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A REVIEW OF THE MULTIFACETED NATURE OF CORROSION: THE IMPACT OF STEEL FORMABILITY AND SURFACE ROUGHNESS ON CORROSION RESISTANCE (PART 2)

A KORRÓZIÓS MEGHIBÁSODÁSOK ÁTTEKINTÉSE: AZ ACÉL ALAKÍTOTTSÁGÁNAK ÉS FELÜLETI ÉRDESSÉGÉNEK HATÁSA A KORRÓZIÓÁLLÓSÁGRA (2. RÉSZ)

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Abstract

This two-part review article presents the diverse nature of corrosion, focusing on the effects of steel formability and surface roughness. In the first part of our article, we introduced corrosion and its main types, followed by a case study. In this article, we present additional case studies. The case studies partly confirm our general views and highlight the properties of individual corrosion-resistant steels. The results emphasise the need for comprehensive testing methods to use these factors, ensuring that the quality of the chemical composition and the manufacturing technology are also taken into account when selecting materials for safety-critical applications.

Absztrakt

Ez a két részes áttekintő cikk a korrózió szerteágazó természetét mutatja be, fókuszban az acél alakítottságának és felületi érdességének hatására. Cikkünk első részében a korróziót, és annak főbb típusait mutattuk be, melyet követően bemutattunk egy esettanulmányt. E cikkben további esettanulmányokat mutatunk be. Az esettanulmányok részben igazolják az általános nézeteinket, illetve rámutatnak egy-egy korrózióálló acél tulajdonságára. Az eredmények hangsúlyozzák az átfogó tesztelési módszerek szükségességét, amelyek figyelembe veszik ezeket a tényezőket, biztosítva, hogy a biztonságkritikus alkalmazásokhoz használt anyagok kiválasztásakor a kémiai összetétel mellett a felületi minőséget és a gyártástechnológiát is figyelembe vegyék.

Keywords

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

Kulcsszavak

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

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INTRODUCTION

Corrosion is a significant problem in the industry, as the degradation of metals and other structural materials due to environmental influences can cause severe economic damage. It can significantly reduce the service life of industrial equipment, pipelines, tanks, and other structures, increasing maintenance and replacement costs. In addition, corrosion can pose safety risks, especially in industries such as the oil and gas, chemical, and energy sectors.

In the first part of our two-part review article, we described the main types of corrosion, reviewed the environmental influences that affect corrosion, and presented a case study in which the effects of temperature, pressure, the flow rate of the medium in contact with the material, and surface roughness on corrosion were examined. In this article, we present additional case studies.

REVIEW OF CASE STUDIES

Effect of Surface Roughness on Corrosion (Case Studies)

M. D. Giuseppe conducted corrosion tests [1] on AISI 430 (ferritic stainless steel), AISI 430F (martensitic stainless steel), AISI 303 (sulphur-enriched Cr-Ni austenitic stainless steel), AISI 304L (sulphur-free Cr-Ni austenitic stainless steel), and AISI 316L (Cr-Ni-Mo austenitic stainless steel) steels in his thesis. He performed the tests with both drawn and ground surface finishes.

In his work, Giuseppe conducted potentiodynamic polarisation, potentiostatic polarisation, ferric chloride solution, salt spray, and two different atmospheric corrosion tests on his samples. Among these tests, the potentiodynamic and potentiostatic tests are electrochemical corrosion tests accelerated by electricity, the chloride solution immersion and salt spray tests are chemically accelerated tests. In contrast, the atmospheric test is a real-time test. This review will describe the atmospheric salt spray and atmospheric tests.

When exposed to chloride-containing atmospheres, salt spray corrosion tests are used to determine the local corrosion resistance of stainless steel. The test aims to provide a qualitative comparison of different samples' resistance to pitting corrosion attacks in an accelerated real working environment simulation. The observed parameters are the time of corrosion appearance and the rate of spread.

Giuseppe tested three samples of each steel type and surface finish. He performed the tests daily, with weekly photographic reports on the macroscopic condition of the surface and the microscopic condition of the same samples to better observe and document the appearance of pitting corrosion. The following images (Figure 1 – 14) show the samples with a camera and a microscope after 0, 168, 336, and 816 hours.

Figure 1. AISI 430F (drawn surface finish) samples after 0, 168, 336, and 600 hours. [1]

Figure 2. AISI 430F (ground surface finish) samples after 0, 168, 336, and 600 hours. [1]

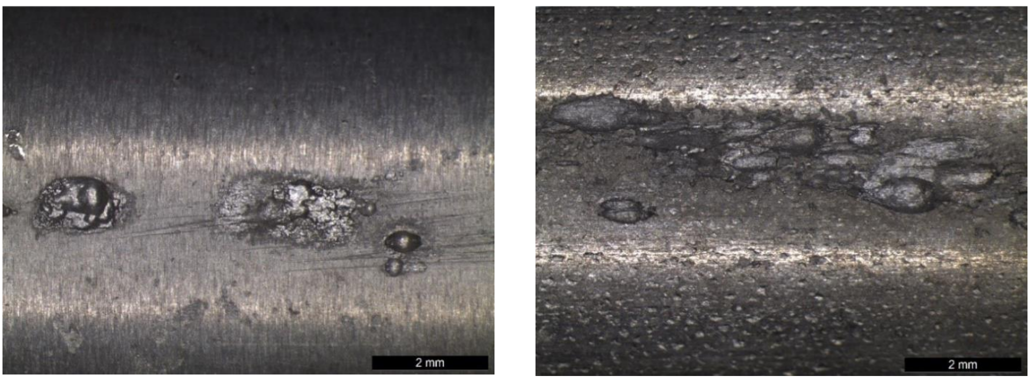


Figure 3. Microscopic image of AISI 430F drawn and ground surface samples. [1]

Figure 4. AISI 430 (drawn surface finish) samples after 0, 168, 336, and 816 hours. [1]

Figure 5. AISI 430 (ground surface finish) samples after 0, 168, 336, and 816 hours. [1]

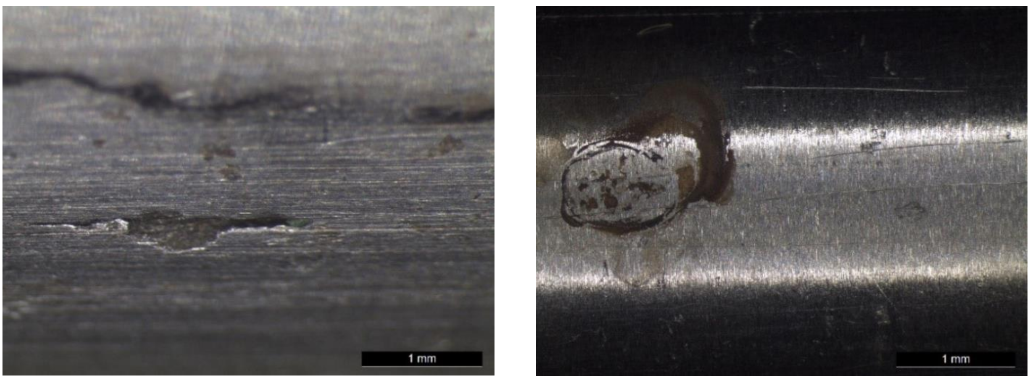


Figure 6. Microscopic image of AISI 430 drawn and ground surface samples [1]

Figure 7. AISI 303 (ground surface finish) samples after 0, 168, 336, and 816 hours. [1]

Figure 8. AISI 303 (ground surface finish) samples after 0, 168, 336, and 816 hours. [1]

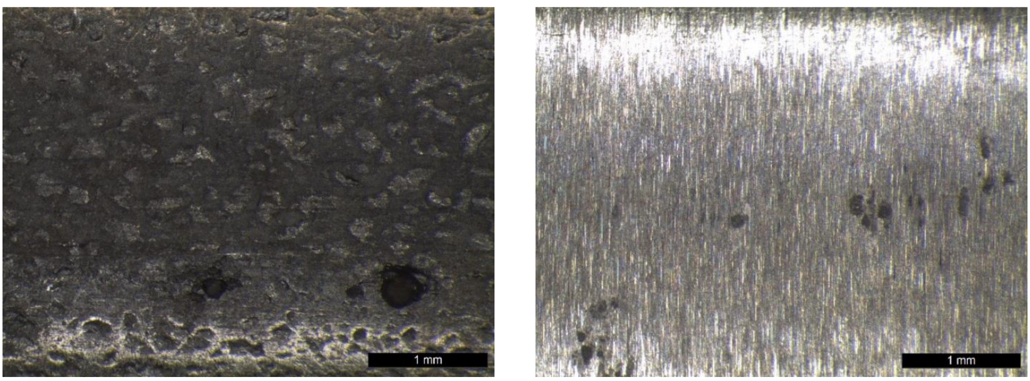


Figure 9. Microscopic image of AISI 303 drawn and ground surface samples. [1]

Figure 10. AISI 304L (drawn surface finish) samples after 0, 168, 336, and 816 hours. [1]

Figure 11. AISI 304L (ground surface finish) samples after 0, 168, 336, and 816 hours. [1]

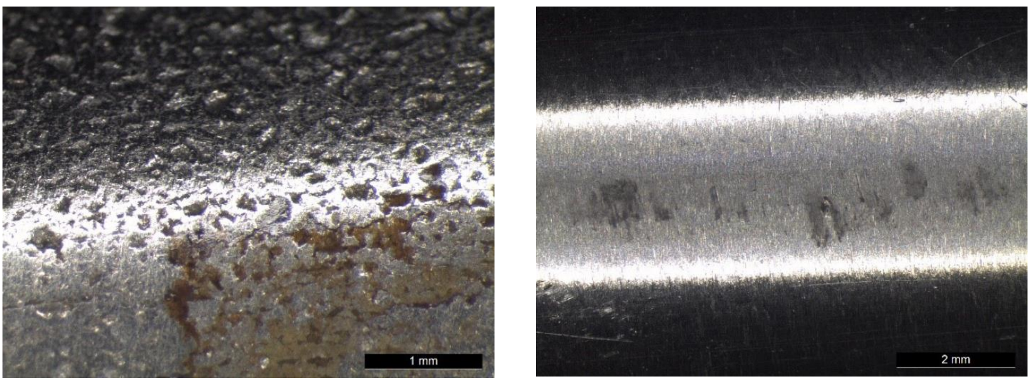


Figure 12. Microscopic image of AISI 304L drawn and ground surface samples. [1]

Figure 13. AISI 316L drawn and ground surface finish samples after 0 and 816 hours (first two images show the drawn sample before and after salt spray, the second two images show the ground sample before and after salt spray). [1]

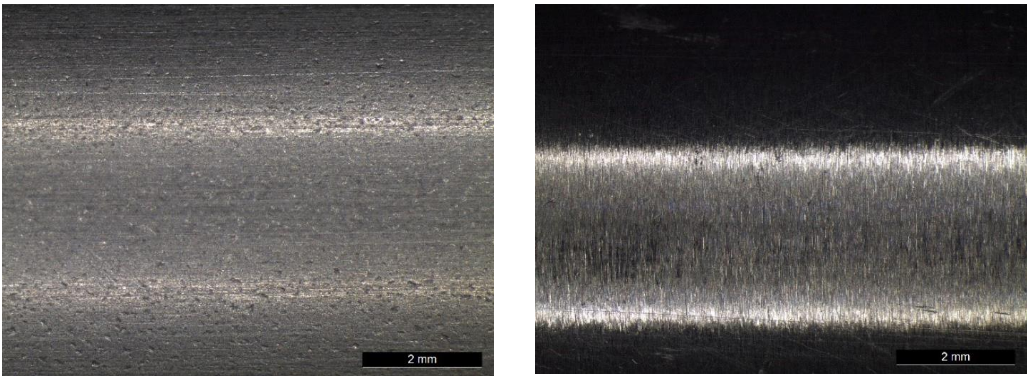


Figure 14. Microscopic image of AISI 316L drawn and ground surface samples. [1]

From his tests, Giuseppe concluded that the ground surface finish samples were more resistant to pitting corrosion than the drawn samples. The AISI 304L and 316L samples showed no signs of corrosion even after 816 hours of continuous exposure. The AISI 430F samples showed significant signs of corrosion early in the test and were removed from the chamber after 600 hours.

His atmospheric tests were interesting due to the choice of locations. These tests compare the results obtained at real, potential usage sites with later laboratory accelerated tests. These comparisons show how much damage occurs in a given time during accelerated tests compared to real conditions. These measurements compare the first appearance of corrosion during the salt spray test (or other lifespan tests) with the first appearance of corrosion in real conditions.

Giuseppe conducted atmospheric corrosion tests in Milan and Cefalù, Northern Sicily, 20 meters from the shore, for nearly 3/4 of a year. During this time, the highest temperature in Milan was 30°C; the lowest was -2°C and the average temperature was 15.6°C. The average humidity during the test period was 73%. The same values in Cefalù were 33°C, -4°C, and 33°C, with an average humidity of 52%. The following figures (Fig. 15-19) show the results of the corrosion tests caused by the marine atmosphere, as the extent of corrosion in the urban environment was not observable.

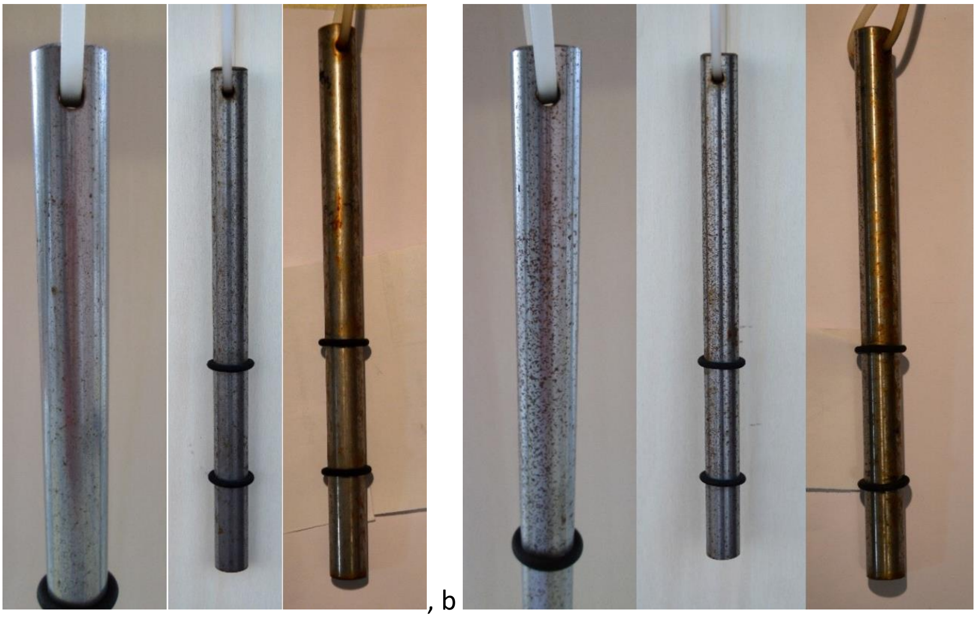
a,  , b

Figure 15. AISI 430F samples in the marine atmosphere after 80, 210, and 270 days a) with drawn surface finish; b) with ground surface finish [1]

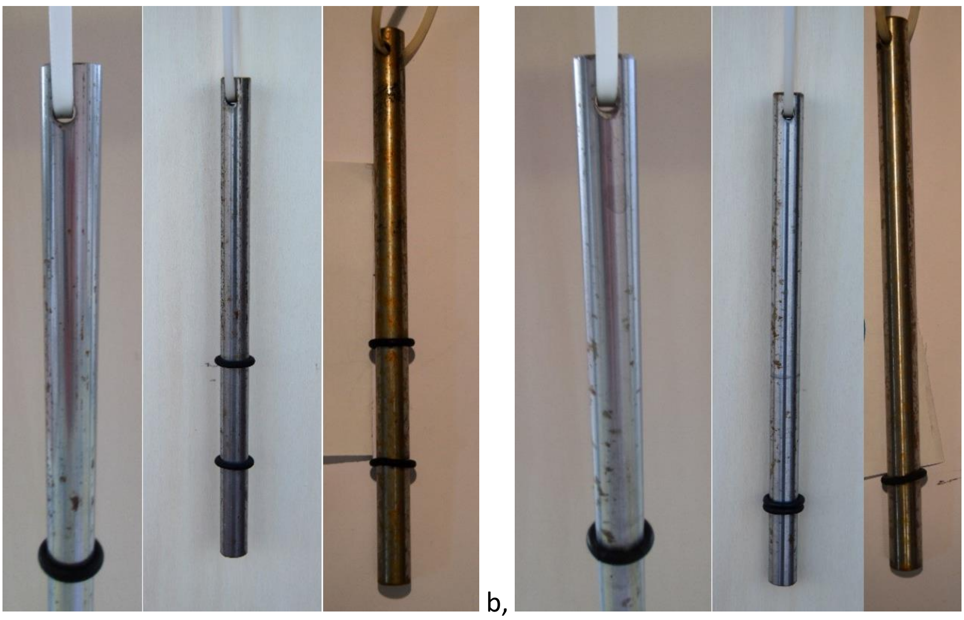
a,  b,

Figure 16. AISI 430 samples in the marine atmosphere after 80, 210, and 270 days a) with drawn surface finish; b) with ground surface finish. [1]

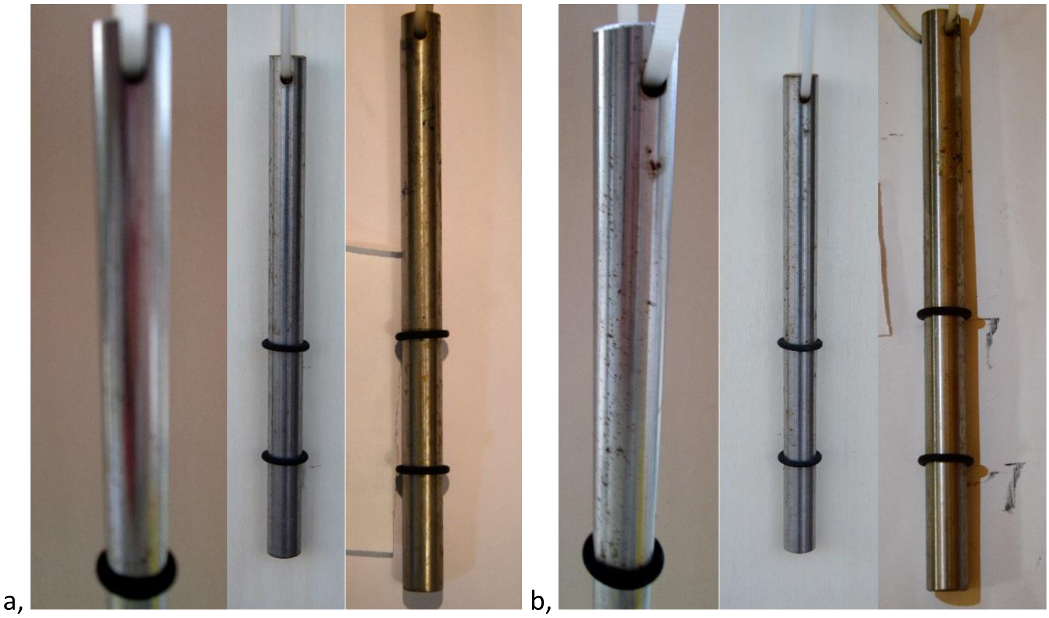


Figure 17. AISI 303 samples in the marine atmosphere after 80, 210, and 270 days a) with drawn surface finish; b) with ground surface finish [1]

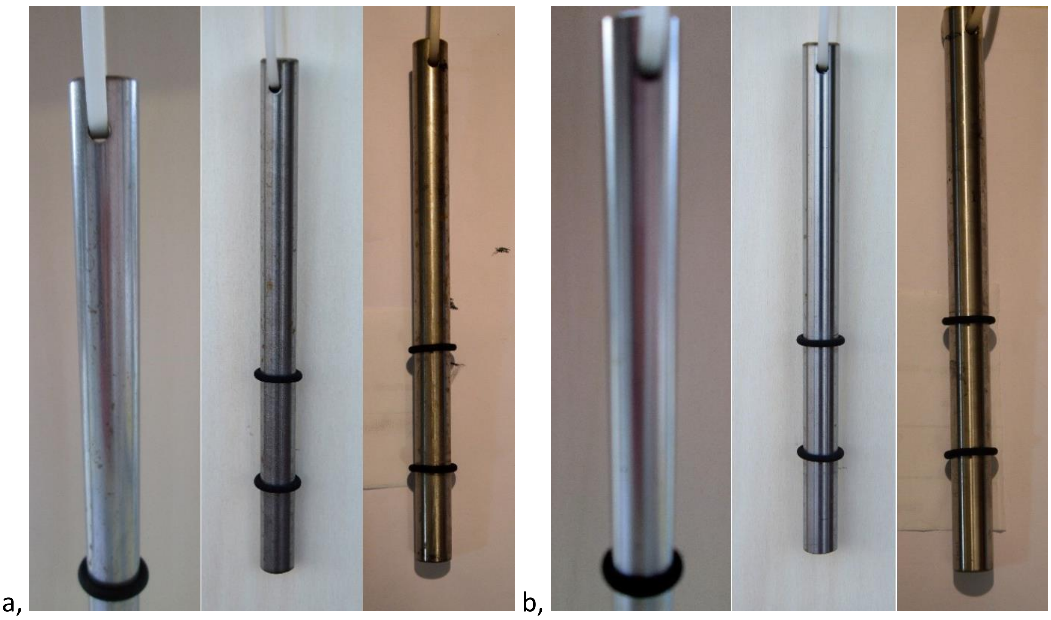


Figure 18. AISI 304L samples in the marine atmosphere after 80, 210, and 270 days a) with drawn surface finish; b) with ground surface finish. [1]

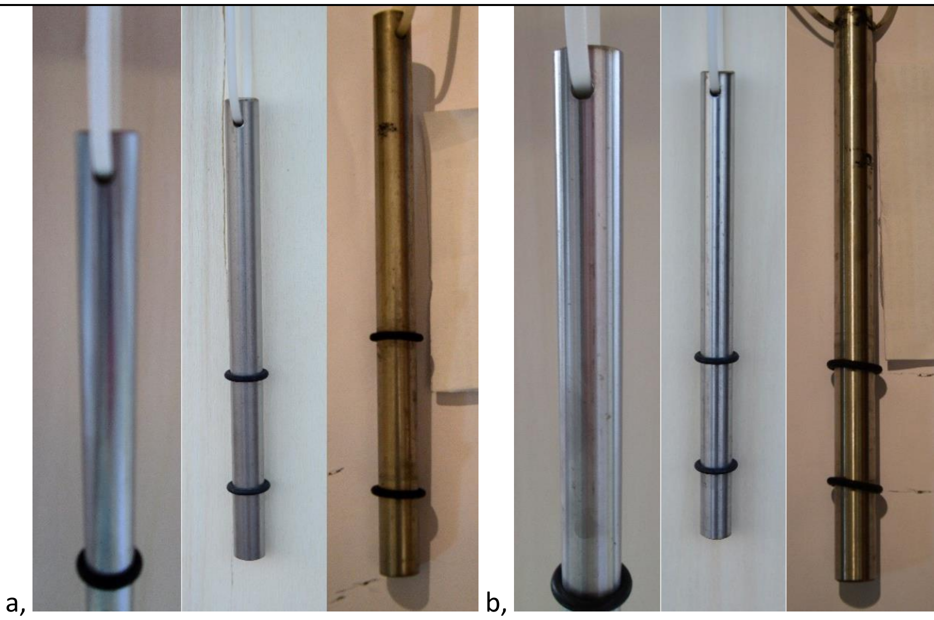


Figure 19. AISI 316 samples in the marine atmosphere after 80, 210, and 270 days a) with drawn surface finish; b) with ground surface finish [1]

Based on the results of these two tests, Giuseppe concluded that in the salt spray test, the ground samples were more resistant to pitting corrosion than the drawn samples. The AISI 304L and 316L samples showed no signs of corrosion even after 816 hours of continuous exposure. The AISI 430F samples showed significant corrosion early in the test.

In the case of the atmospheric exposure test, the samples resisted corrosion in the Milan atmosphere during the nine-month test period, but the marine environment was much more corrosive, as all samples showed discolouration, although none showed pitting corrosion. The AISI 316L samples did not suffer pitting corrosion, but both surface treatments became more opaque compared to the start of the test. The AISI 430 and 430F samples showed high-density dark discolourations on their surfaces, with the drawn samples discolouring more than the ground ones.

Giuseppe concluded from the tests presented here and further tests detailed in his thesis that despite different textures and chemical compositions, samples with ground surfaces showed better corrosion resistance in his tests than those with drawn surface finishes of the same material quality.

Haraszti et al. [2] [3] [4], and Tóth et al. [5] [6] conducted corrosion tests on welded stainless steels. They polished various samples with P120, P180, P320, and P400 grit sandpaper during their study. Some of the samples were heat-treated to simulate the heat-affected zone of the welding process, with the duration and temperature range of the heat treatment comparable to the welding process. The heat-treated and non-heat-treated samples were immersed in a 30°C ferric chloride solution for 96 hours.

In their research, the mass change of the heat-treated test specimens was measured. Based on this, they concluded that the heat-treated test specimens exhibited greater mass change, meaning a larger volume of material corroded during the test period, compared to the non-heat-treated specimens.

Effect of Steel Formability on Corrosion (Case Study)

Corrosion resulting from formability is associated with numerous factors linked to the manufacturing process. This review does not delve into the manufacturing technology and its parameters. This chapter presents a case study focusing on stress corrosion. The study's conclusion highlights that corrosion depends on many factors. The effects of some parameters (e.g., heat treatment) are well-defined, while the impact of other parameters (e.g., rolling) are not clearly defined due to various other phenomena [7] [8] [9] [10] [11].

Xu et al. [12] investigated 3D-printed 316L stainless steel. They prepared test specimens from 3D-printed 316L stainless steel and subjected them to mechanical and microscopic examinations [12]. The samples were made using Wire-Arc Additive Manufacturing (WAAM), a 3D printing method involving a wire electrode arc welding device that builds the desired object through deposition welding. The print head, i.e., the welding wire, was followed by a roller that compacted the object with a force of 8 kN. The schematic diagram and thermal image of this process are shown in the following figure (Fig. 20).

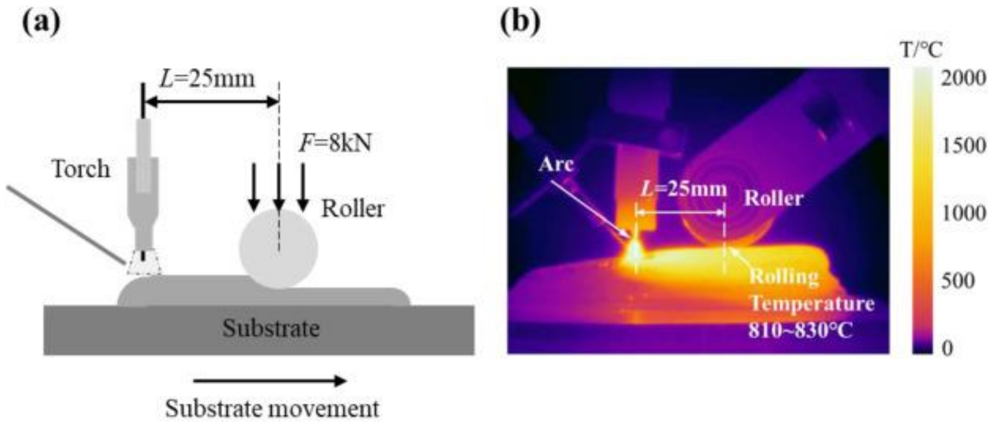


Figure 20. Schematic (a) and thermography photo (b) of the preparation of 3D-printed rolled samples. [12]

After preparing the samples, they were subjected to various heat treatments. The following two figures show the optical microscope images (Figure 21) and Back-Scattered Electron (BSE) scanning electron microscopy images (Figure 22) of the non-rolled and rolled test specimens at different temperatures.

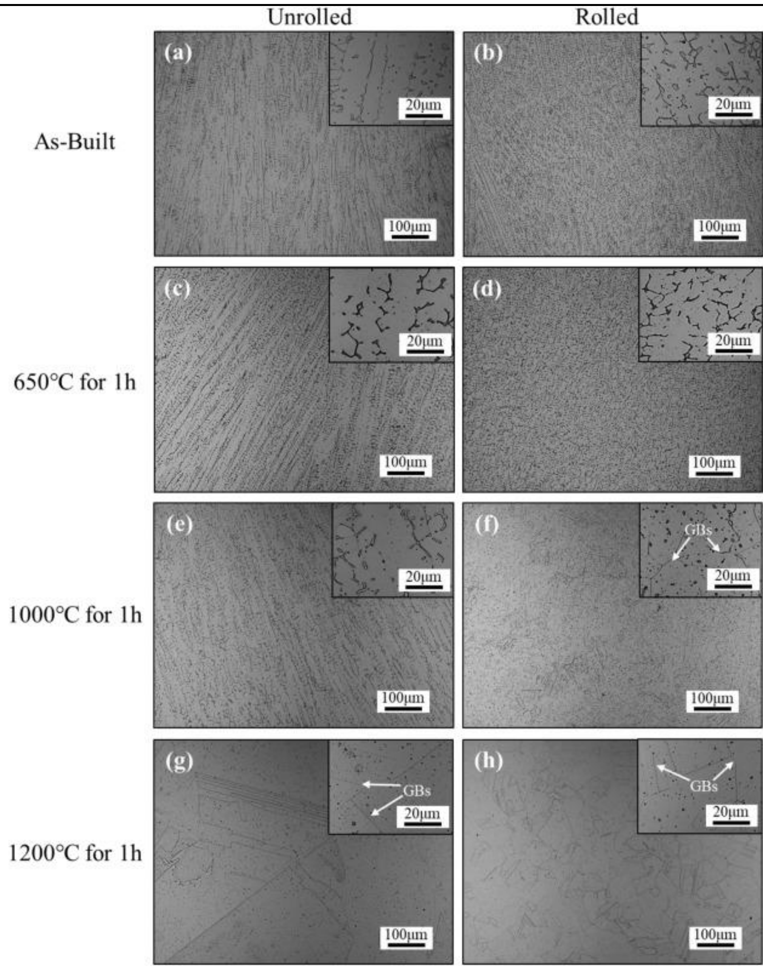


Figure 21. Optical microscope images of test specimens examined at different temperatures non-rolled and rolled test specimens without heat treatment (a, b), heat-treated at 650°C (c, d), heat-treated at 1000°C (e, f), and heat-treated at 1200°C (g, h). [12]

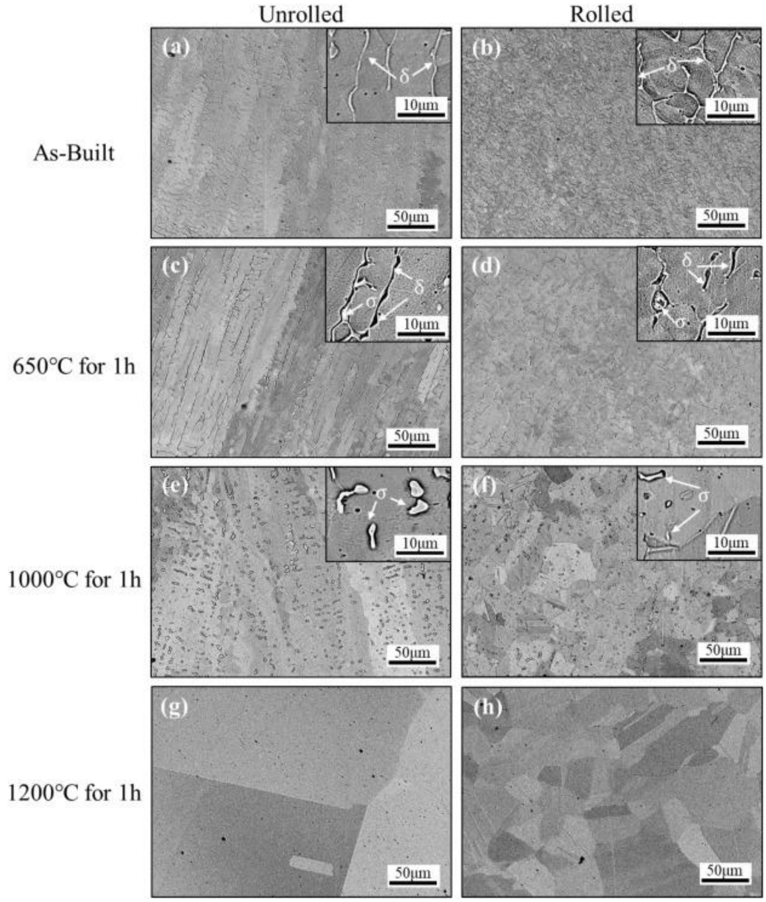


Figure 22. BSE microscope images of test specimens examined at different temperatures non-rolled and rolled test specimens without heat treatment (a, b), heat-treated at 650°C (c, d), heat-treated at 1000°C (e, f), and heat-treated at 1200°C (g, h). [12]

In the previous figures, Xu et al. observed the change in grain size, for which they prepared the schematic diagram shown in the following figure (Figure 23).

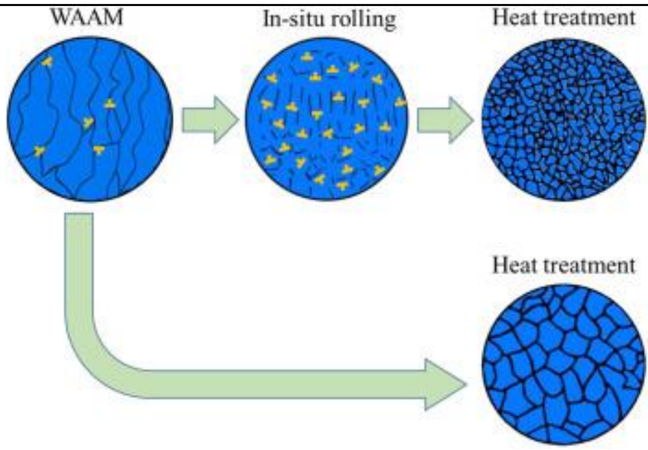


Figure 23. Schematic diagram of recrystallization and the change in dislocation density during rolling and heat treatment following WAAM 3D printing. [12]

Xu et al. found that heat treatment improved the mechanical properties of the 3D-printed samples made using the WAAM method when the samples were heat-treated and rolled. Xu et al. conducted potentiodynamic polarisation measurements in a 3.5% sodium chloride solution to measure the corrosion properties. Generally, lower corrosion current density indicates a slower corrosion rate, and a larger difference between pitting potential and corrosion potential indicates a wider passivation range, which signifies good corrosion resistance.

Xu et al. found that after heat treatment at 650°C, the corrosion current density decreased, and the passivation range also became smaller. This indicates that although the corrosion rate is slower, the stability of the passive film is not as good. After heat treatment at 1000°C, the corrosion current density increased, and the passivation range further narrowed, indicating worse corrosion resistance. This is explained by the precipitation of the σ phase and the formation of chromium-depleted zones. Heat treatment at 1200°C resulted in the best corrosion resistance, as the σ phase and δ ferrite completely dissolved, forming a fully austenitic microstructure [12] [13] [14] [15].

They also examined the effects of rolling in their article but could not draw a clear conclusion. Xu et al. found in their literature review that rolling causes residual stress and high dislocation density, which increases the diffusion path to the surface, thus forming a protective oxide layer, indicating that rolling improves corrosion resistance. If corrosion resistance is approached from the perspective of grain size, rolling results in many fine recrystallised grains, providing more grain boundaries. These grain boundaries are more chemically active and, thus, more susceptible to corrosion, reducing the stability of the passive film.

Xu et al. reached the following three conclusions related to corrosion:

σ phase precipitation: The precipitation of the σ phase significantly deteriorates corrosion resistance by creating chromium-depleted zones near the grain boundaries.

Residual stress: Residual stress and dislocations reduce the corrosion rate by increasing the stability of the oxide layer.

Grain boundaries: Fine grains provide more grain boundaries, which are more susceptible to corrosion, thus reducing the stability of the passive film.

SUMMARY

In this two-part review paper, we have presented the diverse nature of corrosion, particularly emphasising the effects of steel formability and surface roughness. Corrosion resistance is typically determined based on chemical composition alone, often neglecting steel's formability, surface roughness, and other manufacturing-related factors.

Our literature review included numerous environmental factors contributing to corrosion, such as material composition, electrochemical potential, surface roughness, stress and deformation, and temperature. The case studies we presented highlighted that rougher surfaces increase the risk of corrosion (Wang et al.) and that the formability of steel (Xu et al.) plays a key role in corrosion resistance.

The results of the case studies discussed in this review emphasise the importance of considering steel formability and surface roughness when evaluating corrosion resistance. Future research should develop more comprehensive testing methods that include these factors, ensuring that when selecting materials for safety-critical applications involving stainless components, not only the chemical composition but also the surface quality, manufacturing technology, and usage environment are considered.

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