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Review of forms of corrosion and mitigation techniques: A visual guide

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Abstract

Over the years, issues relating to corrosion have been a serious challenge confronting effective scientific and engineering applications of metallic materials in the industry. Annual loss due to corrosion issues has been quite alarming as it runs into trillions of dollars. In this review, forms of corrosion, factors affecting each form, mechanism of formation, and different aggressive environments that propagate corrosion have been identified. Mitigation techniques against this threat were all discussed, especially those involving the use of eco-friendly, cheap, available, and non-toxic materials. It was observed that the principle, process, and conditions governing each form of corrosion must be well understood before it can be effectively mitigated. This can be done either by proper material selection and design, environmental measures, modification and engineering design, modification of corrosive media, use of inhibitors, or sacrificial and protective coatings. However, adequate knowledge of the environment and nature of metal to be deployed in such an environment is essential in ensuring such material's protection, safety, and durability. For efficient and effective corrosion prevention and control, these mitigation techniques can either be implored exclusively or collectively depending on the material's nature and the setting in which it will be used.

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1. Introduction

Metals and alloys are very important industrial materials due to their extensive industrial applications such as transportation, construction, manufacturing of vessels, ships, trains, armored tanks and carries, aircraft, vehicles, furnaces, heaters, heat exchangers, reactors, processing plants, pipelines, oil rigs, etc. However, corrosion has been a major issue limiting the effective use of metals

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and alloys in the industry as it results in the degradation and destruction of the material when exposed to aggressive environments [1]. Corrosion is said to occur when a component of the environment is consumed or dissolved into the substance due to an irreversible interfacial reaction of metallic materials with the environment [2]. Corrosion is a geogenic process that results in an electrochemical reaction between a metal's anodic and cathodic regions, connected via electronic and electrolyte paths, which results in the degradation of the metal [3]. This process returns metals to their original ores or better put a reverse process of metal extraction.

Corrosion is a serious environmental issue as it can lead to material destruction, pollution, contamination of products, and economic loss. Corrosion poses a serious detrimental health challenge because serious health problems might occur when the body is exposed to a certain amount of undesired metal ions. Almost all metallic materials are expected to deteriorate over time especially when exposed to certain aggressive environments [4]. The United States government-commissioned studies revealed that the yearly cost of corrosion was in the tune of $400 billion equivalent to 3% of the nation's gross domestic product (GDP) [5, 6]. Existing literature also showed that in India, the direct cost of corrosion as projected was in the region of $26.1 billion signifying 2.4 % of the country's GDP [7, 8]. Corrosion engineering is the science of preventing and controlling corrosion and when effectively applied could save up to $9.3 billion in costs [4]. The utmost stern effect of corrosion is that it can lead to infrastructural defects, leading to loss of financial wealth, natural resources, equipment, and products [2]. It can also lead to the contamination of products and diseases [2].

Anawe *et al.*, investigated the microstructural and physical characteristics of a newly formulated nano-composite material using the Dual Anode Electrolytic Co-deposition (DAECD) technique and reported that metallic corrosion has significant effects on metallic structures, buildings, and marine applications and this leads to gradual loss of mechanical strength of materials [9]. Ajoku *et al.*, further reported that no engineering alloy is corrosion-resistant as they all have different corrosion rates based on the environment it is deployed [10]. Olsen further highlighted that architectural, industrial designs, construction, and engineering process cannot be complete without first considering how prone or resistant the materials is to corrosion when deployed in the environment [11]. Consequently, the oil and gas industry has been the most hit among other industries that face corrosion crises. This is because corrosion leads to the rupture of pipelines, oil and gas rigs, storage tanks, and flow lines resulting in oil spillage, economic loss, and environmental pollution. Clean-up of oil spillages, litigation process, as well as compensation of affected community where the spillage occurred, are all capital intensive.

Notable catastrophic incidences due to corrosion have been reported and they include the engine failure of a 19-year-old Boeing 737 airliner that was in full flight at 24,000 feet when a significant portion of the upper fuselage broke off close to the front of the plane. [12, 13]. In a related development, the status of liberty in the New York harbor with a height of approximately 91 meters also recorded severe damage due to galvanic corrosion. In addition, it was stated that a sewer explosion in Guadalajara, Mexico, in April 1992 claimed the lives of over 200 individuals. The cause of the sewage explosion was traced to have resulted from corroded water pipelines which dripped water onto gasoline pipelines resulting in its corrosion and leakage of gasoline into the sewers [14]. Trethewey and Roberge in their report on corrosion management in the twenty-first century reported that fatalities and sequence of explosions due to corrosion of underground pipes resulted in the destruction of over 1,600 buildings with approximately 1,500 injuries. The cost of the damage was estimated to be to the tune of $75 million US dollars [15].

To effectively and efficiently control corrosion, dependent factors that encourage corrosion must be carefully identified, scientifically studied, and understood. This will help in product design and material selection to ensure high standards of safety. In addition, safety, as well as economic reasons, are the most crucial elements in corrosion prevention [16]. In addition, corrosion maintenance and repairs of corroded facilities involve time and resources and are also capital-intensive [17, 18]. Even though environmental causes of corrosion vary in the majority of applications, failure will eventually result from iterative combinations of two or more dependent factors [19–21]. This is because, depending on the environment and process, some metallic materials are more susceptible to corrosion than others [22].

Although scientists and engineers have and are still researching new designs and techniques geared towards effective prevention and control of corrosion-related issues. Existing literature has shown that the aspect of providing adequate information regarding forms, causes, mechanism of action, and mitigation techniques of different forms of corrosion has been properly addressed. In other to fill this gap of knowledge, this review provides a holistic overview with visual guides on forms, causes, and mechanisms of action of metallic corrosion in different environments. Different mitigation techniques that can be gainfully implored for effective prevention and control of corrosion-related issues were adequately identified and discussed.

1.1. Dependent Factors Causing Corrosion of Materials

Depending on the corrosive agent and the environment the material is exposed to or used in, several types of corrosion are formed. Corrosion can concentrate locally to form a pit or crack, or it can spread across large regions, corroding the surface more or less uniformly. As a diffusion-controlled process, corrosion can occur on exposed surfaces. Procedures such as passivation and chromate

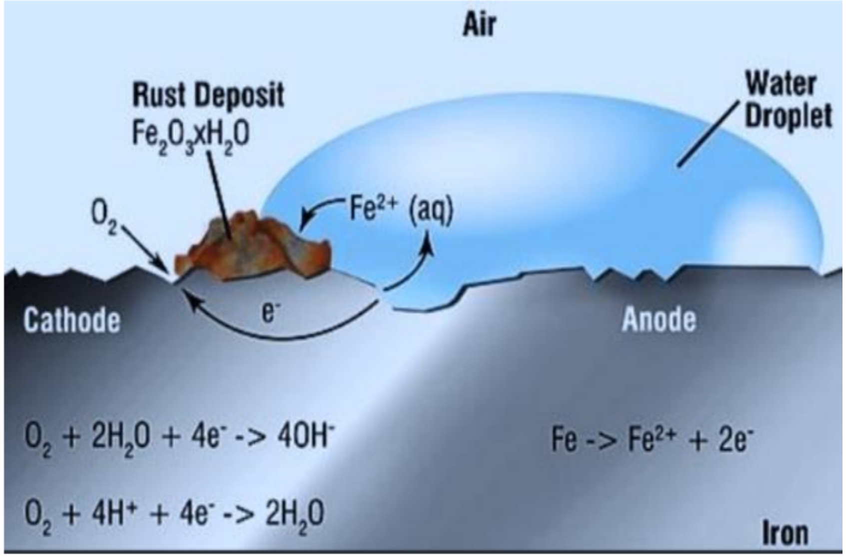

Figure 1. Schematic illustration of a corrosion process [28]

conversion that reduce the activity of the exposed surface may improve the corrosion resistance of a material [23]. Consequently, some forms of corrosion are less predictable and visible to the eyes while some require long propagation times before they can be visible.

2. Chemistry of Corrosion

Virtually every aqueous media or aggressive environment can propagate corrosion and this happens under diverse intricate situations. Anodic and cathodic half-cell reactions make up the two electrochemical half-cell reactions in a corrosion process. For corrosion to occur, three major components of an electrochemical system must be in place and they include; the anode where dissolution/oxidation of metal occurs resulting in the release of metal ions [24]. The second component in the electrolytic cell is the cathode where either oxygen reduction/or hydrogen evolution occurs depending on the medium and this forms the electrical conductor that gets depleted during the corrosion process in the cell [24]. The third component in the electrolytic process is the electrolyte which serves as the corrosive medium that allows for the transfer of an electron from the anode to the cathode [24].

Consequently, when metals and alloys are in contact with corrosive solutions, the metal atom at the anode site loses electron(s), which are subsequently taken up by other metal atoms at the cathodic site. To balance its positive and negative charges, the cathode conducts this exchange while in contact with the anode through the electrolyte. Metal ions that are released into the electrolyte are positively charged ions that can form bonds with negatively charged groups of atoms [25]. The corrosion mechanism showing equations of two main half-cell reaction that takes place in a corrosion process is shown in equations (1)-(7) [26, 27].

Anodic reaction:

$$M_1 \rightarrow M^{n+} + n^{e-} \quad \text{(oxidation reaction)} \tag{1}$$

$$M_n + \text{metal ion} \quad \text{(dissolves in solution)} \tag{2}$$

$$M_n + \text{metal ion} \quad \text{(formation of different oxides and hydroxides)} \tag{3}$$

After the release of electrons by metal atoms, any of the four cathodic reduction reactions can take place depending on the media.

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad \text{(oxygen reduction in acidic solution)} \tag{4}$$

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2\text{OH}^- \quad \text{(oxygen reduction in basic or neutral solution)} \tag{5}$$

$$2H^+ + 2e^- \rightarrow H_2 \quad \text{(hydrogen evolution from acidic solution)} \tag{6}$$

$$2H_2O + 2e^- \rightarrow H_2 + 2\text{OH}^- \quad \text{(hydrogen evolution from neutral solution)} \tag{7}$$

A schematic illustration of the corrosion process involving the process illustrated in equations (1)-(7) is shown in Figure 1 [28]

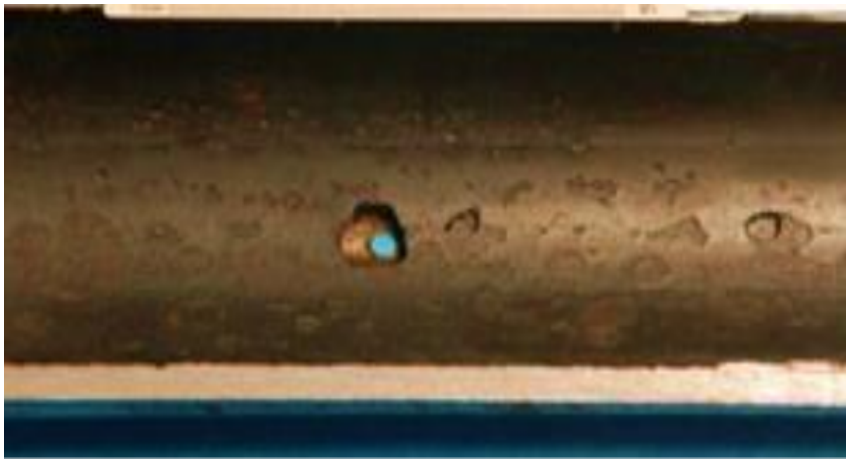

Figure 2. Diagram of pitting corrosion [33]

3. Forms of corrosion

Corrosion can be seen in different forms such as; pitting, galvanic, biological, crevice, high temperature, soil, uniform, intergranular, exfoliation, fretting, filiform, bimetallic, flow-assisted, oxygen, stress corrosion cracking, erosion, and oxygen corrosions.

3.1. Pitting corrosion

Pitting corrosion is a form of localized corrosion due to the fact the corrosion attack is aimed at a particular area of the metal structure. This type of corrosion occurs when there is a break in the metal's forms [29]. Pitting is more challenging to detect, forecast, design against, or control than uniform corrosion, and this makes it more dangerous as it is often masked by corrosion scales and other corrosion products produced during corrosion [30, 31]. The formation of a minor pit with negligible metal damage can subsequently lead to the failure or collapse of the entire engineering system. Pitting corrosion can occur under certain conditions, which may lead to accelerated corrosion in certain areas. These circumstances include low oxygen or high chloride (anions) concentrations, which frequently prevent the alloy from reforming a passivating coating [32]. Pitting corrosion can take on various forms such as hemispherical or cupped shapes, open mouths, or enclosures by thin layers of corrosion products, and is essentially a common denominator of all types of localized corrosion (Figure 2) [30, 33].

3.1.1. Causes of pitting corrosion [30, 31]

- The presence of imperfections like non-metallic inclusions in the component's metal structure.
- A mechanical attack such as scratching or impact takes out part of the protective film.
- Pitting corrosion can be initiated by any or a combination of the following.

Chemical or mechanical deterioration of the protective oxide layer, acidity, low dissolved oxygen concentrations (which tend to make a protective oxide film less stable), and high chloride concentrations in saltwater are all water chemistry circumstances that might cause failure of passivated coatings [30, 31].

3.1.2. Mitigation of pitting corrosion [23]

- Proper material selection with strong resistance to the service environment.
- Cathodic and anodic protection.
- Adequate control of pH, temperature, and chloride concentrations.
- Use of high-resistance alloys.

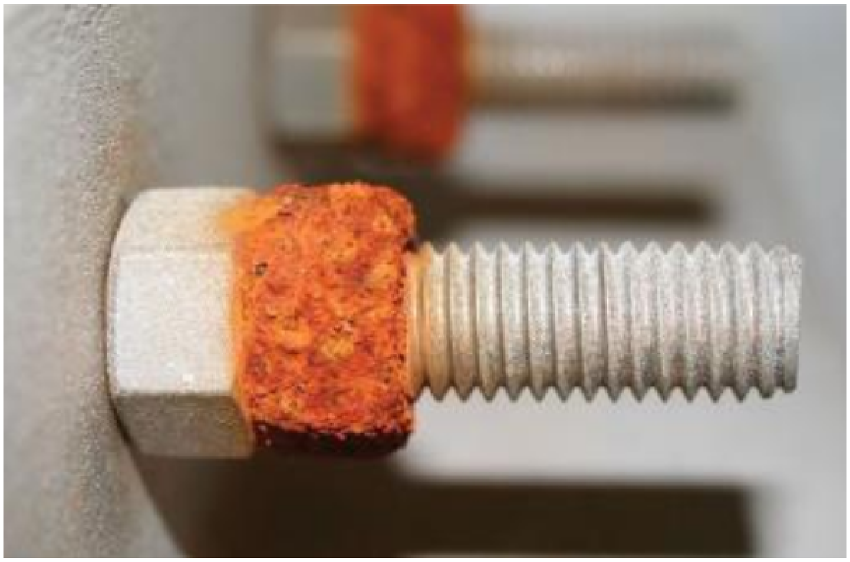

Figure 3. Diagram of galvanic corrosion [34]

3.2. Galvanic Corrosion

The most prevalent and damaging type of corrosion is galvanic corrosion. When two metals with different electrochemical properties come into electrical contact with one another in an electrolytic environment, the result is a deterioration of one of the metals close to the joint or juncture (Figure 3) [29, 34]. In this process, the metal at the anode loses ions to balance the electron flow since metals are made up of crystals, many such cells are set up, causing intergranular corrosion. Problems are most acute when the ratio of the cathode-to-anode area is large [35]. When two distinct metals are exposed to a corrosive environment, galvanic corrosion can also happen since there will be an electrical potential difference. In a galvanic cell created when two metals are electrically connected, the more active metal serves as the anode, increasing the corrosion of the other metal [29]. It has been reported that the area of the cathodic to the anodic metal is directly proportional to galvanic corrosion [36]. The more active metal (anode) corrodes in a galvanic cell (bimetallic pair), while the more noble metal (cathode) is protected. Some of the factors affecting galvanic corrosion are metal type, the relative size of the anode, and the environment (temperature, humidity, and salinity among others.

In addition, the following prerequisites must be met for galvanic corrosion to take place; the presence of electrochemically dissimilar metals, the metal must be exposed to an electrolyte and they must be in electrical contact with each other. The application of steel fasteners to join copper plates together is an illustration of a galvanic corrosion cell [34]. In engineering, construction, architectural and industrial processes, the use of dissimilar metals is discouraged unless it is necessary and the following precautions should be ensured in other to prevent galvanic corrosion [23].

3.2.1. *Galvanic corrosion can be prevented through any of the following ways [23]*

- Electrical isolation of metals.
- Application of protective coatings to the metal surface, usually the cathode.
- Ensuring that the less noble metal is protected.
- Use of inhibitors for corrosion mitigation.
- Imploring designs that make it simple to replace anodic components.
- exposure of metal to moisture.
- Selection of metals from the galvanic series that are near to one another.
- Create a design with a high anode/cathode area ratio.
- Use design allowances to account for the corrosion.
- Avoid unfavorable area effects of a small anode and large cathode.
- Proper insulation of dissimilar metals.

- When applying coatings, use caution, always paint the cathode, and maintain the coatings in good condition.
- When using materials that are far apart in the galvanic series, avoid threaded joints.

3.3. Biological corrosion

Biological organisms can be extremely important in initiating a metal attack that leads to the corrosion of metal. This attack can be categorized into two major attacks namely microbial-influenced corrosion and Macrofouling effects [32].

3.3.1. Microbial Influenced Corrosion (MIC)

This occurs when a metal deteriorates as a result of microorganisms' metabolic activities which can be aerobic or anaerobic bacteria containing enzymes that produce metabolites that accelerate corrosion usually the pitting type of corrosion which occurs on the surface of the metal (Figure 4) [29, 32]. Metallic and non-metallic materials, with or without oxygen, are both susceptible to microbially influenced corrosion. Sulfate-reducing bacteria (SRB) are active and create hydrogen sulfide when oxygen isn't present in the system, which causes sulfide stress cracking. In aerobic conditions, iron is often oxidized to different iron oxides and hydroxides by some of these bacteria. Concentration cells may also develop in corrosion product deposits, which can result in localized corrosion [34]. It has been reported that microbes such as *Micrococcus, Bacillus, Mycobacterium, Clostridium, Pseudomonas, and Escherichia*. It has been found that the bacteria *Escherichia* include a hydrogenase enzyme, which may use molecular hydrogen and may be connected to cathodic hydrogen depolarization, which causes corrosion of oil field pipes, steel casings, and vessels [37]. Literature studies have also shown that microbial-induced corrosion has been investigated in different environments [38–47].

3.3.2. Macrofouling effects

This form of corrosion arises from by-products produced by barnacles, oysters, and other macro-fouler which are usually acidic and can initiate the corrosion of metals. Crevice corrosion can also occur due creation of crevices by this macro-fouler usually at the attachment points [31]

3.3.3. Corrosion mechanism of MIC

Microbially influenced corrosion (MIC) occurs due to the presence of biofilm, an enzyme usually secretes by microbes and can induce local chemistry near the metal surface. Three elements make up a biofilm: the substratum, the biofilm, and the bulk fluid. As the water chemistry at the metal and biofilm interface changes over time, corrosion is started. Biofilm accumulation is a dynamic process. As a result of interactions between multiple compartments that are in a dynamic flux, microbial corrosion is the end outcome. The rotational mechanism for microbially induced corrosion mediated by SRB in an anaerobic environment was first established in 1961 as shown in equations (8)-(13) [48].

$$\text{Anodic reaction}: 4\mathrm{Fe} \rightarrow 4\mathrm{Fe}^{2+} + 8e^{-} \tag{8}$$

$$\text{Dissociation/ ionization of water}: 8H_2O \rightarrow 8H^{+} + \mathrm{OH}^{-} \tag{9}$$

$$\text{Cathodic reaction}: 8H^{+} + 8e^{-} \rightarrow 8H \tag{10}$$

$$\text{Cathodic depolarization by SRB}: \mathrm{SO}_4^{2-} + 8H \rightarrow S^{2-} + 4H_2O \tag{11}$$

$$\text{Corrosion products}: 4\mathrm{Fe}^{2+} + S^{2-} \rightarrow \mathrm{FeS}, \quad 4\mathrm{Fe}^{2+} + 6\mathrm{OH}^{-} \rightarrow 3\mathrm{Fe}\,(\mathrm{OH})_2 \tag{12}$$

$$\text{Overall reaction}: 4\mathrm{Fe} + \mathrm{SO}_4^{2-} + 4H_2O \rightarrow 3\mathrm{Fe}\,(\mathrm{OH})_2 + \mathrm{FeS} + \mathrm{OH}^{-} \tag{13}$$

3.3.4. Prevention of Microbial-Influenced Corrosion [34]

- Control of the population of bacteria through chemical treatment with biocides.
- Frequent mechanical cleaning
- Total drainage and dry storage of materials such as tanks pipes and vessels.

3.4. Crevice corrosion

Crevice corrosion is a form of localized corrosion that typically happens when there is a difference in the concentration of ions between two sections of metal in a stationary medium (Figure 5) [49]. Crevice corrosion can occur under gaskets or seals, clamps, inside cracks and seams, and spaces filled with deposits, unmoving areas, or under shielded areas with low oxygen and acidic conditions can result to corrosion within crevices [11, 32, 34]. Variations in the electrolyte composition of the media can also initiate crevice corrosion and due to the higher oxygen activity at the mouth of the crevice compared to the bottom, this kind of corrosion has a higher electrochemical potential [50]. However, for crevice corrosion to occur, there must be the presence of a crevice, oxygen, and saltwater environment [10, 23, 41]. In places with limited access to fluid from the environment, such as gaps and contact areas between parts, washers, under gaskets or seals, crevice corrosion can also occur [30], insulation materials, lap joints and clamps, threads, fastener heads, surface deposits, disbanded coating inside cracks and seams and spaces filled with exposits [30, 34]

Figure 4. Diagram showing a pipeline affected by MIC [25]

Figure 5. Diagram showing crevice corrosion [32]

Figure 6. Diagram showing high-temperature corrosion [32]

3.4.1. *Changes in the local chemistry within the crevice are what cause crevice corrosion to start. [30]:*

- Depletion of oxygen in the crevice
- Depletion of inhibitor in the crevice.
- A shift to acid conditions in the crevice.
- The build-up of aggressive ion species like chlorides in the crevice.

3.4.2. *Prevention of crevice corrosion [23, 30, 33]*

- Always use reliable, non-absorbent gaskets like Teflon.
- To enhance high resistance to crevice corrosion, always use higher alloys with high resistance.
- When using new equipment, always ensure that welded butt joints are used instead of bolted or riveted joints.
- Always ensure complete drainage of vessels, tanks, and pipes and avoid creating stagnant conditions in these areas.
- Prevent crevices in lap joints by continuously welding or soldering the lap joints.
- Minimize crevice corrosion by proper joint design.

3.5. *High-temperature corrosion*

Another form of metal corrosion is high-temperature corrosion which occurs in an elevated-temperature environment and subsequently leads to the weakening and destruction of the metal as shown in Figure 6. When a metal is exposed to a heated environment with oxygen, sulfur, or other substances that can oxidize the material, this can happen [49]. Sulfates can also create corrosive chemicals that harm carbon steel, which is often resistant to corrosion at high temperatures [34]. High-temperature corrosion occurs at a temperature greater than 200 °C in the presence of gases (H_2S, H_2, O_2, and hydrocarbons) and non-electrolytes or liquids (S8 and naphthenic acids) [51]. Intermittently, two or more of these corrosion components can be present in a system. For instance, sulfidic corrosion is usually intense in the presence of hydrogen [51]. The most hazardous corrosion processes are hydrogen attack and sulfidation because they can cause pipe breakage resulting in the release of combustible media, explosions, fires, and eventually casualties [29].

3.6. *Soil corrosion*

Soil corrosion usually occurs when carbon steel is exposed to humidity in the presence of oxygen in the surrounding soil (Figure 7) [34]. The most corrosive soils are those with high levels of dissolved salts, high electrical conductivity, high acidity, and high moisture content [34]. This is because carbon steel manufacturing accounts for around 85% of all steel production globally, making it important to understand the factors that impair it. Understanding and controlling carbon steel corrosion can help reduce and alleviate the significant expenses linked to this widespread condition [32].

Figure 7. Diagram showing soil corrosion [32]

3.7. Uniform or general corrosion

The most prevalent type of corrosion is uniform corrosion which occurs as a result of an electrochemical or chemical reaction that causes the exposed metal surface to deteriorate and be destroyed. As a result of this, the metal becomes slimmer over time as it gradually fails (Figure 8). The constant shifting of the anodic and cathodic regions of a metal's surface when it comes into contact with the electrolyte also contributes to uniform corrosion, which causes a virtually uniform corrosive attack across the whole surface [31]. The most prevalent type of corrosion is also known as uniform corrosion, which is defined as an even attack on a material's surface. This form of corrosion is also the most benign as the extent of the attack is relatively easily judged, and the resulting impact on material performance is fairly easily evaluated due to the ability to consistently reproduce and test the phenomenon. This type of corrosion typically occurs over relatively large areas of a material's surface like rusting of steel plates in seawater.

3.7.1. Uniform corrosion can be prevented through the following ways [29]:

- Use of corrosion inhibitors.
- Environmental control.
- Barrier coatings.
- Use of thicker materials for corrosion allowance.
- Sacrificial coating.

3.8. Intergranular corrosion

When metals and alloys are exposed to a certain corrosive environment, they are vulnerable to intergranular corrosion. Grain matrices are usually less reactive to grain boundaries, as such, localized attacks do occur adjacent to grain boundaries with little deterioration of the matrix. Intergranular corrosion is usually swift with deep penetration into the metal matrix resulting in loss of mechanical, optical, and lustrous properties of the metal. It can also lead to total collapse/failure of the metal. Impurities at the grain borders, element enrichment in the alloy, or element depletion in the boundary region can all contribute to this form of corrosion [26].

In intergranular corrosion, the grain boundary of metals that are rich with a high concentration of impurities is often attacked as these impurities make them susceptible to this type of corrosion (Figure 9) [34]. Intergranular corrosion can also occur as a result of the potential difference between the adjacent grain boundaries and the grain-boundary region [21]. Some of the factors that enhance Intergranular corrosion are operations like high temperature, welding, and improper heat treatment. Intergranular corrosion can be prevented through the following ways [29]:

- Use of stainless steel
- Effective application of post-weld heat treatment

Figure 8. Diagram showing Uniform corrosion [53]

Figure 9. Diagram showing intergranular corrosion [32]

Figure 10. Diagram showing exfoliation corrosion [32]

Figure 11. Diagram showing fretting corrosion [32]

3.9. *Exfoliation corrosion*

One of the distinctive types of intergranular corrosion is exfoliation corrosion this type of corrosion is formed mainly during cold or hot rolling due to the leveling of grains by massive deformation occasionally in the absence of crystallization (Figure 10) [52].

3.10. *Fretting corrosion*

This form of corrosion develops when the metal's surface develops pits and grooves due to repeated weight, vibration, or wear [34]. When a small amount of slip is permitted to happen, a localized, fast attack known as "fretting corrosion" takes place on mated surfaces under load as shown in Figure 11 [16]. Most frequently, this happens when moving machinery pieces or surfaces vibrate while being transferred from one location to another. [34]. Fretting corrosion can also be seen on shafts, bearings, and gears mounted in vibrating machinery. This results in mechanical damage to the surface and the removal of the protective film on the metal surface. This further triggers an electrochemical corrosion process [16]. Fretting corrosion can be prevented by lubricating the surfaces of the metal and regular inspection and maintenance of lubricated parts [29].

3.11. *Filiform corrosion*

Filiform is a specific type of crevice corrosion in which an aggressive chemical build-up takes place behind a broken protective coating. In filiform corrosion, small microscopic flaws in the coating usually serve as the initial catalyst for filiform corrosion [31].

Figure 12. Diagram showing filiform corrosion [32]

Figure 13. Diagram showing bimetallic corrosion [32]

Filiform corrosion also occurs on a metallic surface coated with a thin organic film that is typically 0.1 mm thick [29]. Additionally, surfaces that have been painted or coated can develop filiform corrosion. A weaker structure results from paint or coating flaws that allow water to penetrate and cause corrosion below the protective layer (Figure 12) [31].

However, when a coating is necessary, it must have low water vapor transfer properties and superior adherence. Because of their cathodic protection capabilities, zinc-rich coatings should also be taken into consideration for coating carbon steel. [31]. Filiform corrosion has been seen to occur on surfaces of coated steel, aluminum, and magnesium with thin coatings of tin, silver, enamel, gold, phosphate, lacquer, and paper-backed aluminum foils. Filiform corrosion can be prevented by using brittle coatings and control of humidity [29].

3.12. Bimetallic corrosion

When two metals come into direct or indirect contact, bimetallic corrosion can happen (Figure 13). These metals, sometimes known as coupling metals, typically differ in composition and property. This kind of corrosion can be seen in a variety of settings. Although this kind of corrosion may seem harmful, there are several situations when using this naturally occurring process is recommended [31, 54].

Figure 14. Diagram showing flow-assisted corrosion [33]

3.13. Flow Assisted Corrosion

When the protective oxide layer is gradually removed over time by the movement of wind or water, flow-assisted corrosion takes place (Figure 14) [33]. Further corrosion is made possible by this corrosion because it exposes the metal's surface oxide. [29]. This form of corrosion can also be called flow-accelerated corrosion and it is seen when a protective film of oxide on a metal surface is removed or dissolved by wind or water, thereby revealing the underlying metal to further corrosion and deterioration [29].

3.14. Stress Corrosion Cracking (SCC)

Stress corrosion cracking is a localized form of corrosion that occurs when metals are subjected to constant stress under a certain environment such as seawater and this constant stress often leads to the cracking of the metal as shown in Figure 15 [25]. This type of corrosion promulgates at a velocity range of (0.001 – 10) $\mathrm{mm.hr}^{-1}$ and depends solely on the combination of alloys or the nature of the environment [25]. Stress corrosion cracking (SCC) is a result of the combination of tensile stress and a corrodent or corrosive environment, often at elevated temperatures. Susceptibility to stress corrosion cracking is due to certain metallurgical factors like chemical composition, composition and distribution of precipitates, preferential orientation of grains, dislocation structure, environmental factors, and structure of metal [26]. Stress corrosion is more severe, external stress like actual tensile pressure on the metal or expansion/contraction brought on by abrupt temperature changes can also cause cracking.

In addition, residual stress from manufacturing processes like cold forming, welding, machining, and grinding may cause it [50]. The majority of the surface is often unaffected by stress corrosion, but the microstructure develops tiny fissures that make the corrosion difficult to see [50]. Controlling and preventing stress corrosion cracking [29, 33]

- Stress Control
- Environmental control
- Testing of susceptible materials
- Material selection and control
- Temperature and potential control.
- By use of materials that have high resistance to cracking under certain environments.
- By controlling the hardness and stress level both load and residual.
- Avoidance of chemicals that encourage environmental cracking.

Figure 15. Diagram showing stress corrosion cracking [32]

3.15. Erosion corrosion

Corrosive fluids/gases are frequently found in high velocities in systems, which is where erosion-corrosion typically occurs and due to the relative mobility between corrosive media and the metal surface, the attack on the metal is also increased. Erosion corrosion can occur in piping systems like elbows, bends, condensers, and pumps as shown in Figure 16 [26]. Corrosive media, chemical composition, dispersed solids, presence of air bubbles, and metallurgical properties of materials are some of the major factors affecting erosion corrosion [26].

3.16. Oxygen corrosion

It is well known that oxygen is a very strong oxidant that reacts very fast with metals. Oxygen is highly corrosive, especially in water-containing environments and corrosion associated with oxygen has become one of the major challenges usually encountered during enhanced oil well recovery in the oil and gas industry. High-pressure air is pumped into a high-gravity, high-pressure oil reservoir with the intention that the injected oxygen will react with a portion of the reservoir oil at a high temperature to form carbon(iv)oxide [55, 56]. The oil downstream of the reaction zone is mobilized by the resultant flue gas mixture of nitrogen and carbon(iv)oxide, which sweeps it to producing wells. [57].

However, the presence of oxygen can trigger a cathodic reaction of a corrosion process which further fast-tracks the anodic dissolution of metal. This action may occur at the surface injection lines, surface tubing, or casing. An increase in the concentration of oxygen will increase that of carbon(iv)oxide which may also lead to carbon(iv)oxide corrosion [58]. Also, the presence of a high-pressure air injector can promote the corrosive actions of acid gases like H_2S and CO_2 which are serious corrosive gases that affect pipelines used in the oil and gas industry (Figure 17). Oxygen corrosion can be mitigated through the injection of corrosion inhibitors and/or oxygen-scavenging agents during high-pressure air injection or by protective coatings [57].

4. Influential factors affecting the rate of corrosion

The rate and extent to which corrosion occurs depend solely on two major factors namely the nature of the material and the environment to which the material is exposed. The nature of the material entails the position of the metal in reactivity series, overvoltage, purity of the metal, physical nature of the metals, nature of scales or protective films formed on the metal surface, the relative area of cathodic and anodic parts of the metal, volatile corrosion products and solubility of products [26]. Nature of the environment includes impurities, water, the humidity of the air, pH of the solution, nature of dissolved gases, salts, and pollutants, presence of suspended particles in the atmosphere, flow velocity of process steam, formation of oxygen concentration cell, conductance of the corrosive media and polarization of electrodes. [26]. Other influential factors that may affect the corrosion rate include the creation and designation of sites for cathodic and anodic reactions in the electrochemical cell. In this case, metal with a more positive (noble) potential in the galvanic series will tend to extract electrons from a metal that is in a more negative (base) position in the series and hence accelerate its corrosion when in contact with it [59]. It is also important to know that chloride and other aggressive ions can impede the development of shielding oxide layers on the surface of metals, increasing [26].

Figure 16. Diagram showing erosion corrosion [26]

Figure 17. Diagram showing oxygen corrosion [25]

5. Techniques for corrosion mitigation

Corrosion is the degradation and subsequent destruction of metal when exposed to an aggressive environment and is one of the major problems confronting industrialization. Corrosion problem though is unavoidable as it is a natural process but they can be curtailed or controlled through the adoption of certain practical anti-corrosion methods. These methods can be implored individually or combined depending on the material's nature and the corrosive medium. Some of the anti-corrosion methods which have been implored overtime include:

- Proper selection of metal
- Modification of metal
- Barrier protection
- Environmental measures
- Sacrificial coatings
- Use of corrosion inhibitors
- Modification/engineering design
- Modification of corrosive media
- Intensive corrosion monitoring and inspection

5.1. Proper Selection of Metal Type

In other prevent the corrosion of metal as well as reduce the addition of corrosion protection materials, proper selection of metal types with high resistance to corrosion like a duplex, nickel alloy, stainless steel, and aluminum should be used. Utilizing these metals eliminated the need to apply additional corrosion protection measures because of their superior ability to resist corrosion [60].

5.2. Modification of metals

Alloys are metallic substances comprising two or more elements as either a compound or a solution. Alloy steels are made to give more special properties like hardness, toughness, ductility, and corrosion resistance to the substrate metal. The production and deployment of alloys that are more resistant to corrosion than their metals are some of the improved ways of mitigating corrosion. Some of the metals used in the production of these alloys are chromium, silicon, tungsten, vanadium, molybdenum, boron, manganese, aluminum, nickel, tin, or zinc. These metals can form passive layers on top of the metal substrates thereby protecting them from corroding.

5.3. Barrier Protection

Barrier protection is one of the methods used for corrosion prevention because of its ability to provide a protective coating that serves as a barrier between the metal and the substrate. Some of the barrier protection systems used for this purpose include paint, powder coating, galvanizing, etc. One simple cost–effective way of preventing the corrosion of metal is the use of paint coating. Paint coating serves as a barricade which also hinders the transfer of electrons of electrochemical charges to the metal under the protective coating from the corrosive environment. The need to isolate metals from the abrasive environment underlies the use of the coating. All coatings can be divided into three categories: organic (polymeric materials, paints, greases, and paraffinic mixes), inorganic (glasses, ceramics, and enamels), and metallic (metals and alloys) [61]. These groups of coatings can be used to stop the corrosion of tanks, pipes, vessels, columns, and equipment in contact with water, natural gas, atmosphere, soil, and different technological solutions [61].

More so, the application of powder coating to the clean metal surface is another known method for corrosion prevention [60]. This method involves the application of dry powder onto the surface of the metal which must be properly cleaned before the application [60]. The powder is then fused into a smooth, uninterrupted coating by heating the metal. This uses powders such as epoxy, acrylic, polyester, urethane, and nylon, among others [60, 62].

5.4. Environmental Measures

Corrosion of metals can be effectively mitigated through the control of the environment which helps in limiting reactions between metals and gases or water and its immediate environment which subsequently leads to corrosion. Reduction of metals exposure to rain, ocean, or more complex procedures like regulating the levels of sulfur, chlorine, or oxygen in the environment are some examples of environmental measures [60].

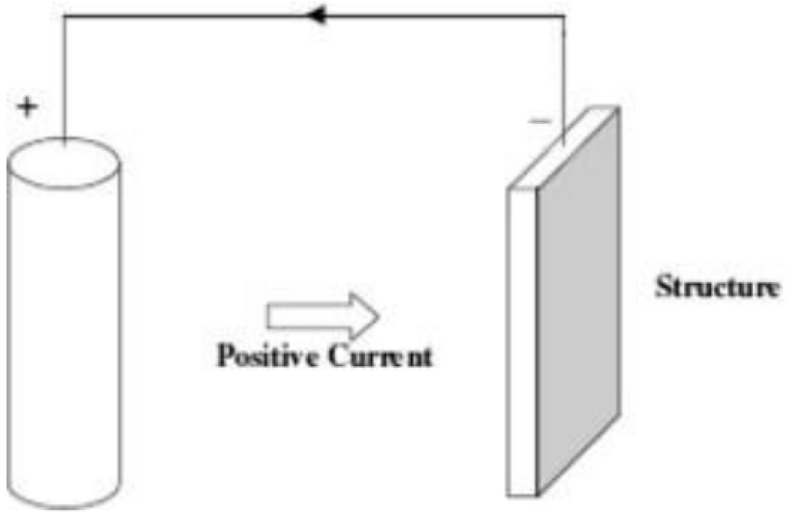

Figure 18. Schematic illustration of sacrificial protection [25]

5.5. *Sacrificial Coating*

The sacrificial coating is a protective method implored in the mitigation of corrosion of metals. This process involves the coating of metal to be protected with a more oxidizable metal(s). Sacrificial coating involves two major techniques namely anodic and cathodic protections.

5.5.1. *Anodic Protection System*

This method works by making the steel the anode of an electrochemical cell as shown in the schematic illustration in Figure 18. An example of anodic protection is the coating of iron alloy steel with a less reactive metal like tin. Tin which is less reactive will not corrode; therefore, as long as the tin coating is intact, the steel will not react with the environment and is further protected. Due to the corrosive nature of caustic soda and sulphuric acid, anodic protection is implored in storage tanks used in storing such corrosive chemicals [60].

5.5.2. *Cathodic Protection System*

This method is the opposite of anodic protection and the technique uses the steel as the cathode of an electrochemical cell. Galvanizing, the application of zinc to iron alloy steel, is the most typical example of cathodic protection. Steel fuel or water pipelines, water heater tanks, ship hulls, and offshore oil platforms all frequently use cathodic protection. [60]. Some limitations of cathodic protection are [61]:

- Coating debonding.
- If metallic structures are near cathodic protection activity but are not connected to impressed current systems, stray current corrosion may result.
- Hydrogen embrittlement (in an overprotective situation).
- Corrosion of aluminum due to the formation of hydroxyl ions which further reacts with the aluminum.

5.6. *Corrosion Inhibitors*

The most investigated corrosion mitigation technique is the effective use of corrosion inhibitors. Inhibition is a preventive method against corrosion attacks on metals and alloys. A schematic illustration of an inhibitive process is shown in Figure 19. Inhibitors can be solid or liquid compounds that, when applied in the proper concentration, slow down the anodic and/or cathodic reactions and subsequently reduce the corrosion rate of the metal [1, 2].

Corrosion inhibitors are compounds which can be polymeric materials, organic compounds, plant extracts, etc., which are capable of reacting with the surface of the metal or the surrounding gases that react with the surface of the metal, thereby restraining the electrochemical reactions between them and the metal [1, 2]. Corrosion inhibitors when applied on the metal surface inhibit corrosion by forming a barrier layer that protects the metal surface as well as prevents it from reacting with components of the environment.

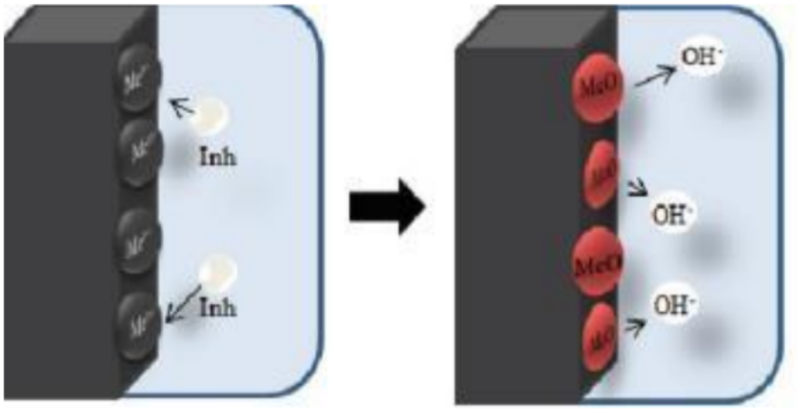

Figure 19. Schematic illustration of the inhibition process [26]

However, factors that influence the rate of formation of corrosive layers on metal surfaces include but are not limited to environmental pH, concentration, and temperature of solution as well as the composition of the surrounding environment. Corrosion inhibitors when applied on the metal passivates to form protective corrosion resistance films on the surface of the metal which reduces the corrosion rates of the metal. Corrosion inhibitors are widely used for corrosion prevention in industries like oil and gas, exploration and production, water treatment works, product additives industries, and chemical and manufacturing industries [60].

5.7. *Engineering Design*

Engineering design is another method used for corrosion prevention by way of enhancing durability as well as reducing the corrosion rate by way of using protective anticorrosive coatings. To achieve good results in terms of corrosion prevention, the design must be modified to promote air movement while avoiding open crevices, and trapping of water and dust particles. Regular monitoring and maintenance culture is very important in ensuring the material is corrosion-free as well as improving the longevity of the material.

Engineering design includes [51, 63]:

- Use of standards, procedures, specifications, reports, and recent information.
- Selection of suitable construction materials, methods of preparation, control, and monitoring of corrosion, selection of suitable coating and inhibiting materials, biocides, anti-scaling agents, cathodic protection, and removing corrosive impurities such as Cl-, H_2S, O_2, and H_2O.
- Proper selection of corrosion monitoring methods such as monitoring for the corrosive environment, construction materials behavior, and efficiency of methods of protection against corrosion.
- Proper understanding and appropriate use of principles, procedures, and potential corrosion phenomena in systems. It is vital to take into consideration the geometry of the equipment or machine to be fabricated or used to create a lesser number of crevices, avoid air penetration and "dead legs" as well as have power over the flow rate.

5.8. *Intensive corrosion monitoring and evaluation*

Corrosion monitoring, inspection, and evaluation is an exercise aimed at evaluating the corrosivity of metal or process stream conditions using probes. This probe can be an either electrical, mechanical, or electrochemical device which is implanted into the process streams and is regularly exposed to the process stream condition. The rate of metal loss and corrosion in oil and process systems can be directly and online measured using corrosion monitoring techniques alone [64]. To evaluate the material conditions and corrosion rates, one way is to conduct an on-stream inspection by taking wall thickness measurements periodically in fixed and vulnerable areas of equipment, piping, and pipelines [64]. This practice is usually done in industries that use metallic pipes by which liquids flow through as seen in chemical manufacturing and oil and gas industries.

6. Conclusion

Corrosion is a geogenic process that lowers the binding energy in metals and well as destroys the valuable properties of metals leading to subsequent oxidation of metals through loss of electrons. This work has provided an overview of forms of corrosion, dependent factors that lead to corrosion, as well as the mechanism of action in various environments. Some of the best techniques and measures for corrosion mitigation like a proper selection of metal type, barrier protection, environmental control, sacrificial coating, application of suitable corrosion inhibitors which inhibit corrosion, adequate engineering design as well and proper and regular cleaning and equipment maintenance are all important and must be adhered to for longevity of materials and equipment.

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