

Corrosion Protection of Aluminum/ Aluminum Alloys using Polymeric Composite Coatings and Techniques: A Review

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Abstract

Corrosion of aluminum and its alloys presents a significant challenge across various industries due to its widespread use in critical applications. This review provides a comprehensive overview of the corrosion mechanisms affecting aluminum and its alloys, along with an analysis of coating materials and techniques for corrosion prevention. The paper begins with an introduction to aluminum and its alloys and various forms of corrosion, including pitting, crevice, intergranular, galvanic, stress corrosion cracking, and atmospheric corrosion. Subsequently, it delves into the importance of corrosion prevention strategies and the limitations of coating techniques. The review then examines the latest advancements in coating materials. Special emphasis is placed on the role of various researchers in corrosion control and enhancing corrosion resistance of different grades of aluminum alloys. The review concludes with the challenges and future directions in corrosion prevention for aluminum and its alloys, emphasizing the need for interdisciplinary research and collaboration to develop effective and sustainable coating solutions.

Keywords: Aluminium alloys, polymer matrix, fillers, composite coatings, electrochemical impedance spectroscopy, potentiodynamic polarization, corrosion resistance, corrosive environments

1. Introduction

Corrosion of aluminum alloys is a longstanding and pervasive challenge in numerous industrial applications, and it remains a subject of continual concern [1, 2]. The detrimental effects of corrosion on aluminum alloys, ranging from structural degradation to economic losses and safety hazards, necessitate the development of effective corrosion protection strategies [3, 4]. One approach that has gained considerable attention and significance is the application of polymer-based composite coatings, which offer a protective barrier against corrosive environments [5, 6]. Within this context, this review serves as a critical exploration of the existing body of knowledge. Polymeric composite coatings have emerged as a promising solution for the corrosion protection of aluminum alloys due to their excellent adhesion properties, chemical resistance, and mechanical strength [7-9]. Coatings form a protective layer that acts as a physical barrier, preventing the interaction between the metal substrate and the corrosive elements in the environment [10-12]. The application of polymeric composite coatings can significantly enhance the lifespan and performance of aluminum alloys in corrosive conditions [13, 14]. In recent years, research efforts have focused on improving the efficacy of polymeric coatings through the incorporation of fillers, which are microparticles or nanoparticles dispersed within the polymer matrix. Fillers have the potential to augment the protective properties of polymeric coatings, thereby enhancing their resistance to corrosion [15-17].

In addition to an analysis of cutting-edge coating materials and corrosion control strategies, this paper offers a thorough understanding of the corrosion mechanisms that influence aluminium and its alloys. The first section of the paper provides an overview of aluminium, its alloys, and the different types of corrosion that might occur, such as atmospheric, stress, cracking, intergranular, pitting, and galvanic. It then explores the limitations of coating techniques and the significance of corrosion prevention strategies. The role that different researchers play in controlling corrosion and improving the corrosion resistance of various grades of aluminium alloys is given particular attention.

2. Aluminum and its alloys

2.1 Aluminum Metal

Louis Guyton de Morveau (1736–1816), a chemist and co-worker of Antoine Laurent Lavoisier (1743–1794), used the word ‘alumine’ for one sulphate which is present in alum. ‘Alumine’ is derived from the word alumen, used for $KAl(SO_4)_2 \cdot 12H_2O$ (potassium alum) during the Roman period. Aluminum was used in huge magnitudes in dyestuff, traditional pottery, and medicine as an astringent [18]. The word “alumine” was not used to designate the ore of aluminum and the

word 'bauxite' was used. This name was assigned to a mining engineer Pierre Berthier (1782–1867), who revealed about the red soil of a place having the name Les-Baux-de-Provence that it consists of 40 to 50% alumina, and the rest is included principally of iron oxide and silica. Aluminum was not considered an industrial metal till the end of the 19th century though it was widely available in the earth's crust. The aluminum oxides i.e. alumina are the most stable ones and are very hard to reduce [19]. The metallic aluminum was discovered by Humphrey Davy (1778–1829) and in 1809 he referred to use the word 'aluminum' [20].

2.2. Aluminum Advantageous Properties

Aluminum is a leading metal in the family of non-ferrous metals with consumption of twenty five million tons annually in the world. The aluminum production has been growing progressively since 1950. Applications of aluminum in various fields and its continuous rise in consumption could be accredited to its properties which devise decisive criteria for the selection of metals, particularly in the field areas of transportation, building structures, packaging, and electrical engineering[21, 22]. The attracting properties on which aluminum and its alloys become favorable to use in various engineering applications are their lightness, electrical conductivity, thermal conductivity, variety of aluminum alloys, suitability for surface treatments, corrosion resistance, easiness in recycling, ease with which aluminum can be formed and machined and operational advantages of extruded and cast products.

2.3 Aluminum Alloys and their Series

It is obvious that pure aluminum has very good corrosion resistance but it has poor ductility and strength. Therefore, other elements are added with pure aluminum to make an alloy to improve its mechanical properties and to fulfill the technical requirements of various applications. There are about fifteen alloying elements that are mixed with aluminum with a quantity of less than ten percent by weight in the alloy composition while both changing the characteristics of the pure aluminum metal [23]. Generally aluminum alloys are categorized in two sub-classes: Cast aluminum alloys: which are obtained from pouring of a molten material into a mold to give a desired shape. It is almost near net shape [24]. Wrought aluminum alloys: Further manufacturing work is required to get the final desired shape for these alloys [25]. Each class of aluminum alloys has its own designation system. The designation depends on the alloying elements used with pure aluminum. For cast aluminum alloys the designation system consists of 3 digit-plus decimal designation xxx.x. The first digit number shows the principal alloying element in cast aluminum alloy. The second and third digits are arbitrary numbers while after decimal digits

show either it is final casting (designated with 0) or ingot (designated with 1 or 2) [26]. There are nine series of cast aluminum alloys based on this designation system as shown in **Table 1**.

For wrought aluminum alloys, the designation of the Aluminum Association (AA) is based on a numeric four-digit number. The first digit of the numeric number indicates the principal alloying element in aluminum alloy. The second digit shows the modification to the particular alloy while the third and fourth digits are arbitrary numbers assigned to a particular alloy in a series. There are eight series of wrought aluminum alloys based on this designation system as shown in **Table 1**. [27]

Table 1 Aluminum alloys series designation system [27]

Cast Aluminum Alloy Series		Wrought Aluminum Alloy Series	
Alloy Series	Principal Alloying Element	Alloy Series	Principal Alloying Element
1xx.x	Minimum 99% Al	1xxx	Minimum 99 % Al
2xx.x	Cu	2xxx	Cu
3xx.x	Si +Cu / Mg	3xxx	Mn
4xx.x	Si	4xxx	Si
5xx.x	Mg	5xxx	Mg
6xx.x	Unused series	6xxx	Mg +Si
7xx.x	Zn	7xxx	Zn
8xx.x	Sn	8xxx	Other elements
9xx.x	Other elements		

2.4 The 6xxx and 7xxx series

The **6xxx series** of wrought aluminum alloys is known for its excellent combination of strength, weldability, and corrosion resistance. These alloys are primarily used in structural applications

and for components where high strength and lightweight properties are essential. The primary alloying element in this series is magnesium, and silicon is also a common addition. The most common alloy in the 6xxx series is 6061, but there are other variations as well. AA6061 is the most widely used alloy in the 6xxx series. It's often referred to as an architectural alloy due to its excellent combination of strength, weldability, and corrosion resistance. 6061 contains approximately 1.0% magnesium, 0.6% silicon, and is available in various tempers (T4, T6, etc.). It's used in a wide range of applications, including aerospace components, automotive parts, and structural components. AA6063 has a slightly lower magnesium content than 6061 but contains around 0.45% silicon. It is well-known for its excellent extrudability, making it the preferred choice for extruded profiles and shapes used in architectural and structural applications. AA6101 is similar to 6061 but with a higher electrical conductivity. It's used in electrical conductors, especially for bus bars and high-voltage power lines. AA6005 has properties similar to 6061 but with improved extrudability, making it suitable for applications requiring complex shapes. AA6056 is known for its high strength and good corrosion resistance, making it suitable for aerospace and other high-performance applications. AA6082 is similar to 6061, 6082 offers a good balance of strength, corrosion resistance, and weldability. It's commonly used in transportation and structural applications. AA6111 is primarily used for automotive body sheet panels due to its excellent formability and high strength [28]. The 6xxx series alloys can be heat-treated to achieve different temper conditions, which can further modify their properties, such as T4, T6, T651, etc. These heat treatments can increase strength and hardness, improve formability, and enhance other properties as needed for specific applications. The **7xxx series** of wrought aluminum alloys is known for its exceptional strength and high-performance properties [25]. These alloys are primarily used in aerospace and military applications where high strength, toughness, and stress corrosion resistance are critical. The primary alloying element in this series is zinc, and they also contain small amounts of copper, magnesium, and other elements. AA7075 is one of the most well-known and widely used alloys in the 7xxx series. It is admired for its high strength-to-weight ratio and excellent fatigue resistance. The composition typically includes around 5.6% zinc, 2.5% magnesium, 1.6% copper, and small amounts of chromium and other elements. 7075 is often used in aircraft, marine and aerospace components, as well as in high-performance applications where strength and durability are essential. AA7050 is similar to 7075 in terms of strength and toughness but with slightly better corrosion resistance. It contains approximately 6.1% zinc, 2.1% magnesium, 2.0% copper, and smaller amounts of other elements. This alloy is also used in aerospace applications, particularly for aircraft structural

components. AA7175 is similar to 7075 but with improved fracture toughness. It is often used in high-performance military aircraft and aerospace applications where toughness and strength are both important. AA7475 is an even stronger variant within the 7xxx series, mainly used in aerospace applications, including structural components in spacecraft and missiles. AA7020 is known for its excellent fatigue resistance, making it suitable for aerospace and military applications. The 7xxx series alloys can be heat-treated to achieve various temper conditions (e.g., T6, T73, T7351), which can further modify their properties, such as strength and toughness. These alloys are known for their ability to maintain their strength at elevated temperatures, which is important in aerospace applications. The 7xxx series are divided into two sub-groups: aluminum alloys without and with the addition of copper. One of the most widely used aluminum alloys of the 7xxx series without copper is 7020 alloy. This alloy is rolled and extruded to make system components used in various applications. The areas in which this alloy is commonly used are transport, armaments, and other similar fields. In the artificially aged and quenched condition, T5 or T6, the mechanical strength is in the range of 360-400MPa. Moreover, it has satisfactory corrosion resistance, unless welding is performed. If the alloy is exposed to temperatures above 200 °C, exfoliation corrosion occurs. By the addition of copper in the 7xxx series, it produces alloys having excellent mechanical properties in the T6 temper. Further by duplex aging of T73 and T76 tempers the alloys are obtained having better corrosion resistance in highly corrosive and stress environments, however, it causes about a 20 % reduction in mechanical strength. In this subgroup 7075 alloy is the most widely used in the manufacturing of various products prepared by extrusion, rolling, hand forging, and die-forging processes. It has excellent mechanical properties but is susceptible to corrosion in humid and aggressive atmospheres. Due to their best mechanical properties, they are mostly used in the areas of aerospace, sports items, the mechanics industry, and other universal applications [27].

3. Corrosion of metals and alloys

Corrosion is spontaneous damage of metallic materials caused by biochemical, electro-chemical, and chemical interaction between metallic materials and the environment. The environments that include moisture, oxygen, organic or organic acids, chlorides, and high temperatures accelerate the corrosion rate. As a result of corrosion, the metals tend to change to more thermodynamically stable states such as carbonates, hydroxides, and oxides. Due to spontaneous corrosion metals and alloys are recovered to their original state in the form of ores and minerals. The free energy of the metallic materials decreases as a result of the corrosion phenomenon[29, 30].

3.1 Financial Impact of Corrosion

The phenomenon of corrosion is very slow and unprompted. There are various factors influencing the corrosion rate (CR). The parameters that effect the corrosion rate are composition, environment, and chemical, electrochemical, and metallurgical properties of the metal or alloy. It is a time-consuming process to estimate the corrosion extent, so it is often ignored in many applications i.e.; structural components of the system and industrial appliances. Due to corrosion the structural integrity of the material is compromised and is a principal cause in the disastrous failure in aerospace components, bridges and the machinery used in construction, transportation, petrochemical, chemical, and marine sectors. There is huge financial impact of corrosion while estimating maintenance and production costs in any type of industry. A study was carried out recently on the direct corrosion cost in the United States and it was estimated around 276 billion dollars. The financial budget is provided by the government and borne by respective industries and jointly it is 3.2% of GDP. The cost of replacing the corroded system components and labor costs are both considered direct corrosion costs. Corrosion indirect costs consist of billions of dollars. Some indirect costs are due to: product contamination, component loss, shutdown, over design of system structure by using highly expensive materials[31].

3.2 Forms of metallic corrosion

Most often corrosion of metals and alloys occurs in an aqueous environment either acidic or basic. Various types of corrosion are responsible for material degradation and affect the structural integrity of the material in such conditions. In this section, the following types will be explored shown in **Figure 1**.

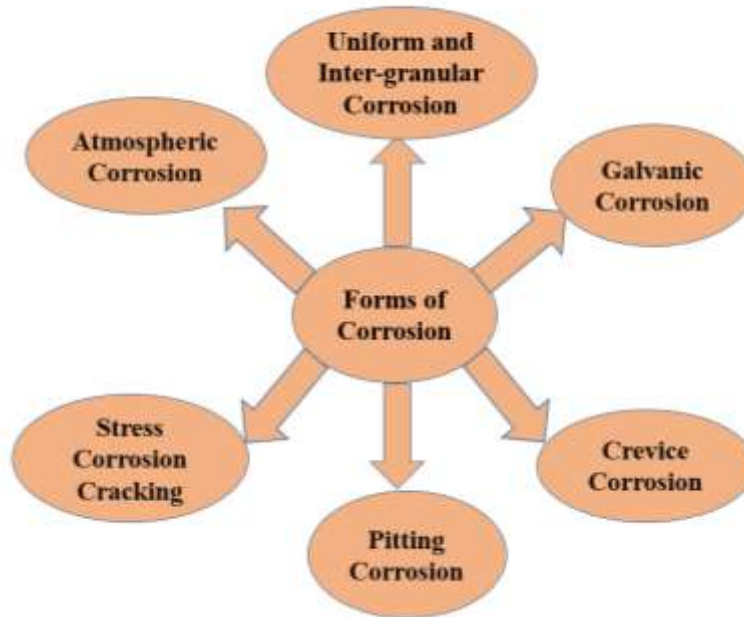


Figure 1 Various forms of corrosion

3.2.1. Galvanic Corrosion

The difference in electric potential of two dissimilar metals in contact with a conducting media generates flow of electrons. There is a preference of corrosion among the metals. Mostly it is observed that metals having greater negative potential are corroded first. The metals having greater positive potential act as cathodes, which are protected from corrosion by the metals having greater negative electric potential and act as anode material. In this type of corrosion the driving force is electric potential difference and therefore it is known as galvanic corrosion. There are various examples of galvanic corrosion in practical applications i.e.; copper plate or pipe with solder, aluminum sheet having steel fasteners and galvanized steel connected with stainless steel. Galvanic corrosion occurs in the same metal if the metal comes in contact with an environment having different concentration levels as well. For example soil with changing salinity percent, pH, and other specific physical properties, if comes in contact with an iron-buried pipe, it makes an electrochemical cell and galvanic corrosion may occur [32]. The potentials for metals are shown in **Table 2**, representing the metals half-cell potentials w.r.t the reference standard hydrogen electrode (SHE) at 25 °C [33].

Table 2 Standard galvanic series for various metals [33]

Nature of Metal	Metal/ Metal-Ion Equilibrium	Electrode Potential (V) vs. SHE at 25 °C
Noble or Cathodic	Au ⁺³ / Au	1.50
	Pt ⁺² / Pt	1.20
	Cu ⁺² /Cu	0.34
	H ⁺ /H ₂	0.00
	Sn ⁺² / Sn	-0.14
Active or Anodic	Ni ⁺² / Ni	-0.25
	Cd ⁺² / Cd	-0.40
	Zn ⁺² / Zn	-0.76
	Al ⁺³ / Al	-1.66
	Mg ⁺² / Mg	-2.36

Under standard thermodynamic conditions the potentials of metals can be used to guess the corrosion trend of the metal when coming in contact with electrolyte. The values in **Table 2.2** are listed as a result of reduction reactions, while following the guidelines prescribed by the international union of pure and applied chemistry (IUPAC) in Stockholm convention, which was held in 1953. It is obvious that in an electrochemical cell, the electrode having lower standard potential will undergo oxidation and will transfer electron to the electrode having higher standard potential, while reducing at interface. The composition of the electrolyte and the variation in temperature can inverse corrosion trends. In galvanized steel there is Fe and Zn, Fe has standard electrode potential value of -0.440V while Zinc has standard electrode potential value of -0.763V. Therefore Fe is protected by Zn due to its more reactivity. Actually zinc metal is less corrosion resistant and will not be used a coating for barrier purpose. Zn can protect alloy (iron in steel) from corrosion due to its sacrificial nature and acts as an anodic metal while consuming itself. Magnesium, aluminum and zinc are used as sacrificial anodes in many applications [34]. Various metals and alloys corrosion potentials vs. saturated calomel electrode (SCE) are given in **Figure 2** and are influenced by electro-chemical kinetics such as current density and Tafel's

slopes [30, 35]. These corrosion potentials shown are thermodynamically uncontrolled. They are dependent on electro-chemical kinetic parameters of the anode and cathode reactions both [35]. The corrosion potentials are different than the standard galvanic series potentials for various metals shown in **Table 1**. The corrosion potential is achieved by polarization of at least two half-cell reactions on corroding material surface. The boxes in **Figure 2** shows the highly reactivity for given active-passive alloys. The values tabulated in the emf/galvanic series are not used to predict corrosion behavior or rate of corrosion reliably. It only shows the corrosion tendency qualitatively and not quantitatively. Generally, the most active metal having higher negative corrosion potential will show greater corrosion rate, while the least active metal having higher positive corrosion potential will show lesser corrosion rate.

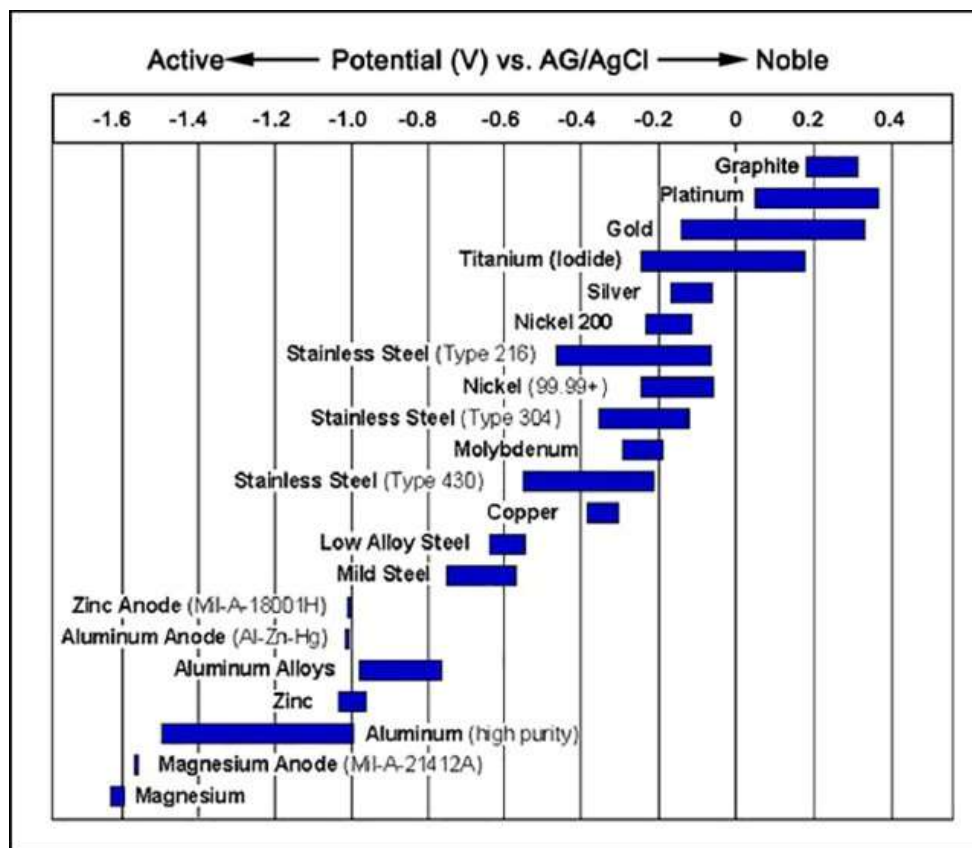


Figure 2 Galvanic series of metals in seawater [36]

3.2.2. Pitting Corrosion

Pitting is an extremely localized corrosion and is the most destructive form of corrosion. Corrosion pits are mostly in the form of holes and cavities that have the same or greater depth than their diameter at the surface of the material. The pits on the surface grow with a porous

layer or cover and are present as a white deposit with minimum loss of the base metal, due to which it is very tough to investigate. When the white deposit is removed as a result pits and small holes are generated. Usually, pits penetrate through the metal, while causing failure of the system components and disintegration of the material due to weight loss. The severity of pitting corrosion can be controlled by some influencing parameters i.e.; the acidity of the electrolyte, concentration of chlorides, corrosive environment, concentration of oxidizer, geometric features, temperature, , composition of metals or alloys, less dissolved concentrations of oxygen and the potential scan rate [30, 37-45]. Localized chemical or mechanical damage to passive oxide, non-uniformities in the metals or alloys structure due to the presence of impurities and inadequate inhibitor coverage lead to pitting corrosion on the surface of the material. Halogen ions are the most common hostile species. Among halogen ions chloride is the anion of very strong acid and is very much soluble with higher diffusivity. In the electrolyte chloride prevents the formation passive films on various metals and alloys containing iron, nickel, aluminum and stainless steel. The extent of surface pitting is proportional to the logarithmic chloride concentration present in the electrolyte [46-48]. The electrolyte should act as an oxidizer and must favor the passive state to start pitting corrosion. Ferric and cupric halides are oxidizing metals ions, which act as electron acceptors and do not need oxygen to start and promote pitting corrosion. Some other ions, like S_2O_3 causes pitting corrosion as well. Pitting corrosion may also starts by non-metallic insertions or second phase inter-metallics present in the microstructure of stainless steel [37]. MnS dissolution at the interface of MnS and matrix is the first step to form pit on the surface of stainless steel [49]. The electrolyte containing dissolved oxygen causes less stable protective film on the surface of stainless steel and in the existence of chloride ions, starts pitting corrosion.

3.2.2.1. Pitting corrosion mechanisms

There are three types of pitting corrosion mechanism which are reported in the literature and are responsible for the breakdown of the passivity of the material. They are penetration mechanism, film breaking mechanism and adsorption mechanism [50]. These mechanisms are explained below.

i. Penetration Mechanism

Hoar et al discussed this mechanism which is shown in **Figure 3**. In this mechanism the transference of anions occur from the material oxide film while coming to the surface of the metal to start their particular activity [51].

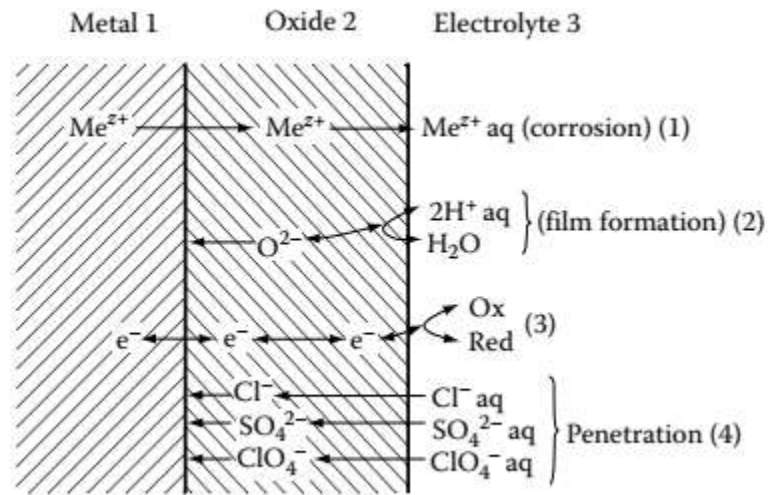


Figure 3 Penetration mechanism demonstrating the process leading to pit nucleation
Strehblow et al [50]

The high concentration of defect and the high electric field both present in a considerably disorder structure of the passive layer of oxide may well explain this transfer. Numerous researchers even assume the structure of oxide film as an amorphous [52].

The direct proof is provided by several X-ray Absorption Fine Structures (EXAFS) while using the technique of X-ray Absorption Spectroscopy (XAS). The three regions of XAS data are shown in **Figure 4**. Organized studies with this technique are still very difficult and missing. Moreover, it is unclear that the failure events occur locally for a high dis-ordered structure.

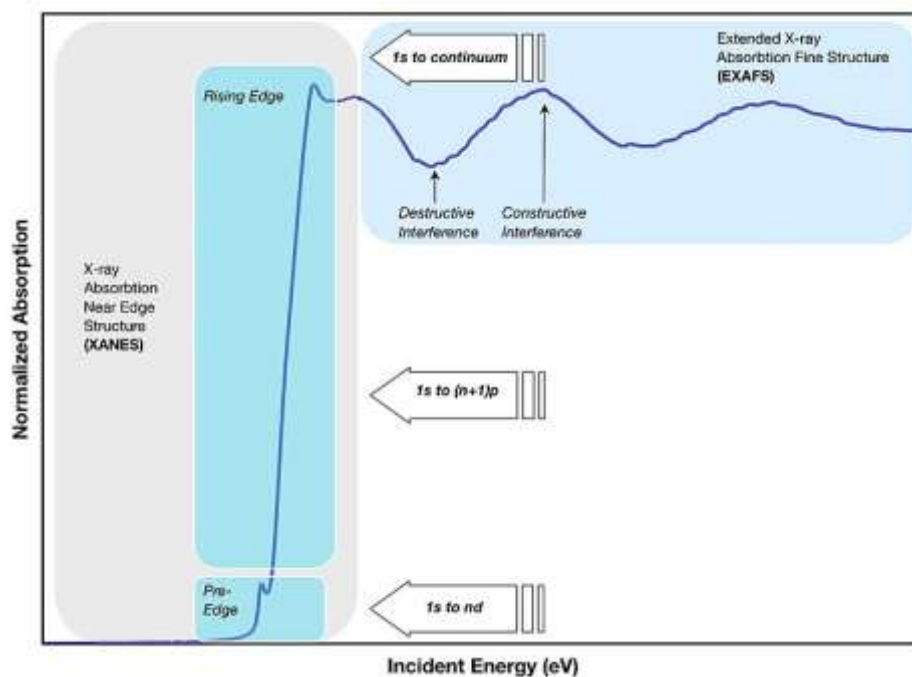


Figure 4 Three regions of XAS data [53]

The ideas given above were followed by Macdonald and his coworkers to develop the model of passivity and the breakdown due to the action of vacancies present in the passive or oxide layer. It is supposed that the vacancies are migrating through the electrolyte-oxide interface to the oxide-metal boundary and the transportation of cations is equivalent in the reverse direction. If the penetration of vacancies occurs at lower rate to the metal phase as compared to the transportation via oxide layer, then accumulation occurs at oxide-metal interface which may lead to a localized concentration finally. The resultant voids produced may also leads to produce stresses in the passive layer and will cause breakdown finally. It is very unfortunate that surface analytical characterization techniques give unclear response regarding the penetration of negatively charged ions (anions). Few researchers used Auger electron spectroscopy (AES), secondary ion-mass spectroscopy (SIMS) and XPS characterization techniques and found chloride ion in the layer [54], while other researchers were unable to find the chloride ion in the layer [45, 55-57]. The contrary results may be interpreted in terms of the sensitivity of the technique and sample preparation.

ii. Film-breaking mechanism

Strehblow, Sato et al and Vetter proposed this mechanism shown in **Figure 5**. In this mechanism film breaks are required to provide direct access to the anions in order to attack on the exposed surface of the metal [58, 59].

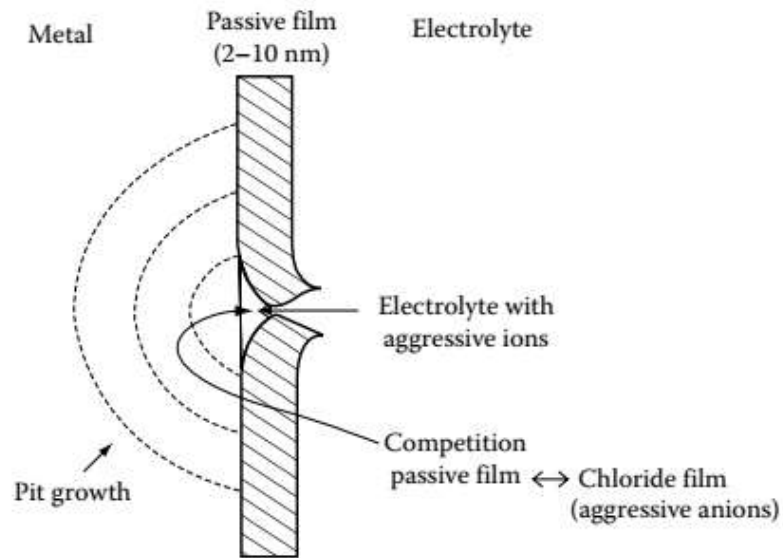


Figure 5 Film breaking mechanism and relevant competing actions Strehblow et al [50]

The presence of very small holes in the passive film is a possible reason for the observation made, particularly for a non-stationary state of the passive film. Stresses are developed with in the layer due to abrupt variation in the electrode potential even in the negative direction. Electrostriction and chemical change are realistic explanations to provide. Using XPS technique, when negative potential was applied to the electrodes while passivated at positive potential in the passive range, the reduction of iron (III) to iron (II) was observed [60]. Moreover the direct evidence of the film- break event is present there for the non-stationary situation in accordance with Fe-disk–Pt-ring electrode rotation. Not only the presence of aggressive anions but also an abrupt decrease in potential from 1.3V to 0.7V produce Fe^{+2} ions and are released to the electrolyte after few seconds [61].

iii. Adsorption Mechanism

Kolotyркиn, Hoar and Jacob first discussed the adsorption mechanism. In this mechanism the aggressive ions are adsorbed on the oxide surface while facilitating the transfer of metallic cations to the electrolyte from the oxide film. Due to this thinning of the passive film occurs to start the localized dissolution of the film on the surface [62, 63].

3.3. Crevice Corrosion

This corrosion type is a particular form of localized corrosion which takes place in physical occluded regions or in the constrained flow zones. The surface of the metal comes in contact with small volume of stagnant and restricted fluids particularly liquids and the remaining metal surface is exposed to bulky liquid environment. The possibilities for the creation of crevice zones are due to the geometry of the components, fabrication of mechanical assembly as shown in **Figure 6** and deposits formation during shutdown or in service. The deposits are generated from suspended particles in the liquid environment, biological activities, corrosion products and restricted flow regions.

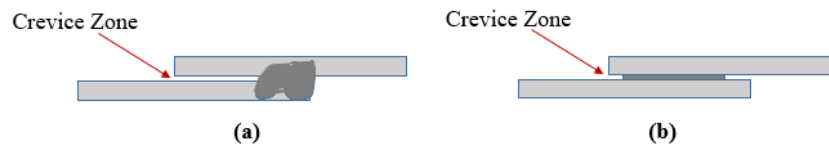


Figure 6 Crevice zones due to design (a) Overlapping weld (b) Gasket between flanges

The morphology of crevice corrosion is usually characterized by three regions shown in **Figure 7** and are un-attacked metal portion to the crevice mouth, the region of penetration at a deeper position and followed by the deepest metal region having less- attack suffering. In the figure L and h represent the crevice length and the crevice gap respectively. This specific morphology is termed as intermediate attack and its presence symbolizes significant means to recognize the contributions of various mechanisms of crevice corrosion.

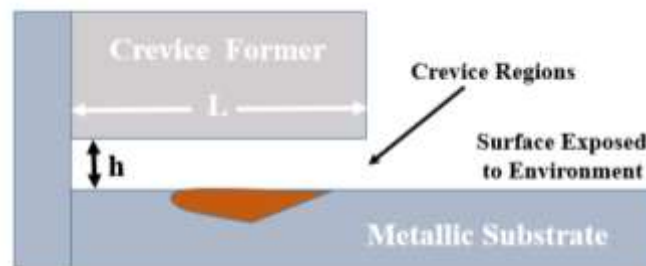


Figure 7 Schematic of crevice formation

Crevice corrosion is a form of localized corrosion and has many similarities with pitting corrosion. For both types of corrosion, the variation of the environment is an essential condition for significant damage to collect. In few cases, the crevice corrosion is considered to initiate from the pits formation at the constrained site [64, 65]. The main difference between the crevice and pitting corrosion is the necessity of a physical occluded site for crevice corrosion, while pitting occurs on an exposed material surface, even though we have some cases in which it

occurs at the interface between the matrix and an inclusion. The crevice corrosion of stainless steel is possibly the most commonly alloy system, which is widely used in industrial applications. In some structures and mechanical assemblies crevices are created i.e. flanges installed at the pipes ends. Moreover other alloys systems are aluminum alloys, [66-68] nickel alloys [69-71] and titanium alloys [72, 73] also suffer under adequately severe environments due to crevice corrosion.

3.3.1. Stages of crevice Corrosion

There are three stages of crevice corrosion in which the time course can be divided: (1) incubation, (2) propagation, and (3) stifling. During the incubation time there is no macroscopically observable localized attack. However during this period the chemical circumstances within the restricted zone are evolving. Propagation occurs when the critical condition is obtained. In this step moderate attack rates are involved usually 10 mA/cm^2 [74] with an attack area growing until a steady state is obtained [75]. Crevice corrosion is a form of meta-stable corrosion. Stifling of the attack which consists of whole re-passivation could occur at any-time if the composition of CCS, critical crevice solution is not kept inside the crevice. The loss of CCS occurs when the mouth of the crevice is opened, which further increase the mass transport and could not CCS at an adequate pace or if the sample potential lowers below the re-passivation potential [76].

3.4. Atmospheric Corrosion

This type of corrosion is different from other types of corrosion. The metals are exposed to various atmospheres and not immersed in the electrolytes. This corrosion is dependent on the relative humidity, wetness time, temperature, electrolyte pH and the existence of other impurities i.e. chlorides, SO_2 , NO_2 , NH_3 and acid based fog. The rate equations used mostly have restricted rationality due to diverse local atmospheric circumstances. Many metals form a metal oxide film on their surface when they are exposed to dry atmosphere. This oxide film acts as a barrier and its thickness varies in range of 2 to 5 nm [77-80]. The metals corrosion rates in a wet atmosphere is comparable to that witnessed in an aerated water, in which oxygen has dissolved. The corrosion rate decreases in dry atmosphere as compared to in wet atmosphere.

3.4.1. Factors Affecting Atmospheric Corrosion

The following are the major factors which affect the atmospheric corrosion and will be explained in this section.

- i. Temperature

- ii. Moisture
- iii. Atmospheric pollutants

i. Temperature

Normally, when atmospheric temperature is lower than the dew point, the wetting phase is prolonged. The metals corrosion rates increase with rise in the atmospheric temperature in humid conditions. The relative humidity percentage decreases with increase in temperature. Therefore, corrosion does not occur 15° beyond dew point. Metals are quickly heated and cooled as compared to the atmospheric air, the existence of condensation is highly prolonged on metals surfaces.

ii. Moisture

Moisture is available in various forms: fog, rain, sea breeze, dew and humidity. The rain water contains a chemical pollutant which adds moisture to the surface of metals and promotes the atmospheric corrosion. The beginning of the corrosion is due to the formation of thin film at particular humidity levels. Moisture resulted from condensation on the surface of metal is harmful as well. Further the critical level of humidity is dependent on the tendency of metals to corrode when moisture is in contact and the chemical pollutants contained in the moisture [81]. At some critical humidity level the initiation of continuous and severe attack occurs to cause corrosion. The droplets of water present on the surface of metal for a longer period of time may initiate corrosion. When wetting time is increased, the chemical pollutants concentration increases which later on contributes to increase the atmospheric corrosion rate. Therefore, in such geographic areas where there are no chemical pollutants in air, then the increase in atmospheric corrosion rate may be due to the increase in the surface wetness.

iii. Atmospheric Chemical Pollutants

The chemical pollutants which take part in the atmospheric corrosion are chlorides, SO_2 , phosphates and nitrogen oxides. The Troposphere gases i.e. He, Ne, Kr and Xe don't take part in the atmospheric corrosion [82]. In a cathode reaction oxygen behaves as an oxidizing agent. Moreover, the electrolyte containing CO_2 concentration value 300 ppm has low pH value, acts as an acidic medium and accelerates the rate of metal corrosion.

3.5. Stress Corrosion Cracking (SCC)

Generally, the mechanical failure having brittle nature due to the joint action of tensile stress generated within the material and the environment is called Environmentally Induced Cracking

(EIC). Based on the various failure mechanisms, EIC is divided into Stress Corrosion Cracking (SCC), Hydrogen Induced Cracking (HIC) or Hydrogen Embrittlement (HE) and Corrosion Fatigue Cracking (CFC). SCC is a type of EIC is defined as a degradation of a metal or alloy due to the collective action of tensile stress developed and environmental conditions causing the formation of a crack. When stress level reaches to a threshold value, then further increasing the intensity of stress results in crack initiation and grows according to environmental conditions. The time required from the start of tensile test to the crack detection is known as crack initiation time. Usual SCC of metals and alloys is due to residual stress and sensitization. Addition of corrosion products in matrix of an alloy could also create stress. Cracks are produced from initiation, then corrosion pits growth and the union and spread of macro and micro cracks [83, 84].

3.5.1. Electrochemical Effects

Electro-chemical conditions which may lead to SCC in corrosive environments comprise:

- a. Chloride based localized corrosion in titanium alloys, stainless steel and aluminum alloys [85].
- b. Existence of frail passive film near to an active-passive transition [86].
- c. SCC caused due to de-alloying.
- d. Films creation on the surface, which could lead to inter-granular corrosion and cracking at higher temperatures [87].
- e. Hydrogen induced SCC in high strength alloys [88].

Figure 8 displays a classic potentiodynamic anodic polarization plot for passive-active alloys with specific zones and SCC happens for susceptible alloys in corrosive atmospheres [89]. The arrows show ranges for potential which are critical to SCC of passive-active alloy. The existence of passive film on the metallic or alloy surface is a pre-condition for SCC. The various zones shown in the potentiodynamic anodic plot, show the susceptibility to SCC, and are in the potentials range where the alloy has unsteady passivity.

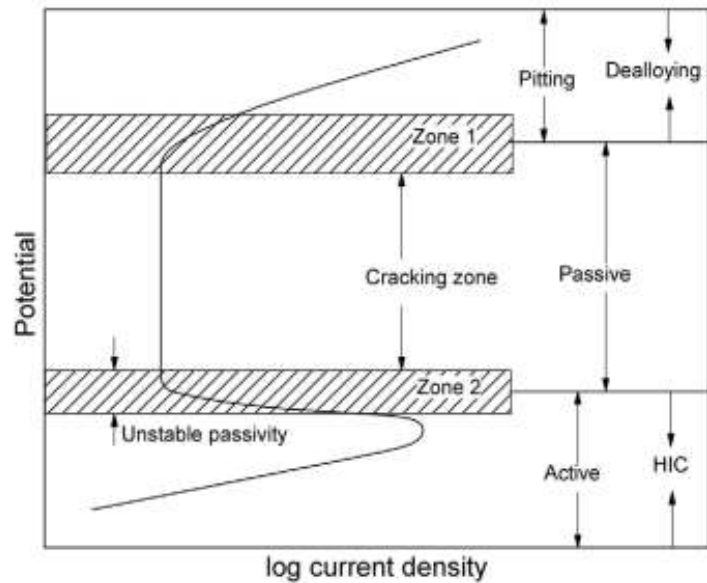


Figure 8 Zones of susceptibility to stress corrosion cracking presented in NACE International 1990

3.6. Inter-granular corrosion (IGC)

Inter-granular corrosion (IGC) is a form of localized corrosion which favorably occurs on the grains boundary. It attacks when corrosion kinetic rate at boundary or thermodynamic driving force is larger as compared to interior of the grain. This is a well-known form of corrosion for austenitic stainless steels. The IGC study has been started since 1940's for aluminum alloys.

Mostly, IGC attacks in the conditions i.e. active precipitates formation at the grain boundaries and its dissolution, in solid solution, unfavorable elements segregate near grain boundaries and their dissolution. Moreover, IGC is related to composition, heterogeneity and microstructure of materials as well [90]. Dix et al. carried out research on the corrosion behavior of an alloy (aluminum with 4% Copper) contained in NaCl-H₂O₂ electrolyte. Al₂Cu Precipitates were found near the grains boundary and the copper depleted zones were identified. The corrosion potential measured and observed that the copper corrosion potential value of the depleted zone was 44 mV, which shows more activeness compared with the grain matrix. It was summarized that in Al-Cu alloys, IGC occurs due to corrosion potential difference between the zones [91, 92].

In AA 7xxx alloys series, AA7150 and AA7075, Cu and Zn both were observed to be depleted in PFZ. Zn and Cu have inverse effects on aluminum for dissolution. Cu depletion makes the PFZ more vulnerable than the matrix, while the depletion of Zn can be valuable to the PFZ. So it's more difficult to define the PFZ role in IGC of AA7xxx as compared in to the binary alloys [93].

In AA7xxx alloys when placed in sodium chloride solution, the IGC morphology was studied. A complicated and irregular corrosion and even the matrix surrounding the grain boundaries is dissolved as well. The corrosion occurs due to the crevice and acidic environment as Buchheit et al explained such type of corrosion phenomenon in Al-Cu-Li alloys. Usually in such case the solution of an aqueous environment remains inside the pits and it becomes more severe with the passage of time while attacking the grain boundaries preferentially and then on the surrounding matrix. If the quantity of the solution in the pits is short then the corrosion is restricted to the grain boundaries only [94]. When AA7xxx samples were pretreated in NaCl solution and then moved to a humid environment it was observed that very severe IGC occurred as discussed in this thesis [90]. From the above discussion it could be concluded that the difference in potentials among precipitates of grain boundaries and grain surrounding matrix make AA7xxx alloys more susceptible to IGC.

4. Polymeric Coating Techniques

Polymeric coatings are applied on diverse types of surfaces. By using various coating applying techniques they are widely applied on the surfaces of ceramic, metallic, alloy and fabricated materials [95]. The polymeric layer must have good adhesion with the substrate material and must be unsusceptible to salt, moisture, heat and various chemicals.

Mostly for an efficient coating the following properties are desirable [96]:

- Good adhesion with the surface of substrate material
- Excellent resistance to chemicals and stains
- Excellent barrier resistance
- Softer touching effect
- Good corrosion and abrasion resistance
- Good stability and durability
- Non-yellowing when exposed to UV radiation or sun light
- Short curing time for fast hardening
- Easy to synthesize

The coating technique used effect the properties of the applied coatings and plays a vital role in the surface quality of the finished product. In **Figure 9**, some coating fabrication methods are enlisted.

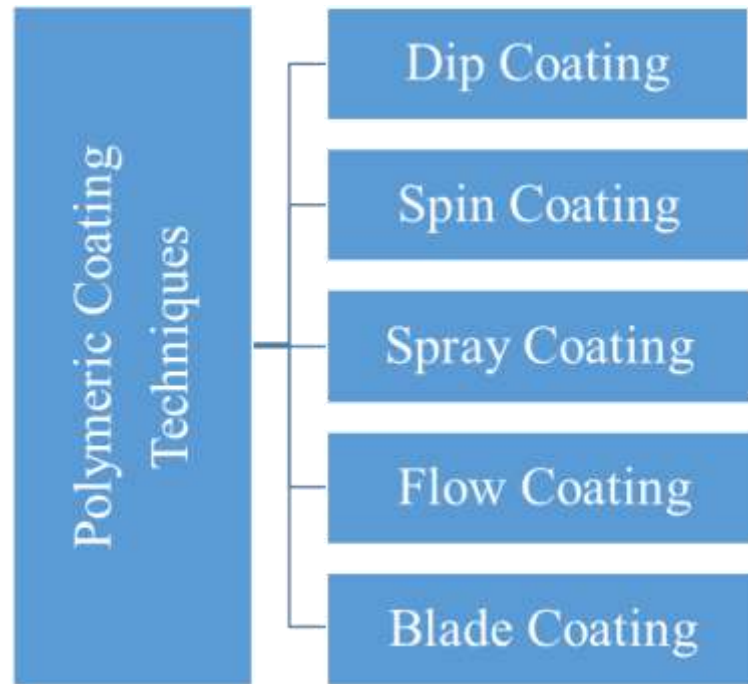


Figure 9 Fabrication Methods for Polymeric Coatings

4.1 Dip coating method

Dip coating or Immersion coating is reflected one of the most primitive existing coating methods. In 1939 the original patent given to Jenaer Glaswerk Schott for reproduction of silica films via sol-gel [97]. Nowadays, this technique is widely used in many applications in the derived sol-gel coatings formulation. Some fields of application are passivation layers, dielectrics, ferroelectrics, superconducting layers, membranes, protective coatings, sensors and actuators. There are three steps involved in this kind of technique:

- i. Dipping and dwell time: In this step the substrate material is placed in the solution used for sufficient interaction and wetting. Therefore the substrate is immersed at a stable rate in the coating solution and for some time it is allowed to stand.
- ii. Film making and discharging: In this step film is generated on the surface of substrate. A thin layer is formed when the substrate is pulled upward at steady velocity while discharging the excess coating material from the substrate surface.

- iii. Evaporation of solvent: In this step the solvent used is evaporated from the coating and the film is cured by supplying heat for certain period of time.

4.2 Spin Coating technique

The spin coating technique is mostly used for applying thin layer on the surface of substrate. This method is widely used in various types of industries. The main benefit of this coating technique is the capability to fabricate smoother coating very easy and quick. The thickness size of the film ranges from nano to micro level. Spin coatings are specifically used in the field of nanotechnology and electronics [98]. Residual organic in the coating system are burned by performing heat treatment. Further, the functional oxides are crystallized by heat treatment. This coating technique seems quite simpler but needs microscopic examination to further explore the details for adaption of coatings on the surfaces of the substrate material. The coating layer formed and its microstructure are inter-connected with each other. This inter-connection is provided by the coating method. The substrate material is pulled upward from the coating solution with steady velocity as per standardized operation [99]. When the substrate is moved, the fluid is dragged from the interface of substrate and coating layer [100].

4.2.1. Mechanism

In this method coating solution is dropped on the center of substrate material. The substrate is rotated at high rpm and the solution is spread on the whole surface due to centrifugal effect. To get the required thickness, the rotation is carried out for a certain period of time. There are various parameters which are optimized for each specific application. These parameters are viscosity of coating material, spinning speed, spinning duration, surface tension of fluid, resins type and substrates on which the coating is applied. Some problems which can be faced during processing may include uncoated surface, swirl pattern, streaks, comets and non-uniform thickness films. For film quality improvement fillers are introduced with in the coating systems which play a vital role in the structural integrity of the coating.

4.2.2. Parameters

i. Coating Time/Duration

Universally, the spinning of the substrate is carried out until the coating film is completely formed and dried. The vapor pressure, boiling point of the solvent used and environmental factors i.e; humidity and temperature in which coating is made affect the coating duration. A

spinning time of 30 seconds is recommended for coating in most cases and is considered to be adequate.

ii. Spinning Speed

To achieve a range of coating thickness from using a solution, the spin coater rotation is important to define that range. Homogeneous coating films may be produced at a rotating speed of 1000 rpm relatively very quickly and easily. Moreover, to produce coatings with higher quality the spinning speed can range between 500 rpm and 600 rpm or having low speed than this.

4.2.3. Advantages and Limitations

The main advantage of spin coating as discussed earlier is its simplicity and easiness to operate while producing an ultrathin homogeneous layer on the surface of the substrate. Very quick drying is achieved by very high air convection caused by spin coater rotation. For micro and nano levels it provides greater stability. On the other hand the main dis-advantage is the use of a single sample during spin coating. In some applications, time is required for crystallization or self-assembling. Very quick drying during spin coating may therefore leads to poorer coating performance [98].

4.3. Spray coating method

This spray coating method is a versatile, fast and economical for diverse geometries and sizes having greater surface area. A very uniform and better quality coatings can be obtained by applying viscous as well as non-viscous fluid coatings via manual or automatic manner with a greater transfer efficiency. Various types of spray equipment and spray guns are used for optimum material usage and application oriented works to obtain required film thickness, coating quality and desired performance. The characteristics required for coating may be controlled by varying discharge rates and spray pattern.

4.3.1. Mechanism

The spray coating method the material for printing is restricted passing from the nozzle while making very thin aerosol [101]. The disadvantages/ disturbing factors which affect the performance of polymeric solar cells are non-uniform surfaces, isolated droplets and having

holes at surface. The various parameters which play a key role in the fabrication of coatings are pressure, discharge rate, temperature of the substrate, density, the spraying duration and the distance between the spray nozzle and substrate surface [102]. For best flow and atomization the controlling parameters should be selected and used carefully. Defect free coating films set a benchmark for spraying techniques used in various applications while facilitating coating transfer efficiency. To obtain a high quality surface finish for coating, good spray pattern and nozzle distance as well as angle are necessary.

4.3.2. Spray coating factors

There are various factors which control the characteristics of the applied coating. The major factors are distance between nozzle and substrate, the substrate temperature/ annealing treatment and solvent/mixed solvents effect. Further explanation of each factor is described below.

i. Nozzle-Substrate Distance

Nozzle-substrate distance is an important process factor which has a huge impact the morphological properties of the coating film deposited during spray coating. Many researchers carried out significant work to identify and obtain the optimum distance between the nozzle and substrate for best coating application. Vak et al. [103] identified three positions between the nozzle and substrate, namely wet, intermediate and dry and found that the best linear distance was at the intermediate position. Susanna et al. [104] noticed that, by using the same material, the applied coating stayed wet when the air brush nozzle-substrate distance was less than 15 cm. The powdered and dried coatings fabricated at a distance of 20 cm. It was concluded that the intermediate position was at a distance of 17 cm.

ii. Substrate Temperature and Annealing

Green et al. [105] studied the effect of annealing on the performance of devices having spray coatings. It was noted that the device efficiency remarkably alter with temperature of annealing. It is due to variation in short circuit current. Lee et al. [106] observed that the surface morphology of spray coatings are not influenced at 150°C annealing for micron level. However, some contradicting results have presented by Dang et al. [107]. It was examined that surface morphology was effected by annealing for rotary casting and improvement were seen in phase separation.

iii. Solvent and Mixed Solvents

Many types of solvents used in coating formulation by researchers to examine the effect of efficiency and quality of coatings. Few most commonly solvents used are toluene, p-xylene, chloro-benzene, dichloro-benzene and trichloro-benzene. Selection of solvent influences the choice of distance between nozzle and substrate for obtaining the proper thickness and the desired morphology. Therefore, it is very important in about all techniques of spray coating. Primarily, the principle for selecting a suitable solvent is to choose a rapid-drying solvent and to prevent droplets from resolving the substrate [108]. Thin films having pin holes are undesirable because these films make the coating less efficient. The sufficient quantity of liquid solution for coating must be used in order to fabricate pin hole free and finished surface [102].

4.3.3. Advantages and Disadvantages

The spraying process is carried out at a vertical angle and thus helps in providing safe work situation, which is a major advantage of spraying. This technique has some limitations as well. Few most arising problems are non-uniform coating, sagging, over spraying, pinholes and spluttering.

4.4. Flow Coating technique

To apply liquid coatings on the substrate, flow coating is a quick, reliable and easy technique to use manually or automatic. It is widely used on flat sheets and large panels. Moreover, with a single coat the required thickness can be achieved.

4.4.1. Mechanism for operation

The flow coating method is appropriate form of coating to make a polymeric coating having thickness range in the submicron region. The equipment used has a blade which is fixed and moving stage. There is a gap between the fixed blade and moving stage, varying from ten microns to hundred microns. The surface on which the coating is applied is tightly attached to the moving stage and the liquid polymeric coating is sandwiched between the substrate surface and the fixed blade and compaction is carried out for the coating material. In the flow coating the polymeric coating is dragged under force, which is caused by capillary force between the substrate and fixed blade. Principally this technique is very much similar to other techniques namely blade coating and dip coating. With the passage of time, the volume of liquid coating slowly decreases as evaporation of the solvent occurs at the edges. At very low speed, frictional pulling cause material to escape beneath the blade, however the capillary force is planned to keep

the coating liquid between the fixed blade and substrate surface. The coating is dried when the solvent is evaporated and finally get wet coating shape [109, 110].

4.4.2. Advantages and limitations

Flow coating requires very small space, reduces waste, having greater transfer efficiency and an economical option to use. The liquid coating material is dispensed on the upper part and flows down to conceal the full surface area. The gravity flow around the substrate is the function of viscosity of the fluid. The quality of coating is highly affected by the corresponding curing conditions i.e; temperature and humidity. Flow coating is undesirable for the geometries having pultrusion and holes on the surface.

4.5. Blade coating method

In the blade coating technique a certain quantity of coating material is used and the extra material is removed by a blade to achieve the required coating film thickness [102, 111]. There are some advantages for achieving a better coating quality. The features of the coatings are; homogeneous coating, prevention of melting for intermediate layer, very little material waste and economical [112, 113]. The coating thickness can be controlled by adjusting the fabricating conditions i.e.; gap between the blade and substrate, covering velocity of the blade and the sol concentration [113].

5. Polymeric composite coatings

The various types of thermosetting polymeric resins and their applications are demonstrated in **Table 3**. These polymers are commonly used in the synthesis of composite coatings. For synthesis of polymeric composite coatings, curing agents are used in specific ratio with the resin. Various types of curing agents are used in practice. Some curing agents used in combination with the polymeric resins are shown in **Table 4**.

Table 3 Various thermosetting resins for coating applications

Thermosetting polymeric resins	Precursor(s)	Applications
Epoxy Resin	Epoxide monomers, such as bisphenol A and epichlorohydrin	Coatings, adhesives, electronic encapsulation, composite materials

Phenolic Resin	Phenol and formaldehyde	Insulation materials, molded products, adhesives, laminates, coatings
Polyurethane	Polyols and diisocyanates	Foams, coatings, adhesives, elastomers
Polyester Resin	Unsaturated polyesters and reactive monomers	Fiberglass reinforced plastics, automotive parts, marine applications, coatings
Melamine Formaldehyde Resin	Melamine and formaldehyde	Decorative laminates, dinnerware, coatings
Silicone Resin	Siloxane monomers	Electrical insulation, high-temperature coatings, release agents
Alkyd Resin	Polyol, oil, and fatty acids	Paints, varnishes, coatings
Vinyl Ester Resin	Epoxy resin and unsaturated monocarboxylic acid	Corrosion-resistant coatings, fiberglass reinforced composites
Polyimide Resin	Diamine and dianhydride	Aerospace components, electronics, high-temperature applications

Table 4 Various curing agents for polymeric resins

Curing Agents (Hardeners)	Composition	Advantages	Limitations
Amine hardeners	Amines (such as polyamines, aromatic amines)	Fast curing, good chemical resistance, high bond strength	Potentially hazardous, limited shelf life

Anhydride hardeners	Anhydrides (such as nadic anhydride, methyl nadic anhydride)	Excellent heat resistance, good electrical properties	Slower curing, longer processing time
Polyamide hardeners	Polyamides (such as dimer fatty acid-based polyamides)	Good flexibility, resistance to moisture and chemicals	Longer curing time, limited compatibility
Phenolic hardeners	Phenolic compounds (such as phenol-formaldehyde resins)	High thermal stability, good mechanical properties	Limited color options, potential brittleness
Acid anhydride hardeners	Acid anhydrides (such as maleic anhydride)	Excellent adhesion, high chemical resistance	Longer curing time, requires elevated temperatures
Latent hardeners	Latent curing agents (such as dicyandiamide)	Long shelf life, low-temperature curing capability	Slower curing, potential blooming or exudation

6. Corrosion Control

This is the responsibility of the corrosion protection engineer's team to eliminate or minimize the degradation of the metallic structures due to corrosion. There are various methods which can be used to minimize the corrosion rate of the materials. The protection elements by which this process rate can be reduced are material selection, environmental control, design of the structure, anodic-cathodic protection and coatings. The research work conducted by different researchers regarding the corrosion protection of metallic/aluminium substrates is given in **Table 5**.

Table 5 Investigations performed by various researchers for corrosion control

<p>Zhang Tianyua et al 2021 [114]</p>	<ul style="list-style-type: none"> • Used epoxy primer coated aluminum alloys UVA, UVA neutral and UVA-acidic engagement. • UVA-acidic engagement layer thickness decreases linearly. • Impedances vary differently for the above three environments due to the post-curing of the primer. • Electrochemical Equivalent Circuits (EEC) and mechanisms of degradation were analyzed to fully explore the corrosion nature.
<p>Przemysław Kwolek 2020 [115]</p>	<ul style="list-style-type: none"> • The effect of sodium molybdate on the corrosion kinetics of aluminum alloy 7075 in acidic water solution was studied. • Heteropolyoxomolybdate species play the role of inhibitor during corrosion. • Corrosion rate considerably decreased to 3.24 g/ m².day from 75.98 g/ m² .day.
<p>O. Dagdag et al 2021 [116]</p>	<ul style="list-style-type: none"> • Epoxy coating composed of DGEBA cured with polyaminoamide, which was applied AA 7075-T6, AA 5086 and AA 2024-T3 to minimize the corrosion. • Epoxy coated samples were used in solution having 3.0 wt% of NaCl while using the test chamber of salt spray. • $Z _{0.01 \text{ Hz}}$ values for epoxy coated samples of AA 7075-T6, AA 5086 and AA 2024-T3 started from 2.63, 1.46 and 0.43 MΩ.cm² after 1 h of dipping and lastly touched 0.27, 0.26 and 0.24 MΩ.cm² after 4392 h of dipping, correspondingly.
<p>M. K. Srinath et al 2019 [117]</p>	<ul style="list-style-type: none"> • This study is about the TiCN coated on aluminum alloy, Al-7075 • The tests were conducted at a heat treatment temperature of 500 °C for 1, 4, 8 and 12 hrs in order to explore the samples corrosion. • Following ASTM, D-1193 standard, with 5 wt% of NaCl and 95 wt% of type IV water at 95 °F having pH value range 6.5-7.2, samples treated for 1 hr time have better corrosion resistance as compare to the samples treated for longer duration of time.

<p>Sheng Zhang et al 2018 [118]</p>	<ul style="list-style-type: none"> • Long-term atmospheric coastal environment corrosion behavior of epoxy prime coated aluminum Alloy 7075-T6 discussed. • The research carried out for the coated samples of AA-7075-T6 for different exposure time of 7, 12 and 20 years. • Corrosion resistance of coated samples decreased while increasing the exposure time.
<p>J. van den Brand et al 2004 [119]</p>	<ul style="list-style-type: none"> • Two methods proposed for improvement of adhesion and its durability in epoxy coated aluminum alloy, AA1050 (99.5% Al, 0.40 wt.% Fe and 0.25 wt.% Si). • Polyethylene-alt-maleic anhydride (PEMah showed great initial adhesion and its durability in the water for the epoxy coated samples as compared to polyvinyl phosphonic acid (PvPA) and polyacrylic acid (PAA) both. • Pseudoboehmite-based system showed a great adhesion and its durability in the water as well.
<p>Yuanyuan Qian et al 2015 [120]</p>	<ul style="list-style-type: none"> • The main objective of this review is to explore the coatings corrosion behavior for different types of metals and alloys which are widely used in various applications. • Identified high performance/economical inhibitors for corrosion which protects the equipment. • Further the emphasis is on metallic corrosion caused by chlorides at standard pressure and temperature (STP) having pH range of 6-8.
<p>Youbin Wang et al 2021 [121]</p>	<ul style="list-style-type: none"> • Prepared ZnLaAl layered double hydroxides (LDHs) nano-sheets, and then inserted in sol-gel coating for protection of aluminum alloy Al 6061 from the corrosion. • Tests results of long-term corrosion revealed that the sol-gel/ ZnLaAl-LDHs coating displays greater corrosion resistance and greater stability as compared to sol-gel/ ZnAl-LDHs coating, which shows that 'La' improves the anticorrosion performance of nano-sheets LDHs and enhances the permanency of sol-gel/LDHs.

<p>Diping Zeng et al 2021 [122]</p>	<ul style="list-style-type: none"> • Prepared bis-silane-modified epoxy coatings and were applied on aluminum alloy consists of Al, Zn, Mg and Cu. • Using tetraethoxysilane (TEOS) and γ-glycidoxypropyl trimethoxysilane (GPTMS) the prepolymer bis-silane prepared. • Comparing both silane monomer-modified coating and bis-silane-modified coating the later has poorer coating capacitance (C_c), lesser double layer capacitance (C_{dl}) and greater charge transfer resistance (R_{dl}) for long-term immersion in water.
<p>S. Lin et al 1992 [123]</p>	<ul style="list-style-type: none"> • Used epoxy as a polymeric coating and $CeCl_3$ which is a rare earth chloride for chemical passivation for aluminum alloy A1 6061 and aluminum matrix composites Al/SiC, Al/graphite and Al-Li 2091-T6. • Corrosion resistance is significantly improved for these alloys/AMCs. • Evaluated the coatings quality to forecast the lifespan of coated alloys/AMCs in a limited time.
<p>Jingyi Yue and Yan Cao 2015 [124]</p>	<ul style="list-style-type: none"> • Worked on the corrosion resistance coated samples of aluminum alloy AA5086 using different blends of coatings. • The corrosion resistance was investigated with the Tafel electrochemical technique in both simple and salt water. • Ceramic coating with a primer and topcoat is environment friendly with chromium free combination, shows greater polarization resistance and lower corrosion rate as compared to the conventional chromate combination coatings.
<p>Qian Zhao et al 2018 [125]</p>	<ul style="list-style-type: none"> • Fabricated a super-hydrophobic film of Ni-Co alloy on the surface of aluminum alloy AA5052 using electro-deposition method. • Modified with amino-1,3,5-triazine-2,4-dithiol monosodium (AF17N) and 6-(N-allyl-1,1,2,2-tetrahydro-perfluorodecyl). • Hydrophobicity of the surface enhanced for a contact angle of 160° when exposed in the atmosphere for a period of 240 days. • In 3.5 wt.% NaCl solution environment, the coating material considerably improved the corrosion resistance of substrate material.

<p>H. M. Hajar et al 2016 [126]</p>	<ul style="list-style-type: none"> • The corrosion behavior of aluminum alloy AA5083, which was carried out at ambient temperature. • By varying the percentages of henna extract, three different paint compositions were made. • By increasing the percentage of henna extract in the coating composition, the corrosion rate of AA5083 decreases. • Henna extract in coating formulations lead to superior protective obstruction to the corrosion.
<p>Ayse Z. Aroguza et al 2020 [127]</p>	<ul style="list-style-type: none"> • Used two different hybrid sols of tetrapropyl orthotitanate/(3-Glycidioxypropyl) trimethoxysilane (TPOT/GPTMS) and tetraethyl orthosilicate/(3-Glycidioxypropyl)trimethoxysilane (TEOS/GPTMS). • Dip-coating method was used to coat the aluminum alloy AA7020 with these sols. • Using potentio-dynamic polarization (T_p) and EIS to investigate the corrosion behavior of coated aluminum alloy in 3.5% NaCl solution. • TPOT/GPTMS and TEOS/GPTMS sol-gel coatings have higher corrosion protection

7. Conclusions

The research discussed in this review reveal that, while significant progress has been made, numerous questions and challenges remain. It is clear that considerable research has been carried out the corrosion and its protection of metallic surfaces. Furthermore, the practical application of polymeric coatings in real-world scenarios and industrial settings requires further attention, addressing issues such as durability, adhesion, and scalability. In this review, it becomes evident that the effect of composite polymeric coatings on the corrosion resistance of aluminum alloys in marine environments is a multifaceted and evolving field of study. The potential benefits of these coatings are substantial, offering the promise of extended service life for aluminum alloy components in critical applications. However, the realization of these benefits requires continued research, experimentation, and innovation to refine the technology, optimize its performance, and facilitate its integration into industry practices.

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Conflicts of interest

The authors declare that they have no affiliations with or involvement in any organization with any financial or non-financial interest in the subject matter and materials discussed in this article.

Ethical Approval

Not Applicable

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