Corrosion and its different types: A Review

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Abstract: **Corrosion is the deterioration of materials, typically metals, due to chemical reactions with the environment, leading to functional failure of components. Corrosion is a reverse extractive metallurgy that relies on environmental concentration, stress, erosion, and temperature. It results in significant economic losses ranging from 1% to 5% of GNP annually for every nation. Moreover, rust not only escalates component costs but also contributes to fatalities and safety hazards. Therefore, the objective of this review paper is to present an overview of various types of corrosion. Therefore, Avidness of crones related problems should be underlined to mitigate the corrosion related issues.**

Keywords: **Corrosion Mechanism, Pitting, Crevice, Galvanic, Erosion.**

INTRODUCTION

Corrosion is the irreversible degradation of a metal surface caused by chemical processes, leading to the transformation of a pure metal into its more chemically stable forms, such as sulfides, oxides, and hydroxides, inside a corrosive environment. The corrosive environment might be in any form, including solid, liquid, or gas. Corrosion is typically seen as a ubiquitous phenomena [1] . These settings are commonly referred to as electrolytes. These electrolytes facilitate the movement of ions (cations and anions) and generate two reactions (anodic and cathodic). In the presence of two distinct metals within a certain electrolyte, the less noble metal functions as the anode and undergoes corrosion, while the more noble metal serves as the cathode and remains protected. The electron flow occurs from the anodic metal to the cathodic metal. In a specific environment containing two distinct metals, the metal with a larger reduction potential, positioned higher in the electrochemical series, or the less noble metal, will undergo corrosion. For instance: Copper and Zinc in a conductive solution. Zn possesses a larger reduction potential than Cu, thus functioning as the anode and undergoing corrosion, while Cu serves as the cathode and remains protected. The electron transfer occurs from Zn (less noble) to Cu (more noble). Oxidation occurs at the anode, where electrons are lost, whereas reduction occurs at the cathode, where electrons are gained. Corrosion deteriorates the entire surface when the majority or all metal particles undergo oxidation. The oxidation of iron is the most prevalent instance of corrosion. Rust is hydrated ferric oxide $[Fe_2O_3xH_2O]$. Corrosion is a surface phenomenon, occurring at the material's surface. Corrosion occurs in various forms. An first comprehensive surface assault gradually diminishes the metal's thickness. Secondly, rather than a comprehensive surface assault, only certain regions are impacted. Third, it also manifests at grain boundaries or other zones of weakness because to variations in resistance to corrosive environments [2] . The process is gradual, causing deterioration of industrial machinery, metallic apparatus, and diminishing the total worth of the product. Annually, the overall economic loss from various forms of corrosion in India amounts to approximately US$6.5 billion. In the United States, total direct waste is projected to be approximately 3.2% of the domestic product. Effective corrosion control hinges on proper awareness and the implementation of appropriate and timely procedures [3] .

WHAT CAUSES CORROSION

Most naturally occurring metals exist as compounds, with the exception of noble metals like gold and platinum. This is because the metals in their compound form are thermodynamically more stable than in their elemental form [4] . Since most metals reside as oxides, substantial energy is required for their extraction into a free state. This supplied energy allows them to revert to their combined condition when subjected to environmental factors such as moisture and oxygen. For instance, when iron is subjected to external circumstances, it experiences corrosion and generates brown-hued hydrated ferrous oxide. This indicates that corrosion is a process that opposes metal extraction.

$$\text{Metal} \underset{\text{Metal Extraction}}{\overset{\text{Corrosion}}{\rightleftharpoons}} \text{Metal Oxides + Energy}$$

Corrosion can occur in predominantly pure and unpolluted waters at a temperature of around 1300°C on the product side. This type of corrosion is known as classical hot spot corrosion [5].

FACTORS INFLUENCING CORROSION

The corrosion rate mostly hinges on two factors:
1) Characteristics of the metal
2) Characteristics of the corrosive environment.

Additional elements influencing corrosion include metal purity, characteristics of the surface coating, properties of the corrosive agent, temperature, air humidity, and electrolyte pH.

1)The characteristics of metal are contingent upon:
(a) It's position in the galvanic series.
(b) Metal purity
(c) Characteristics of surface film
(d) Characteristics of the corrosive substance.

(a) Position in the galvanic series: When two dissimilar metals are electrically coupled in a specific electrolyte, the metal with a larger oxidation potential, or the one positioned higher in the galvanic series, undergoes corrosion, while the other metal is safeguarded. The corrosion rate is also influenced by the relative locations of the two metals.

The rate of corrosion is directly proportional to the differential location of the two metals; thus, a greater difference results in an accelerated rate of corrosion. Figure 1 illustrates the corrosion susceptibility of metals.

Metallic corrosion susceptibility

For instance, when cast iron and copper are present as distinct metals in a certain electrolyte, cast iron undergoes corrosion but copper remains protected.

(b) Metal purity: Typically, the corrosion rate escalates with a higher concentration of impurities. This occurs because impurities create small electrochemical cells, resulting in the corrosion of the anodic component. Zinc containing impurities such as iron or lead corrodes more rapidly.

(c) Characteristics of surface film: All metals develop a thin layer of metal oxide when exposed to an aerated environment. The volume ratio of metal oxide to metal influences the impact of the surface coating. It is referred to as the "specific volume ratio." A higher ratio corresponds to a lower oxidation rate. The specific volume ratios of Ni, Co, and W are 1.6, 2.0, and 3.6, respectively. The oxidation rate of W is minimal, even at elevated temperatures.

(d) Nature of corrosive product: Corrosion progresses more rapidly if the resultant product is soluble in the corrosive medium. If the corrosive product is volatile, it evaporates immediately upon formation, exposing the metal surface to further attack. Consequently, rusting intensifies further.

CHARACTERISTICSOF THE CORROSIVE ENVIRONMENT

It additionally relies on:
(a) Temperature
(b) Humidity of the atmosphere
(c) Impact of pH
(a) Temperature: The corrosion rate escalates with increasing temperature. The corrosion rate is anticipated to nearly double for every 100-degree increase in temperature, assuming other biological variables remain unchanged [6]. This augmentation is typically depicted as an exponential curve. Nevertheless, one observes not alone the basic reliance on temperature represented by exponential curves. In numerous instances, temperature variation alters the impact of additional elements as well. The rise in temperature manifests in two distinct manners [7].

(b) Humidity inair significantly influences the rate of corrosion. The corrosion rate escalates significantly beyond a specific threshold of relative humidity. This phenomenon is referred to as critical humidity. The increase in corrosion due to humidity is attributed to the oxide film's propensity to absorb moisture, hence initiating more electrochemical corrosion. The moisture in the atmosphere will provide water to the electrolyte, which is crucial for the establishment of an electrochemical cell.

(c) Impact of pH: It is the paramount aspect in determining the rate of corrosion. Generally, a lower pH correlates with increased corrosion. This indicates that acidic medium with a pH below 7 are more corrosive than alkaline or neutral media [9]. The initial and most basic diagram depicting corrosion in relation to the pH of the solution is illustrated for noble metals (gold and (platinum) in Fig. 2.

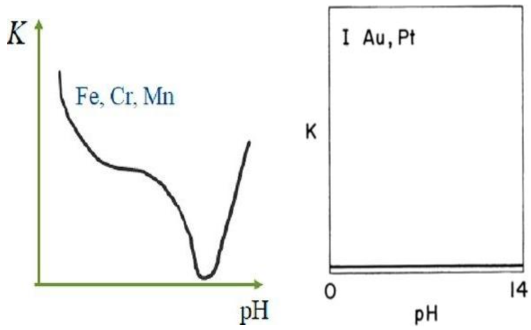


Figure 2. Corrosion versus pH for precious metals (Fe, Cr, Mn, gold and platinum)

The correlation between the corrosion rate and the pH of the solution is represented by a linear relationship at the lower section of the diagram. The graphic indicates that the corrosion rate is minimal and is mostly unaffected by the solution's pH. At elevated pH levels, a modest increase in the curve can be observed. In other words, there is a noticeable escalation in corrosion. Nonetheless, this increase holds minimal practical importance [7].

The second category of pH corrosion diagram pertains to some technically significant metals such as zinc, aluminum, and lead (Fig. 3). The graphic illustrates a significant escalation in the corrosion rate of these metals in both acidic and alkaline environments compared to neutral solutions. The configuration of the curve transforms
It is possible when considering that the oxides of the aforementioned metals are soluble in both acidic and alkaline solutions [7].

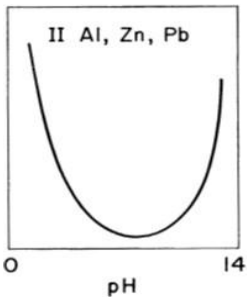


Figure 2. Corrosion versus pH for precious metals (gold and platinum)

COST OF CORROSION TO SOCIETY

Corrosion, recognized as a significant societal issue, incurs annual losses up to hundreds of billions of dollars [8]. The following are significant losses attributed to corrosion:

(i) It causes damage to industrial machinery and unanticipated equipment malfunctions, perhaps resulting in loss of life.
(ii) It adversely affects metallic apparatus, including boiler tubes in thermal power facilities [5,6,7].
(iii) It diminishes the total worth of the product and squanders important resources.
(iv) Certain metallic qualities, including conductivity, ductility, malleability, and brilliance, are diminished as a result of corrosion.
(v)Approximately 20% of total iron production is annually lost due to corrosion.It also pollutes potable water.
(vi) Therefore, to mitigate the impacts of corrosion, we must meticulously examine its mechanism.

FUNCTION OF OXYGEN IN CORROSION

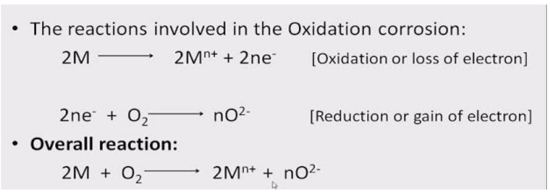
Atmospheric oxygen interacts with metals to produce their corresponding oxides. Certain metals, such as lithium, sodium, and potassium, undergo oxidation at low temperatures, whereas others, like silver, gold, and platinum, oxidize at elevated temperatures. When the metal surface is exposed to the atmosphere, it donates electrons while oxygen receives them. The metal transforms into metal ions, while the oxygen converts into oxide ions.

The oxide layer inhibits more oxidation. The oxide layer may be either porous or non-porous. The porous layer is susceptible to continued oxidation via its pores and fissures until the entire metal surface is oxidized, whereas the non-porous layer serves as a protective barrier, inhibiting further oxidation. The "Pilling-Bedworth" Rule is utilized to determine if the layer generated is porous or non-porous. “Pilling-Bedworth Principle:” This criterion states that an oxide coating is considered protective (non-porous) if its volume is at least equal to or exceeds the volume of the metal from which it originates. Nonetheless, if the volume of the oxide is inferior than that of the metal, the oxide coating is non-protective (porous). For instance, metals such as aluminum develop an oxide layer that occupies a higher volume than the metal itself, resulting in a non-porous oxide layer that inhibits further oxidation of the metal. Conversely, the iron oxide layer possesses a reduced volume relative to the metal, resulting in a porous oxide layer that permits continued exposure to ambient oxygen through the pores until the metal surface is entirely corroded. The corrosion rate is exactly proportional to the concentration of dissolved oxygen when the oxidizing agent is oxygen [9] .

CORROSION MECHANISM

Corrosion entails the transfer of electrons from the anode to the cathode within a conductive solution. The metal at the anode experiences the release of free electrons (oxidation), whereas the metal at the cathode accepts these electrons (reduction). The metal with the larger reduction potential functions as the anode, while the metal with the lower potential serves as the cathode, resulting in the corrosion of the anodic metal. For corrosion to occur, the following criteria must be met:

1. Distinct areas (cathodic and anodic) must exist, allowing current to traverse through a conductive media.
2.At the anode, metal oxidation transpires, resulting in the depletion of the metal surface by its reaction with oxygen. Consequently, corrosion invariably occurs at the anode.



- The reactions involved in the Oxidation corrosion:

$2M \longrightarrow 2M^{n+} + 2ne^-$ [Oxidation or loss of electron]

$2ne^- + O_2 \longrightarrow nO^{2-}$ [Reduction or gain of electron]

- **Overall reaction:**

$2M + O_2 \longrightarrow 2M^{n+} + nO^{2-}$

3. At the cathode, reduction occurs as dissolved oxygen accepts electrons from the anode, resulting in the formation of ions such as OH- or O2-.
4. A corrosive product is generated at an intermediate location due to the combination of ions released at the distinct electrodes.

7.2. Stress Corrosion Cracking

Stress corrosion cracking is a phenomenon of significant concern to various metal users. When it transpires under operational conditions, frequently without any forewarning of imminent failure, its consequences can be disastrous [10] . The schematic diagram is illustrated in Fig. 5.

This type of corrosion occurs due to stress given to the material, initially in an inert environment, leading to the formation of cracks in a corrosive environment. The process can be expedited by residual internal tensions inside the metal or by externally induced stress (Eliaz, 2019). It predominantly transpires at elevated temperatures. It is more prevalent in alloys than in pure metals. SCC can only transpire if the subsequent three criteria are met: (i). Existence of vulnerable material, exposure to a corrosive environment, and tensile stresses.

The issue cannot be characterized as reducing, as the quantity of alloys recognized as vulnerable to stress corrosion cracking and the amount of conditions that induce cracking have both increased to date. For approximately the past 25 years, a substantial, widely distributed, and predominantly uncoordinated initiative has been undertaken in the Western World to address stress corrosion cracking [10]. An important aspect of all cracking processes that must be considered in elucidating the mechanics of stress corrosion cracking is the influence of time. A quantitative assessment of a stress corrosion mechanism must encompass not only the metallurgical or electrochemical phenomena but, crucially, it must also specify the rates at which these processes occur. It has been broadly proposed that a critical aspect of stress corrosion crack propagation is the temporal sequence of events, such as the emergence rate of slip steps or the rate of re-passivation [10].

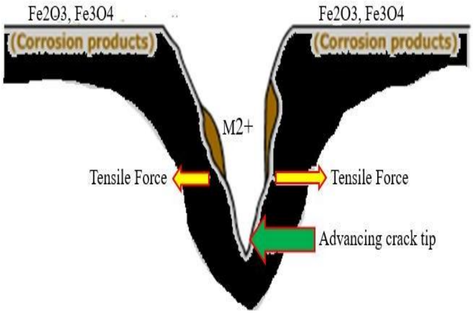


Figure 5. Schematic representation of stress corrosion cracking

Localized Corrosion

Localized corrosion markedly differs from overall corrosion. General corrosion occurs over a very extensive area, while localized corrosion manifests in a comparably restricted area [11]. This corrosion transpires when localized regions of a metal surface erode more readily than the entirety in a corrosive environment. These localized regions exhibit partial corrosion of the metal surface due to the accelerated presence of a corrosive liquid. The region with a restricted oxygen supply functions as the anode, while the part with an abundant supply serves as the cathode. It consists of two categories: (i) Pitting corrosion (ii) Crevice corrosion

Pitting Corrosion

Pitting corrosion constitutes a significant form of localized corrosion. This form of corrosion initially manifests in a relatively confined region of a material. Eventually, the region expands and deepens, resulting in the formation of surface pits. This form of localized corrosion results in the formation of pits on the material's surface. An area contaminated by impurities or water exhibits a reduced concentration of oxygen, functioning as the anode, while the other part serves as the cathode. The electrochemical mechanism is believed to be responsible for the dissolution of the metal (Hoar & Agar, 1947). To date, two hypotheses are predominantly employed: One is proposed by Hoar. He associated the formation and proliferation of the pits with the elevated acidity levels of the solutions in active regions (Hoar, 1949; Vaniukova& Kabanov, 1948). Another possibility is proposed by Russian investigators. The creation of pits was associated with the displacement of anions from the metal surface (Kabanov et al., 1947; Altenpohl& Zeiger, 1965; Kolotyrkin, 1963; Curley-Fiorino & Schmid, 1980; Akpanyung&Loto, 2019; Popova & Kabanov, 1961; Kolotyrkin, 1963). The ratio of the deepest pit to the average penetration is referred to as the pitting factor. The pitting factor serves to assess the severity of pitting corrosion. This sort of corrosion is highly detrimental, as it is difficult to detect, predict, and mitigate against. It is typically encountered in passive materials. The existence of non-uniformities exacerbates the progression of this corrosion. The reaction may occur as follows:

At Anode: $Fe \longrightarrow Fe^{2+} + 2e^-$

At Cathode: $\frac{1}{2} O_2 + H_2O + 2e^- \longrightarrow 2OH^-$

Overall: $Fe^{2+} + 2OH^- \longrightarrow Fe(OH)_{2\,(ppt)}$

$$Fe(OH)_{2\,(ppt)} \longrightarrow Fe(OH)_3$$

Crevice Corrosion

[14], [15]. It is a restricted space corrosion to which the approach of working fluid from the corrosive environment to the space (crevices) is inadequate. The joint area has comparatively lower content of oxygen as compared to the outer area, so joint area acts as anode whereas the outer area acts as cathode. This corrosion is started by concentration gradients. The grouping up of chlorides ions inside a crevice will begin it. It occurs at comparatively lower temperature than pitting corrosion. Various factors that impact crevice corrosion are as follow.

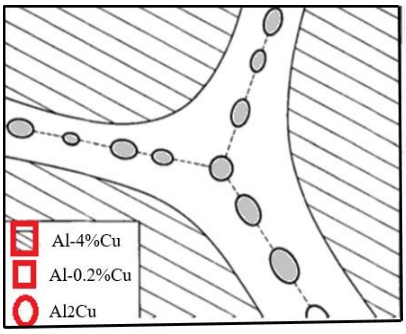
(i). The type of material i.e. alloy, metal.

(ii). Geometric characteristics of crevices such as surface roughness

(ii). Environmental conditions such as pH level, temperature, etc.

Inter Granular Corrosion

This phenomenon, known as intergranular attack (IGA), happens when the edges of the metal surface are more susceptible to corrosive environments than the center. This corrosion obscures the material's corrosion resistance in many situations. This is referred to as the IGA Test. The intergranular corrosion of old Al-4%Cu alloys has been extensively studied. The microstructure of the aged Al-Cu alloy is widely recognized as depicted in Fig. 6 [16]. Inter-granular corrosion is unaffected by the introduction of impurities such as C, N, O, Mn, and S, however the incorporation of Si and P influences the corrosion [17].



Galvanic Corrosion

The galvanic corrosion process, as per electrochemistry, occurs at certain areas on the metallic surface due to the presence of anodic and cathodic regions [16]. Galvanic corrosion refers to the preferred corrosion of one metal over another when both are in electrical contact and immersed in a suitable electrolyte. It is additionally referred to asbimetallic corrosion. It is an electrochemical event involving two dissimilar metals that are electrically linked and immersed in an appropriate electrolyte. The metal at the cathode is safeguarded, whereas the metal near the anode undergoes corrosion. Galvanic corrosion occurs exclusively between dissimilar metals. The less reactive metal is designated as the cathode, whereas the more reactive metal is designated as the anode. The rate of galvanic corrosion is directly proportional to the potential disparity between the two metals. It escalates with the augmentation of the potential difference between the two metals. Figure 7 illustrates the process of galvanic corrosion. The potential difference is determined using the following relation:

P.d. = $-\Delta G/nF$

Where dG represents the Gibbs free energy of the reaction, n denotes the number of moles of electrons transported, and F signifies the Faraday constant, valued at 23.06 kcal/volt.

Consider an instance where zinc (Zn) and copper (Cu) are electrically interconnected. In the electrochemical series, zinc is positioned higher than copper, hence zinc functions as the anode while copper serves as the cathode. This indicates that Zn experiences electron loss, while Cu receives electrons. Zn undergoes corrosion due of its inferior nobility relative to Cu.

$$Zn + 2H^+ \longrightarrow Zn^{2+} + H_2$$

In neutral or slightly alkaline solution.

$$½\, 0_2 + H_2O + 2e^- \longrightarrow 2OH^-$$

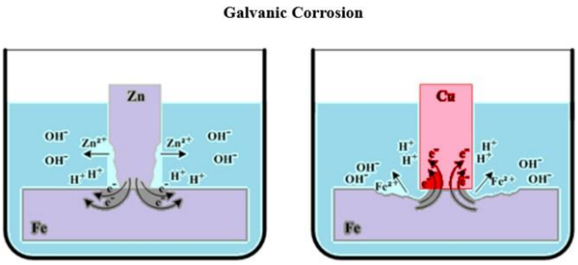


Figure 7. Schematic Representation of Galvanic Corrosion

EROSION

The relative motion between the metal surface and the corrosive fluid results in corrosion of the metal surface. This phenomenon is referred to as erosion. Erosion occurs through the combined effects of corrosion and abrasion when the fluid contains solid particles that are harder than the metal surface; conversely, when the particles are softer than the metal, erosion results from corrosion and attrition (Kumar et al. 2018). The relative flow rate indicates the extent of abrasion. The process of chipping and cracking identifies the cause of erosion, resulting from the simultaneous production and removal of scale from the material's surface (Prutton & Frey, 2016).

Cavitation corrosion is a specific type of erosion. The vapor bubbles in liquids adjacent to the metal surface develop and collapse, resulting in this corrosion. Several fundamental methods to mitigate erosion include: Utilize more resilient materials (ii) Employ reduced liquid velocity.

CONCLUSION

Corrosion is the natural phenomena that cause degradation and failure of component. Although, the general or uniform attack leads to maximum destruction of metal component ,but it is easier to prevent.

However, other types of corrosion such as inter granular or stress corrosion are very destructive for engineering components. All these types of corrosion have impact on environment, economy and human life. It has been concluded from the results of various researches that timely protective measures could resist corrosion.

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