Journal of Building Technology, 2025, Volume 7, Issue 1
DOI: 10.32629/jbt.v7i1.3273
ISSN Online: 2717-5103
ISSN Print: 2705-1390

Corrosion, Types and Prevention

Francisco Martínez Pérez

Center for Maintenance Engineering Studies, Technological University of Havana, Cuba.
Orcid: 0000-0002-8947-7870
Email address: fmartinezperez2013@gmail.com

Abstract: Corrosion is defined as the degradation of materials as a consequence of electrochemical attack. In general, it can be understood as the general tendency of materials in search of a more stable form and less internal energy of its structure. The rate at which corrosion occurs depends on the temperature, the characteristics of the fluid in contact with and on the properties of the material. Nonmetallic materials also suffer corrosion by different mechanisms. The present work characterizes corrosion processes in metals, as well as in ceramic materials and polymers. Different types of corrosion are explained based on a modern form of their classification. In each case, effective forms of prevention are explained. Information on cathode prevention is included. Finally, the economic and social consequences of corrosion due to corrosion are pressented.

Key words: corrosion; types of corrosion; prevention against corrosion

1. Introduction

Corrosion is defined as the deterioration of materials as a consequence of electrochemical attack by the environment. In a general form, it can be understood as a general tendency of materials to reach a more stable form or state of less free energy. When corrosion is caused by chemical reactions (oxidation), its rate of occurrence depends to some extent on temperature, salinity of the fluid in contact with the metal, and material properties. Other nonmetallic materials also suffer corrosion but by other mechanisms [1].

In chemical reactions (oxidation-reduction), three factors come into play:

- Manufactured element
- Ambient
- Water

In electrochemical reactions, the most well-known factors are chemical reactions of metals caused by air, such as the rusting of iron and steels or the formation of a green film on copper and its alloys (bronze, brass).

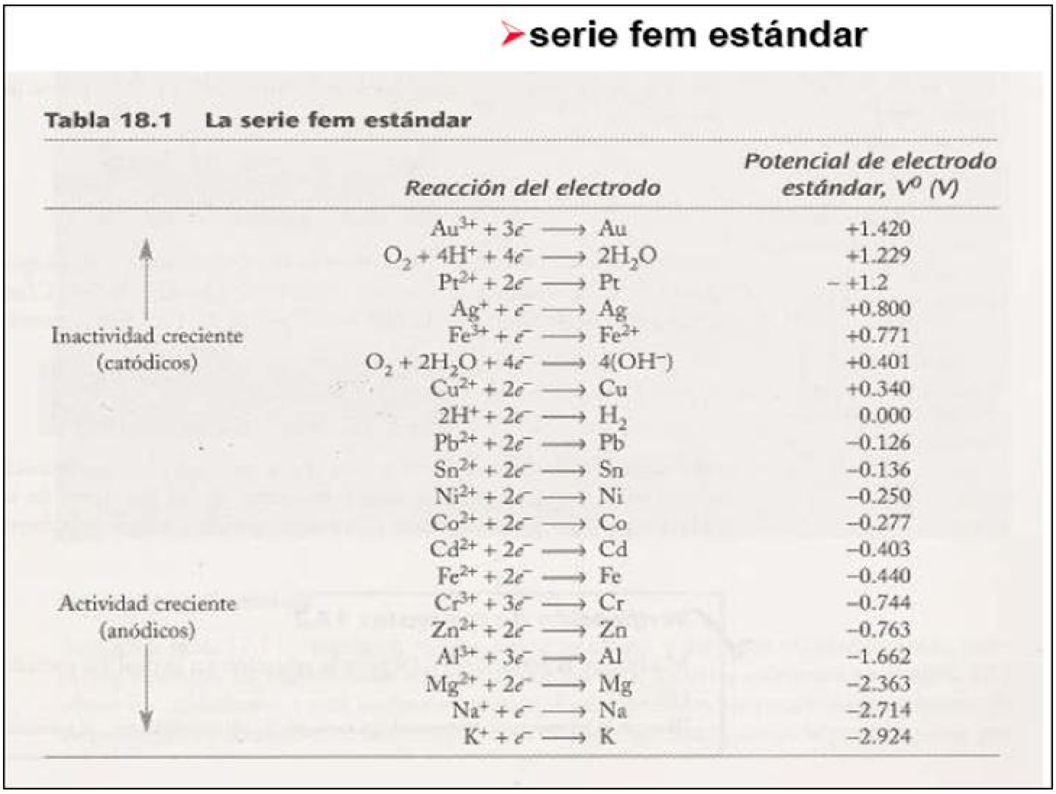
Corrosion is a widespread phenomenon that affects all materials (metals, ceramics, polymers) in all environments (aquatic, atmospheres, high temperatures). It is an important industrial issue, as it can cause accidents (elements fracture) and represents significant costs, as it is calculated that in a few seconds, 5 tons of steel are dissolved worldwide. It is invisible in each element, but multiplied by the amount of steel in the world, it represents an important figure [2].

Corrosion belongs to the field of materials science, which includes knowledge of chemistry and physics (physical chemistry).

Corrosion is due to a massive electrical current generated by the chemical differences between the elements involved. Corrosion is an electrochemical phenomenon. A flow of electrons is established when a potential difference exists between one point and another. When electrons are given from chemical part and migrate to other part, the part that give is called anode (occur oxidation) and the part that receive is called cathode (occur reduction).

For this to happen, there must be an electrochemical difference. If one part is separated, it is called a half-electrochemical part and if both halves are together, it forms an electrochemical part. Each half is associated with a potential of reduction (oxide potential reduction). The metal in which the more negative oxide potential reduction takes place is called the reduction zone [3]. Table 1 shows the reduction potentials of various metal elements.

Table 1. Potential reduction of different metals elements



➢serie fem estándar

Tabla 18.1 La serie fem estándar

	Reacción del electrodo	*Potencial de electrodo estándar, V^0 (V)*
	$Au^{3+} + 3e^- \longrightarrow Au$	+1.420
↑	$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$	+1.229
	$Pt^{2+} + 2e^- \longrightarrow Pt$	~+1.2
	$Ag^+ + e^- \longrightarrow Ag$	+0.800
Inactividad creciente	$Fe^{3+} + e^- \longrightarrow Fe^{2+}$	+0.771
(catódicos)	$O_2 + 2H_2O + 4e^- \longrightarrow 4(OH^-)$	+0.401
	$Cu^{2+} + 2e^- \longrightarrow Cu$	+0.340
	$2H^+ + 2e^- \longrightarrow H_2$	0.000
	$Pb^{2+} + 2e^- \longrightarrow Pb$	−0.126
	$Sn^{2+} + 2e^- \longrightarrow Sn$	−0.136
	$Ni^{2+} + 2e^- \longrightarrow Ni$	−0.250
	$Co^{2+} + 2e^- \longrightarrow Co$	−0.277
	$Cd^{2+} + 2e^- \longrightarrow Cd$	−0.403
	$Fe^{2+} + 2e^- \longrightarrow Fe$	−0.440
Actividad creciente	$Cr^{3+} + 3e^- \longrightarrow Cr$	−0.744
(anódicos)	$Zn^{2+} + 2e^- \longrightarrow Zn$	−0.763
	$Al^{3+} + 3e^- \longrightarrow Al$	−1.662
	$Mg^{2+} + 2e^- \longrightarrow Mg$	−2.363
↓	$Na^+ + e^- \longrightarrow Na$	−2.714
	$K^+ + e^- \longrightarrow K$	−2.924

1.1 Iron and iron alloys

Pure iron, with low carbon content or low alloy content, has low resistance to corrosion and, in general, requires the application of protective films or cathodic protection to increase resistance to corrosion, even if the conditions are not severe. However, low carbon steels are passive in the presence of alkaline solutions with high pH. Low alloy steels corrode in saline solutions, especially those with high chloride content.

Alloyed steels containing Cr form what are known as ferrite steels, due to their ferrite structure. They are used in the petroleum, gas, and some chemical industries. Austenitic steels, which contain Cr-Ni and have an austenitic structure, come in various forms depending on their composition. They are employed in chemical and marine environments, as well as in valves and pump shafts. Some of these steels are also resistant to corrosion in the food and electrical industries, as well as in heat exchangers and turbine blades [1].

1.2 Copper and copper alloys

Copper alloys have a low susceptibility to corrosion. Strong acids attack copper alloys, and this susceptibility can be increased with the addition of elements such as antimony. Commercially pure copper (99%) exhibits excellent corrosion resistance in soil. Brass, a mixture of copper and zinc, with up to 40% zinc, has a significantly lower corrosion resistance than pure copper. Bronzes, which are more resistant to corrosion, are copper alloys containing nickel and other elements such as Si and Mn. They are used in the food and chemical industries, as well as in marine environments and kitchen appliances [4].

1.3 Aluminum and aluminum alloys

Aluminum alloys are highly resistant to ambient attack due to the rapid formation of an oxide film. They are widely used in residential applications (such as doors and windows), as well as in kitchens and the chemical industry. Under neutral pH conditions, aluminum alloys may be susceptible to attack by the presence of chlorides, including pure chloride. Some alloying elements added to aluminum alloys (Zn, Cu, Mg, Mn) significantly affect the corrosion resistance of these alloys.

1.4 Ceramic materials

Ceramic materials have a wide and diverse application in the world. This is due to the wide form of structures and properties that are obtained from the diversity of chemical compositions and processes. They are used in the electrical and electronic industry, in metallurgical processes in the chemical industry and in the processing of glass. In general, they have a high resistance to corrosion.

Corrosion of these materials occurs by simple chemical dissolution rather than by electrochemical processes as in metals. Refractory materials must not only withstand high temperatures, but also scoria attack, glass melting and salts over long periods of time [4].

1.5 Polymers

Polymeric materials also undergo degradation when they come into contact with certain substances. For this reason, the term "degradation" is used instead of "corrosion," as the processes are different. Polymer degradation is a physicochemical process that has significant adverse effects. Polymers degrade through swelling and dissolution. The rupture of their covalent bonds occurs due to the action of thermal energy, chemical reactions, and radiation effects. Many polymers, in the presence of solutes such as gasoline, absorb solute molecules that insert themselves between the polymer molecules, causing them to separate, dilate, and swell. This process is more pronounced when the structures of the solute and the polymer are more similar. The influence of temperature also plays a role. Polymers generally have greater resistance to chemical attack than metals in the presence of acids and basic solutions [5].

2. Development

2.1 Types of corrosion and its prevention

The driving force behind the corrosion process, as with most metallurgical processes, is the reduction of the system's free energy to achieve a more stable structure. There are various ways to classify corrosion types. The most common one can be seen in Fig. 1.

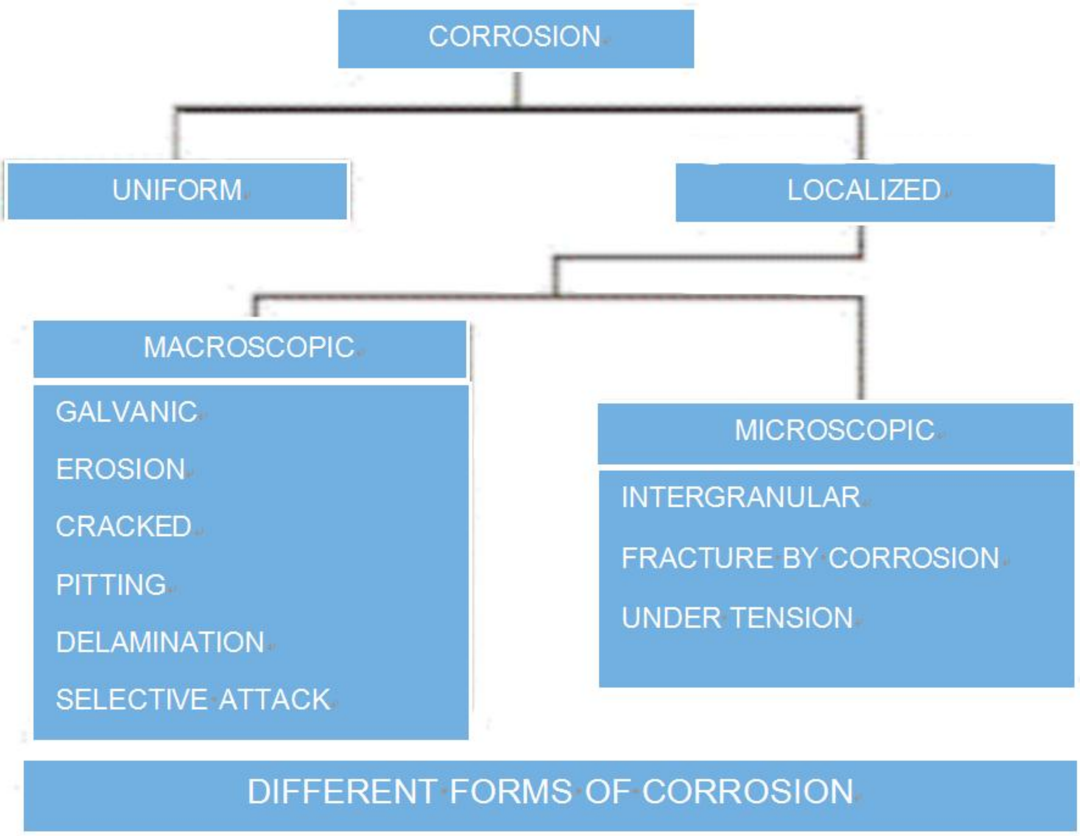


Fig. 1. Forms of classification of corrosion (uniform or localized).

Uniform attack on large areas of a metallic surface is the most common form of corrosion and it can be wet or dry, electrochemical or chemical; it is necessary to select construction materials and a form of its protection to control it (like paints). Uniform corrosion is the most common one to measure and that's why non-waiting failures could be avoided by simple regular inspection.

Homogeneous corrosion refers to material wear that occurs uniformly. An example is the gradual dissolution of zinc in dilute sulfuric acid solution, or the corrosion of copper and copper alloys in an aqueous environment. It is relatively easy to prevent and control. This type of corrosion is a typical form of metal oxidation that occurs at high temperatures and requires a high activation energy. However, it occurs to a lesser extent at room temperature [7].

Heterogeneous corrosion is the most widespread form. It is highly dangerous and difficult to control. It is characterized by the presence of anodic and cathodic zones. This type of corrosion is more intense in some areas [7].

Different factors contribute to corrosive processes. Some of them are shown in Table 2.

Table 2. Factors that contribute to corrosive processes

Factors that affect corrosive processes	
Stress concentration	Not enough air in some places
Rapid change in section	Unions with stress concentration
Different materials union	Turbulence
Different phases in same material	Environment
Bad surface quality	Bad selection of materials
Deposition places	Not good maintenance

2.1.1 Galvanic corrosion and its preventive methods

Galvanic corrosion occurs when two different metals, either in direct contact or connected by an electrical conductor, are exposed to a conductive solution. In this scenario, there exists a difference in electrical potential between the two metals, which acts as a driving force for the establishment of an electrical current through the corrosive medium. As a result, the electrical current corrodes one of the metals in the pair. This type of corrosion can also occur due to concentration cells, which arise from potential differences within structures, potential differences between metallic ions, or the presence of an oxidizing medium.

The greater the potential difference between the metals, the higher the probability of galvanic corrosion will occur. This type of corrosion only causes degradation to one of the metals; the other metal does not suffer any damage. The corroded metal is named the active metal, and the other one is called the inert metal.

Galvanic corrosion can be recognized by an increase in the attack on the metal junction. It can be controlled by isolating the metals or limiting their contact when there is a significant potential difference in the medium where they operate. Another preventive method is to avoid creating large areas of active and noble metals in contact. The most important strategy is to avoid selecting different materials for the same equipment; if it is necessary, choose metals with a similar electrical potential. It is also recommended to insert isolating materials or to cover the active metal to maintain an optimal distance.

Also recommended are measures such as avoiding the presence of holes or slots, and avoiding connections between different metals. It is recommended to add substances to the medium that consume oxygen, such as sodium hyposulfite or hydrazine, and to use paints. In fluids, avoid areas where corrosion products can accumulate, known as "dead zones". Figure 2 illustrates galvanic corrosion [8].

Fig. 2. Galvanic corrosion.

2.1.2 Pitting corrosion and its preventive methods

Pitting corrosion appears as small holes on a surface that is almost unaffected. These pits can take various forms. The form of the pitting influences its development, meaning that a pit can be considered as a slot formed by itself. In general, the holes are shallow with small diameters and can be isolated or clustered on rough surfaces of pipes or equipment. It is the most widespread form of corrosion in Caribbean countries.

Pitting corrosion is caused by the presence of aggressive anions or chloride ions. Aggression tends to vary logarithmically with chloride concentration. In this process, when pitting tends to develop, conditions are created such that pitting tends to continue. The growth of the process also depends on the metal composition. The process is more common on heat exchangers, pipes and on the bottom of tanks with residues of clean products.

Causes of this type of corrosion [9]:

- The presence of metallic inclusions or different alloy phases with different electrical potential.
- Corrosion deposition, making oxygen access more difficult, causing the appearance of concentration cells.
- Rupture of passive sites by the appearance of halogen anions Cl^-, Br^-, I^-, and others such as ClO^-, $ClO4^-$; the most dangerous being Cl^-. This type of corrosion is more common in passive metals (iron, low alloy steels, alloy steels, Al and its alloys).

Measures for the prevention of this type of corrosion are:

- ✓ Adequate selection for the metals to be used.
- ✓ Not to use passive metals in media with the presence of chloride ions, halogens or sea water.
- ✓ Use copper or copper alloys such as Monel metal or Cu-Ni.

Fig. 3 shows the pitting corrosion.

Fig. 3. Pitting corrosion.

2.1.3 Intregranular or intercrystaline corrosion and its preventive methods

To understand this type of corrosion, it is necessary to consider that when a metal in a foundry is placed in a mold, its solidification begins with the formation of nuclei. Each nucleus grows in an atomically random yet regular arrangement to form what are called grains or crystals. The atomic arrangement and the space between the grains are consistent within all crystals of a given metal; however, due to the randomness, the atomic planes near the grain boundaries do not exhibit good coherence, and there is some disorder in the spacing between them. This is referred to as the "grain boundary".

Corrosion typically occurs because the corrosive agent preferentially attacks the grain boundaries or the zones near them. These zones have lost a necessary element for providing adequate corrosion resistance. This phenomenon is sensitive to heat, which is why it often results from heat treatments such as welding or stress relieving, and it can be mitigated by other heat treatments or by using a modified alloy [10]. The most common case is the corrosion of unstabilized alloy steels.

The measures to prevent this type of corrosion are to establish the maximum homogeneity of the materials used. This could be achieved in Ti or Mo stabilized alloyed steels, treated at temperatures in the range of 950-1050^{0}C cooled in water; also by using steels with low carbon content. Figure 4 shows an example of intergranular corrosion.

Fig. 4. Intergranular corrosion.

2.1.4 Corrosion by exfoliation or selective dissolution

Corrosion by exfoliation is a subsurface corrosion that begins on a clean surface and spreads under it and differs from pitting on its aspect, which is laminar. Complete layers of the material are corroded and the attack is known for the formation of scales.

At the end of the attack, the appearance is like cards as if some of them had been extracted in aluminum alloys. This mechanism is well known in aluminum alloys and it is stopped by proper alloys and heat treatment.

Selective dissolution corrosion occurs when one of the alloy elements is absent. A well-known example is the elimination of zinc from copper-zinc alloys, which is known as dezincification. This phenomenon results in a porous metal with very low mechanical properties, and the prevention method is to produce alloys that are not susceptible to this process.

The only way to prevent exfoliation is to choose the right alloy and heat treatment. For dezincification it is necessary to consider:

- The environment aggression, the no presence of oxygen and the use of cathode protection.
- The use of Cu-Zn alloys with a zinc content of 15-20%.
- To add low quantities of Sn, As, Sb and P.

Figure 5 shows an example of exfoliation.

Fig. 5. Exfoliation corrosion on water treatment plant.

2.2 Corrosion under the influence of mechanical factors

2.2.1 Erosion corrosion

When the corrosive environment moves more rapidly over the metallic surface, the velocity of attack due to mechanical wear increases. This is known as erosion-corrosion.

The relative importance of mechanical wear and corrosion is sometimes difficult to establish, and it varies greatly depending on the specific situation. The erosion mechanism, in general, is attributed to the removal of surface protective layers, such as oxide layers formed by air or corrosion products. The appearance of erosion-corrosion typically resembles shallow pitting on a smooth surface, and the attack may exhibit a directional distribution due to the movement of the corrosive agent over the metal surface. This type of corrosion can be observed in Fig. 6.

Fig. 6. Erosion corrosion.

Erosion-corrosion develops under high-velocity conditions, turbulence, and shock, and is frequently observed on pumps, agitators, and elbows with directional changes in tubes. Liquids with hard solid particles in suspension can also cause this damage. The surface is characterized by directional grooves. Failure times are very short, and this type of corrosion preferentially affects soft metals like copper. It is caused by hot gases with high velocity and hard particles in suspension, as well as by moving organic systems. This type of corrosion can be avoided through design changes or by using more resistant materials.

2.2.2 Corrosion by wear (fretting corrosion)

Corrosion by wear (fretting corrosion) occurs when metal pieces slide one over the other, causing mechanical wear to one or both pieces and the sliding is the result of vibration. This type of corrosion can be attenuated by the use of harder construction materials, lubrication or increasing vibration to the point where sliding is impossible.

2.2.3 Cavitation

Cavitation is a special form of erosion-corrosion. This type of corrosion occurs when vapor bubbles condense on a liquid near a metal surface. It is typically found in line pipes, propellers, impellers, and other surfaces where turbulence and high-velocity zones coexist with low pressure. For carbon steel, it occurs at velocities of ≥ 4.5 m/s. The bubbles impact the surface and produce noise that locally damages the surface.

Preventive methods to this type of corrosion are:

- To employ resistant alloys from mechanical point of view with strong adherent protective layers like Cr-Ni steel alloys, aluminum bronzes and Monel metal.
- Avoid the use of current foundry irons.
- Operate rotors and impellent to the maximum possible pressure charge to avoid bubbles formation.
- Avoid turbulence.

- Eliminate suspension solids.
- Employ passive substances such as chromates and dichromate and cathode protection.
- Cover surfaces with rubber, porcelain or special resins.

In Figs 7 and 8, it is possible to observe the process development and its consequence.

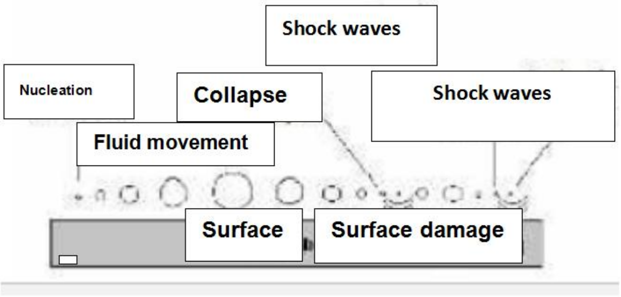


Fig. 7. Cavitation process.

Fig. 8. Cavitation damage.

2.3.4 Under tension corrosion

The joint action of a tension stress and a corrosive environment will result in fracture of metallic alloy. The majority of alloys are susceptible to this attack, but fortunately, the number of combinations of corrosive alloys that cause this problem are relativity few. Nevertheless, this problem is one of the more serious metallurgical problems.

The factors causing fracture may come from cold working, welding, and heat treatment, or external forms during equipment operation. Fracture may appear in an intergranular or transgranular manner, which in some cases shows ramification.

Some of the characteristics of under tension corrosion fracture are:

- ✓ It requires a stress tension.
- ✓ Have a great influence on alloy's metallurgical conditions.
- ✓ Time of exposition is very important.

To avoid under stress corrosion, it is necessary to resist the applied stress, relieve tensions by heat treatment or select a more resistant material.

In Fig. 9, it can be observed an example of under stress corrosion.

Fig. 9. Under stress corrosion.

2.3.5 Fatigue corrosion

Fatigue corrosion is a special case of corrosion failure under stress, which can occur even in the absence of a corrosive environment under cyclic repeated stress. This type of failure is common in structures with continued vibration. It is, of course, increased in the presence of a corrosive environment. The stress required for fatigue corrosion can be reduced to half of that of dry air in some cases.

This corrosion takes place in metallic materials that support simultaneously the action of tensile stresses in a specific corrosive environment. In this type of corrosion, the surface is less damaged, but scars in the form of intergranular or transgranular structures are formed inside the material. When stress is an alternative solution, this situation can occur even if the applied stress is less than the allowable stress. In this case, the corrosion is intergranular with ramification. Its presence appears in carbon steels, seawater and combustion products; in propellers, steam boilers, pistons and wires.

The more effective preventive method of preventing this corrosion is the cathode protection. In addition, methods to prevent intergranular corrosion can be used, such as eliminating internal stress through heat treatment and using inhibitors such as hydrazine, sodium sulfite, and phosphate solutions. It is also effective:

- To diminish concentration of chloride ions.
- To employ inhibitors such as sodium dichromate.
- Employ cathode protection with zinc, cadmium or the use of protective layers.
- Educe vibration and cyclic stresses.
- Generate compression stresses on surface by different methods.

Figure 10 shows an example of fatigue corrosion.

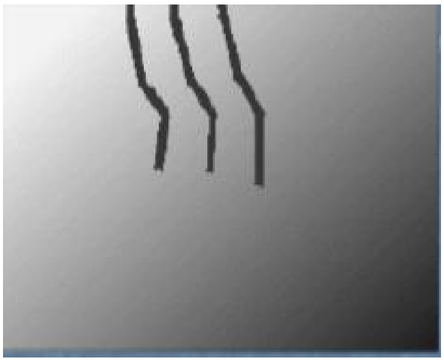


Fig. 10. Fatigue corrosion.

2.3 Principles of cathode protection

Considering the electrochemical series of metals, a metal will have anodic character in respect to other one, if the first is over the second in the electrochemical series. For example, iron will be anodic in respect to copper and cathode in respect to zinc. The anodic metal sacrifices in relation to the cathode one; that's why this system is so called cathode protection by a sacrifice anode [7].

Nevertheless, the majority of anodes are produced by foundry or gravitation, with some of them produced by continuous foundry or by extrusion. The foundry method produces the appearance and physical structure of the anode and its commercialization and behavior. From the point of view of behavior, the anode must be produced by a foundry in order for the metal to solidify without segregation, and strange substances, blowing or inhaling air are never allowed, as the anode often undergoes passive or physical decomposition if this occurs. It will never form passive substances or be blocked by corrosion products, nor will it obtain hydrogen under tension.

From a technical point of view, anodes must possess a series of fundamental properties, such as:

- Have a dissolution potential negative enough to polarize the structure (in iron - 0.8 volts).
- The anode has to corrode uniformly.
- Must have a high electrical weariness in A/hkg.
- Must have easy acquisition and must have the possibility to be foundered on different forms and sizes.
- Must have a reasonable cost to obtain a reasonable protection in amperes/year.

A.S.T.M. NORM B6-46 and USA specification Mil-A 18001 H defined anode compositions for zinc, magnesium and aluminum alloys.

3. Social Economic Aspects of Corrosion

First estimation of corrosion costs indicate that they are approximately of 4 % of a country's PBI [11].

Corrosion is a phenomenon that can affect practically any material and if it is not controlled or prevented, it may reduce the efficiency of components, equipment and structures.

The economic waste of corrosion can be divided into direct waste and indirect waste. Direct waste is related to the necessary cost of relocating structures, equipment, machinery, or components that cannot be used due to corrosive effects.

Indirect waste may include interruption, product loss, by-product pollution waste, fatigue loss, and accident loss. It is estimated that the relationship between direct and indirect costs is about 1/6 or 1/10. In addition, it is estimated that 10% to 12% of steel production is lost annually due to corrosion.

Social and human aspects. The following aspects could be considered:

a) Safety, as violent failures can cause fires, explosions and release of toxic products and loss of human lives.
b) Unhealthy conditions such as contamination by the corroding products or a product of corrosion.
c) Desiccation of natural resources in metals and fuels used in production.
d) Appearance: as corroded materials are unpleasant to see.

4. Conclusions

Corrosion is an electrochemical process, and like all metallurgical processes, its driving force comes from the reduction of the free energy of the system.

All materials undergo a corrosion process, but the corrosion process of polymers has different mechanisms of occurrence, therefore it is called a degradation process.

There are various forms of corrosion classification, with the most common being uniform corrosion (homogeneous corrosion) and localized corrosion (heterogeneous corrosion). In some cases, localized corrosion is caused by mechanical factors. There are preventive measures in all cases.

Corrosion produces important social and economic consequences.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Martínez F. "Temas importantes en el Mantenimiento. Ingeniería de Superficies, Corrosión, Materiales de Construcción, Aceros inoxidables". Monografía, Universidad Tecnológica de La Habana, 2016, ISBN 978-959-261-526-7.

[2] García O. "Gestión Moderna del Mantenimiento Industrial". 2012, Bogotá, ISBN-078-958-762-051-1.

[3] Callister W "Materials Science and Engineering, John Wiley and Son Inc., 2000, ISBN-0-471-32013-7.

[4] Askeland D. "Ciencia e Ingeniería de los Materiales", Cuarta Edición, Impreso en México, ISBN 970-686-361-3.

[5] Ashby M. "Engineering Materials 2", Butterworth Heinemann, Oxford, 1999, ISBN 0-7506-4019-7.

[6] Tomashov N. D. Theory of corrosion and protection of metals. Edición Revolucionaria, Instituto del Libro, 1971.

[7] Domínguez, J.A. y col. Introducción a la Corrosión y Protección de Metales. Ediciones ENPES, 1987.

[8] Schweitzer PA. Fundamentals of corrosion: mechanisms, causes, and preventative methods. Chapter 3, Forms of metallic corrosion. New York, Taylor and Francis Group, 2010.

[9] Denny A. Jones "Principles and Prevention of Corrosion", Second Edition, 1996, by Prentice-Hall, Inc. ISBN 0-13-359993-O.

[10] Cary H, "Modern Welding Technology", Prentice Hall, 1989, ISBN 0-13-241803-7.

[11] Nace Corrosion Engineer's Handbook, Third Edition, Nace International, 2002, ISBN 1-57590-139-0.