metals

Editorial

Corrosion and Protection of Metals

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1. Introduction and Scope

During the last few decades, an enormous effort has been made to understand corrosion phenomena and their mechanisms, and to elucidate the causes that dramatically influence the service lifetime of metal materials. The performance of metal materials in aggressive environments is critical for a sustainable society. The failure of the material in service impacts the economy, the environment, health, and society. In this regard, corrosion-based economic losses due to maintenance, repair, and the replacement of existing structures and infrastructure account for up to 4% of gross domestic product (GDP) in well developed countries.

One of the biggest issues in corrosion engineering is estimating service lifetime. Corrosion prediction has become very difficult, as there is no direct correlation with service lifetime and experimental lab results, usually as a result of discrepancies between accelerated testing and real corrosion processes. It is of major interest to forecast the impact of corrosion-based losses on society and the global economy, since existing structures and infrastructure are becoming old, and crucial decisions now need to be taken to replace them.

On the other hand, environmental protocols seek to reduce greenhouse effects. Therefore, low emission policies, in force, establish regulations for the next generation of materials and technologies. Advanced technologies and emergent materials will enable us to get through the next century. Great advances are currently in progress for the development of corrosion-resistant metal materials for different sectors, such as energy, transport, construction, and health.

This Special Issue on the corrosion and protection of metals is focused on current trends in corrosion science, engineering, and technology, ranging from fundamental to applied research, thus covering subjects related to corrosion mechanisms and modelling, protection and inhibition processes, and mitigation strategies.

2. Contributions

This Special Issue comprises a large variety of interesting corrosion and protection of metal-based studies, including research on stainless steel, carbon steel, Inconel, copper, and magnesium alloys. Sensitization and surface modification, coatings, and processing influence on corrosion. The different corrosion mechanisms are also included in this collection, including intergranular corrosion, localized pitting corrosion, stress corrosion cracking, atmospheric corrosion, galvanic corrosion, numerical simulation, and modeling. In addition, a wide spread of electrochemical, microstructural and surface characterization techniques (CPP, EIS, DL-EPR, SEM, XPS, DRX, OM) are described in the aforementioned studies.

The work by Ha et al. found Mo to impart a positive effect on pitting corrosion resistance of high interstitial alloyed (HIA) FeCrMnMoNC austenitic stainless steel [1]. The alloyed Mo suppressed metastable pitting corrosion and raised both pitting and repassivation potential E_{pit} and E_{rp}, respectively.

In addition, Mo reduced the critical dissolution rate of the HIA in acidified chloride solutions, and the HIA with higher Mo content was able to resist active dissolution in stronger acid.

In a study by Song and coauthors [2], the impact of high-speed rotating wire-brushing nanocrystal surface modification (SNC) on the corrosion of extruded Cu-0.4%Mg alloys was reported. Strain-induced grain refinement weakens the corrosion resistance of the SNC alloy during the initial corrosion period in 0.1 M NaCl solution, resulting in the lower E_{corr} value and higher I_{corr} values in polarization tests, a smaller capacitive loop and Rp value in EIS tests, higher mass-loss rate, and a partially corroded surface. The SNC sample with a smaller grain size has lower corrosion resistance, indicating that the increased crystal defects and higher surface roughness results in increased corrosion activity.

Lee et al. investigated the effect of shot peening on the corrosive behavior of spring steel electrochemical polarization tests and the Mott–Schottky analysis [3]. The passive current density of the specimens with stress was higher and showed fluctuation. It was found that compressive stress produced passive films with lower point defect density than non-stressed specimens, thus revealing that the growth mechanism of passive film and the transport of vacancies in the film on metals and alloys depend on the residual stress on the metallic surface.

Veleva et al. discussed the initial stages of corrosion of AZ31B magnesium alloy in Ringer's solution at 37 °C [4]. Among the main findings, the corrosion current densities estimated by hydrogen evolution are in good agreement with the time-integrated reciprocal charge transfer resistance values estimated by electrochemical impedance spectroscopy (EIS). Moreover, the formation of corrosion products with poorer protection properties and the increase in the tendency for pitting corrosion are promoted by the significant content of Cl^- in the form of aluminum oxychlorides salts. A marked decrease in the EIS inductive loop was found to reflect the dissolution of aluminum oxychloride salt, which is probably formed across the uniform corrosion layer during the initial stages, as suggested by the EDS analysis.

The study by Zanotto et al. found that microstructural modifications imparted by heat treatment produced sensitization and influenced the localized corrosion and stress corrosion cracking of 2304 duplex stainless steel [5]. Pitting and intergranular corrosion mainly initiated in Cr- and Mo-depleted regions (ferrite/austenite interphases), near to the $Cr_{23}C_6$ precipitates within the γ_2 and γ phases, then propagated in the ferrite matrix. Moreover, SCC failure initiated at the bottom of pits and was likely stimulated by hydrogen penetration.

In a study by Kim et al., the multi-galvanic effect of an Al fin-tube heat exchanger with cathodic or anodic joints was evaluated using polarization tests, numerical simulation, and the seawater acetic acid test (SWAAT) [6]. Determination of the polarization state using polarization curves was well correlated with numerical simulations using a high-conductivity electrolyte, thus envisaging a novel approach to improve the design of products subject to multi-galvanic corrosion. Results were verified by SWATT, and the leakage time of the Al fin-tube heat exchanger assembled with the anodic joint was 42% longer than that of the exchanger assembled with the cathodic joint.

The work by Ahledel et al concluded that TiC additions into a Fe_3Al matrix, prepared by high-velocity oxy-fuel (HVOF) spraying, increased the corrosion resistance of Fe_3Al/TiC composite coating in 3.5 wt.% NaCl solution [7]. The addition of Cr contributed to the decrease in the corrosion rate of Fe3Al-Cr/TiC HVOF coating, three times lower than that of Fe3Al/TiC. Furthermore, the addition of TiC particles into Fe_3Al matrix benefit the wear resistance while keeping corrosion-resistant properties.

A new atmospheric corrosion sensor utilizing strain measurements (ACSSM) was developed by Purwasih et al. [8]. The sensor fundamentals are based on the influence of the strain variations ($\Delta\varepsilon$) on the compressive surface of a low-carbon steel under a bending moment, considering the corrosion product layers formed, and assuming three different stages: stage I, free corrosion Fe surface ($\Delta\varepsilon = 0$); stage II, tight corrosion products ($\Delta\varepsilon < 0$); and stage III, porous corrosion products layer ($\Delta\varepsilon > 0$).

In the review paper by Mohtadi-Bonab [9], the important damage modes in pipeline steels including stress corrosion cracking (SCC) and hydrogen induced cracking (HIC) are reported. Based on a literature survey, it was concluded that many factors influence SCC, such as the microstructure of steel, residual stresses, chemical composition of steel, applied load, alternating current, surface texture, and grain boundaries, influencing the crack initiation and propagation in pipeline steels. Crystallographic texture plays a key role in crack propagation. Grain boundaries associated with {111} and {110} parallel to the rolling plane, coincident site lattice boundaries and low angle grain boundaries are recognized as crack resistant paths, while grains with high angle boundaries favor the SCC intergranular crack propagation.

Choucri et al. studied a corrosion failure in service of copper pipes in drinking water distribution systems, mostly related to their high β' phase content, which undergoes dezincification and selective dissolution attacks [10]. The corrosive behaviors of two representative $\alpha + \beta'$ brass components were compared to that of brass alloys with nominal compositions $CuZn_{36}Pb_2As$ and $CuZn_{21}Si_3P$, marketed as dezincification resistant. Analyses evidenced that the highest dezincification resistance was afforded by $CuZn_{36}Pb_2As$ (longitudinal section of extruded bar), exhibiting dealloying and subsequent oxidation of β', only at a small depth. Limited surface dealloying was also found in $CuZn_{21}Si_3P$, which underwent selective silicon and zinc dissolution and negligible inner oxidation of both α and κ constituent phases, likely due to galvanic effects.

A study by Bautista et al. observed the performance of lean duplex stainless steel (LDSS) reinforcements (UNS S32304 and S32001) after long term exposure to chloride contained corrosion environment [11]. The authors concluded that a decrease in the alkaline reserve of the mortars can affect the corrosive behavior of the LDSS exposed to environments with high chloride concentrations. In the pits formed in regions of the corrugated surface which were only moderately strained, the austenite phase was dissolved selectively, while ferrite tended to remain uncorroded. The higher tendency of ferrite to dissolve Cr can explain this observation. Ferrite should be more Cr-rich that austenite, and therefore more corrosion-resistant. The duplex structure of the stainless steel influences the selective dissolution of the phases, and austenite corrodes preferentially except in the most strained areas of the corrugated surface, where ferrite dissolves selectively.

Both works by Santana et al. reported on atmospheric corrosion of zinc, copper and carbon steel [12,13]. It was found that the most influential environmental parameter affecting the corrosion rates was the chloride deposition rate (S_d), and on the contrary, the environmental temperature (T) showed the smallest influence. The influence of test-coupon orientation and exposure angle on the time of wetness (*TOW*) was of major interest. The authors summarized that corrosivity mathematical models would need to be redefined, introducing the time of wetness and a new set of operation constants. Therefore, they concluded that atmospheric corrosion classification standards need to be revisited.

The work by Galván-Martínez et al. on X70 pipeline steel immersed in acidified and aerated synthetic soil solution [14] found a higher susceptibility to stress corrosion cracking (SCC) as the cathodic polarization increased (E_{cp}). Nevertheless, when the E_{cp} was subjected to the maximum cathodic potential (−970 mV), the susceptibility decreased; this behavior is attributed to the fact that the anodic dissolution was suppressed and the process of the SCC was dominated only by hydrogen embrittlement (HE). The EIS results showed that the cathodic process was influenced by the mass transport (hydrogen diffusion) due to the steel undergoing so many changes in the metallic surface as a result of the applied strain that it generated active sites at the surface.

Research studies by Martin and coauthors revealed the influence of ultrasonic nanocrystal surface modification (UNSM) on the degree of sensitization (DOS) in Inconel 718 [15]. The double-loop electrochemical potentiodynamic reactivation method (DL−EPR) showed that for UNSM processed samples with no thermal treatment, the DOS increased, while for UNSM treated samples that were post-annealed at 1000 °C and water quenched, the DOS notably decreased. It was found that the annealing at 1000 °C and the water quenching of the UNSM treated specimens promoted the transformation of γ'' to form the δ phase on the grain boundaries, which reduces the intergranular corrosion susceptibility.

3. Conclusions and Caveats

This Special Issue on the corrosion and protection of metals presents a collection of research articles covering the relevant topics and the current state of the art in the field. As the guest editor, I hope that this collection of original research papers and reviews may be useful to researchers working in the field, promoting more research studies, debates, and discussions that will continue to shed light and bridge the gap in the understanding of corrosion and protection fundamentals and mechanisms.

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Conflicts of Interest: The author declares no conflict of interest.

References

1. Ha, H.Y.; Lee, T.H.; Bae, J.H.; Chun, D.W. Molybdenum Effects on Pitting Corrosion Resistance of FeCrMnMoNC Austenitic Stainless Steels. *Metals* **2018**, *8*, 653. [CrossRef]
2. Song, D.; Jiang, J.; Guan, X.; Qiao, Y.; Li, X.; Chen, J.; Sun, J.; Ma, A. Effect of Surface Nanocrystallization on Corrosion Resistance of the Conformed Cu-0.4%Mg Alloy in NaCl Solution. *Metals* **2018**, *8*, 765. [CrossRef]
3. Lee, K.H.; Ahn, S.H.; Seo, J.W.; Jang, H.J. Passivity of Spring Steels with Compressive Residual Stress. *Metals* **2018**, *8*, 788. [CrossRef]
4. Veleva, L.; Fernández-Olaya, M.G.; Feliu, S., Jr. Initial Stages of AZ31B Magnesium Alloy Degradation in Ringer's Solution: Interpretation of EIS, Mass Loss, Hydrogen Evolution Data and Scanning Electron Microscopy Observations. *Metals* **2018**, *8*, 933. [CrossRef]
5. Zanotto, F.; Grassi, V.; Balbo, A.; Monticelli, C.; Zucchi, F. Resistance of Thermally Aged DSS 2304 against Localized Corrosion Attack. *Metals* **2018**, *8*, 1022. [CrossRef]
6. Kim, Y.S.; Park, I.J.; Kim, J.G. Simulation Approach for Cathodic Protection Prediction of Aluminum Fin-Tube Heat Exchanger Using Boundary Element Method. *Metals* **2019**, *9*, 376. [CrossRef]
7. Ahledel, N.; Schulz, R.; Gariepy, M.; Hermawan, H.; Alamdari, H. Electrochemical Corrosion Behavior of Fe_3Al/TiC and Fe_3Al-Cr/TiC Coatings Prepared by HVOF in NaCl Solution. *Metals* **2019**, *9*, 437. [CrossRef]
8. Purwasih, N.; Kasai, N.; Okazaki, S.; Kihira, H.; Kuriyama, Y. Atmospheric Corrosion Sensor Based on Strain Measurement with an Active Dummy Circuit Method in Experiment with Corrosion Products. *Metals* **2019**, *9*, 579. [CrossRef]
9. Mohtadi-Bonab, M.A. Effects of Different Parameters on Initiation and Propagation of Stress Corrosion Cracks in Pipeline Steels: A Review. *Metals* **2019**, *9*, 590. [CrossRef]
10. Choucri, J.; Zanotto, F.; Grassi, V.; Balbo, A.; Ebn Touhami, M.; Mansouri, I.; Monticelli, C. Corrosion Behavior of Different Brass Alloys for Drinking Water Distribution Systems. *Metals* **2019**, *9*, 649. [CrossRef]
11. Bautista, A.; Velasco, F.; Torres-Carrasco, M. Influence of the Alkaline Reserve of Chloride-Contaminated Mortars on the 6-Year Corrosion Behavior of Corrugated UNS S32304 and S32001 Stainless Steels. *Metals* **2019**, *9*, 686. [CrossRef]
12. Santana, J.J.; Ramos, A.; Rodríguez-González, A.; Vasconcelos, H.C.; Mena, V.; Fernández-Pérez, B.M.; Souto, R.M. Shortcomings of International Standard ISO 9223 for the Classification, Determination, and Estimation of Atmosphere Corrosivities in Subtropical Archipelagic Conditions—The Case of the Canary Islands (Spain). *Metals* **2019**, *9*, 1105. [CrossRef]
13. Santana, J.J.; Cano, V.; Vasconcelos, H.C.; Souto, R.M. The Influence of Test-Panel Orientation and Exposure Angle on the Corrosion Rate of Carbon Steel. Mathematical Modelling. *Metals* **2020**, *10*, 196. [CrossRef]

14. Galván-Martínez, R.; Carmona-Hernández, A.; Mejía-Sánchez, E.; Morales-Cabrera, M.A.; Contreras, A. Corrosion Study of Pipeline Steel under Stress at Different Cathodic Potentials by EIS. *Metals* **2019**, *9*, 1353. [CrossRef]
15. Martin, U.; Ress, J.; Bosch, J.; Bastidas, D.M. Evaluation of the DOS by DL−EPR of UNSM Processed Inconel 718. *Metals* **2020**, *10*, 204. [CrossRef]