

Corrosion of Metals: Behaviors and Mechanisms

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1. Introduction and Scope

Corrosion of metals and alloys represents one of the most persistent challenges in materials science and engineering, resulting in significant economic losses and safety concerns across numerous industries. With global infrastructure increasingly exposed to harsh environments—from marine atmospheres to high-temperature industrial settings—understanding corrosion mechanisms and developing effective mitigation strategies has never been more critical.

This Special Issue, *Corrosion of Metals: Behaviors and Mechanisms*, brings together nine original research articles and one comprehensive review recently published in the journal *Metals*. It aims to bridge fundamental corrosion mechanisms with practical engineering applications, providing a thorough elucidation of material degradation processes under diverse service environments. By integrating findings from laboratory experiments with results from field exposure studies, this body of work offers a basis for developing more durable material selection criteria, improving predictive corrosion models, and refining protection strategies for critical infrastructure, thereby supporting their reliable operation under increasingly demanding conditions. The ultimate goal is to extend service life, enhance safety margins, and mitigate the substantial economic burdens caused by corrosion-related failures across multiple industrial sectors.

2. Contributions

This Special Issue compiles ten studies on metal corrosion, covering cutting-edge research findings across diverse material systems—including aluminum alloys, stainless steel, carbon steel, weathering steel, martensitic steel, and metallic glass—under various environmental conditions such as marine atmospheres, submerged zones, low-latitude coastal regions, and high-temperature service environments.

Zhou et al. (Contribution 1) systematically examined the corrosion behavior of typical 5xxx series Al–Mg alloys (5052, 5083, and 5182) in a 3.5 wt.% NaCl solution. The influence of Mg, Cr, and Mn on passivation stability, pitting susceptibility, and corrosion evolution was elucidated. Increasing Mg content destabilized the passive film and promoted Al(OH)₃ formation, thereby aggravating localized corrosion. In contrast, Cr addition favored the formation of uniformly distributed precipitates and reduced micro-galvanic effects. Corrosion preferentially initiated at Fe-rich Al₆(Fe,Mn) intermetallics, while adjacent Al₃Mg₂ phases acted as anodic sites and dissolved preferentially, leading to pit

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initiation. The study clarifies the governing role of the Mg/Cr ratio in Al–Mg alloy corrosion behavior and provides mechanistic guidance for alloy design in marine environments.

Cui et al. (Contribution 2) systematically evaluated the atmospheric corrosion behavior of four representative aluminum alloys (2024, 5083, 6061, and 7075) through a one-year outdoor exposure test at Zhongshan Station in Antarctica. Freeze–thaw cycling and salt deposition were identified as dominant factors governing pitting initiation and propagation. During freeze–thaw processes, corrosion products generated wedge-induced stresses along grain boundaries, leading to surface spalling in high-strength alloys such as 2024 and 7075. Alloy composition played a decisive role in corrosion resistance, with Cu-rich 2xxx and 7xxx alloys exhibiting pronounced corrosion susceptibility. In contrast, the 5xxx (Al–Mg) alloy demonstrated superior corrosion resistance, attributed to the enhanced inertness of its secondary phases. The results highlight the critical influence of alloy chemistry and microstructure on corrosion behavior in Antarctic environments and provide guidance for alloy selection and protection in extreme service conditions.

Liu et al. (Contribution 3) systematically examined the corrosion inhibition performance of triethanolamine phosphate (PTEA) and sodium hexametaphosphate (SHMP) on ductile cast iron under pH conditions relevant to pipeline service environments. Both inhibitors effectively suppressed corrosion, with inhibition efficiency increasing with immersion time. SHMP exhibited superior performance in alkaline media, markedly reducing corrosion current density and forming a stable, compact iron phosphate protective film. By contrast, PTEA provided corrosion protection mainly through molecular adsorption, predominantly inhibiting cathodic reactions, but showed comparatively lower long-term stability. The results demonstrate that inhibitor chemistry and pH conditions critically govern protection mechanisms. This study provides experimental support for inhibitor selection in cement-lined ductile iron pipelines, particularly favoring SHMP for alkaline thermal network systems.

Carvalho (Contribution 4) investigated the formation mechanisms, structural evolution, and phase transformations of oxide layers on AISI 4140 steel during high-temperature oxidation at 1000 °C for varying exposure times (20, 40, and 60 min). The study systematically elucidated the kinetics and microstructural evolution of oxide scale growth and highlighted the governing role of alloying elements in oxidation behavior. Distinct oxidation stages and compositional changes within the oxide layers were identified as oxidation progressed. These findings provide mechanistic insight into high-temperature oxidation processes in low-alloy steels. The results offer a scientific basis for optimizing hot-working parameters, controlling surface quality, and developing oxidation-resistant strategies. This work is of practical relevance to high-temperature manufacturing processes such as hot rolling and forging.

Šefl et al. (Contribution 5) investigated the accelerated abnormal corrosion of carbon steel pipelines in crude oil storage systems, focusing on the combined effects of water phase separation, stagnant conditions, and differential aeration cell formation. The results demonstrated that the primary driver of severe corrosion was not the intrinsic corrosivity of crude oil, but water accumulation and prolonged stagnation caused by operational interruptions. These conditions limited oxygen transport and promoted the establishment of stable differential aeration cells at the pipe bottom. Under continuous daily operation, corrosion remained negligible, whereas extended shutdowns of several weeks shifted the corrosion mode from uniform attack to pitting, with localized corrosion rates exceeding 1 mm·a^{−1}. Low-lying sections, water pooling, restricted oxygen supply, and sediment deposition further facilitated the transition from shallow pits to enclosed pitting corrosion. Based on the mechanistic analysis, practical mitigation strategies—such as minimizing stagnation, optimizing pumping schedules, controlling water separation, and applying

internal coatings—were proposed to effectively reduce corrosion risk without major structural modifications.

Wang (Contribution 6) investigated the formation of uniformly nanoporous structures on Fe–Si–B metallic glass ribbons fabricated via chemical etching in dilute HF solution. The effects of etching conditions on pore evolution and Fenton-like catalytic performance toward methyl orange degradation were systematically examined. Increasing etching time from 30 to 90 min increased the nanoporous layer thickness from ~92 to 223 nm while preserving the amorphous structure. Porous formation followed a pitting corrosion mechanism, involving preferential dissolution of Si and B, followed by selective Fe corrosion that promoted pore growth and interconnectivity. Owing to the intrinsically high activity of the amorphous phase and the enlarged specific surface area, the nanoporous metallic glass exhibited markedly enhanced catalytic performance. The degradation process obeyed quasi-first-order kinetics and was governed by the synergy of heterogeneous surface reactions and homogeneous reactions in solution, offering a promising route for waste amorphous alloy utilization and wastewater treatment catalyst development.

Yu (Contribution 7) systematically investigated the microstructural evolution and impact toughness degradation of G115 martensitic heat-resistant steel during long-term aging at 700 °C for up to 10,000 h. With increasing aging time, the microstructure evolved from fine lamellar martensite to a markedly coarsened grain and lamellar structure, accompanied by continuous precipitation and growth of $M_{23}C_6$ carbides and Fe₂W Laves phases along grain boundaries and lamellar interfaces. EBSD analysis revealed a slight increase in high-angle grain boundaries and a progressive reduction in local misorientation and residual strain, indicating partial recovery during aging. Impact toughness rapidly decreased from 51.3 J to ~17 J within the initial 500 h and remained nearly constant thereafter. The pronounced toughness loss was mainly attributed to coarse carbides and Laves phases, which reduced local plasticity and facilitated crack initiation and propagation, while matrix softening and boundary evolution partially mitigated further degradation. This work clarifies the microstructure–property relationship of G115 steel under long-term ultra-high-temperature service and provides guidance for life assessment and safe operation of ultra-supercritical power plant components.

Yang (Contribution 8) conducted a two-year atmospheric and submerged exposure study in the tropical marine environment of Sanya, comparing the corrosion behavior of conventional low-alloy high-strength steel (Q345qe) with two weathering steels, including a high Ni–Cu–Mo design. In the atmospheric zone, synergistic effects of alloying elements (Cr, Ni, Cu, Mo) promoted the transformation of γ -FeOOH into dense α -FeOOH, forming protective rust layers and reducing corrosion rates, with the high Ni–Mo steel showing the best performance. In contrast, low-alloy steels formed loose Fe₃O₄-dominated rust prone to cracking and failure. In seawater immersion zones, high Cl[−] concentrations rapidly converted γ -FeOOH to Fe₃O₄, degrading rust density and diminishing corrosion resistance differences, with severe localized corrosion observed for all steels. The results demonstrate that alloy design effectively enhances corrosion resistance only under atmospheric exposure, while additional protection such as coatings is necessary for long-term immersion conditions.

Liu (Contribution 9) investigated the atmospheric corrosion behavior of 45# steel in low-latitude coastal regions of China, including Guangzhou, Wanning, and the South China Sea. Weight loss measurements, electrochemical tests, and XRD characterization were used to assess corrosion rates, rust layer composition, and protective performance. Corrosion severity was found to correlate with latitude and local environmental conditions, decreasing in the order South China Sea > Wanning > Guangzhou, with high humidity, temperature, and Cl[−] deposition accelerating degradation. Rust layers comprised α -FeOOH, β -FeOOH, and γ -FeOOH and Fe₃O₄, but the protective ability index remained

below 1, indicating limited substrate protection. Coating defect tests revealed rapid corrosion propagation and severe delamination at defects, especially in the South China Sea environment. The study highlights the synergistic effects of high humidity and Cl⁻ on rust layer evolution and underscores the necessity of targeted protective measures for steel structures in low-latitude coastal environments.

Borgioli (Contribution 10) systematically reviewed the formation and corrosion behavior of “expanded phases” (expanded austenite, ferrite, and martensite) in stainless steels subjected to low-temperature thermochemical treatments, including nitriding, carburizing, and nitrocarburizing. The study highlighted how nitrogen and carbon suppress Cr compound precipitation, modify the semiconductor properties of passivation films, and enhance localized corrosion resistance. Corrosion responses of various stainless steel types—ferritic, martensitic, austenitic, duplex, and precipitation-hardening—were compared under chloride-containing and chloride-free environments. When a modified layer dominated by expanded phases forms without CrN/CrC precipitation, corrosion resistance is typically maintained or improved, while surface hardness and wear resistance are enhanced. Conversely, excessive chromium compound formation or microstructural inhomogeneity promotes micro-galvanic corrosion and reduces protection. The review emphasizes that corrosion behavior strongly depends on steel grade, microstructure, treatment parameters, and testing methods, highlighting the need for systematic studies to guide engineered applications of expanded phases in service environments.

3. Conclusions and Outlook

This Special Issue systematically highlights recent advances in the corrosion behavior and mechanisms of metals across diverse environments. It underscores the complex interactions among material microstructure, environmental conditions, and protective strategies, while emphasizing the pivotal role of advanced characterization and experimental techniques in elucidating corrosion processes. Despite significant progress, challenges remain in predicting long-term corrosion under extreme conditions, designing corrosion-resistant microstructures, and developing sustainable, intelligent protection technologies. This issue aims to provide a foundation for in-depth discussion of these cutting-edge topics, thereby advancing corrosion science and supporting the durability and safety of engineering materials and infrastructure.

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