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A REVIEW OF THE MULTIFACETED NATURE OF CORROSION: THE IMPACT OF STEEL FORMABILITY AND SURFACE ROUGHNESS ON CORROSION RESISTANCE (PART 1)

A KORRÓZIÓS MEGHIBÁSODÁSOK ÁTTEKINTÉSE: AZ ACÉL ALAKÍTOTTSÁGÁNAK ÉS FELÜLETI ÉRDESSÉGÉNEK HATÁSA A KORRÓZIÓÁLLÓSÁGRA (1. RÉSZ)

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Abstract

This two-part review article explores the diverse nature of corrosion, focusing on the impact of steel formability and surface roughness on corrosion resistance. Corrosion is a significant issue in various industries, leading to economic losses and safety risks. Traditional methods often overlook the effects of steel's formability and surface roughness, which can influence stress distribution, microstructure, and areas prone to corrosion. This article reviews environmental factors contributing to corrosion, such as material composition, electrochemical potential, surface roughness, stress, deformation, and temperature. A case study by Wang et al. presented in this article, while the 2nd part of our paper focuses more on case studies.

Absztrakt

Ez a két részes áttekintő cikk a korrózió sokrétű természetét vizsgálja, különös tekintettel az acél alakítottságának és felületi érdességének hatására. A korrózió jelentős problémát okoz különböző iparágakban, gazdasági veszteségeket és biztonsági kockázatokat eredményezve. A hagyományos módszerek gyakran figyelmen kívül hagyják az acél alakítottságának és felületi érdességének hatásait, amelyek befolyásolhatják a feszültségeloszlást és a mikroszerkezetet. E cikk áttekinti a korrózió főbb típusait, a hozzájáruló környezeti tényezőket, mint például az anyagösszetétel, az elektrokémiai potenciál, a felületi érdesség, a feszültség és a hőmérséklet. Cikkünk első része Wang esettanulmányára épül és azt mutatja be, míg cikkünk második része további esettanulmányokat mutat be.

Keywords

Safety Critical Components, Corrosion, Surface Roughness, Corrosion Resistance, Structural Safety

Kulcsszavak

Biztonságkritikus komponensek, Korrózió, Felületi érdesség, Korrozióállóság, Szerkezeti integritás

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INTRODUCTION

Corrosion is a significant problem in industry, as damage to metals and other structural materials can cause serious economic losses and pose a safety risk. It can significantly reduce the lifespan of industrial equipment, pipelines, tanks, and other structures, increasing maintenance and replacement costs. Additionally, corrosion can pose safety risks, especially in industries such as oil and gas, chemical, and energy sectors.

There are several traditional methods for determining corrosion resistance, the most common of which are [1] [2]:

- Laboratory Tests: These involve exposing metals to various corrosive environments and measuring the rate and extent of corrosion.
- Electrochemical Methods: This includes the potentiodynamic polarisation test, which measures metals' corrosion potential and current.
- Field Tests: These involve testing metals under actual environmental conditions over an extended period to determine the actual effects of corrosion.

When examining steel's corrosion resistance, the formability and surface roughness are often overlooked. However, these factors can significantly impact corrosion. Steel's formability can affect stress distribution and microstructure, while surface roughness can increase the number and size of areas prone to corrosion.

THE BASICS OF CORROSION

Corrosion processes primarily occur through chemical and electrochemical reactions, during which metals lose electrons, i.e., they oxidise and turn into ions. Any reaction involving electron donation and acceptance is called a redox reaction. The particle that donates electrons oxidises, while the one that accepts electrons reduces. Thus, corrosion is a reaction between metals and other structural materials with the environment, during which the material reverts to a more stable, lower energy state through chemical or electrochemical processes. This causes changes in size and mass, as well as a decrease in the component's strength. A disadvantageous property is that it damages machine parts during operation and storage if protection is neglected.

The most common corrosion mechanisms include hydrogen evolution corrosion, where metals dissolve in acidic environments, and oxygen absorption corrosion, where metals oxidise in aqueous solutions. Several factors, including chemical affinity, concentration, pressure, temperature, and the size of the reacting surfaces influence the corrosion rate. Corrosion can occur in liquid, gas, and solid media, leading to liquid corrosion, atmospheric or gas corrosion, and soil corrosion.

Based on the mechanism of the corrosion process, we can distinguish between chemical, transitional, and electrochemical corrosion. In chemical corrosion, the reactions between the metal and the environment are chemical, while in electrochemical corrosion, the cathodic and anodic positions of the metal, as well as the location of metal ion and electron release and the conditions for electron acceptance, determine the process. Transitional corrosion is a combination of chemical and electrochemical processes [1].

The chemical reactions occurring during corrosion can be divided into two main types: hydrogen evolution and oxygen absorption reactions. Hydrogen evolution reactions occur on the surface of metals in contact with aqueous solutions, where metal ions are formed and pass into the solution. The general reaction equation is the following, where *Me* can be any metal:

$$Me + 2H^{+} \leftrightarrow Me^{++} + H_2$$

Oxygen absorption corrosion occurs in aqueous solutions with low H^+ concentration and follows the reaction equation:

$$2Me\ +\ 2H2O\ +\ O2\ \leftrightarrow\ 2Me++\ +\ 4OH-$$

In this case, the presence of oxygen is also necessary, and metals with higher potential than hydrogen only dissolve in acid after oxidation.

Types of Corrosion

Several types of corrosion affect metals and alloys in different ways. Some common types include general (uniform) corrosion, which uniformly thins the metal surface; localised corrosion, such as pitting and crevice corrosion, which attack specific areas; and stress corrosion cracking, which causes cracks due to the combined effect of mechanical stress and a corrosive environment. Additionally, intergranular corrosion attacks the grain boundaries of metals, while selective corrosion affects specific components of alloys. Other specific types of corrosion, such as boric acid corrosion, can occur in specific environments. In the following some of the previously mentioned corrosion types are presented [1] [2] [3] [4] [5] [6] [7] [8] [9].

General (Uniform) Corrosion: This type of corrosion involves the approximately uniform thinning of the metal surface due to chemical reactions in an aggressive environment. It is particularly characteristic of equipment and pipelines made from unalloyed and low-alloy steels. The rate and other characteristics of general corrosion depend significantly on the material's chemical composition, the operating medium's properties, the operating conditions, and other environmental factors such as temperature, humidity, and the presence of acidic or alkaline vapours. This type of corrosion is presented in Figure 1/a.

Pitting Corrosion: Pitting corrosion is a form of corrosion that localises in narrow areas where the corrosion rate is significantly higher than elsewhere. As a result, relatively deep cavities form, often filled with chemically active contaminants that promote further growth. Pitting corrosion can be particularly problematic for passive metals, such as austenitic stainless steel. This type of corrosion is presented in Figure 1/b.

Crevice Corrosion: Crevice corrosion is locally accelerated damage that occurs in constructional gaps, between fitting parts, cracks, and under deposits. The crevice must be wide enough to allow the medium to enter but narrow enough to prevent the medium from flowing further, resulting in a stagnant condition. Microbiological effects generally accelerate the corrosion process, especially in pitting and crevice corrosion characterized by stagnant or slow medium flow. This type of corrosion is presented in Figure 1/c.

Intergranular Corrosion (IGA): Intergranular corrosion involves the damage of grain boundaries, leading to the loss of cohesion between grains and the disintegration of the damaged parts of the material. The sensitivity of grain boundaries can be due to several factors, such as greater deformation work or the formation of chromium carbides at the grain boundaries. One way to avoid IGA is through chromium chemistry. This type of corrosion is presented in Figure 1/d.

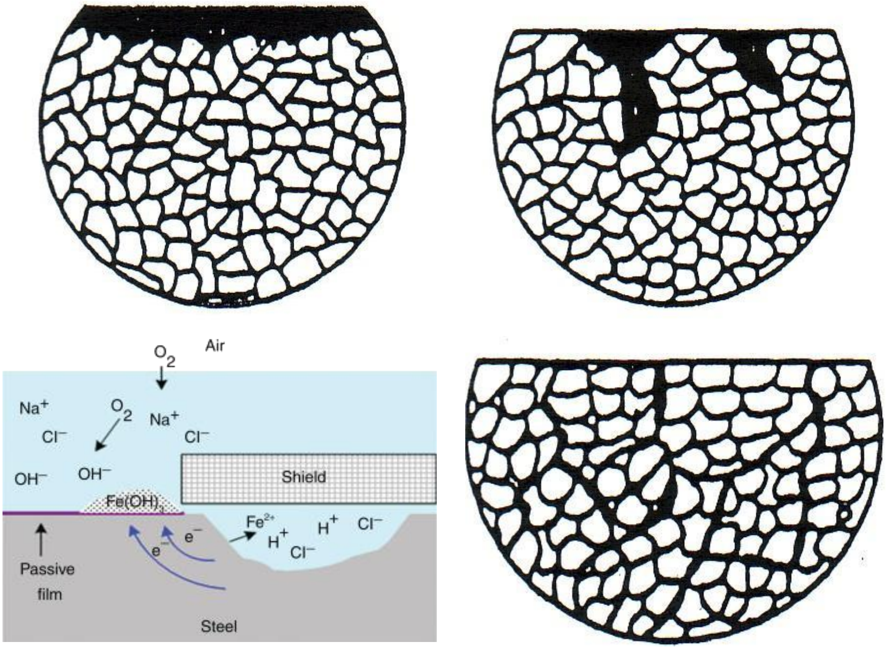

Figure 1: Different types of corrosion. a, General (Uniform) Corrosion. b, Pitting Corrosion. c, Crevice Corrosion. d, Intergranular Corrosion. [4] [10]

Layered Corrosion: A variant of intergranular corrosion observed in sheet metal parts, where the sheet separates into layers. Another variant is stress corrosion, which is caused by mechanical stress. The rate of intergranular corrosion can be characterised by the decrease in strength and elongation over time. This type of corrosion is presented in Figure 2/a.

Selective Corrosion: This type of corrosion attacks alloys, particularly those where one component has a nobler potential than the others. For example, zinc is leached out in the selective corrosion of brass (a copper-zinc alloy), leading to a spongy material. The rate of selective corrosion can also be characterised by the decrease in strength and elongation over time. This type of corrosion is presented in Figure 2/b.

Stress Corrosion Cracking (SCC): SCC can occur in materials sensitive to the combined presence of an aggressive medium and tensile stress. Several factors, such as the fragmentation of oxides, the effectiveness of passivation, or the renewal of the corrosive medium along the crack front influence the development and progression of SCC. SCC damage can be intergranular (IGSCC) or transgranular (TGSCC) and is extremely dangerous as it can cause sudden and unexpected fractures. This type of corrosion is presented in Figure 2/c.

Erosion Corrosion: Erosion corrosion occurs when the flowing corrosive medium locally accelerates the dissolution rate of the material. This damage is often referred to as flow-accelerated corrosion (FAC). The essence of erosion corrosion is that the protective oxide layer on the material surface is continuously or cyclically, locally removed by the operating medium. The process is influenced by several factors, such as the structural material, geometric and hydrodynamic conditions, the temperature of the medium, its pH, and dissolved oxygen content. This type of corrosion is presented in Figure 2/d.

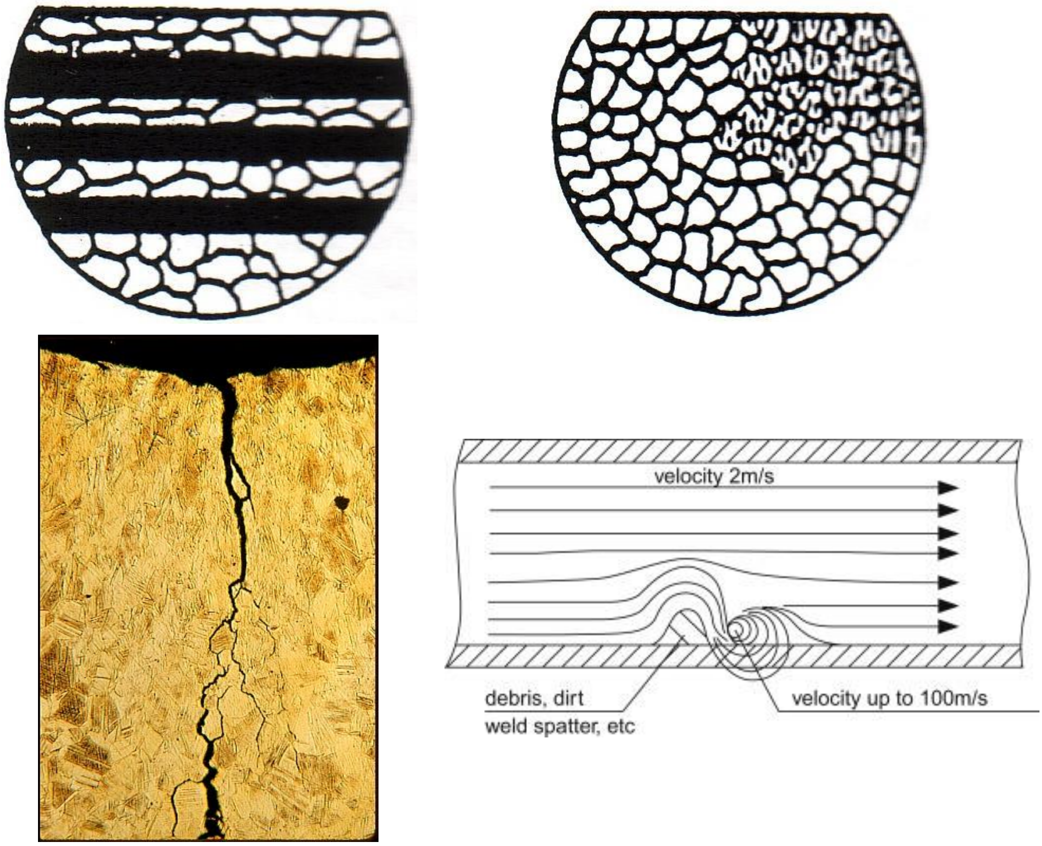

Figure 2: Different types of corrosion. a, Layered Corrosion. b, Selective Corrosion. c, Stress Corrosion Cracking. d, Erosion Corrosion. [4] [11] [12]

Stainless Steels and Their Corrosion Resistance

The chemical composition of metals significantly affects their corrosion resistance. Alloying elements such as chromium, nickel, and molybdenum can enhance corrosion resistance by forming a protective oxide layer on the surface. Unalloyed steels are generally less corrosion-resistant, while high-alloy steels, such as austenitic stainless steels, exhibit excellent corrosion resistance under various environmental conditions.

Austenitic stainless steels, such as types 304 and 316, exhibit excellent corrosion resistance due to their high chromium and nickel content. These steels are particularly resistant to uniform corrosion and pitting. Type 316 also contains molybdenum, which further enhances corrosion resistance, especially in chloride environments [6] [13] [14].

Ferritic stainless steels, such as type 430, have lower chromium and nickel content, making them less corrosion-resistant than austenitic steels. However, these steels still show good corrosion resistance in many industrial applications, particularly due to their lower cost [15].

Duplex stainless steels, such as type 2205, combine the advantages of austenitic and ferritic steels. Their high chromium and molybdenum content provides excellent corrosion resistance, particularly against pitting and crevice corrosion. Additionally, they are favoured for their high strength and good weldability [5].

Due to their low nickel content, superferritic stainless steels, such as E-Brite and SEA-CURE, offer cost-effective solutions in chloride environments. These steels exhibit excellent corrosion resistance, particularly against pitting and crevice corrosion. They also have high strength and good thermal conductivity, making them advantageous [16].

Improving Corrosion Resistance

Several surface treatment processes, such as electropolishing, passivation, and coating, can improve corrosion resistance. These processes help remove surface contaminants and form a uniform, protective layer on the metal surface.

Adding alloying elements such as chromium, nickel, molybdenum, and nitrogen increases the corrosion resistance of metals. These elements help form a protective oxide layer on the metal surface, preventing corrosion [1] [3] [4] [5] [6].

Heat treatment processes, such as solution heat treatment and post-heat treatment passivation, help improve the corrosion resistance of metals. These processes help remove surface contaminants and form a uniform, protective layer on the metal surface [1] [2] [3].

Testing Corrosion Resistance

There are different types of testing, one of these types is laboratory tests which involve exposing metals to various corrosive environments and measuring the rate and extent of corrosion. These tests allow for comparing corrosion resistance among different materials and evaluating the effectiveness of corrosion protection measures. Laboratory tests include salt spray, potentiodynamic polarisation, and cyclic corrosion tests. Contrary to the laboratory test, the field test involves testing metals under real environmental conditions over an extended period. These tests allow for determining the actual effects of corrosion, considering changes in environmental factors such as temperature, humidity, and contaminants. Data collected from field tests help validate laboratory test results and refine corrosion protection strategies [17] [18].

Corrosion Monitoring Systems

Corrosion monitoring systems continuously monitor the corrosion status of metals and the environmental conditions. These systems provide real-time data on corrosion processes, allowing for quick intervention and minimizing corrosion damage. Corrosion monitoring systems include electrochemical sensors, corrosion potential meters, and corrosion current meters [3] [19] [7] [8].

FACTORS INFLUENCING CORROSION

Numerous environmental factors influence corrosion. Many of these factors are listed below. This list is relatively long but not exhaustive. The factors influencing the rate and spread of corrosion are listed in alphabetical order [1] [3] [6] [7] [8] [12] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36].

- Atmospheric Conditions: Weather patterns, pollution levels, and other atmospheric factors.
- Chemical Composition of the Environmental Medium: For example, the hardness and alkalinity of water or the pH, moisture content, and composition of soil can affect underground corrosion.
- Conductivity: The presence of conductive media can influence electrochemical reactions.
- Electrochemical Potential: Differences in electrochemical potential between metals can cause galvanic corrosion.
- Electromagnetic Fields: The effect of electric and magnetic fields can influence corrosion processes.
- Environmental Medium: Air, water, soil, and other environments that the metal comes into contact with.
- Exposure Time: The duration of the metal's exposure to corrosive conditions affects the extent of corrosion.
- Exposure to Chemicals: Industrial chemicals and pollutants can cause or accelerate corrosion.
- Flow Rate of Fluids: The flow rate of water or air over the metal can influence the extent of corrosion.
- Galvanic Contact: Contact between different metals can lead to galvanic corrosion.
- Human Activity: Maintenance practices, handling, and usage patterns can affect corrosion.
- Humidity: Higher humidity can increase the rate of corrosion.
- Industrial Emissions: Exposure to industrial pollutants can accelerate corrosion.
- Ion Concentration: Certain ions, such as chloride and sulphate, can accelerate corrosion.
- Material Composition: The type of metal and its alloys can significantly affect the extent of corrosion.
- Mechanical Wear: Wear and abrasion of the metal surface can expose fresh metal to a corrosive environment.
- Microbial Activity: The presence of bacteria and other microorganisms can lead to microbiologically influenced corrosion.
- Oxygen Concentration: The availability of oxygen can influence the corrosion process.
- pH Level: Acidic or alkaline environments can significantly affect the extent of corrosion.
- Presence of Contaminants: Contaminants such as salts (e.g., NaCl) can accelerate corrosion.
- Presence of Organic Materials: Interaction with organic materials can affect corrosion.
- Pressure: High or low-pressure conditions can affect the rate of corrosion.
- Protective Coatings: The presence or absence of coatings such as paint or galvanisation.
- Radiation Levels: Exposure to radioactive materials can affect corrosion.

- Salt Concentration: The salt content of the environment can significantly increase the extent of corrosion.
- Stress and Deformation: Mechanical stresses can lead to stress corrosion cracking.
- Surface Roughness: Rougher surfaces can trap moisture and contaminants, accelerating corrosion.
- Temperature: Higher temperatures generally increase the rate of corrosion.
- UV Radiation: Exposure to sunlight and UV rays can damage protective coatings and materials.

The phenomena listed in this list can initiate corrosion on metallic surfaces and influence its spread. Their combined effect, however, can accelerate this process. Three factors are highlighted: surface roughness, stress and deformation, and temperature.

Case studies related to surface roughness and stress corrosion caused by stress are presented in the following two subsections. The effect of temperature on processes is highlighted briefly, with the rule of thumb being that temperature accelerates the reaction rate of chemical processes. The empirically derived Arrhenius equation describes this observation [37], which states that the reaction rate doubles with every 10°C increase in temperature.

Effect of Surface Roughness on Corrosion (Case Studies)

In general, rough surfaces provide more sites for corrosive substances to adhere to, increasing the risk of corrosion. The passive layer forms less effectively on such surfaces, reducing corrosion resistance. In contrast, smoother surfaces provide fewer sites for corrosive substances to adhere to, thereby improving corrosion resistance. Polished and electropolished surfaces are particularly effective in forming and maintaining the passive layer.

Wang et al. [22] in their article examined the effects of temperature and pressure (T and P), velocity (V), and surface roughness (Ra) on the corrosion properties of HP-13Cr stainless steel. For their study, they varied these four parameters as follows:

Four temperature and pressure values:

- 95°C – 2.8 MPa
- 120°C – 3.2 MPa
- 150°C – 3.6 MPa
- 180°C – 3.8 MPa

At these temperature and pressure values, they examined the following four surface roughness samples:

- 0.987 ± 0.031 μm (prepared with 120-grit sandpaper)
- 0.675 ± 0.025 μm (prepared with 240-grit sandpaper)
- 0.288 ± 0.014 μm (prepared with 600-grit sandpaper)
- 0.035 ± 0.009 μm (prepared with 1000-grit sandpaper)

With two different flow rates:

- Static medium (0 m/s)
- 3 m/s medium

The following figure shows the surface roughness profiles of surfaces prepared with 120, 240, 600, and 1000-grit sandpaper.

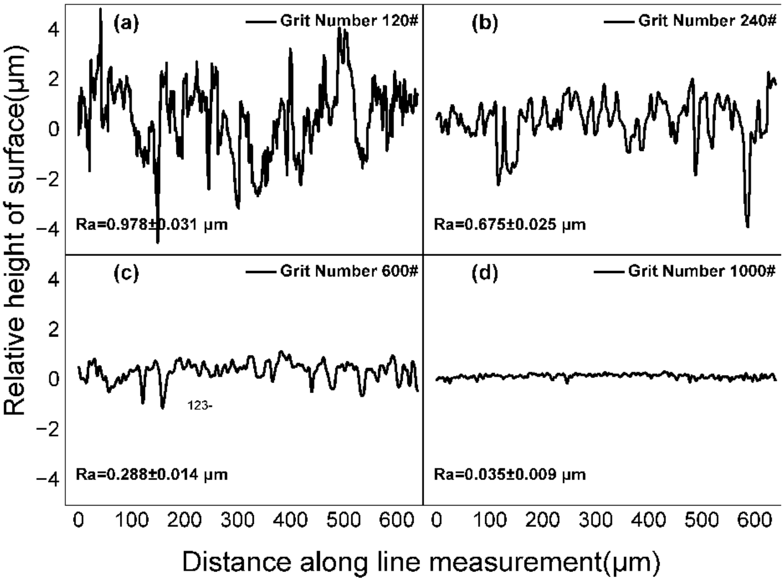

Figure 3. Surface roughness profiles [22]

They also examined their samples using SEM and 3D surface topological analysis, which they modelled with a 2D fluid dynamics simulation. The result of this simulation is shown in the following figure.

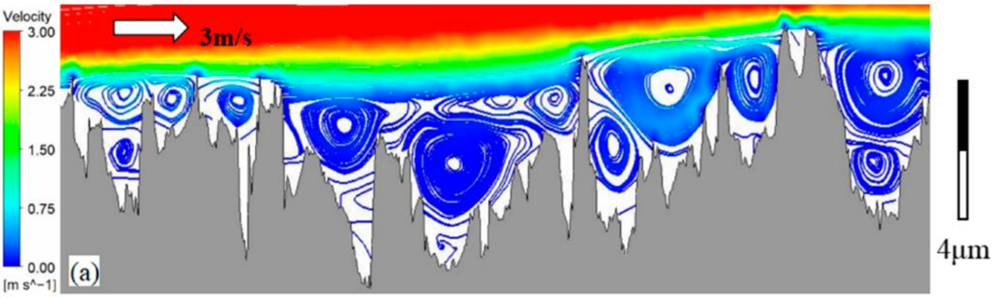

Figure 4. Effect of surface roughness on flow velocity along the surface [22]

The previous figure shows that the flowing medium slows down next to the wall and vortices form in the "trenches" of the surface roughness. The further down towards the bottom line, the more the vortices get trapped in the surface irregularities until their speed becomes zero. This phenomenon is known as the adhesion law in fluid dynamics. Wang et al. highlighted in their study that the moving medium at 3 m/s causes more corrosion than static air.

This phenomenon is also visible in the following two figures. In both figures, the test specimens were cut, and the upper layer of their cross-section is visible. The following figure (Fig. 5.) shows the corrosion test results with the static medium, while Figure 6 shows the results with the flowing medium.

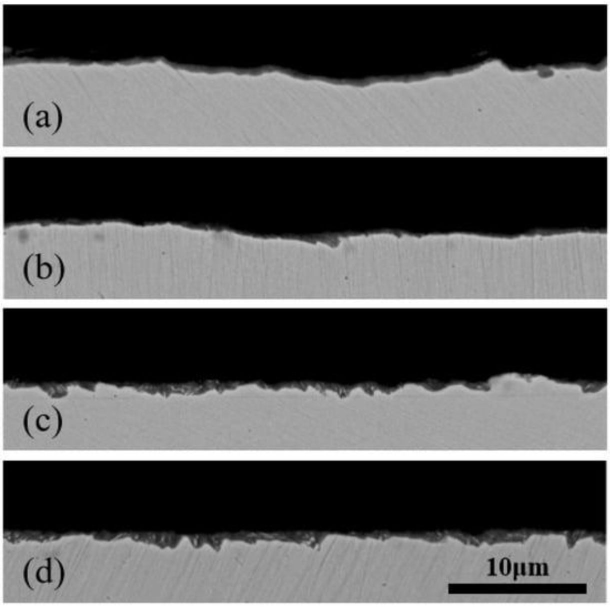

Figure 5. Cross-section upper layer of samples roughened with 120 (a), 240 (b), 600 (c), and 1000 (d) grit sandpaper after immersion test, with 0 m/s flow rate at 150°C and 3.6 MPa. [22]

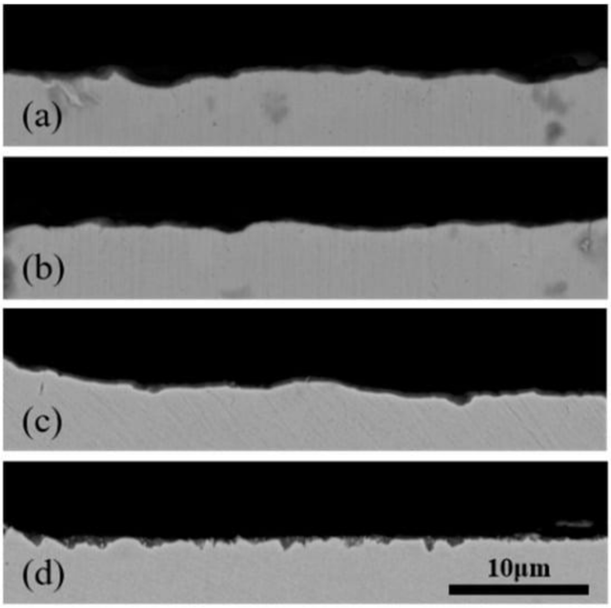

Figure 6. Cross-section upper layer of samples roughened with 120 (a), 240 (b), 600 (c), and 1000 (d) grit sandpaper after immersion test, with 3 m/s flow rate at 150°C and 3.6 MPa. [22]

The following three figures use SEM imaging to show the surfaces of the same test specimens. The first figure shows the state before the immersion corrosion test, the second shows the samples tested with the static medium, and the third shows the samples tested with the flowing corrosive medium.

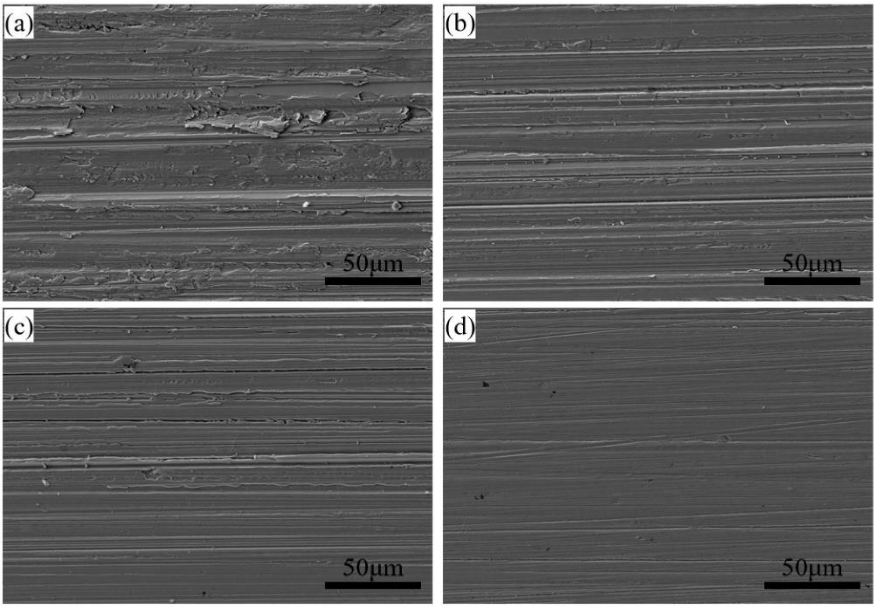

Figure 7. The surfaces of the samples were roughened with 120 (a), 240 (b), 600 (c), and 1000 (d) grit sandpaper before the immersion test. [22]

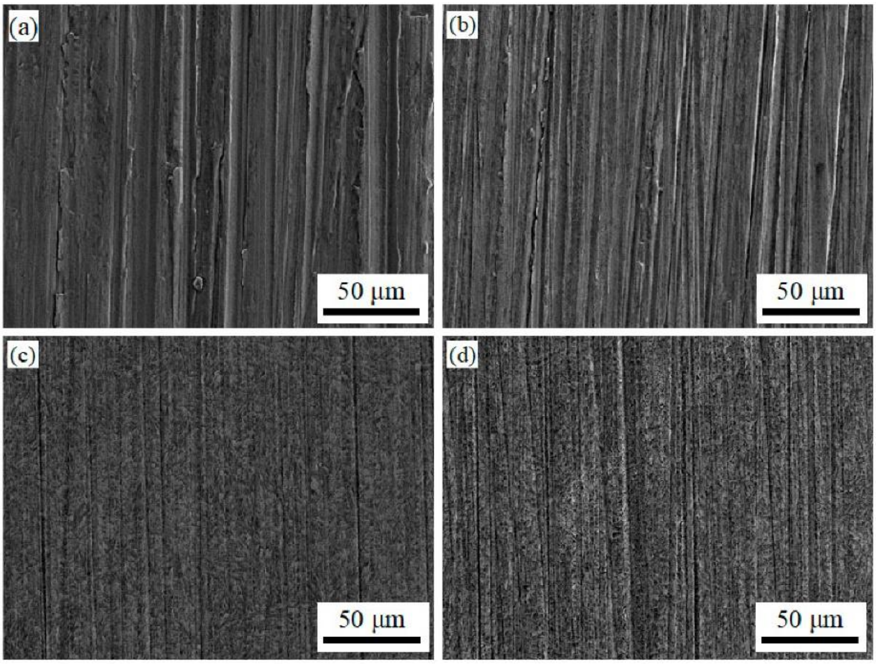

Figure 8. Surfaces of samples roughened with 120 (a), 240 (b), 600 (c), and 1000 (d) grit sandpaper after the immersion test, with 0 m/s flow rate at 150°C and 3.6 MPa. [22]

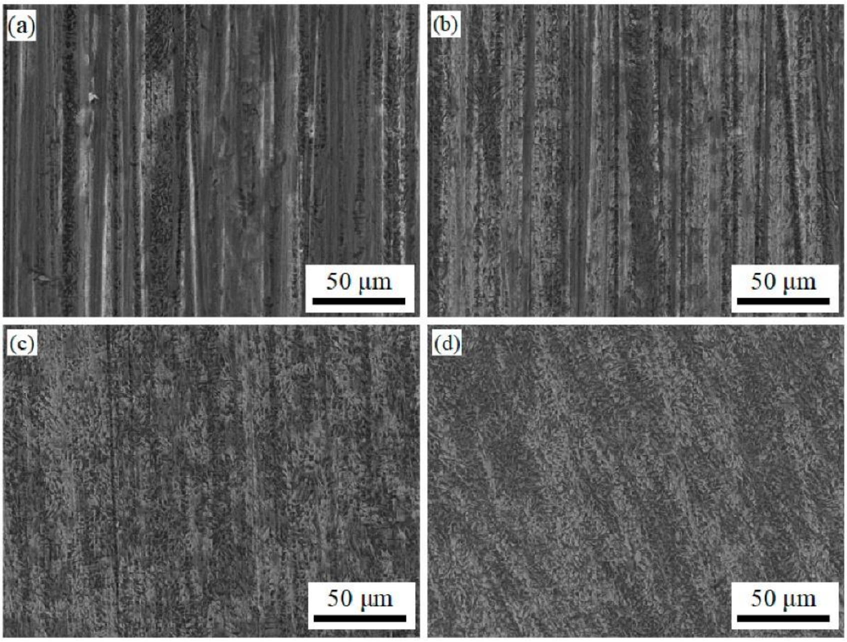

Figure 9. Surfaces of samples roughened with 120 (a), 240 (b), 600 (c), and 1000 (d) grit sandpaper after the immersion test, with 3 m/s flow rate at 150°C and 3.6 MPa. [22]

The surface roughness profile was also measured after the corrosion test. The roughness profile of the sample roughened with 120-grit sandpaper is shown in the following figure.

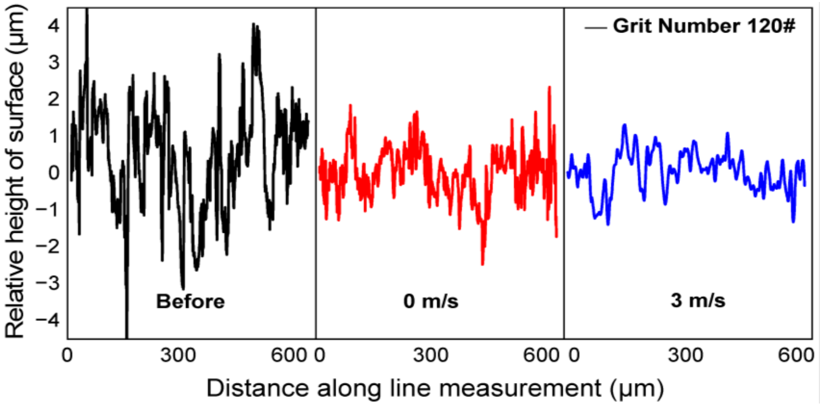

Figure 10. The surface roughness profile of the sample was roughened with 120-grit sandpaper before and after the corrosion tests. [22]

The following figure summarises the results of the tests conducted at the previously outlined temperature and pressure values.

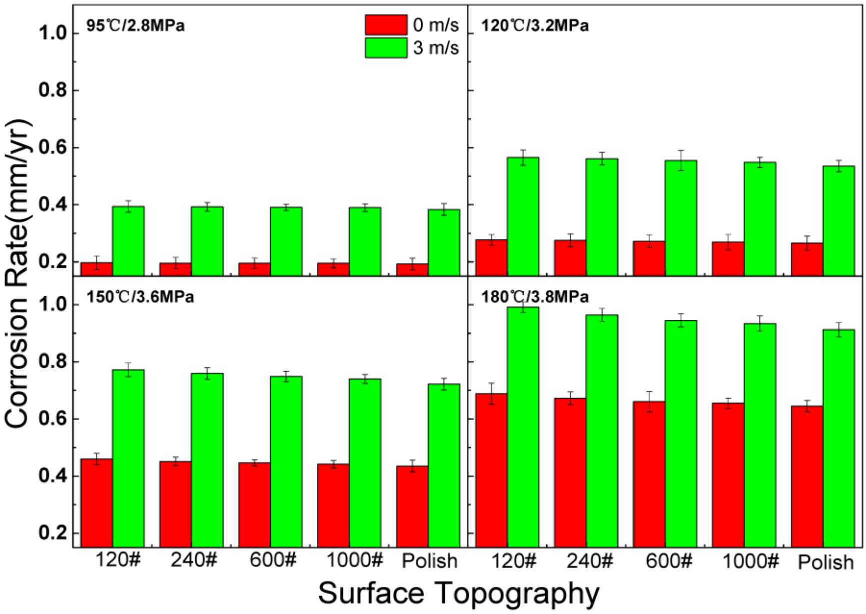

Figure 11. Effect of surface roughness, flow rate, temperature, and pressure on the extent of corrosion [22]

From their measurements, Wang et al. concluded that the interface between the metal and the corrosive solution can be divided into a static and a moving flow layer. The thickness of the surface boundary layer was not affected by the flowing medium, but the thickness of the static layer was reduced. The diffusion of corrosion-causing cations accelerated due to the smaller stagnant layer.

Multi-step vortices formed in the surface boundary layer, hindering the diffusion of Fe^{2+} ions, leading to local acidification along the wall, promoting greater pitting and deeper surface roughness grooves.

Increasing the temperature and pressure reduced the corrosive medium's viscosity, which decreased the thickness of the stagnant layer. This thinning static layer increased the corrosion process.

SUMMARY

In the first part of our two-part review, we presented the multifaceted nature of corrosion, with particular attention to the effects of steel formability and surface roughness. Corrosion resistance is typically determined solely on the basis of chemical composition, often ignoring steel formability, surface roughness, and other manufacturing-related factors.

Our literature review included a number of environmental factors that contribute to corrosion processes, such as material composition, electrochemical potential, surface roughness, stress and strain, and temperature.

This article presents a case study. Corrosion is influenced by the combined effects of many factors, four of which were examined in this case study (temperature, pressure, contact medium flow rate, and surface roughness).

In the second part of our article, we present additional case studies that focus on the corrosion of the corrosion-resistant steels.

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