesium alloys as biodegradable materials, *Frontiers of Materials Science in China* 4(2) (2010) 111-115.
- [122] S. Sathiyarayanan, S.S. Azim, G. Venkatachari, Corrosion protection of magnesium ZM 21 alloy with polyaniline-TiO₂ composite containing coatings, *Progress in Organic Coatings* 59(4) (2007) 291-296.
- [123] Y. Guo, S. Jia, L. Qiao, Y. Su, R. Gu, G. Li, J. Lian, A multifunctional polypyrrole/zinc oxide composite coating on biodegradable magnesium alloys for orthopedic implants, *Colloids Surf B Biointerfaces* 194 (2020) 111186.
- [124] Y. Wang, The Electrochemical Corrosion Properties of PANI/Coal Composites on Magnesium Alloys, *International Journal of Electrochemical Science* (2017) 4044-4055.
- [125] J. Li, Y. He, Y. Sun, X. Zhang, W. Shi, D. Ge, Synthesis of Polypyrrole/V2O5 Composite Film on the Surface of Magnesium Using a Mild Vapor Phase Polymerization (VPP) Method for Corrosion Resistance, *Coatings* 10(4) (2020).
- [126] A.S. Najibzad, R. Amini, M. Rostami, P. Kardar, M. Fedel, Active corrosion performance of magnesium by silane coatings reinforced with polyaniline/praseodymium, *Progress in Organic Coatings* 140 (2020) 105504.
- [127] V. Jothi, A.Y. Adesina, A.M. Kumar, M.M. Rahman, J.S.N. Ram, Enhancing the biodegradability and surface protective performance of AZ31 Mg alloy using polypyrrole/gelatin composite coatings with anodized Mg surface, *Surface and Coatings Technology* 381 (2020) 125139.
- [128] A. Samadi, R. Amini, M. Rostami, P. Kardar, M. Fedel, Preparation of polyaniline-modified praseodymium nanofibers as a novel eco-friendly corrosion inhibitor to protect AZ31 magnesium alloy, *Pigment & Resin Technology* 50(1) (2020) 58-65.
- [129] R. Maurya, A.R. Siddiqui, P.K. Katiyar, K. Balani, Mechanical, tribological and anti-corrosive properties of polyaniline/graphene coated Mg-9Li-7Al-1Sn and Mg-9Li-5Al-3Sn-1Zn alloys, *Journal of Materials Science & Technology* 35(8) (2019) 1767-1778.
- [130] Y. Li, J. Li, X. Gao, S. Qi, J. Ma, J. Zhu, Synthesis of stabilized dispersion covalently-jointed $SiO_2@$ polyaniline with core-shell structure and anticorrosion performance of its hydrophobic coating for Mg-Li alloy, *Applied Surface Science* 462 (2018) 362-372.
- [131] X. Gao, X. Jing, Y. Li, J. Zhu, M. Zhang, Synthesis and characterization of phosphorized polyaniline doped with phytic acid and its anticorrosion properties for Mg-Li alloy, *Journal of Macromolecular Science, Part A* 55(1) (2018) 24-35.
- [132] M. Saremi, S.H. Mortazavi, Effect of polypyrrole coating modified by sodium fluoride and polyethylene glycol on corrosion behaviour of AZ31 magnesium alloy, *Micro & Nano Letters* 11(12) (2016) 866-869.
- [133] X. Chen, K. Shen, J. Zhang, Preparation and anticorrosion properties of polyaniline-SiO₂-containing coating on Mg-Li alloy, *Pigment & Resin Technology* 39(6) (2010) 322-326.
- [134] M. Hosseini, M. Jafari, R. Najjar, Effect of polyaniline-montmorillonite nanocomposite powders addition on corrosion performance of epoxy coatings on Al 5000, *Surface and Coatings Technology* 206(2-3) (2011) 280-286.
- [135] M. Ghafaripoor, K. Raieisi, M. Santamaria, A. Hakimzad, The corrosion and tribocorrosion resistance of PEO composite coatings containing $\alpha-Al_2O_3$ particles on 7075 Al alloy, *Surface and Coatings Technology* 349 (2018) 470-479.
- [136] I. Tajzad, E. Ghasali, Production methods of CNT-reinforced Al matrix composites: a review, *Journal of Composites and Compounds* 2(1) (2020) 1-9.
- [137] S. Nasibi, K. Alimohammadi, L. Bazli, S. Eskandarinezhad, A. Mohammadi, N. Sheysi, TZNT alloy for surgical implant applications: A systematic review, *Journal of Composites and Compounds* 2(3) (2020) 62-68.
- [138] K. Kamaraj, S. Sathiyarayanan, G. Venkatachari, Electropolymerised polyaniline films on AA 7075 alloy and its corrosion protection performance, *Progress in Organic Coatings* 64(1) (2009) 67-73.
- [139] E. Akbari, F. Di Franco, P. Ceraolo, K. Raieisi, M. Santamaria, A. Hakimzad, Electrochemically-induced TiO₂ incorporation for enhancing corrosion and tribocorrosion resistance of PEO coating on 7075 Al alloy, *Corrosion Science* 143 (2018) 314-328.
- [140] K. Zhang, H.W. Jang, Q. Van Le, Production methods of ceramic-reinforced Al-Li matrix composites: A review, *Journal of Composites and Compounds* 2(3) (2020) 77-84.
- [141] E. Asadi, A.F. Chimeh, S. Hosseini, S. Rahimi, B. Sarkhosh, L. Bazli, R. Bashiri, A.H.V. Tahmorsati, A review of clinical applications of graphene quantum dot-based composites, *Journal of Composites and Compounds* 1(1) (2019) 36-47.
- [142] M. Yan, C.A. Vetter, V.J. Gelling, Corrosion inhibition performance of polypyrrole Al flake composite coatings for Al alloys, *Corrosion Science* 70 (2013) 37-45.
- [143] M.A. Hussein, S.S. Al-Juaid, B.M. Abu-Zied, A.-E.A. Hermas, Electrodeposition and corrosion protection performance of polypyrrole composites on aluminum, *International Journal of Electrochemical Science* 11 (2016) 3938-3951.
- [144] M. Hosseini, L. Fotouhi, A. Ehsani, M. Naseri, Enhancement of corrosion resistance of polypyrrole using metal oxide nanoparticles: Potentiodynamic and electrochemical impedance spectroscopy study, *J Colloid Interface Sci* 505 (2017) 213-219.
- [145] K. Shah, Y. Zhu, G.S. Akundy, J.O. Iroh, O. Popoola, Corrosion and Bonding Behaviors of Intrinsically Conductive Polymers on Aluminum (Al 2024-T3), *Key Engineering Materials* 197 (2001) 111-120.
- [146] V. Tomaev, K. Levin, T. Stoyanova, A. Syrkov, Synthesis and Study of a Polypyrrole-Aluminum Oxide Nanocomposite Film on an Aluminum Surface, *Glass Physics and Chemistry* 45(4) (2019) 291-297.
- [147] A.M. Kumar, R.S. Babu, S. Ramakrishna, A.L. de Barros, Electrochemical synthesis and surface protection of polypyrrole-CeO₂ nanocomposite coatings on AA2024 alloy, *Synthetic Metals* 234 (2017) 18-28.
- [148] M. Ates, E. Topkaya, Nanocomposite film formations of polyaniline via TiO₂, Ag, and Zn, and their corrosion protection properties, *Progress in Organic Coatings* 82 (2015) 33-40.
- [149] M. Ates, O. Kalender, E. Topkaya, L. Kamer, Polyaniline and polypyrrole/TiO₂ nanocomposite coatings on Al1050: electrosynthesis, characterization and their corrosion protection ability in saltwater media, *Iranian Polymer Journal* 24(7) (2015) 607-619.
- [150] F. Alvi, N. Aslam, S.F. Shaukat, Corrosion inhibition study of zinc oxide-polyaniline nanocomposite for aluminum and steel, *American Journal of Applied Chemistry* 3(2) (2015) 57-64.
- [151] M.B. Jensen, M.J. Peterson, N. Jadhav, V.J. Gelling, SECM investigation of corrosion inhibition by tungstate- and vanadate-doped polypyrrole/aluminum flake composite coatings on AA2024-T3, *Progress in Organic Coatings* 77(12) (2014) 2116-2122.
- [152] G. Gupta, N. Birbilis, A.B. Cook, A.S. Khanna, Polyaniline-lignosulfonate/epoxy coating for corrosion protection of AA2024-T3, *Corrosion Science* 67 (2013) 256-267.
- [153] N. Jadhav, C.A. Vetter, V.J. Gelling, The effect of polymer morphology on the performance of a corrosion inhibiting polypyrrole/aluminum flake composite pigment, *Electrochimica acta* 102 (2013) 28-43.
- [154] M. Shabani-Nooshabadi, S.M. Ghoreishi, M. Behpour, Direct electrosynthesis of polyaniline-montmorillonite nanocomposite coatings on aluminum alloy 3004 and their corrosion protection performance, *Corrosion Science* 53(9) (2011) 3035-3042.
- [155] K.R. Castagno, V. Dalmoro, R.S. Mauler, D.S. Azambuja, Characterization and corrosion protection properties of polypyrrole/montmorillonite electropolymerized onto aluminium alloy 1100, *Journal of polymer research* 17(5) (2010) 647-655.
- [156] M. Hosseini, M. Raghbi-Boroujeni, I. Ahadzadeh, R. Najjar, M.S. Dorraji, Effect of polypyrrole-montmorillonite nanocomposites powder addition on corrosion performance of epoxy coatings on Al 5000, *Progress in organic coatings* 66(3) (2009) 321-327.
- [157] K. Wu, C. Chao, C. Liu, T. Chang, Characterization and corrosion resistance of organically modified silicate-NiZn ferrite/polyaniline hybrid coatings on alumi-

- num alloys, *Corrosion science* 49(7) (2007) 3001-3014.
- [158] D. Wroblewski, Corrosion resistant coatings from conducting polymers, Meeting of the Division of Polymer Chemistry, 1994, pp. 265-266.
- [159] A. Cascalheira, S. Aeiach, P. Lacaze, L. Abrantes, Electrochemical synthesis and redox behaviour of polypyrrole coatings on copper in salicylate aqueous solution, *Electrochimica acta* 48(17) (2003) 2523-2529.
- [160] Y. Meng, J. Yin, T. Jiao, J. Bai, L. Zhang, J. Su, S. Liu, Z. Bai, M. Cao, Q. Peng, Self-assembled copper/cobalt-containing polypyrrole hydrogels for highly efficient ORR electrocatalysts, *Journal of Molecular Liquids* 298 (2020) 112010.
- [161] W.N. Nyairo, Y.R. Eker, C. Kowenje, I. Akin, H. Bingol, A. Tor, D.M. Onger, Efficient adsorption of lead (II) and copper (II) from aqueous phase using oxidized multiwalled carbon nanotubes/polypyrrole composite, *Separation Science and Technology* 53(10) (2018) 1498-1510.
- [162] M. Menkuer, H. Ozkazanc, Electrodeposition of polypyrrole on copper surfaces in OXA-DBSA mix electrolyte and their corrosion behaviour, *Progress in Organic Coatings* 130 (2019) 149-157.
- [163] L.A. Cheah, G. Manohara, M.M. Maroto-Valer, S. Garcia, Layered Double Hydroxide (LDH)-Derived Mixed Metal Oxides (MMOs): A Systematic Crystal-Chemical Approach to Investigating the Chemical Composition and its Effect on High Temperature CO₂ capture, *ChemistrySelect* 5(19) (2020) 5587-5594.
- [164] A.J. Rad, Synthesis of copper oxide nanoparticles on activated carbon for pollutant removal in Tartrazine structure, *Journal of Composites and Compounds* 2(3) (2020) 99-104.
- [165] M. Arefian, M. Hojjati, I. Tajzad, A. Mokhtarzade, M. Mazhar, A. Jamavari, A review of Polyvinyl alcohol/Carboxy methyl cellulose (PVA/CMC) composites for various applications, *Journal of Composites and Compounds* 2(3) (2020) 69-76.
- [166] A. Abuchenari, M. Moradi, The Effect of Cu-substitution on the microstructure and magnetic properties of Fe-15% Ni alloy prepared by mechanical alloying, *Journal of Composites and Compounds* 1(1) (2019) 11-17.
- [167] A. Moghanian, A. Ghorbanoghli, M. Kazem-Rostami, A. Pzshouheshgar, E. Salari, M. Saghafi Yazdi, T. Alimardani, H. Jahani, F. Sharifian Jazi, M. Tahri, Novel antibacterial Cu/Mg-substituted 58S-bioglass: Synthesis, characterization and investigation of in vitro bioactivity, *International Journal of Applied Glass Science* (2019).
- [168] G. Kilinceker, B. Yazici, A. Yilmaz, M. Erbil, Effect of phosphate ions on electrochemical behaviour of copper in sulphate solutions, *British Corrosion Journal* 37(1) (2002) 23-30.
- [169] B. Tan, S. Zhang, Y. Qiang, L. Guo, L. Feng, C. Liao, Y. Xu, S. Chen, A combined experimental and theoretical study of the inhibition effect of three disulfide-based flavouring agents for copper corrosion in 0.5 M sulfuric acid, *Journal of colloid and interface science* 526 (2018) 268-280.
- [170] H. Alhumade, A. Abdala, A. Yu, A. Elkamel, L. Simon, Corrosion inhibition of copper in sodium chloride solution using polyetherimide/graphene composites, *The Canadian Journal of Chemical Engineering* 94(5) (2016) 896-904.
- [171] A. Asan, M. Kabasakaloglu, M. Işiklan, Z. Kılıç, Corrosion inhibition of brass in presence of terdentate ligands in chloride solution, *Corrosion Science* 47(6) (2005) 1534-1544.
- [172] B.M. Thethwayo, A.M. Garbers-Craig, Laboratory scale investigation into the corrosion of copper in a sulphur-containing environment, *Corrosion science* 53(10) (2011) 3068-3074.
- [173] J. Chen, Z. Qin, D. Shoosmith, Long-term corrosion of copper in a dilute anaerobic sulfide solution, *Electrochimica acta* 56(23) (2011) 7854-7861.
- [174] A.M. Fenelon, C.B. Breslin, The electrochemical synthesis of polypyrrole at a copper electrode: corrosion protection properties, *Electrochimica Acta* 47(28) (2002) 4467-4476.
- [175] T. Tüken, B. Yazıcı, M. Erbil, Polypyrrole/polythiophene coating for copper protection, *Progress in organic coatings* 53(1) (2005) 38-45.
- [176] A. Guenbour, A. Kacemi, A. Benbachir, Corrosion protection of copper by polyaminophenol films, *Progress in organic coatings* 39(2-4) (2000) 151-155.
- [177] M. Redondo, C.B. Breslin, Polypyrrole electrodeposited on copper from an aqueous phosphate solution: Corrosion protection properties, *Corrosion science* 49(4) (2007) 1765-1776.
- [178] W. Prissanaroon, N. Brack, P. Pigram, J. Liesegang, Electropolymerisation of pyrrole on copper in aqueous media, *Synthetic metals* 142(1-3) (2004) 25-34.
- [179] M. Bzzaoui, J. Martins, E. Bzzaoui, T. Reis, L. Martins, Pyrrole electropolymerization on copper and brass in a single-step process from aqueous solution, *Journal of applied electrochemistry* 34(8) (2004) 815-822.
- [180] L.M. Dos Santos, J. Lacroix, K. Chane-Ching, A. Adenier, L. Abrantes, P. Lacaze, Electrochemical synthesis of polypyrrole films on copper electrodes in acidic and neutral aqueous media, *Journal of Electroanalytical Chemistry* 587(1) (2006) 67-78.
- [181] P. Herrasti, A. Del Rio, J. Recio, Electrodeposition of homogeneous and adherent polypyrrole on copper for corrosion protection, *Electrochimica acta* 52(23) (2007) 6496-6501.
- [182] M.M. Gvozdenović, B.Z. Jugović, J.S. Stevanović, B. Grgur, T.L. Trišović, Z.S. Jugović, Electrochemical synthesis and corrosion behavior of polyaniline-benzoate coating on copper, *Synthetic Metals* 161(13-14) (2011) 1313-1318.
- [183] T.J. Pan, X.W. Zuo, T. Wang, J. Hu, Z.D. Chen, Y.J. Ren, Electrodeposited conductive polypyrrole/polyaniline composite film for the corrosion protection of copper bipolar plates in proton exchange membrane fuel cells, *Journal of Power Sources* 302 (2016) 180-188.
- [184] İ. Çakmakçı, B. Duran, G. Bereket, Influence of electrochemically prepared poly(pyrrole-co-N-methyl pyrrole) and poly(pyrrole)/poly(N-methyl pyrrole) composites on corrosion behavior of copper in acidic medium, *Progress in Organic Coatings* 76(1) (2013) 70-77.
- [185] F. Branzoi, V. Branzoi, Z. Pahom, Monolayer and bilayer conducting polymer coatings for corrosion protection of copper in 0.5 M H₂SO₄ solutions, *Rev. Roum. Chim* 58(1) (2013) 49-58.
- [186] B.P. Singh, B.K. Jena, S. Bhattacharjee, L. Besra, Development of oxidation and corrosion resistance hydrophobic graphene oxide-polymer composite coating on copper, *Surface and Coatings Technology* 232 (2013) 475-481.
- [187] H. Kim, H. Lee, H.-R. Lim, H.-B. Cho, Y.-H. Choa, Electrically conductive and anti-corrosive coating on copper foil assisted by polymer-nanocomposites embedded with graphene, *Applied Surface Science* 476 (2019) 123-127.
- [188] B.P. Singh, S. Nayak, K.K. Nanda, B.K. Jena, S. Bhattacharjee, L. Besra, The production of a corrosion resistant graphene reinforced composite coating on copper by electrophoretic deposition, *Carbon* 61 (2013) 47-56.
- [189] S. Wan, C.-H. Miao, R.-M. Wang, Z.-F. Zhang, Z.-H. Dong, Enhanced corrosion resistance of copper by synergetic effects of silica and BTA codoped in polypyrrole film, *Progress in Organic Coatings* 129 (2019) 187-198.
- [190] Y. Jafari, S. Ghoreishi, M. Shabani-Nooshabadi, Polyaniline/graphene nanocomposite coatings on copper: electropolymerization, characterization, and evaluation of corrosion protection performance, *Synthetic Metals* 217 (2016) 220-230.
- [191] M. Shabani-Nooshabadi, F. Karimian-Taheri, Electrosynthesis of a polyaniline/zeolite nanocomposite coating on copper in a three-step process and the effect of current density on its corrosion protection performance, *RSC advances* 5(117) (2015) 96601-96610.
- [192] A. Davoodi, S. Honarbakhsh, G.A. Farzi, Evaluation of corrosion resistance of polypyrrole/functionalized multi-walled carbon nanotubes composite coatings on 60Cu-40Zn brass alloy, *Progress in Organic Coatings* 88 (2015) 106-115.
- [193] S. Dhibar, S. Sahoo, C. Das, R. Singh, Investigations on copper chloride doped polyaniline composites as efficient electrode materials for supercapacitor applications, *Journal of Materials Science: Materials in Electronics* 24(2) (2013) 576-585.