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Review of electrodeposition perspectives towards anti-corrosion mitigation of mild steel

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Abstract
The study of corrosion is vital to reducing the overhead costs in the manufacturing industries. However, finding suitable application methods for prevention is a concern due to manufacturer specification and resource investment procedure. The coating is recognized as one of the foremost ways of applying resistance to corrosion damage. Electrodeposition is a unique technology because of its fine control of the chemical properties, mechanical strengthening behavior, and structural evolution over time. Thus, these overview studies discuss the possible protective coatings, corrosion as a major problem and its protection methods, electrodeposition process, and inherent characteristics. It intricacy of mild steel structural responses and its efficacy was also established.
Keywords: Electrodeposition, coating, anticorrosion, corrosion

1 Introduction

Metallic coatings can become susceptible to wear, corrosive attacks and surface disintegration. This largely is dependent on the method of application and furthermore due to the various process parameters and conditions for coating. A prominent method of applying these coatings to a substrate is the electrodeposition method [1]. Electrodeposition is the process whereby a coating is applied to the surface of a metal in order to bring about a change in its properties [2]. Electrodeposition specifically describes the process of using the principles of electrolysis to effect a deposition of some coating material on a metal's surface. This process is carried out by an electric current acting on a conductive material submerged within a solution which itself contains a salt of the metallic coating being deposited [3]. Electrodeposition, and by extension, metallic coating is carried out in order to modify the properties of a metal at the surface, thereby obtaining a particular value. These properties could be hardness, conductivity, wear resistance, ductility, failure stress, strength, corrosion rate, and sometimes simply aesthetics [3, 4].

The process of electrodeposition is markedly slow, requiring a significant amount of time to complete. A study into electrodeposition could require several months and large quantities of prerequisite materials to complete due to the need to iterate on and optimize the process. This has hindered both the progress of electrodeposition research and the attempts at improvement of the electrodeposition process and resultant coating effectiveness [4]. The use of zinc for the purpose of coating mild steel, known as zinc plating, is a relatively common method to protect steel and other iron alloys. This is due to the properties zinc possesses such as its natural ability to resist corrosive effects. Almost a third of all zinc processed is utilized on the protection of metals through coatings [5-7].

2 Corrosion as Major Problem and Its Protection Methods

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Corrosion is defined by [5] as the degradation of a metal resulting from a reaction with its environment and specifically corrosive agents therein. A multifaceted process, corrosion can take several forms depending on environmental factors such as morphology, topology, temperature, humidity level, and so on, as well as affect more than metals alone, thereby affecting composite materials amongst others. [6] posited that corrosion cuts across several industries worldwide, causing damages to systems and machinery such as offshore rig equipment, industrial piping, and chemical plant machinery to name a few cases. Corrosion losses come in several forms including increased overhead costs due to repairs, an increased health risk, significant material wastage, and reduced productivity [7]

Chemicals or particulates added in relatively small quantities in order to prevent, retard, or otherwise minimize the corrosion and corrosion process are known as corrosion inhibitors [8]. The use of corrosion inhibitors is a relatively cheap method of corrosion protection as corrosion control can be achieved with the use of common metals and materials as bases for corrosion inhibitors. These materials could also serve multiple purposes besides corrosion protection such as increasing structural integrity, improving aesthetics, and enhancing materials properties. According to [9] corrosion inhibitors can generally be classified thusly as Cathodic or Anodic, Inorganic and Organic (based on the chemical nature of the inhibitor), and Film-forming and non-film-forming (Mechanism of inhibitor action). [10] posited that corrosion inhibitors generally control corrosion through one of the following mechanisms:

- ❖ The formation of a protective inhibitory film on the surface of the metal as a result of the inhibitor being chemically adsorbed on said surface, or a combination between the inhibitor ions and the metallic surface.
- ❖ The formation of a protective inhibitory film through oxide protection of the base metal
- ❖ A reaction with any potentially corrosive components present in aqueous media, for the applicable cases

A prominent method of applying inhibitors to material surfaces, especially metallic, is the development of a coating or protective layer, as mentioned in the previous corrosion control mechanisms. These are layers applied to material surfaces in order to modify the properties of the material at its surface. [12] One of the more prominent methods of applying inhibitors, due to the intrinsic control afforded on the coating result. Protective coatings can generally be classified as:

2.1 Metallic coatings

Metallic coatings are meal-based coatings which are produced through the deposition of metals and metal –based composites. Usually produced though the use of electrodeposition, as metals has relatively high potential values which aid the electrodeposition process. Several metals are utilized when producing metallic coatings, however, the most prevalent according to literature have been Zinc, Aluminum, Nickel, Cadmium, and Chromium [11]. The listed materials are favored for application cases which have prerequisites of increased strength, high adhesive properties, and a good aesthetic surface finish. A significant aspect of metallic coatings, increasing their desirability and preference for use, is the impartation of increased corrosion resistance in the case of some specific metals. Methods usually applied when creating metallic coatings include hot-dipping and electrodeposition.

2.2 Inorganic Coatings

These coatings are composed primarily of materials such as composites, ceramics or glass which are produced through chemical processes which alter the surface of the metal into an oxide film or layer, increasing the corrosion resistive properties of the base metal. Because inorganic coatings are less dense, they can sometimes be applied over several layers or as the base layer before another deposit is developed on the same surface [7].

2.3 Organic Coatings

Organic coatings are usually paints, lacquers, or powders composed of bio-materials such as polymers, pigments and additives; acting as barriers to corrosion and environmental attack. These coatings have grown in prominence in recent times, due to their relatively low environmental pollution level and protective capabilities. Organic coatings slow down the diffusion of dangerous chemicals and corrosive media to a base material being protected; slowing down the diffusion of water, or oxygen primarily [13].

3 Electrodeposition process and its inherent characteristics

The process of electrodeposition, otherwise known as electro-kinetic deposition, electrocoating or electroplating, is a coating technique which involves the deposition of a metallic alloy, composite, or oxide film on the surface of a base metal utilizing the principles of electrolysis in order to modify the surface characteristics of that base metal [15]. The production of metallic coatings as a result of the effects of an electric current acting on a conductive material while immersed in a solution containing a salt of the metal being deposited The coating process achieved through electrodeposition occurs through several interacting, continuous stages which are described by [14] as follows:

- A power supply drives the flow of electrons into the cathode
- The negatively charged electrons are then attracted to the positively charged ions on the surface of the cathode and reduce the ions into a particulate that adheres to the cathodic surface.
- Simultaneously, the anode surface atoms give up an electron to the metal while simultaneously travelling into the electrolyte solution as a positively charged ion. This ion then proceeds to replace the ion used up at the cathodic surface.
- The closed circuit leads the electron released by the anode to the power supply.

The resulting thickness of the deposited layer is based on Faraday's law, the postulates of which govern relationship between the mass/weight of a material released during an electrolytic reaction and the quantity of electric charge being supplied to the cell per unit time.

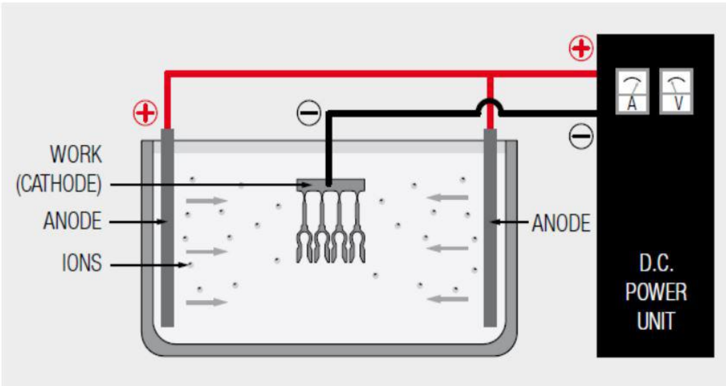

Figure 1: Electrodeposition Cell [11]

Electrodeposition is a widely used technique which has applications in several manufacturing ecosystems as the coatings developed can be at scales several microns thin up to layers multiple millimeters thick. The thickness of the resulting film can be varied by the control of the process conditions used in the synthesis process. This allows the morphology, texture, thickness or composition of the film coating to be controlled by the modification of experimental process parameters such as potential, current density, deposition time, and the makeup of the plating solution [3]. In recent times, the process of electrodeposition has been the subject of significant scientific research efforts, as it is a prominent technique for obtaining surface properties desirable for engineering applications. It is, however, only one of the many coating methods utilized in generalized surface finishing [11].

The conditions specified for electrodeposition, such as time of electrodeposition, current density, temperature of reaction, and bath composition, vary in value or degree between various metals due to the differences in intended application, desired property and structural composition of the metals. The deposit used to plate a metal is intended to imbue the substrate metal with desired mechanical, chemical, and physical properties, therefore each metal requires a specific electroplating procedure, capable of providing a homogenous deposit on the metal, without unintended material modification in as wide a range of environments as possible [2].

Electrodeposition possesses many unique process characteristics which serve as advantages when compared with other coating methods; some of which are: the relatively low cost associated with electrodeposition techniques, the wide range of material types which can be deposited on substrates, the fine control over the deposition process, and the avoidance of the material wastage associated with other techniques. The aforementioned properties unique to electrodeposition have made it stand out as a prominent method ubiquitous in its application within the industry [15].

The process of electrodeposition, as well as the microstructure of the resulting composite coating is determined by the interaction of several factors, primary of which are the electrolyte, current, and particle states, each defined by several further parameters. Some of the major effectors being current density, temperature of system, type of applied current, particle size, type of particle dispersion in the electrolyte, amongst others. However, the critical factor in determination of the validity of an intended electrodeposition reaction is the relative proximity of their electrode potentials, as it is widely accepted within literature that the standard electrode potential (the electromotive force between two electrodes in a cell measured in relation to a standard hydrogen electrode) of a metal is expressed relative to the equilibrium potential of these metals (the equilibrium potential being a measure of the difference between the potential of a metal in its pure state and its potential as an alloy) [16]

Table 1. Standard Electrode Potentials of Metals [17]

Metal	Reaction	Electrode Potential
Gold	$Au^{+} + e^{-} = Au$	+ 1.692
Silver	$Ag^{+} + e^{-} = Ag$	+ 0.7996
Copper	$Cu^{2+} + 2e^{-} = Cu$	+ 0.342
Iron	$Fe^{3+} + 3e^{-} = Fe$	-0.037
Lead	$Pb^{2+} + 2e^{-} = Pb$	-0.126
Nickel	$Ni^{2+} + 2e^{-} = Ni$	-0.257
Cadmium	$Cd^{2+} + 2e^{-} = Cd$	-0.403
Iron	$Fe^{2+} + 2e^{-} = Fe$	-0.447

Zinc	$Zn^{2+} + 2e^- = Zn$	-0.762
Aluminum	$Al^{3+} + 3e^- = Al$	-1.662

Mild steel structural responses and its efficacy

Mild steel has become one of the most widely-utilized forms of steel due to the combined effects of relatively low cost, ease with which it is shaped and machined, good material properties, and ubiquity in several industrial applications. By composition, Mild Steel contains anywhere between 0.05% carbon, such as used in sheet metal applications, and 0.30% carbon, such as used in structural plates [15]. Mild steel, however, is susceptible to corrosion attacks in several media, especially in applications whereby the material is used in outdoor environments. The material is also susceptible to rusting, as it contains significant levels of Iron. This has led to significant research effort with the primary aim of bringing about the improvement of the performance characteristics of mild steel within its various applications. The study of mild steel as relates to its carbon content is aided with the use of an iron-carbon equilibrium diagram, this being a representation of the various phases and structures of an iron-carbon alloy as described by specific temperature and composition values.

The equilibrium diagram proliferated in literature, however, is the iron-iron carbide diagram, a portion of the larger phase diagram for the Iron –Carbon alloy; the Iron-Carbide diagram is prominent due to its significance in engineering applications as many structural Iron-Carbon alloys are found within this region of the larger diagram [15]. The region of interest in this study focusing on mild steel is an area between the 0%wt Carbon and 1%wt Carbon, as well as between 0◦C and 1200◦C. Mild steel has properties unique to it which are based on the carbon content levels within the alloy, usually having the aforementioned levels of carbon along with small percentages of silica, Sulphur, phosphorous or manganese, lending the alloy an increased resistance to breakage. The carbon content levels of Mild steel impart increased hardness, strength and malleability properties to the material [18]. These properties are of great import as they are major factors which control the application area of the steel product. Mild steel, however, is especially susceptible to corrosion attacks in several media, especially in applications whereby the material is used in outdoor environments. The material is also susceptible to rusting, as it contains significant level of Iron; with a tendency to oxidize at relatively increased temperature; without the ability to absorb impact at significantly lower temperatures.

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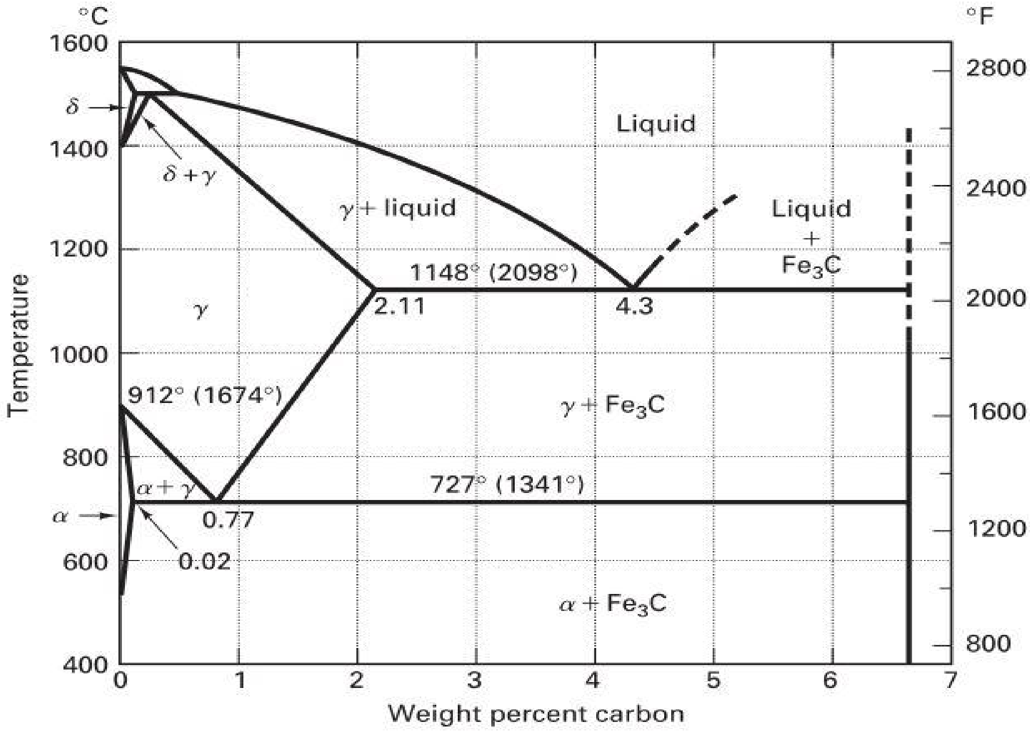

Figure 2. Iron-Carbide Equilibrium Diagram (Black & Kohser, 2010)

Metals are utilized extensively in industries worldwide. Metals are widely utilized as raw materials in several nations across the world. This is due to their various mechanical, electrical, thermal properties which make them viable for application in several structures [7]. They are prominent in the development and sustenance of the economy of almost every country, as metals have significant trade value with almost all nations engaging in global trade [19].

As such, research into prolonging the lifetime of use of metals is an important and widely-researched endeavor. Corrosion of metals has been a significant factor in recurring overhead costs in many industries [20]. Several methods are used to study and predict the effects of anti-corrosive coating methods on metallic materials, with varying effectiveness [7]. Numerical models are prominent in carrying out such studies due to their intrinsic level of control on the factors of a model, compared to other analytical methods of modelling. The mathematical model created for a study can be adjusted without any significant time or resource investment, allowing for rapid iteration and processing [4].

Conclusion

From above overview, it is established that anti-corrosive coating methods have varying effectiveness ratings, with some not sufficient enough to provide a lasting effect and thus require significant trial and error iterations in order to optimize. Deposition methods have great impact on the result and longevity of inhibitor coatings. However, deposition methods are difficult to optimize due to the time and energy involved in testing.

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