

Editorial

Corrosion Resistance of Innovative Composite Coatings Based on Nanoparticles

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Organic coatings remain a cornerstone of corrosion protection strategies for metallic substrates due to their cost-effectiveness, ease of processing, and adaptability to diverse industrial applications. These coatings primarily act by forming a protective barrier that impedes the ingress of aggressive species such as chloride ions, moisture, and acidic components, which are notorious for accelerating corrosion damage under service conditions. However, traditional organic coatings often exhibit limited long-term durability in highly aggressive environments, where degradation mechanisms such as blistering, microcracking, increased porosity, and loss of adhesion can compromise performance and accelerate substrate deterioration [1,2]. The global economic impact of corrosion on costs, premature equipment failure, loss of product and plant, highlights the urgent need for improved protective systems that are both highly efficient and environmentally friendly. In this context, nanotechnology has emerged as a powerful enabler for next-generation organic coatings, allowing for the design of multifunctional nanocomposite systems with superior corrosion resistance, mechanical strength, and enhanced service life [3–5]. Nanocomposite coatings, which incorporate finely dispersed nanoparticles into polymer matrices, effectively create tortuous pathways for corrosive agents, reduce defect populations, and improve barrier effectiveness, resulting in significantly enhanced anti-corrosion behaviour compared to conventional coatings [3,6]. Graphene and its derivatives have been extensively studied as reinforcement agents in anticorrosion coatings due to their exceptional impermeability, mechanical stiffness, and large specific surface area, which contribute to enhanced barrier performance and reduced ion transport [5,7]. The incorporation of graphene oxide into epoxy and polyurethane coatings can significantly delay the onset of corrosion and improve coating stability in aggressive chloride environments [8,9]. Complementary research has focused on other nanomaterials, including metal oxides (e.g., ZrO_2 , Al_2O_3 , and TiO_2), carbon nanotubes (CNTs), and hybrid organic–inorganic clusters, which improve corrosion performance through synergistic effects on coating morphology, adhesion, and electrochemical stability [10–12]. Environmentally sustainable nanocomposite coatings that utilise bio-derived components and green synthesis methods are also gaining attention as efforts increase to minimise the ecological footprint of protective coatings without compromising performance [12,13]. Beyond passive barrier enhancement, smart anticorrosion coatings that incorporate nanocontainers, self-healing agents, and responsive inhibitors capable of releasing corrosion inhibitors upon damage have been developed, thereby enabling active protection mechanisms [4,14]. These smart systems represent a paradigm shift in coating design, as they actively mitigate corrosion progression rather than solely delaying corrosive ingress. Recent advances have also explored multifunctional nanocomposite systems that combine corrosion resistance with antifouling, antibacterial, or thermal-management properties, further expanding the potential applications of advanced coatings in marine,



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biomedical, and energy sectors [11,15]. Factors such as nanoparticle dispersion, matrix compatibility, coating thickness, and microstructure optimisation are increasingly recognised as key determinants of long-term performance, with numerous studies addressing strategies to control these parameters for enhanced protection [3,7]. Despite considerable progress, substantial challenges remain, particularly in scaling up manufacturing processes, maintaining uniform nanoparticle dispersion, ensuring environmental sustainability, and rigorously validating long-term stability under real-world conditions. Future research should therefore emphasise the development of highly scalable, eco-friendly nanocomposite coatings with integrated smart functionalities, coupled with comprehensive field testing to demonstrate reliable performance in practical applications.

This Special Issue on “Corrosion Resistance of Innovative Composite Coatings Based on Nanoparticles” aimed to bring together cutting-edge research on the synthesis, characterisation, and application of functionalized nanomaterials in advanced anticorrosion coatings. By deepening our understanding of structure–property relationships, corrosion mechanisms, and multifunctional design strategies, we hope to stimulate further innovation and facilitate the translation of laboratory discoveries into commercially viable solutions.

The article by Kurtela et al. investigated the electrochemical corrosion performance of three PACVD coatings—TiN, TiCN, and TiBN—deposited on WC-Co hardmetal substrates. Using a combination of direct current (potentiodynamic and linear polarisation) and alternating current (electrochemical impedance spectroscopy, EIS) techniques in 3.5 wt.% NaCl solution, the coatings’ protective abilities were systematically compared. TiN exhibited the highest corrosion resistance, characterised by the most positive open circuit potential, the lowest corrosion current density, and the highest polarisation and charge transfer resistance. TiBN exhibited moderate protection, while TiCN showed comparatively higher corrosion rates and lower electrochemical stability, likely due to its multilayer microstructure facilitating electrolyte penetration. EIS analysis confirmed these trends, showing that TiN’s dense, uniform barrier layer effectively impedes charge transfer, whereas TiCN is the most permeable. These results highlight the critical influence of coating architecture, chemical composition, and microstructural properties on corrosion protection, providing insights for optimising multilayer gradient coatings for enhanced durability in aggressive environments [16].

In another article, Aperador et al. investigated the development of silver (Ag)-doped zirconia (ZrO_2) coatings deposited on 316LVM stainless steel via the unbalanced magnetron sputtering technique. The Ar/ O_2 ratio during deposition significant influence on the microstructure, tribological behaviour, and corrosion resistance of Ag- ZrO_2 coatings. Increasing oxygen content enhances ZrO_2 crystallisation, reduces surface roughness, and improves wear as well as electrochemical performance. Coatings deposited at a 50% Ar/ O_2 ratio exhibited the best overall properties, including low friction, minimal material loss, and high polarisation resistance, due to the formation of a dense, stable passive ZrO_2 layer. These results highlight the potential of optimised Ag- ZrO_2 coatings for biomedical applications, particularly in implants, and underscore the need for long-term in vitro and in vivo studies to assess their stability and biocompatibility [17].

In their work, Huo et al. report a scalable and efficient strategy to enhance the corrosion resistance of nickel coatings through precise microstructural design, eliminating the need for complex alloying. Using a one-step electrodeposition approach, nanocrystalline Ni coatings with tunable heterogeneous grain structures were systematically developed by controlling the applied current density. An optimal heterostructure, obtained at 10 mA/cm², exhibits the best corrosion performance in a 3.5 wt.% NaCl solution, characterised by the lowest corrosion current density and the highest charge-transfer resistance. This superior behaviour is attributed to the synergistic interaction between fine and coarse grains, which

effectively redistributes chloride adsorption sites and facilitates the formation of a stable and protective NiOOH passive layer. Through a combined approach involving electrochemical analysis, advanced microscopy, and molecular dynamics simulations, the study elucidates the fundamental corrosion mechanisms. Grain boundaries are identified as preferential sites for Cl^- adsorption; however, their negative impact is mitigated in heterostructure systems by spatially dispersing corrosion activity. Conversely, higher current densities induce grain coarsening, crystallographic texture evolution, and amorphous, porous corrosion product formation, ultimately diminishing protective performance. Importantly, this study underscores the potential of compositional planification, demonstrating that tailored microstructural heterogeneity in pure metals can achieve high performance comparable to, or exceeding, that of more complex alloy systems. The findings provide valuable mechanistic insight and establish a practical framework for the design of durable, cost-effective, and sustainable coatings for demanding offshore and industrial environments [18].

Yang et al. demonstrate that the presence of the nickel interlayer reduced the corrosion current density from and significantly decreased the stress between the coating and the substrate. It successfully suppresses crack initiation at the ceramic coating/Ni interface and promotes the formation of a more stable passive film, as reflected by the improved corrosion potential and reduced corrosion current density. However, the protective capability of the Ni interlayer is constrained by the inferior corrosion resistance of the substrate, leading to stress concentration and crack formation at the Ni/substrate interface. This highlights the critical importance of substrate properties in determining overall system durability. The stress state transition from tensile to compressive along the thickness direction further emphasises the complex mechanical interactions governing coating performance. Moreover, under combined corrosion and mechanical impact conditions, coating degradation is dominated by the synergistic action of through-thickness cracks and corrosion pit formation. Through-thickness cracks serve as the primary pathways for interfacial failure, while corrosion pits originate from progressive layer delamination, accelerating coating breakdown. Overall, the findings underscore the importance of interfacial and microstructural design in achieving durable coating systems. The results provide valuable insight into coupled mechanical–electrochemical degradation mechanisms, establishing a solid foundation for the development of advanced, multi-layered protective coatings for demanding industrial and marine applications [19].

Borko et al. investigated carbon steel AISI 1018, reporting that it is highly prone to corrosion in CO_2 -saturated brine, a common challenge in oil production and transportation systems. In their study, they demonstrated cerium chloride (CeCl_3) and imidazoline oleic acid (IOA), individually and in combination, as environmentally acceptable corrosion inhibitors at 60 °C. Weight-loss, electrochemical, and surface analyses consistently showed that the CeCl_3 -IOA mixtures provided superior inhibition efficiency, reaching up to 97.9%, significantly outperforming individual components. IOA forms an adsorbed surface film that contains voids, while cerium carbonate from CeCl_3 fills these voids, resulting in a denser, more protective layer. The combination of $15 \text{ mg} \cdot \text{dm}^{-3}$ IOA and $15 \text{ mg} \cdot \text{dm}^{-3}$ CeCl_3 yielded the lowest corrosion rate ($0.03\text{--}0.05 \text{ mm} \cdot \text{year}^{-1}$) and provided stable long-term protection. Mechanistic insights indicate that IOA primarily acts as an anodic inhibitor, whereas CeCl_3 and the mixture function as mixed inhibitors with predominant anodic effects. These findings highlight the synergistic potential of combining adsorption-based and film-forming inhibitors, offering a practical and sustainable strategy for CO_2 corrosion control in carbon steel systems [20].

Ortiz et al. demonstrated that electroless Ni-P coatings significantly improve both the corrosion resistance and mechanical properties of ductile iron. The coatings are uniform, strongly adherent, and predominantly amorphous, leading to a substantial increase in

surface hardness. Electrochemical studies confirm that the Ni-P layer effectively blocks electrolyte access, facilitates the formation of protective corrosion products, and stabilises localised corrosion mechanisms. These results indicate that electroless Ni-P coatings offer a practical and scalable solution for extending the service life of ductile iron components in harsh environments, making them highly suitable for automotive, energy, and industrial applications. Ductile iron is widely used in engineering applications due to its favourable combination of strength, toughness, and machinability, yet its susceptibility to corrosion limits its service life. In this study, electroless Ni-P coatings were deposited on ductile iron to enhance corrosion resistance and mechanical performance. Comprehensive characterisation using SEM, EDS, X-ray diffraction, and microhardness testing confirmed that the Ni-P coatings are homogeneous, compact, strongly adherent, and predominantly amorphous, leading to a 53% increase in surface hardness. Electrochemical evaluations in 0.1 M NaCl solution revealed that the Ni-P coatings significantly improve corrosion resistance. EIS and phase angle analyses demonstrated that the coating effectively blocks electrolyte access, promotes the formation of a protective corrosion product layer, and shifts the corrosion mechanism toward more stable and localised processes. The impedance of coated samples increased by an order of magnitude compared to the uncoated substrate, highlighting the protective role of the amorphous Ni-P layer. Equivalent circuit modelling further corroborated these findings, showing the formation and evolution of corrosion product films over prolonged immersion. Overall, the study illustrates that electroless Ni-P coatings represent an effective and industrially scalable approach to mitigate corrosion in ductile iron while simultaneously enhancing mechanical properties. These findings provide valuable insights for extending the lifespan of ductile iron components in demanding environments across automotive, energy, and manufacturing sectors [21].

In their work, Fan et al. introduced a scalable and environmentally benign strategy for the fabrication of coloured superhydrophobic stainless steel surfaces, combining high-temperature oxidation with subsequent nano-silica film deposition. The oxidation process enables controllable surface colouration through optical interference effects, while the nano-silica modification effectively transforms initially hydrophilic oxide layers into highly water-repellent, self-cleaning interfaces. Systematic microstructural and electrochemical analyses demonstrate that oxidation temperature plays a critical role in governing surface morphology, wettability, and corrosion performance. Oxide films formed at intermediate temperatures ($\sim 600^\circ\text{C}$) exhibit optimal corrosion resistance, whereas higher temperatures lead to increased roughness and hydrophilicity. Notably, the application of the nano-silica coating overcomes these limitations, producing superhydrophobic surfaces with contact angles exceeding 150° and markedly reduced corrosion current densities. Electrochemical results further confirm a substantial enhancement in protective performance, with polarisation resistance increasing by several orders of magnitude and corrosion inhibition efficiency approaching 99%. This improvement is attributed to the synergistic effect of hierarchical surface roughness, air entrapment, and the formation of a dense, adherent barrier that effectively restricts electrolyte penetration. Overall, this study provides a compelling pathway for integrating aesthetic functionality with advanced surface protection, offering significant potential for applications in architecture, decorative engineering, and harsh service environments [22].

In this comprehensive review, Samardžija et al. highlight the key role of scanning electrochemical microscopy (SECM) as a superior analytical technique for investigating degradation and corrosion mechanisms of nanocomposite epoxy coatings. SECM's high spatial resolution has been shown to enable detailed, localised electrochemical analysis of surface defects and active sites, providing key insights into how nanoparticle modifications—such as ZrO_2 , TiO_2 , and graphene oxide—improve coating performance. By examining dif-

ferent modes of operation and emphasising the importance of accurate calibration and data interpretation, the review demonstrates SECM's ability to assess coating integrity under realistic environmental conditions. Its ability to deliver spatially resolved electrochemical information surpasses traditional methods, facilitating a deeper understanding of localised corrosion processes that govern coating durability. Integrating SECM with complementary surface analysis techniques shows promise for accelerating the development of next-generation nanocomposite coatings with superior protective properties. Ultimately, adopting SECM in coating research advances the design of more resilient materials, extending service life and ensuring reliability in aggressive environments [23].

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