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Review Article

An Overview of Corrosion Types, Corrosion Testing and Strategies to Inhibit Corrosion

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ABSTRACT

This review offers an insightful overview of literature related to corrosion, its types, mechanism, laboratory scale testing approaches and strategies to inhibit corrosion. Corrosion is the deterioration of metals and alloys as a result of their contact with environment that leads to the sacrificed properties of these materials. Corrosion is a perilous concern due to its significant cost-effective, protection, safety concerns, and environmental impact. Various types of corrosion are described by researchers that are insidious and detrimental for infrastructures. Corrosion rate is affected by various factors such as humidity, oxygen exposure, the faulty structure, etc. The defective parts lead to the corrosion such as pitting corrosion (PC) that is most hazardous in all the types of corrosion, as it is unnoticeable and lead to the sudden damage of infrastructures. Laboratory scale testing of corrosion provides a futuristic approach to predetermine the approximate economic losses that occur due to corrosion, the reliability of used materials, and their estimated life span. Structural morphology provides a deep insight to find the occurrence of corrosion without destroying the material or employing any specific method. Corrosion monitoring (CM) is another valuable tool to check the efficiency of metal-based objects with time. Corrosion is inevitable, so in order to enhance the efficacy and durability of materials, preventive measures are employed to inhibit or minimize corrosion. The inhibitors used may include polymeric organic coatings and certain inorganic, organic, and sustainable eco-friendly inhibitors. Through the application of inhibitors, specifically eco-friendly inhibitors reduce infrastructure damage, economic losses, corrosion cost, metallic waste, industrial shut-downs, and hazardous chemicals.

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Introduction

Corrosion is an old age phenomenon known by several names throughout history. Rust, as it is often used damages the appearance and the durability of materials. In his book Ferrum Corruption, Pliny the Elder (AD 23-79), a Roman philosopher, describes iron's corrosion. Despite its long history, scientific investigation into corrosion began with Robert Boyles's work, earlier findings by Pliny and Herodotus (5th century BC) suggested using tin to protect iron. Later Lomonosov (1743-1756) and Austin (1788) studied the effect of water on iron, Thennard (1819) described corrosion as an electrochemical process, Hall (1829) discovered that iron rust only when exposed to oxygen, Davy (1824) introduced zinc for sacrificial protection and De La Rive (1830) investigated zinc microcells [1].

Corrosion is the decomposition of metals caused by environmental exposure through chemical or redox reaction processes. The corrosion of metals is a significant adverse chemistry effect that has garnered worldwide attention from scientists [2]. Physical damage such as erosion, galling, or wear differs distinctly from corrosion. When chemical and physical processes combine, they result in corrosion, and erosion also called fretting corrosion while non-metals may deteriorate, but they do not undergo rusting in the same manner as the same manner as metals. Rusting specifically affects iron and iron alloys, forming hydrous ferric oxides as the main corrosion products [3]. Corrosion sometimes known as metallic cancer is an irreversible process that causes the gradual degradation of metal structures resulting in permanent damage and large financial losses due to chemical or electrochemical processes [4]. Corrosion is a natural process where metals deteriorate due to environmental factors like moisture, oxygen, acids, bases, salts, and pollutants, causing oxidation and potential failure of infrastructure, machinery, and equipment [5]. Corrosion is the surface phenomenon triggered by temperature ambient contaminants, ionic species, and humidity when the surface is shattered the deterioration proceeds into the structure acidic elements in the environment can exacerbate this, ultimately dimensioning the metal's durability [6]. Corrosion can take several forms including pitting, galvanic, intergranular, and stress corrosion, all of which are metallic structures including rods, wires, pipes (which cause leaks), metallic bases, and electrical systems some representations are displayed in Figure 1.

The corrosive process alters the microstructure of metals, reducing their ductility, systematic strength, and ultimate resistance before changing them into easily broken and brittle textured, this decline has a direct impact on nations' GDP.

Figure 1: Corrosion effects on various metal constructions [7]

The corrosion protection market was valued at over $2.5 trillion in 2018 and is expected to reach more than $3 trillion by the conclusion of the year [8]. Implementing effective strategies for corrosion protection can play a fundamental role in reducing the impact of severe infrastructure damage and decreasing both economic costs and environmental degradation [9]. The primary method for preventing corrosion encompasses cathodic protection, anodic protection, the application of corrosion inhibitors and the use of protective coatings. Among these methods, chemical inhibitors and coatings are the most widely employed approaches for corrosion in many industries and applications. Natural and artificial anticorrosive mixtures are effective but hazardous to the environment and humans. Green inhibitors, like dried stems, seeds, peels, and leaves, offer secure and environmentally friendly treatments [10]. Metal coating plays a crucial role in safeguarding metal surfaces from corrosion and preserving the long entity of metal structures. Various types of coatings, including metallic, chemical conversion, organic, inorganic, and nanocomposite coatings have been developed to provide effective protection against corrosion. These coatings serve as a barrier, shielding the metal from environmental factors and preventing deterioration [1,11]. Coatings with rapid drying, high adhesion, and environmental resilience are being researched due to their limited use in complex designs and high-rise structures, meanwhile, corrosion inhibitors function by adding small quantities to help minimize corrosion [12]. Corrosion refers to the degradation of materials and their fundamental properties due to environmental factors. These issues have a broad impact, affecting transportation, infrastructure, utilities, manufacturing, and production. Corrosion affects a variety of materials including metal, alloy, plastic, paints, and rubbers as well as ionic and covalent compounds, composite, concrete, and wood. It is commonly found in acidic environments such as (hydrochloric, sulphuric, and nitric acids), alkaline solutions (sodium and potassium hydroxides) as well as seawater and saline solutions [13,14]. Fontana characterizes corrosion in metals as a spontaneous process in which a metal achieves its stable thermodynamic condition this process is mostly electrochemical, including oxidation-reduction reaction, and is significantly impacted by environmental conditions .The goal of the study in the given article seems to be to present a thorough analysis of corrosion, covering its kinds, processes, testing procedures, and preventative measures. Besides outlining laboratory and field-testing procedures and investigating developments in environmentally friendly and sustainable corrosion prevention strategies, the research intends to address the economic, safety, and environmental ramifications of corrosion. This is in line with the overarching goal of reducing the damaging impacts of corrosion on the environment, industry, and infrastructure. Several factors have led to the expansion of the corrosion research area. Scientists need to better understand how innovative materials such as alloys behave in a corrosion environment. In addition, rising pollution and acidity have made aquatic and atmospheric environments more corrosive and prompting further research [15]. The novelty lies in its focus on sustainable corrosion prevention methods and detailed evaluation of destructive and non-destructive testing techniques to improve material reliability and longevity. Figure 2 depicts many characteristics that influence metal and alloy corrosion in solution this section will look at the factors that contribute to metallic corrosion, elevated temperature accelerates the kinetics of electrochemical reactions which increase corrosion rates. The flow of corrosive fluids can significantly affect the corrosion rate of mechanical components, increased flow can cause more corrosion while higher flow velocities may reduce corrosion damage in passivated materials, the state of the metal surface is also crucial since deposits or coatings may initiate corrosion, and biological growth impacts surface chemistry. Corrosion is influenced by the microstructure which includes grain size and orientation. Immersion time is an essential issue since certain corrosion processes are fast and severe while others are sluggish [16].

Because of their formability and resistance to corrosion, austenitic stainless steels are often used in engineering applications. Their low yield strength, however, restricts their application in energy absorption. Although it decreases ductility and fracture toughness, severe plastic deformation is essential for creating high-strength steel. For SS 316 to be used in industry, it is essential to research its fracture characteristics because of the large-angle grain boundaries that can lead to crack propagation [17].

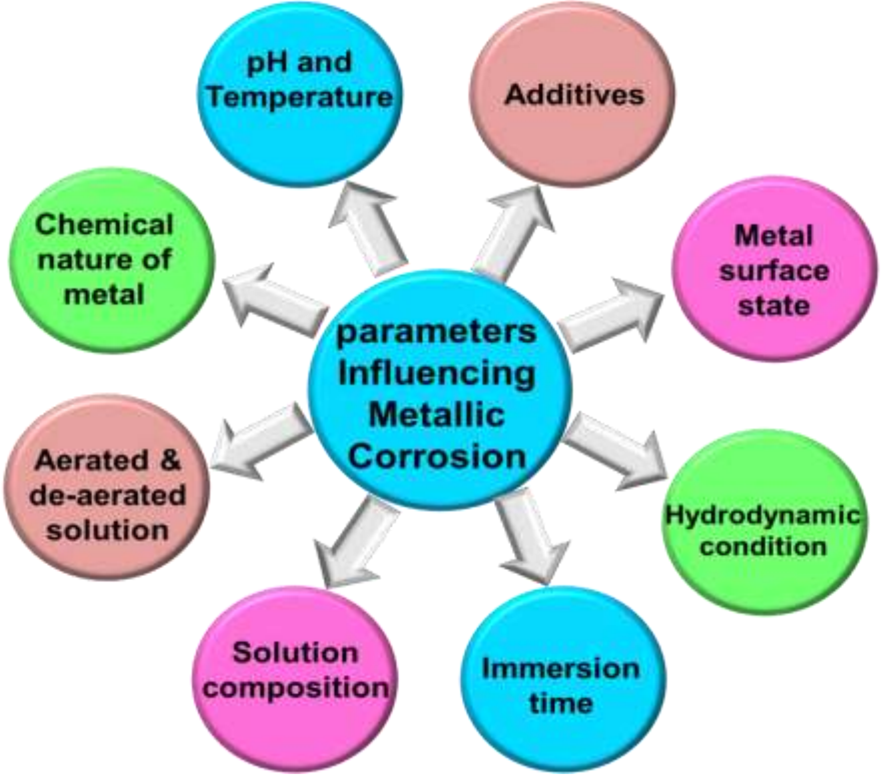

Figure 2: Parameters influencing the rate of metallic corrosion in aquatic settings [16]

Corrosion is a critical issue due to its significant cost-effectiveness, protection, and environmental impact. Corrosion engineers strive to minimize the material and financial loss resulting from deteriorated metallic components in various infrastructures such as pipes and tanks. Corrosion can comprise safety by leading to equipment failures for example in pressure vessels and aircraft components. In addition, metal components deplete metal, energy, and resources. Corrosion-related economic losses can be classified as direct or indirect, direct losses include the price of replacing rusted equipment and structures such as metal roofs and pipelines as well as the personal costs. Repainting to prevent corrosion and maintaining cathodic protection devices for pipelines are both direct costs. Corrosion costs the United States around $276 billion per year or 3.1% of GDP with potential savings of 30% with improved corrosion control. Corrosion expenses are comparable to other countries amounting to approximately 3-4% of GDP while more difficult to access, this increases the overall economic burden [18]. Corrosion is a major issue that affects not only the economy, but also causes safety concerns and the environment. Vigilant corrosion may cause bridges and other structures to be abolished resulting in major consequences such as injuries or death. Corrosion has an economic cost including both direct and indirect losses, these expenses are divided into 4 categories: structures (e.g., equipment and replacement), control (corrosion cost and management), scheme (corrosion allowance and construction materials), and related (*e.g.*, policy and technical services). Table 1 indicates the expected corrosion in several nations throughout the world. National corrosion cost might reach 2-4% of gross national product. Effective management may prevent around 25% of these losses.

Corrosion not only causes financial losses, but also poses substantial safety issues, corrosion of key infrastructure such as steam pipes, bridges, gas pipelines, and airplanes, potentially leading to terrible accidents. Moreover, corrosion may degrade and contaminate the environment, destroying critical Fauna and flora.

Table 1: Corrosion cost in different countries [19]

Country	Corrosion costs (year)
United States	$2.1 trillion (2022)
Japan	¥4.3 trillion (2015)
Middle East and Africa	$6.34 million (2024)
United Kingdom	3.8% of GDP in 2016

Corrosion-induced breakdowns of oil pipelines, tanks, or gas pipes can cause water and air pollution. Furthermore, rust can reduce the effectiveness of air pollution control systems, these adverse conditions allow gaseous impurities from production methods to escape into the environment. Corrosion, on the other hand, can affect the environment using an excessive amount of precious metallic material resources as well as related manufacturing techniques [20].

Corrosion of steel is an automatic charge transfer reaction; this happens in the oxygen occurrence, the anode delocalizes metal ions via oxidation into the solution whereas the cathode mobilizes electrons by reducing metal ions to a receiving agent such as an electron acceptor, oxygen, or hydrogen ions. Corrosion occurs mostly in a moist environment on metal surfaces. Corrosion is the gradual process caused by environmental interaction with metal surfaces, corrosion can be explained as the removal of a substance from the interface of any metal or non-metal [21]. The corrosion mechanism is a complicated method that includes the transport of negatively charged particles from the metal interface to the charge carrier solution which is facilitated by the existence of oxygen, as shown in Figure 3. This method happens because of metals' natural inclination to return to their original valence state releasing energy. The metal oxidizes at the anode releasing electrons in the electrolyte whereas the reduction process happens at the cathode, consuming electrons frequently in the existence of oxygen the corrosion method is driven by the combined reactions at both electrodes which gradually degrade the metal surfaces. At anode:

$$Fe \rightarrow Fe^{+2}+2e^{-} \qquad (1)$$

$$Fe^{+2} \rightarrow Fe^{+3}+e^{-} \qquad (2)$$

At cathode:

$${}^{1}/_{2}O_2+H_2O+2e^{-} \rightarrow 2OH^{-} \qquad (3)$$

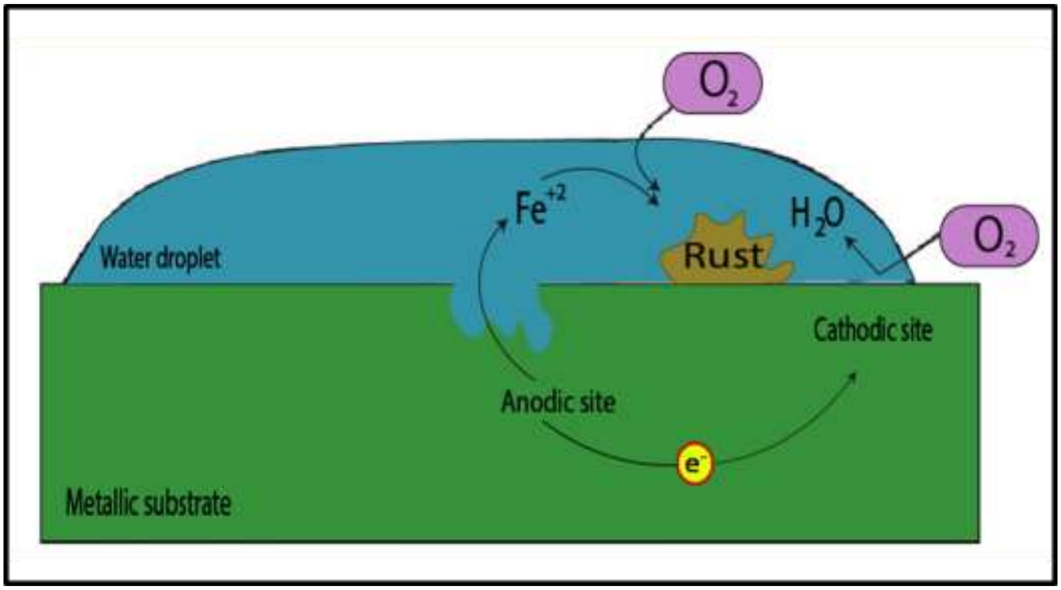

Figure 3: Mechanism of corrosion [7]

Types of corrosion

Metallic corrosion is a complicated mechanism that takes eight forms illustrated in Figure 4 and is described as stress corrosion, PC, galvanic corrosion, intergranular corrosion, dry corrosion, wet corrosion, microbial corrosion, and waterline corrosion (WLC). These formations are equally distributed throughout the metal surface.

Dry corrosion also known as oxidation happens when there is no water or humidity to induce corrosion, and the metal oxidizes. This type of corrosion occurs when a material and gases interact in a dry atmosphere resulting in an oxide layer on the material surface, as illustrated in Figure 5 [22]. Dry corrosion is less damaging as compared to wet corrosion, and it is very subtle to temperature fluctuations. Wet corrosion of metals occurs through electron transfer (through loss of electrons and gain of electrons). Metal atoms lose electrons during oxidation which are then reduced and transported into the environment, the metal where electrons loss occurs is called the anode while the metal accepting electrons is called the cathode. Air, with an average of 21% of oxygen, 78% of nitrogen, and 1% of argon may also contain atmospheric moisture, ozone, or carbon dioxide. Corrosion rates are influenced by factors such as oxygen availability, water or moisture content, and other elements, ions, and compounds, these factors can affect corrosion in various contexts like industrial rural and maritime settings, these environments contain oxygen and other pollutants like ozone, salt, dust, sulfur dioxide, hydrogen, and hydrogen sulfide. When a metal is completely submerged in the water the rate of corrosion is modulated by the migration of dissolved oxygen to the metal surface, this process is often slow due to oxygen's low solubility [22].

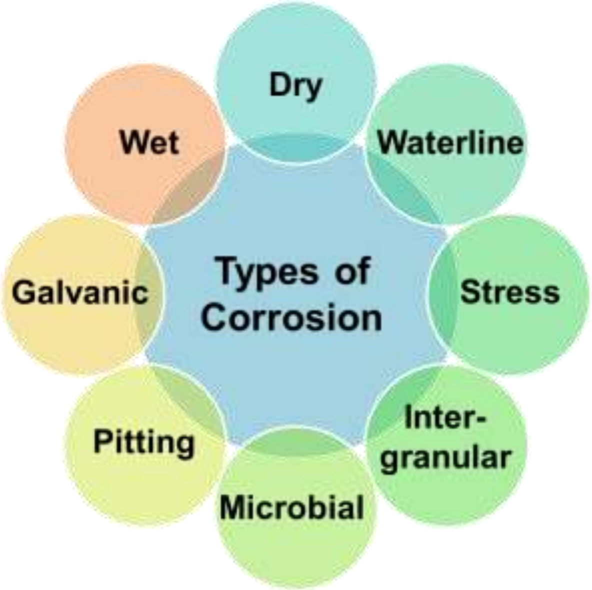

Figure 4: Types of corrosion [7]

PC is the most destructive type of corrosion because the attack of the corrosion charge particle is confined and directed to the creation of pits, this category of corrosion causes machinery to fail with minimal loss, pitting takes longer but once it starts it permeates the region quickly [23,24]. PC is the localized attack in which metal corrosion is penetrated locally resulting in a metal loss. Pit formation is a lengthy process that might take several months or years. Among several types of corrosion pitting is the most harmful it is more deadly than conventional corrosion due to it developing in tiny spots that are tricky to notice [25]. Notably, these holes tend to spread in the direction of gravity continually advancing and threatening the metal's load-bearing capacity. It is a type of area-specific metal-derived surface degeneration that develops in specific locations such as cavities [26]. The emergence of such pits is typically linked to a localized rupture in the protective layer that had previously formed on the metal coating (functioning as an obstacle against corrosive substances). Pitting rusting is a common deteriorating mechanism for metal exposed to corrosive environments, causing fracture initiation, propagation, and failure due to localized degeneration on microscopic to macroscopic surfaces [27]. Chemical or physical flaws on the interface of the target metal typically trigger this early disintegration of the protective coating. These imperfections can take various functions including minute scratches, fractures, or chemical impurities, creating holes that allow corrosive substances to enter and initiate the pitting process. Pits formed by PC via partially permeable barrier output can have open or covered mouths, cup-shaped or hemispherical shapes, flat-walled structures, or irregular shapes. They are classified into trough and sideway pits, with cavities accumulated, with degraded products, creating caps, nodules, or tubercles [28,29]. Environmental factors, pitting potential, metal-like structure, thermal condition, and external state influence PC, with aggressive ion concentration, pH, and modulation ratio being the most critical parameters [30]. In addition, galvanic corrosion also known as bimetallic corrosion is an electrolysis-based technique in which two unlike metallic components are electrically associated in a corrosive liquid in this type of corrosion one metal (the anode) corrodes while the other (the cathode) metal remains preserved [31]. Metals with overlapping voltage ranges such as manganese-bronze and silicon-bronze can serve as anodes based on the exposure requirement, more details are required to predict the couple's actions, and the negative electrode to positive electrode region fraction determines the couple's behavior.

In couple A the aluminum rivet is small (C/A) and the C/A ratio is high but in couple B, the stainless steel rivet is small and the C/A ratio is lower [32], as shown in Figure 6.

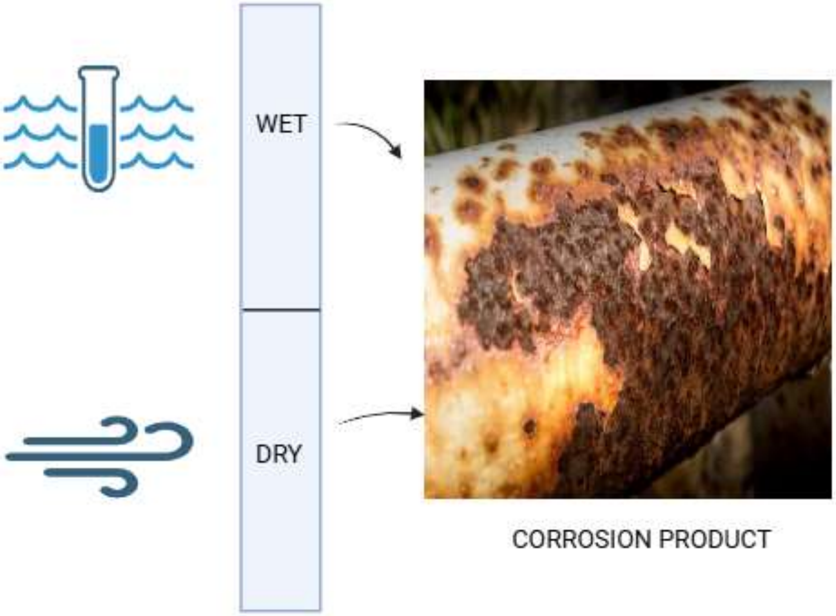

Figure 5: Wet and dry corrosion [23]

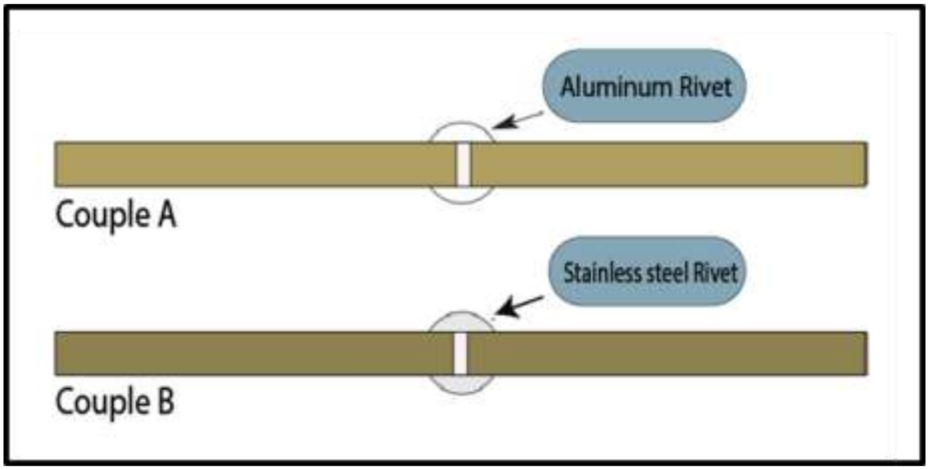

Figure 6: Effect of cathode to anode (C/A) ratio on galvanic corrosion [33]

Galvanic corrosion is the common type of corrosion where metal comes in contact with other conductive materials in a corrosive medium it can occur in mains, microelectronic devices, metal matrix composites, and ships with different metal alloys [34]. Galvanic corrosion is a complex subject but its quantitative nature has been challenging. Recent advances in computer technology and software have made significant progress in understanding and predicting galvanic corrosion. This corrosion is strongly relevant to the direct current and is regulated by Faraday's laws. The differential effect, which can be positive or negative, distinguishes between localized and typical corrosion. A direct current reduces the cathodic component's total corrosion rate, making it catholically protected. Depending on the circumstances of some or all of the elements, the impact of geometric factors on galvanic activities may be analytically examined. Galvanic corrosion is more sophisticated than conventional corrosion since it considers geometrical, material, and environmental aspects. All the factors involved in galvanic corrosion are displayed in Figure 7.

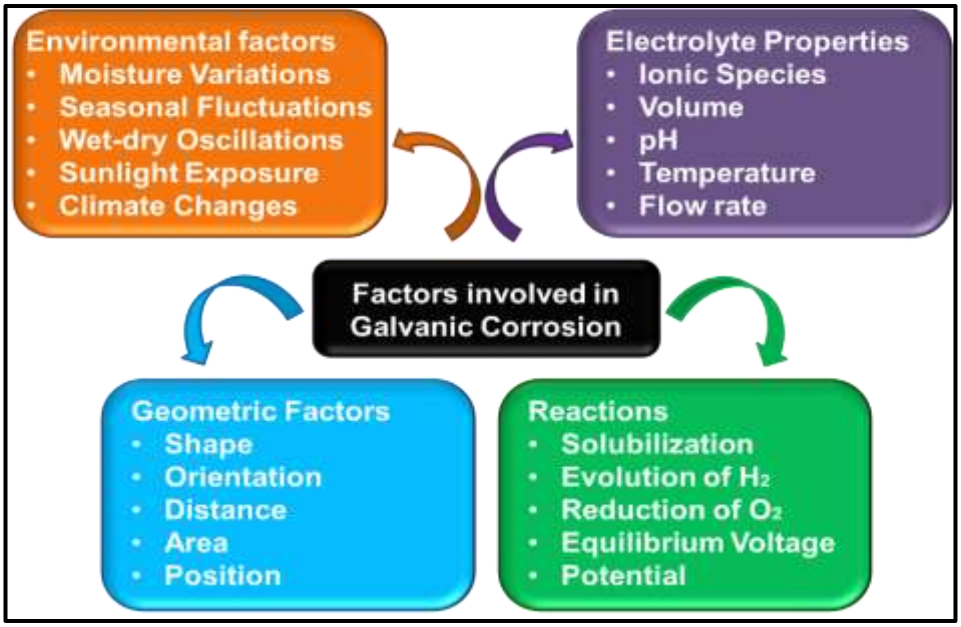

Figure 7: Factors involved in galvanic corrosion [33]

Microbial corrosion is also known by many names. Microbial corrosion is often referred to as bacterial corrosion, bio corrosion, microbiologically influenced corrosion, or microbially induced corrosion (MIC) [35,36]. Biological organisms and microorganisms cause this kind of corrosion and corrosion can be confined and generalized depending on the metal substrate and environment. MIC occurs often due to the prevalence of microorganisms, nutrients, and corrosive chemicals in fluid systems and industrial processes, it may influence both metallic and non-metallic items [37]. MIC is the metals degradation caused by microorganisms. Acid-producing bacteria, sulfate-producing bacteria, and iron-reducing bacteria are the most prevalent cause of MIC [38]. The term microorganisms-influenced corrosion describes corrosion produced by microorganisms in biofilms on metal surfaces [39]. In recent years, scientists and engineers have been interested in MIC corrosion due to its unique character. Surface analytical and electrochemical approaches have been developed to measure the effect of bacteria on electrochemical phenomena and reveal corrosion causes [40,41]. Moreover WLC is a localized corrosion phenomenon produced by the creation of differential aeration cells (DACs). In the elevated region, the water is oxygenated to a high degree and executes as a cathode whilst the area below serves as an anode. As a result, most, serious corrosion takes place near the WLC is a well-known phenomenon. Traditional methodologies such as weight loss metrics make it difficult to fully understand the process and dynamics at work [42]. There has been no recorded comparison between WLC in natural and artificial saltwater. Marine water is noteworthy for various microorganisms;

aerobic microorganisms require oxygen to function correctly. Aerobes metabolic assumptions about oxygen alter oxygen distribution, potentially affecting DACs and WLCs [43,44]. It is a common problem in the water industry due to oxidation in which the base material reacts to fluctuations in oxygen exposure, corrosion is common in assets such as pipelines, and tanks where water is stagnant or near the waterline, the waterline oxidation process takes place when material comes in contact with water, WLC occurs when one portion of the substrate is immersed in water while superfluous part is linked with atmosphere [45]. In this case, Figure 8 the quantity of oxygen that interacts with the metal, which is frequently coated with rust and other corrosion products, is much lower than the amount that interacts with regions where the coating is either nonexistent or extremely thin. The development of DACs as a result of this phenomenon can cause localized corrosion, especially around pits and cracks. Materials like nickel, aluminum, stainless steel, and other passive metals are particularly vulnerable to this type of crevice corrosion, especially when they are exposed to extreme conditions like saltwater. Over time, the electrochemical imbalance caused by the differing oxygen availability might worsen corrosion and jeopardize the structural integrity of the impacted materials. This results in the difference in oxygen exposure of the material coating of the waterline system forming DACs that is responsible for a corrosive reaction. In this instance, there is less oxygen getting into touch with the metal (which is rusted, *etc.*) than there is with other parts. when there is either no porous or permeable covering layer or it is extremely thin. When materials like stainless steel, aluminum, nickel, and other passive metals come into contact with saltwater, etc., DACs have the potential to cause localized corrosion at pits (crevice corrosion).

Stress corrosion is a particularly harmful and insidious kind of corrosion that occurs when two critical components come together tensile tension and a corrosive environment, which is typically exacerbated by high temperatures. This risky combination starts a localized corrosion process that affects the strained regions of the metal, causing them to become anodic in comparison to the unstressed sections. Tensile stress rusting is a subtle type of corrosion that can weaken a metal’s structural integrity, resulting in a catastrophic collapse without warning. This sort of corrosion is especially troubling since it can harm even healthy components, resulting in catastrophic results. The combination of tensile stress and corrosion generates a perfect storm, emphasizing the necessity of understanding and managing this form of corrosion in high-risk settings [46]. Therefore, the inter-granular corrosion (IC) is a highly confined and selective kind of corrosive attack that occurs mostly at grain borders. This type of corrosion is differentiated by its preferences for targeting grain boundary locations that are electrochemically isolated from the bulk material because of their unique microstructural characteristics, grain boundary zones exhibit different electrochemical properties than the surrounding bulk material. These differences create a localized corrosion cell, with the grain boundary functioning as the positive electrode and the bulk material as the negative electrode. As an outcome, the grain boundary area becomes prone to corrosive attack resulting in the initiation and development of intergranular corrosion [47].

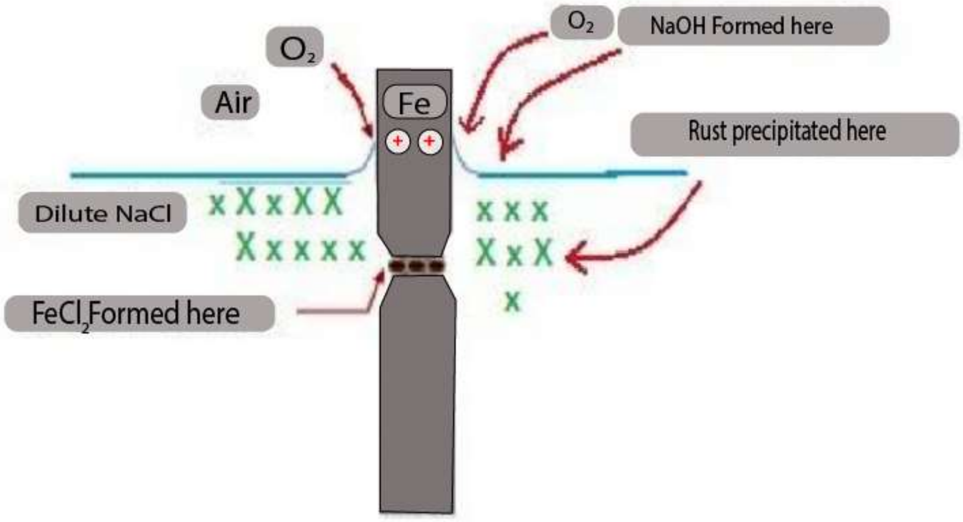

Figure 8: Water-line corrosion, showing DAC [23]

Lab studies on corrosion

Corrosion laboratory testing employs several electrochemical methods both destructive and nondestructive. These approaches enable researchers to completely examine the corrosion performance of metallic materials in a wide range of corrosive situations, providing critical insights into their behavior. Scientists may use these methods to measure corrosion rates, estimate material susceptibility, and qualitatively describe corrosion mechanisms, all of which help guide material selection, design, and mitigation activities.

Destructive techniques

The material's corrosion and electrochemical behavior were examined using destructive techniques, including the weight loss method, the thermometric method, the measurement of the volume of released hydrogen gas, and potentiodynamic polarization. By subjecting materials to certain corrosive conditions, destructive testing methods investigate their electrochemical and corrosion behavior, one of the common methods is the weight loss method that also identified as the weighing-based method to be a destructive testing procedure, this method entails weighing a test specimen with a precisely specified surface area (S, indicated in square centimeters) before (W_i in grams) and after (W_f in grams) exposure to a corrosive environment for a predetermined duration (t, in hours). To ensure accuracy and reliability, the specimen surface must be treated according to established standards and protocols such as those outlined in the american society for testing and materials (ASTM) standard procedures. Although this method provides a quick-forward technique for evaluating corrosion rates it has also significant advantages. The weight loss technique offers an overall view of corrosion activity but does not provide a detailed review of the corrosion process. Furthermore, the destructive nature of this technique prohibits the test material from being reused or further studied. The weight loss method employs the following equation to determine the material's corrosion rate (C_R) [48].

$$C_R = \frac{W_i - W_f}{S \times t} \tag{4}$$

Another damaging strategy, known as the gasometric technique, measures the amount of released hydrogen gas. This approach is especially beneficial when the corrosion process causes the emission of gas, typically dihydrogen gas (H_2). Figure 9 demonstrates the development of the hydrogen gas release over for hot dip galvanized (HDG) steel displayed to imitated new concrete pore solution including sodium chloride (NaCl) both in the deficit and the existence of sodium molybdate (Na_2MoO_4). This plot gives useful information on corrosion kinetics and the effect of various elements in the corrosion process. According to the findings, there was a discernible reduction in hydrogen evolution, especially in sample molybdate-coated (MC), when Na_2MoO_4 was added to the solution. Na_2MoO_4 significantly hindered the water reduction process during the early phases of corrosion.

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \quad (5)$$

This inhibitor shows how Na_2MoO_4 can reduce the production of hydrogen gas by interfering with the cathodic process. The surfaces of the samples subjected to Na_2MoO_4 developed a compact and stable coating of corrosion products over time. By preventing corrosive substances like oxygen and water from reaching the metal substrate, this thin coating lowers the corrosion rate of 2. Furthermore, the layer that developed in the presence of Na_2MoO_4 was noticeably more compact, guaranteeing superior protection and reducing hydrogen development over time, as demonstrated by the comparison of sample MC with sample Ref. Na_2MoO_4 is very successful in reducing corrosion because of its dual function of inhibiting the cathodic process and creating a protective layer. The hydrogen evolution in sample Ref. was progressively repressed after two days of immersion due to the accumulation of corrosion products on the surface. After seven days, the evolution continued, but for sample MC, it was reduced during the early corrosion stage and nearly stopped after five days due to Na_2MoO_4's suppression of cathodic reactions [49].

The thermometric technique is another damaging methodology for assessing the corrosion actions of metal and alloys this approach entails tracking temperature variations in the corrosion system which can either be metal or corrosive fluid over a certain period. To ensure reliable results, keep all system components at a constant starting temperature before commencing the experiment. The initial temperature stability is necessary to provide a consistent baseline for subsequent temperature readings [50].

Figure 9 displays temperature variations produced by aluminum corrosion in a 2 M HCl solution, in the presence and in the absence of an inhibitor at varying intensities. This graphical representation delivers high-quality reports on corrosion kinetics and the inhibitor's impact on the corrosion process. By analyzing temperature function over time researchers can get an optimal knowledge of corrosion causes and the performance of corrosion mitigation strategies. The thermometric approach offers a unique perspective on corrosion behavior, however being a destructive method, it has limitations that must be carefully addressed when planning tests and evaluating data [51]. Researchers can use a calibrated thermometer to observe the corrosion process and then compute the reaction number using:

$$R_N = \frac{T_m - T_i}{t} \quad (6)$$

Where, T_m and T_i signify the corrosion system maximum temperature in °C and beginning temperature in °C, and also t signifies the time to achieve T_m in minutes.

Potentiodynamic polarization corrosion is another destructive method that helps determine the corrosion behavior of various alloys even when exposed to the same electrolyte. This method is quite useful for determining the corrosion resistance of alloys under identical conditions. However, it is vital to highlight that this method only applies to metallic surfaces or metallic coatings; because it is destructive, the same sample cannot be reused for future research [52,53]. Figure 9 displays a typical polarization curve for a copper electrode immersed in an acid solution, emphasizing the prominent anodic Tafel line. Researchers may use such curves to derive electrochemical corrosion features such as corrosion current identity (I_{corr}), corrosion potential (E_{corr}), and cathodic and anodic Tafel slopes. The current corrosion density is instantaneously associated with the corrosion rate, which means that increasing current density leads to an increase in the corrosion rate and vice versa. Using potentiodynamic polarization testing, scientists can better know about corrosion mechanisms and create more efficient techniques for safeguarding metallic objects from corrosive conditions [49,54].

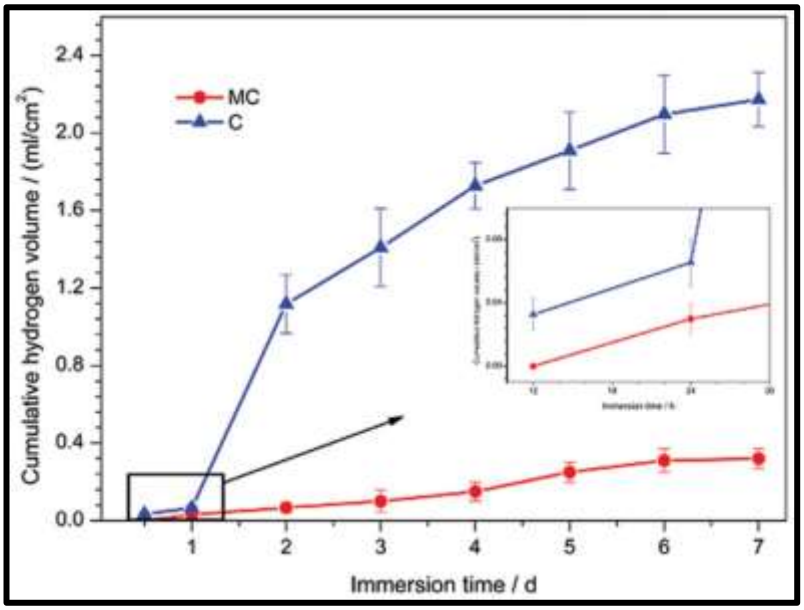

Figure 9: Changes in the total volume of developed hydrogen in solutions MC and Reference sample concerning the exposure time [49]

Non-destructive techniques

To examine the material's integrity without creating harm, non-destructive methods such as surface morphology characterization, localized electrochemical impedance, open circuit potential (EOCP), and electrochemical impedance spectroscopy (EIS) were used.

The EOCP is a prominent electrochemical approach in corrosion and coating research offering valuable insights into material behavior in a range of conditions. Researchers may learn important information about systems stability by continuously monitoring the EOCP measurements over time and identifying when they reach a steady state. Furthermore, this method identifies various states, such as the shift from passive to active behavior, which is crucial for understanding the corrosion process and protective coating performance. The EOCP techniques give scientists a dynamic perspective of the corrosion process allowing them to monitor changes in the material electrochemical properties in real time. For example, the ECOP also known as free corrosion potential, is the difference between two conductors submerged in an electrolyte with no current running between them.

Figure 10 shows a typical EIS spectrum of copper electrodes submerged in a hydrochloric acid solution, exhibiting the complex interplay between the electrochemical properties and the corrosive environment. The EIS spectrum may provide researchers with valuable information on corrosion kinetics, coating integrity, and material degradation, which can be utilized to develop more effective corrosion mitigation methods and coating formulations [55]. Nyquist and Bode charts are the two primary ways that EIS data may be shown. These plots give several viewpoints on the impedance behavior of materials and provide important information on the electrochemical processes involved in coating deterioration and corrosion [56,57]. An electric current runs through a circuit with various components and the combination is used to calculate impedance. Generally, it is a transient approach that involves adding excitation to the system and evaluating the reaction. Many electrical characteristics of the system may be identified. To better understand the relationship between materials, coatings, and corrosive environments and develop more robust and efficient corrosion protection systems, numerous studies employ EIS to evaluate the stability and protective efficacy of coatings. EIS was used by Nardeli *et al.* to assess the corrosion protection efficacy of several coating formulations, demonstrating variations in their efficacy over time. The fast charge transfer mechanism, in which copper dissolves into the acidic media, is responsible for the corrosion behavior in the high-frequency area of the Figure 10. In a 1M HCl solution, the copper Nyquist impedance diagram illustrates how copper (Cu) interacts with chloride ions (Cl^-) to create adsorbed intermediate species ($CuCl_{ads}$) and release electrons, which is a crucial stage in the corrosion process.

$$Cu+Cl^-\rightarrow CuCl_{ads}+e^- \qquad (7)$$

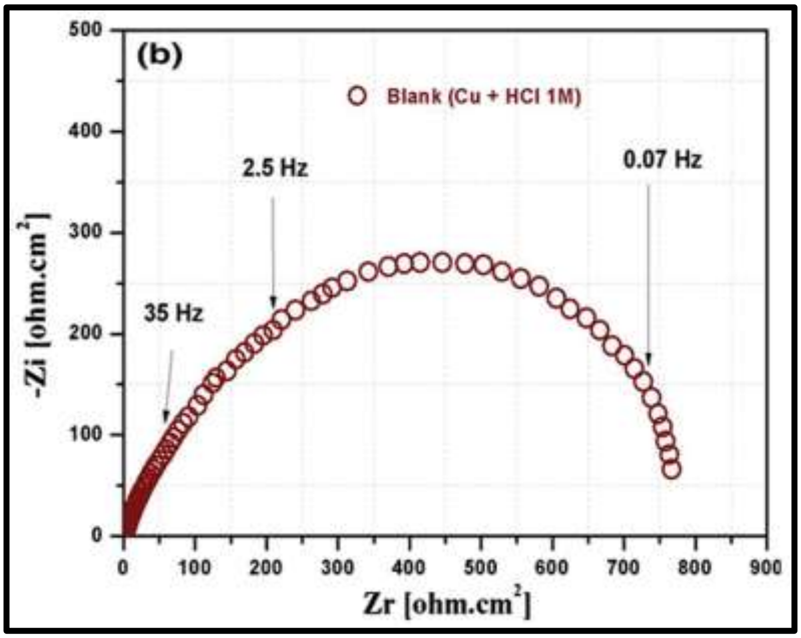

Figure 10: Nyquist plot of an EIS spectrum for a copper electrode in naturally aerated hydrochloric acid at 20 °C [58]

Localized EIS is done on a smaller sample than an EIS inquiry because the analysis time is frequently shorter, it allows for the use of conditions intended to speed up corrosion. This method enables researchers to concentrate their studies on a specific region of interest accelerating the corrosion process and allowing for a more thorough evaluation of the insuring damage. Controlled defects like scratches, notches, or other simulated damage are added to speed up corrosion studies. By forming distinct zones, these defects enable targeted examination of corrosion behavior. By focusing on particular regions, scientists may assess the impact of protective coatings, environmental factors, and material composition, facilitating the creation of efficient mitigation plans. This method allows researchers to investigate the effect of various factors on corrosion behavior such as material's composition, environmental conditions, and formulation of protective coatings resulting in the development of more effective corrosion mitigation strategies and improved material durability in harsh environments [59,60].

Visual inspection of material with optical microscopy or scanning electron microscope (SEM) is a quick and easy approach to determine the presence or absence of corrosion, regardless of length of immersion. Optical microscopy provides a rapid method for analyzing surface morphology and detecting corrosion but compared to optical microscopy, SEM offers higher-resolution pictures for analyzing corrosion morphology and surface topography. Visual observation rather than time-dependent measurements allows scientists to rapidly assess the corrosion resistance of material and coatings [61]. Researchers can use the samples to detect early signs of corrosion and evaluate the efficiency of corrosion by using several corrosion-protecting agents such as coating or inhibitors, in avoiding damage. These findings can provide critical insights into the protection process allowing corrosion prevention strategies to be modified and optimized. For example, Figure 11 (a) depicts a SEM image of a mild steel coupon following exposure to an acidic solution these photographs provide a detailed visual representation of the coupon surface morphology after immersion including changes in morphology caused by a corrosive environment [62]. Elaborating, energy-dispersive X-ray (EDX) spectroscopy is a valuable analytical technique extensively utilized to determine the elemental composition or chemical properties of a sample undergoing corrosion. This information is essential for understanding the corrosion mechanisms and developing effective corrosion strategies. EDX is commonly used with a SEM to provide a more comprehensive understanding of corrosion. Atomic force microscopy (AFM) micrographs such as those shown in Figure 11 (b) provide a careful micrograph produced using AFM that shows the three-dimensional surface topography of a corroded material at the nanoscale. This cutting-edge microscopy method enables researchers to precisely see and quantitatively evaluate the surface texture and roughness. The distribution and shape of corrosion inhibitors and byproducts on the material's surface are revealed by AFM. Researchers can improve methods for avoiding and reducing corrosion-related damages in various materials and applications by examining the comprehensive topographical data that AFM provides. With surface-sensitive analysis, XPS assesses the chemical and electrical makeup of corroded surfaces.

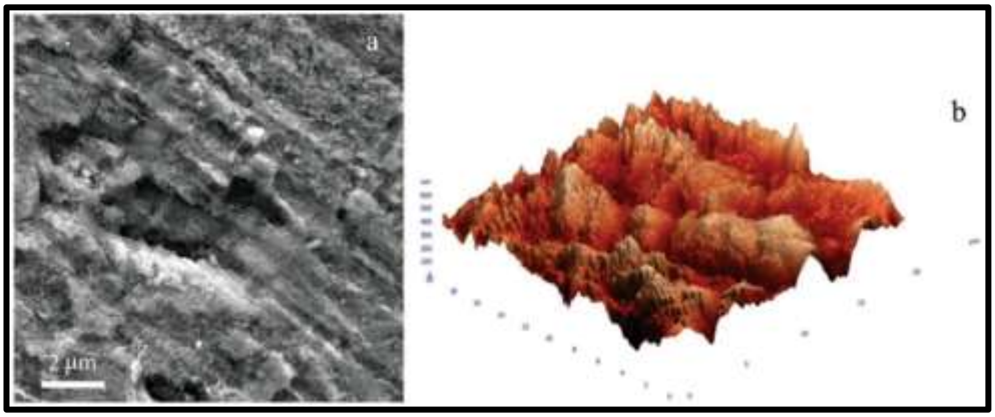

Figure 11: (a) SEM and (b) AFM micrographs of metal surfaces following immersion in hydrochloric acid solution [16]

CM

CM assesses metal loss, crack or pit development, erosion scale deposition, and fouling on a specific piece for a piece of metallic equipment or structure that is exposed to the environment. CM assesses the corrosiveness of an environment. CM tries to forecast and slow down the deterioration of equipment and structures. Enterprise attempts to increase shutdown intervals and reduce incidents that risk workers and the environment corrosion can result from insignificant production losses and unexpected shutdowns, together with the need for excellent plant management and safety, emphasize the value of efficient online CM.

Corrosion causes 70-90% of failure in various industries resulting in unplanned downtime, environmental damage, and productivity penalties [63,64]. The effect of efficient corrosion management can have serious implications, including equipment failures, dangerous chemical releases, and catastrophic environmental disasters without adequate CM. Corrosion can continue unnoticed and unregulated resulting in catastrophic failures that can cause major economic loss/injury to human health and environmental degradation [65,66]. The majority of corrosion-related damage occurs during brief, essential intervals such as process starting, modifications, upsets, or shutdown. These traditional stages typically create favorable circumstances for corrosion to accelerate causing severe damage in a short period. Therefore, it is critical to apply efficient corrosion control measures during these susceptible periods to limit the risk of damage and manage the life span of equipment [67]. Corrosion management is essential in many sections and serves as the foundation of corrosion management, it is a critical component of asset management that ensures the integrity and dependability of equipment and infrastructure. By incorporating CM, companies may decrease corrosion-related hazards save minimal cost, and improve operating efficiency [68,69]. In industrial sectors, a multimodal approach is necessary combining two or three approaches to provide a comprehensive understanding of the corrosion process throughout. This is because corrosion may manifest in various ways, including localized and general corrosion and each monitoring method has its own set of advantages and limitations. To effectively monitor corrosion, two essential characteristics should be considered: response time and sensitivity which are inversely proportional to each other. A monitoring system with great sensitivity may have a longer time reaction whereas a system with a rapid response time may have some sacrifice on sensitivity. Industries can utilize a variety of methods to obtain accurate and timely information regarding the corrosion process [70].

CM has been defined variously since its broad adoption in the United States and Europe some definitions that have appeared in the literature are as follows:

1) The deliberate and systematic process of monitoring and measuring corrosion or deterioration in an atom of apparatus with the primary aim of getting a full understanding of the corrosion mechanism and processes. This approach aims to gather detailed insights and values that can be used to form and develop effective corrosion regulation techniques, mitigate the negative effect of corrosion control, and ultimately ensure the equipment's dependability, integrity, and longevity as well as the overall safety and efficiency of the operation. By collecting systematic measurements, operators may identify potential corrosion issues, track their progress, and implement target damage prevention and mitigation measures, minimizing maintained cost and environmental costs [71].

2) The evaluation of deterioration or disintegration of material properties and structure caused by environmental factors, chemical reactions, or biological interactions which can lead to loss of functionality, strength, or performance over time [72].

3) Any method or process used to monitor, detect, or evaluate corrosion progressions such as visual examination, non-destructive testing, laboratory analysis, or other types of evaluation to assess the degree, rate, or severity of corrosion damage [73].

Effective corrosion management in companies is critical for ensuring adequate safety, health environmental sustainability, and economic viability. CM and inspection are critical components of any corrosion system including proactive and reactive strategies for controlling corrosion hazards as follow [74]:

1) Proactive methods include establishing and executing monitoring and inspection programs before corrosion or degradation develops, this can be accomplished by conducting a corrosion risk assessment or another type of examination to identify possible corrosion locations.

2) Reactive measures are implemented in reaction to detected problems, which are usually discovered by proactive monitoring, event detection, or frequent inspections. These steps are performed after a problem has been

identified, to reduce its impact and prevent additional damage.

CM is particularly beneficial in capital inspective sectors such as oil and gas (production and refining petrochemical/chemical manufacturing and power generation). These industries have large volume throughputs and lengthy shutdown times which might result in financial fines. CM detects and regulates corrosion regimes during transient activities such as startup and shutdown changing steady-state operating conditions such as temperature or composition beyond the original design parameters can cause corrosion. CM can identify the origin of corrosion damage and assess the effectiveness of corrosion remedies and inspections to indicate a sudden reappearance of the problem in service. CM can assist in optimizing inhibitor levels and save chemical expenditures. Following laboratory screening, a plant trial of corrosion inhibitors is usually done to establish the most powerful moderator and suitable prescribed doses. Observing statistics data with a dosage pump can automate inhibitor delivery, keeping corrosion rates less than the predetermined limits while remaining cost-effective. CM is frequently used for one or more of the following objectives:

1) Early identification and diagnosis of corrosion in operating equipment allows for prompt intervention and focused maintenance, which helps to avoid additional damage and guarantee equipment dependability.

2) Evaluate and optimize the effectiveness of corrosion prevention techniques such as corrosion inhibitors to ensure that they protect operational equipment.

3) Maximizing maintenance efficiency requires informed scheduling decisions, such as strategically planning shutdowns to reduce downtime and optimize resource allocation. This allows maintenance teams to make data-driven choices, decreasing downtime and ensuring that resources are used efficiently.

Including industrial CM programs in proposals can bring significant advantages. By referring to credible sources such as online resources, one can tap into expert knowledge to increase the effectiveness of CM efforts and improve the proposal. This method displays a commitment to proactive corrosion control, which has the potential to enhance asset dependability, lower maintenance costs, and boost operating efficiency.

Prevention from corrosion

Implementing a corrosion protection system requires careful consideration of variables such as corrosion type, metal properties, surface condition, pH, ion presence, temperature, and fluid flow. Vernon categorizes preventative methods into four types: environmental changes, metal enhancements process, alterations, and coatings. Standard industrial practices include using eco-friendly materials and designing equipment to prevent corrosion-prone combinations. Mechanical stress reduction reduces fatigue corrosion, fretting, and stress corrosion cracking. A thorough approach is necessary for successful corrosion prevention [75]. The typical methods that prevent corrosion on metal surfaces are surface coatings and surface modifications using inhibitors, there are various types of coatings each created for a specific use and with varying degrees of durability.

These coatings provide a long-lasting barrier against corrosion elements, increasing the life of metal substrates. The quantity of corrosion protection may be optimized by altering the coating composition to fit the intended purpose. Several researchers have focused on using ecologically sustainable coatings to shield metallic surfaces against corrosion. For example, an environmentally friendly tannic acid/ Zn conversion coating was employed to prevent iron corrosion with a protective efficiency of around 92.39%. Meanwhile, polyurethane coatings produced from vegetable oils with Zn micro flakes increased the corrosion resistance of AA7475 aluminum alloy due to their self-healing characteristics, anodic protection, and cathodic inhibition. The system reaction is crucial for effective protection and self-repair. Another method for protecting metallic substrates from corrosion is to add inhibitors into the solution; a collection of organic and inorganic compounds has been demonstrated to be efficient corrosion inhibitors at a minimal cost. Corrosion inhibitors are critical in reducing metallic waste and minimizing material failure, which can cause industrial activities to shut down suddenly, increasing costs—utilizing corrosion inhibitors to prevent mineral breakdown and reduce acid combustion [76,77]. A wide range of economic corrosion inhibitors are available for use in augmented solidified mixtures, they are used to combat the corrosive effect of chloride ions. Cations (usually sodium, calcium, or magnesium) that intrude the concrete through chloride have no substantial effect on the corrosion method. Steel bars do not corrode in the absence of water or chloride ions, even in concrete at high pH values [58]. Corrosion inhibitors decrease corrosion without compromising concrete quality, they only affect corrosion though. An inhibitor can either increase the quantity of chloride ions required to initiate corrosion or slow it down. Although not considered corrosion inhibitors, additives that reduce chloride ion infiltration may have a corrosion-reducing effect [78]. Corrosion inhibitors function in two ways; first they transport molecules to the metal surface, and then their useful groups collaborate with it. The studied important factors for inhibitors are as follow:

Solvent effectiveness of inhibitors in the corrosive medium; Consistency of inhibitors in corrosive system; Inhibitor cost;
Temperature and pH affect the stability of inhibitors; Environmentally friendly; and Corrosion inhibition efficiency.

However, research has shown that these substances endanger aquatic life and have long-term environmental implications [79]. Zinc coatings have been widely used to enhance corrosion resistance on steel surfaces, but they are fragile and not suitable for harsh environments. Chromatode conversion coatings have shown promising properties, but they are unstable at higher temperatures and can cause white rust. To address these issues, researchers are exploring the use of second-phase reinforced particles in metal matrix composite coatings. These composites have properties such as dispersion hardening, self-lubricity, high-temperature inertness, good wear and corrosion resistance, and chemical and biological compatibility. Electrodeposition is a popular method for fabricating metal matrix composite coatings, as it can be applied at ambient temperatures. Nanoparticles like SiC, TiO_2, Al_2O_3, ZnO, WC, PTFE, SiO_2, CNTs, CeO_2, Ni_3S_4, MoS_2, graphene, and diamond have been incorporated into these coatings due to their high corrosion resistance, self-lubricity, high-temperature inertness, and biological compatibility. This study aims to explore and assess the electrodeposition of Zn-TiO_2 nanocomposites and their corrosion behavior using weight loss, salt spray, electrochemical methods, surface morphology after the corrosion process, and XRD measurements [80].

In recent years, there has been a notable shift in corrosion inhibition with a focus on developing new ecologically friendly alternatives to existing harmful inhibitors. As a result, several researchers have looked at plant-derived corrosion inhibitors as long-term solutions in harsh environments. By emphasizing the potential of plant extracts, scientists seek to create green and effective corrosion prevention treatments that are both ecologically and chemically sustainable. Such extract contains various naturally occurring organic compounds and molecules with a high functional group content, they are effective and eco-friendly corrosion inhibitors [81] which results in the creation of a protective layer that protects the metal from corrosive chemicals. This adsorption process can be divided into two types: direct adsorption, in which the inhibitor molecules interact directly with the metal surface, forming a strong bond that prevents corrosive species from accessing the metal, and indirect adsorption, in which the inhibitor molecules first bind to pre-adsorbed species on the metal surface, such as chlorine ions, enhancing the establishment and stability of the shielding barrier. The organic-based inhibitors effectively decrease the metal's reactivity by adsorption, limiting corrosion processes, and safeguarding the metal from deterioration. Inorganic inhibitors, such as molybdate anions, play an essential role in corrosion prevention by employing a two-fold method that emphasizes increasing the defensive functions of the passive layer formed on the metal surface. First, these inhibitors stabilize the passive film by repairing any faults or imperfections, thereby improving its barrier performance against corrosive elements. Second, they produce insoluble compounds that prevent corrosive anions, such as chloride ions, from adsorbing onto the metal surface through a competitive process. Molybdate anions effectively inhibit corrosive species from gaining access to accessible adsorption sites, reducing the likelihood of corrosion initiation and advancement. Furthermore, the formation of insoluble compounds aids in the restoration of any damaged sections of the metal surface, preserving the passive film's integrity and functionality. Inorganic inhibitors, such as molybdate anions, provide good corrosion protection throughout the process, extending the metal's lifespan and preserving its structural integrity [82,83]. The search of superior corrosion protection and engineering feasibility necessitates the creation of unique technologies that strike a compromise between cost-effectiveness and high performance. Currently, there is a growing interest in researching new, environmentally friendly options that emphasize the use of non-toxic, biodegradable inhibitors, which not only ensure environmental sustainability, but also provide a safer approach to corrosion management. Furthermore, there is an increasing need for protective coatings with self-healing properties, allowing them to repair damages on their own and maintain integrity over time. This combined focus on sustainable inhibitors and self-healing coatings has a transformative impact on anti-corrosion technology by providing a comprehensive solution that combines economic feasibility, environmental responsibility, and better performance. By pushing the boundaries of research and development, scientists and engineers may create cutting-edge technologies that address the complex challenges of corrosion prevention, eventually leading to more lasting, sustainable, and cost-effective solutions.

Conclusion

Corrosion is considered as the degradation of metallic objects and the effect on their physiochemical properties due to the number of environmental factors that lead to the damage of key industrial infrastructures, hazards for human safety, increased metallic waste, and pollution of the ecosystem. The metallic structure as a result of corrosion returns to its metallic oxide state that is thermodynamically stable when comes in interaction with moisture and oxygen. The rate of corrosion in aquatic settings is influenced by certain factors. Corrosion affects the metals and alloys in almost every type of environment from the dry environment (aircraft) to the marine environment even corrosion occurs also due to the influence of microbes (biomedical objects). Corrosion rates are influenced by factors such as oxygen availability, water or moisture content, and other elements, ions, and compounds, these factors can affect corrosion in various contexts like industrial and maritime settings, these environments contain oxygen and other pollutants like ozone, salt, ions, dust, sulfur dioxide, hydrogen, hydrogen sulfide, and microorganisms**.** In each environment, different parameters influence the rate of corrosion, so it is necessary to examine these factors in detail to minimize corrosion. Optimizing these factors and laboratory scale testing helps to minimize the hazards of corrosion and corrosion cost. The methods employed to early testing of corrosion are both destructive and non-destructive in nature (electrochemical in nature or surface morphology). In the destructive techniques, the specimens used for testing are not able for further use or study. CM measures the corrosiveness of an environment for the material being analyzed. CM helps to find out the rough early estimate of corrosion and slow down the worsening of equipment and infrastructures. This technique provides a promise to practical control of corrosion, which has the prospective to augment dependability, lesser maintenance cost, and boost the operating efficacy. Therefore, timely preventive measures are proven to inhibit or slow down the corrosion by applying appropriate protective coating materials on the metallic structures or via using some inhibitors that may be organic and inorganic in nature. The demand for sustainable, eco-friendly, and highly efficient inhibitors is still under research to address the complex and deteriorating process of corrosion which can only be minimized, as it is natural and unavoidable.

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