

RESEARCH PAPER

Corrosion Resistance and Antibacterial Activity of Graphene–Alumina Nanostructured Coatings on 316L Stainless Steel: Experimental Evaluation and AI-Based Modeling

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ABSTRACT

In this study, the corrosion resistance of 316L stainless steel coated with alumina and hybrid graphene–alumina nanostructured coatings prepared by spin coating were systematically explored using experimental characterization and AI-driven modeling. Graphene-modified coatings with different contents of graphene were also prepared to investigate the effect of the addition of graphene on surface morphology, structure durability, electrochemical properties and antibacterial activity. Surface morphology and crystal features were studied by scanning electronic microscopy and X-ray diffraction analysis, an antibacterial activity was tested as a function of inhibition zone against *Staphylococcus* spp. at 37 °C. The results of electrochemical studies showed that the pure alumina coating (C1) outperformed both the uncoated substrate (C0) and graphene–alumina composite coatings among the coatings prepared, with the lowest corrosion current density and a corrosion rate of 0.00131 mm year⁻¹. This is because a dense, uniform, and defect-free protective layer forms. With low amounts of graphene, there was a considerable amount of agglomeration and surface defects, which made the material more susceptible to corrosion, while at higher concentrations a partial recovery in corrosion resistance was observed thanks to improved barrier properties but still less than that of pure alumina. The association between coating composition and corrosion rate was investigated using exploratory Random Forest analysis; however, due to the small experimental dataset, the computational results were viewed as exploratory rather than as independent confirmation of an ideal composition.

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INTRODUCTION

316L stainless steel is one of the most common metal materials, employed in industrial, biomedical, and marine environments for its excellent corrosion resistance, mechanical properties, and biocompatibility. Its austenitic structure and chromium/nickel composition reduce the possibility of material stress corrosion cracking to a minimum - even in sulphuric acid. However, once this passive layer is damaged by an aggressive medium (chloride-rich solutions, acid, and physiological fluids), prolonged exposure results in localized corrosion, ion liberation, and shortened service life. Thus, enhancing the corrosion resistance of stainless steel parts at high temperature is an important issue for industrial and biomedicine applications [1].

Nanostructured coatings have been proposed as a solution to improve the resistance of stainless steel against corrosion. Graphene and graphene oxide (GO), as a class of graphene-based materials, have superior chemical inertness, impermeability, and mechanical strength, which can be used to block the penetration of corrosive ions. Combined with alumina (Al_2O_3) nanoparticles for chemical and mechanical reinforcement, hybrid graphene–alumina coatings can enhance the protective effects on stainless steel surfaces to a great extent. The consistent distribution of these nanoparticles, as well as their optimal graphene content are extremely important in obtaining dense, defect-free coatings having excellent corrosion protection [2].

To deposit thin films with tunable thickness and homogeneous surface coverage, the spin coating method is commonly used. By controlling parameters such as rotation velocity and the quality of dispersion, spin coating allows uniform coatings to be deposited, a necessary feature for multicomponent nanocomposites. Hybrid graphene–alumina nanostructured films are spin-coated onto stainless steel 316L substrates in this work to evaluate the effect of graphene concentration on corrosion resistance [3].

A number of studies have recently considered related systems. Chen et al. [4] prepared and applied a binder-free graphene–alumina composite coating on carbon steel, and they showed the improved resistance of coated samples against a severe medium where the synergistic effect between components consisting of graphene and alumina formed a compact protective layer. Yadav

et al. [5] summarized polymeric coatings based on graphene and found that the addition of graphene derivatives improved barrier properties and slowed down the diffusion of corrosive species; Zhang et al. [6] also studied graphene oxide and layered double hydroxide hybrid coatings on anodized aluminum alloy, they concluded that better corrosion protection was due to a uniform distribution of GO, and more effective sealing of pores. Functionalized GO, cross-linked with amine-cured epoxy, was shown to improve adhesion, electrochemical stability, and corrosion protection properties of 2024-T3 alloy in the presence of non-functionalized GO incorporated into epoxy coatings, who found that functionalization led to better adhesion and electrochemical stability, leading to prolonged corrosion protection. Finally, El-Kady et al. [7] investigated Al–Cu– Al_2O_3 /graphene nanocomposites and suggested that the higher content of graphene could be more advantageous for corrosion resistance; nevertheless, when a large amount of addition is used, agglomeration occurs together with pore formation due to the importance of nanoparticle distribution for effectively stabilizing the material.

However, the systematic investigation has not been reported so far in relation to the stainless steel 316L, depending on the graphene content of alumina-based spin-coated films. In addition, there are limited applications of the predictive model using AI-based techniques applied to simulate corrosion behavior as well as to select the best composition before experiment. These simulations are unique in that they combine experimental characterization (XRD, SEM, electrochemical testing) and machine-learning-based simulation using Random Forest regression for optimization of graphene–alumina coatings for corrosion protection. Such an integrated approach yields both structural and functional understanding of the corrosion performance, which is valuable in designing sustainable coatings for industrial and biomedical applications [8].

The focus of this work is to systematically study the impact of graphene loading in hybrid graphene–alumina nanostructured coatings on corrosion performance for SS316L. Particularly, the study pursues three goals: determination of the content at which maximum corrosion protection is obtained and with minimum defects (agglomerates or pores), development of a relationship between coating architecture and

electrochemical behavior, and demonstration of the feasibility of using AI-guided predictive modeling to guide designing high performing, sustainable nanocomposite coatings [9].

Besides corrosion resistance, peace of mind about their antibacterial performance is another key requirement for the material used in biomedical and healthcare-related environments. Stainless steel 316L is commonly used in medical devices and implants, where bacterial adhesion and biofilm formation can result in infections and prosthetic failure. Hence, examining antibacterial activity of graphene–alumina coatings yields further information on their multifunctional behavior and potential application in biomedical settings.

MATERIALS AND METHODS

For this study, the substrates were stainless steel 316L samples machined into cylindrical specimens of size 10 mm in diameter and 10 mm in height. The sample surfaces were progressively polished according to the ascending order of grit sizes for silicon carbide papers and conditioned until a smooth, defect-free surface was achieved. After mechanical polishing, the samples were cleaned using ultrasonic treatment in ethanol and deionized (DI) water to remove all contaminants, including oils and debris from the surface, before depositing the coating [10].

Commercial plate like multilayer graphene nanopowder (purity $\geq 99\%$ with particle sizes of 100–200 nm) were utilized for synthesis of hybrid graphene–alumina nanocomposite coatings. The main matrix material used in this study was high-purity alumina (Al_2O_3) powder.

Coatings with systematically varying content of graphene were fabricated to probe the effect of graphene content. These samples were labeled as follows:

C0: uncoated stainless steel substrate (control sample);

C1: pure alumina (Al_2O_3) coating without graphene;

C2: hybrid graphene–alumina coating with 0.5 wt% of graphene and 99.5 wt% of alumina;

C3: hybrid graphene–alumina coating with 1.0 wt% graphene and 99.0 wt% alumina.

In every coated sample (C1–C3), the alumina was utilized as a continuous matrix phase, and the graphene adopted as a reinforcing nanofiller. To standardize the nominal amount of material

utilized during coating preparation and enable sample comparison, the total powder mass for each formulation was kept at 2 g. equivalent powder mass, however, does not guaranty equivalent coating thickness or adherence, neither of which were quantified in this investigation.. C0 was the control sample used to determine the effect of coating and addition of graphene on structural, corrosion, and functional properties.

Spin coating was applied for the coating procedure, which is recognized as an appropriate method to grow thin and homogeneous films on metallic substrates. Amalgamation of the graphene and alumina powders: Initially, the graphene and alumina powders were mixed homogeneously in ethanol based on the stoichiometry ratios of the formulation for 30 min at 100 W using a probe sonicator to ensure uniform distribution with no nanoparticle agglomeration. The uniformity of these dispersions was checked by scanning electron microscopy (SEM) images of dried suspension samples before being coated. After the dispersion preparation, each mixture was drop-casted onto stainless steel substrates and spun at 500 rpm for 30 s first and then at a higher speed of 2000–3000 rpm for 60 s to prepare a thin and uniform film. Once spin coating was finished, the samples were dried in air to evaporate a part of the solvent and then oven-dried at 100 °C for 30–60 min for complete evaporation of the solvent and stabilization of the coating without causing cracks.

The agar diffusion method was used for the antibacterial assay in accordance with CLSI recommendations, which are standard microbiological testing protocols. *Staphylococcus* species from the Environmental Research Center at the University of Technology were used to test the antibacterial activity. McFarland Standard No. 5 was used to prepare the bacterial inoculum to a density of $[1.5 \times 10^9 \text{ CFU/mL}]$. The specimens were sanitized prior to testing, and the assay was carried out using Mular Hinton agar growth medium in accordance with [11]. [C0, C1, C2, and C3] were among the experimental groups. To ensure repeatability, the specimens were incubated in triplicate for 24 hours at 37 °C. Millimeters were used to measure the inhibition zone widths, and the results were presented as mean $\pm$ standard deviation.

The structure, morphology, and properties of

the coatings were assessed by means of a variety of analytical methods. The crystalline phases were characterized using X-ray powder diffraction (XRD) with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) at 40 kV and 30 mA, operating in a $\theta/2\theta$ mode, in the range of $10\text{--}80^\circ$ (2θ values), with a step size of 0.04° . Scanning electron microscopy Scanning electron microscopy (SEM) was carried out with a JEOL JSM-6510 operated at 15 kV magnification up to $5000\times$ to determine the coating morphology, homogeneity, and also the graphene and alumina particles distribution. The hydrodynamic particle size distribution and polydispersity index (PDI) could not be quantitatively assessed using dynamic light scattering (DLS) experiments. As a result, DLS data cannot be used to infer judgments on particle agglomeration or dispersion quality. Although they don't take the role of quantitative DLS data, the morphological observations from SEM offer qualitative information regarding particle distribution and aggregation characteristics.

Enabling comparison of the corrosion rates and protective performance of the coatings under an electrochemical stress was accomplished by determining antibacterial activity by inhibition zone measured against *Staphylococcus* spp. after incubation at 37°C for 24h according to [11].

Graphene has a unique particle-size (100–200 nm) and multilayer structure that is important for its dispersion behavior and overall coating performance. This particle size on the nanoscale level promotes incorporation into the alumina matrix and surface coverage, though it also increases surface energy such that agglomeration is more likely when dispersed poorly.

Moreover, multilayer graphene has stronger interlayer Van der Waals interactions than monolayer graphene and can easily aggregate into flakes also easier to form clusters. This becomes even more pronounced with high graphene contents, leading to the establishment of microstructural heterogeneities noted in SEM images.

Graphene must be well dispersed to perform the rheological role and significantly improve barrier properties by increasing tortuosity and limiting ion diffusion. The problems of dispersion (particle size effect), multilayer stacking (defects, discontinuities) will worsen the performance in terms of corrosion if they are not carefully evaluated and also controlled.

Thus, the uniform dispersion of multilayer

graphene is still a strong influencing factor affecting structural integrity and protective performance for coating.

Electrochemical corrosion measurements were made in a three-electrode electrochemical cell. The prepared specimen acted as the working electrode, and the saturated calomel electrode and platinum served as the reference and counter electrodes, respectively. The exposed working electrode surface area was 1 cm^2 . Simulated Body Fluid (SBF) was employed as the electrolyte; it had a reported pH of 7.4. Prior to performing the polarization measurement, the Open Circuit Potential (OCP) was monitored for 15 minutes to evaluate the stability of the potential. Potentiodynamic polarization measurements were performed from -3000 mV to 3000 mV relative to the reference electrode at a scan rate of 2000 mV/sec . Corrosion potentials (E_{corr}) and corrosion current densities (i_{corr}) were obtained from the Tafel extrapolation of the polarization curves using fitting ranges [anodic range] and [cathodic range].

The corrosion rate was calculated using the following equation:

$$\text{CR (mm/year)} = \frac{0.00327 \times i_{\text{corr}} \times \text{EW}}{\rho} \quad (1)$$

The variables for this formula are: i_{corr} is the corrosion current density ($\mu\text{A/cm}^2$), (EW) is the equivalent weight (g/equivalent), and ρ is the material density (g/cm^3).

The results of testing were based upon [N] independent test samples prepared for each material or coating being evaluated. Results have been presented as means $\pm$ standard deviations (SD), where appropriate.

RESULTS AND DISCUSSION

X-ray Diffraction (XRD) Analysis

The diffraction peaks' locations and forms varied slightly between the samples, according to the XRD patterns. These variations are only described as qualitative findings. The observed peak fluctuations cannot be used to determine specific changes in crystallite size, lattice strain, or structural disorder because instrument-corrected FWHM values and quantitative crystallite-size or microstrain calculations were unavailable.

The crystalline characteristics of the substrate and coated samples were evaluated by looking at the XRD patterns. The samples showed slight

variations in peak position and shape. However, these variations cannot be used to determine specific changes in crystallite size, lattice strain, or structural disorder because instrument-corrected FWHM values and quantitative crystallite-size or microstrain calculations were unavailable.

The structure of hybrid graphene–alumina nanocomposite coatings on stainless steel 316L was studied by X-ray diffraction (XRD). It can be seen from the XRD patterns of all coated samples (C1 to C3) that the characteristic diffraction peaks of austenitic stainless steel were observed in each case, with the most intense peak at $2\theta \approx 43^\circ$ assigned to the plane (111). This indicates that spin coating hasn't changed the underlying crystal structure of the substrate. Some small additional peaks at higher angles are found, potentially due to the presence of alumina nanoparticles and the graphene component in the coatings [12].

Pure alumina points XRD pattern. Sample Pure Al_2O_3 Sample C1, with pure alumina as the abrasive phase, as shown in Fig. 1, shows clear and well-defined peaks of high intensity at 43.17° , 50.23° , and 42.75° , implying good crystallinity and homogeneity of deposition of the particles on the steel substrate Sample C1.

For sample C2 (with 0.5 wt% graphene), the main austenitic peaks slightly shifted to larger

angles, where the strongest peak was at 43.28° , showing the slight lattice distortion, probably attributed to the incorporation of graphene sheets into the Al_2O_3 matrix. This small change indicates the interaction between graphene nanoparticles and the alumina lattice, resulting in a slight strain with substrate crystallinity. More low-intensity peaks corresponding to graphene ($25\text{--}26^\circ$) also confirm the incorporation of graphene in the coating [13].

Sample C3 (with 1.0 wt% graphene) showed at 43.47° position with some slight broadening of other austenitic reflections. It means that the increase in the content of graphene creates more lattice strain and lowers the long-range order in the composite film. The wide low-intensity peaks observed at $25\text{--}26^\circ$ confirm the incorporation of graphene into the CPs and also indicate partial agglomeration with higher concentrations. The slight peak shifts and broadening in C2 and C3 indicate that the higher proportion of graphene content changes the structural stability of the coatings, which may have some effects on their barrier property and corrosion resistance.

In general, the XRD results show that the hybrid graphene–alumina coatings retain the austenitic structure of SS 316L, where the presence of graphene as a reinforcing phase leads to that

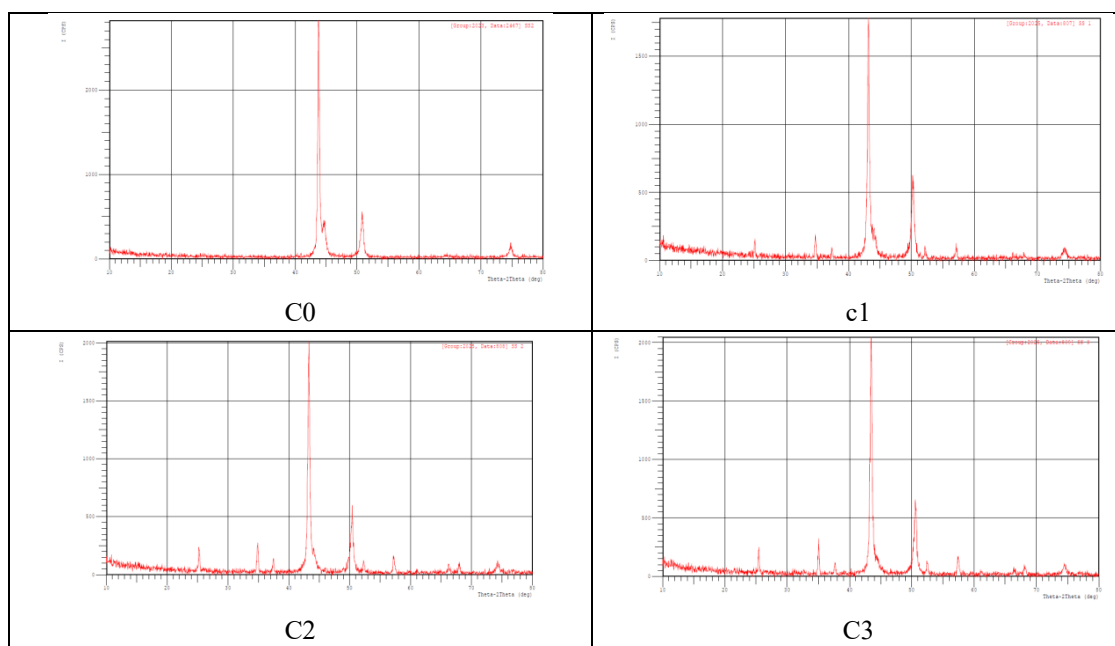


Fig. 1. XRD of SS316L and SS316L – Coated.

correspond to the particle dispersion extent and coating homogeneity. The best structural features, sharp and intense peaks, and less FWHM broadening were seen in C2 (0.5 wt% of graphene), indicating that the addition of a very low amount of graphene gives homogeneous and well-coated materials, probably with better corrosion behavior than those containing more graphene [14].

At low graphene loading (0.5 wt%), the interaction between the graphene sheets and alumina matrix is mainly dominated by interfacial physical mechanisms. With this concentration, relatively good dispersion of graphene nanosheets is attained and they are distributed within the booster alumina matrix and also interact through Van de Waals forces as well as mechanical interlocking.

The addition of graphene introduces interfacial stress concentration due to the elastic modulus and lattice structure mismatch between graphene and alumina. These differences cause a lattice distortion in the neighboring alumina domains.

Moreover, graphene sheets act as nanoscale barriers embedded in the matrix that can affect grain boundary rearrangement and hinder crystallite growth. The interactions work together to provide minor structural changes without significant loss of crystallinity at low levels of graphene.

Any wider peak beyond 1.0 wt% amount of graphene is considered a continuous structural disorder within the coating itself due to increased hybridization or an excess of graphene in the alumina matrix.

The crystalline orders are partially lost due to strong agglomeration and interfacial mismatch between graphene and alumina at higher concentration of graphene. In some extreme scenarios, this could even facilitate a transition to a semi-amorphous or amorphous-like structure in the coating.

Degraded coating uniformity thus seems inevitable; as the structural change leads to disordered regions and defects that favour corrosive ions diffusion.

SEM Morphological Analysis

SEM (C0 – Uncoated Stainless Steel 316L)

SEM image of the uncoated stainless steel 316L substrate (C0). The metallic surface is smooth, with linear grooves from the polishing process.

The linear grooves also orient preferentially on the substrate surface, demonstrating process controllability of morphology development during surface preparation prior to deposition of the coating layer. This is necessary to compare with other samples following deposition.

On the surface, no surface film or nanostructure is present, representing a pristine side-by-side comparison for subsequent deposited samples. Some defects are also observed on the surface, which can act as a favored point for enhancing localized corrosion attacks in corrosive media such as chloride solutions or physiological fluids.

The surface morphology exhibits a mechanically polished feature, which could be compared with samples C1, C2, and C3 after deposition to evaluate the effect of coating with alumina and composite graphene-alumina coating on the homogeneity and corrosion resistance of its surface [15].

SEM (C1 – Al_2O_3 Coated Stainless Steel 316L)

SEM C1 shows the image of the plain substrate coated with alumina and reveals that most of the roughness of this film is induced from the bare sample (C0). The sample surface is almost entirely coated by a uniform layer of alumina, hiding the polishing scratches on the stainless steel substrate surface.

The surface microstructure of the alumina film is observed as dense, and all particles are uniformly dispersed without porosity. The surface has no discernible large cracks or delamination, indicating good adhesion between the alumina film and stainless steel substrate. Nonetheless, very low roughness is also observed on the surface of the sample, possibly due to spin coating.

The surface morphology of the sample shows that alumina film could make the stainless steel substrate surfaces as flat and smooth as possible, therefore, it can be used to act a physical barrier between the modification of hydrogenated amorphous carbon coating (H) at the stainless steel surface in samples C2 and C3 to stainless steel (S), thus providing us with fundamental image reference for understanding how graphene addition effects on the stainless steel substrate surface [16].

SEM (C2 – 0.5 wt% Graphene- Al_2O_3 Coated Stainless Steel 316L)

This qualitative appearance does not prove

greater corrosion protection, even though the SEM image of C2 indicates rather continuous surface coverage in the observed region. According to electrochemical studies, C2 had a corrosion rate of 0.097073 mm/year, which was higher than that of the uncoated substrate C0 (0.083515 mm/year). This disparity suggests that the electrochemical reaction cannot be adequately explained by the reported surface shape alone. The supplied SEM pictures are insufficient to confirm potential effects from local coating flaws, non-uniform dispersion, or variations in coating thickness.

The SEM image of sample C2 (stainless steel 316L coated with a hybrid nanocomposite thin film comprised of 0.5 wt% graphene and alumina) observed surface may appear relatively homogeneous in the available images, this morphological observation does not necessarily indicate superior corrosion resistance. From the SEM image in Fig. 2, it can be seen that the surface morphology for a hybrid-coated sample is denser and homogeneous. This reveals the homogeneous distribution of graphene particles in the alumina.

The high field agglomeration is observed to be very weak for the hybrid-coated sample,

compared to other samples. It can be observed from the figure that surface morphologies for the sample seem to be without cracks and porous. Furthermore, from the image we can see that for the hybrid-coated sample, the polishing grooves of the substrate are almost completely covered (corroborating the thickness and surface coverage of the film prepared by spin coating).

The morphological view of sample C2 shows the uniformity, and the corrosion rate was found from the photo taken from the polarization curve for sample C2. This shows that 0.5 wt% is a good content of graphene for reinforcing the alumina matrix, without any agglomeration on the surface of the sample [17].

SEM (C3 – 1.0 wt% Graphene- Al_2O_3 Coated Stainless Steel 316L)

That is, the surface morphology of the graphene-alumina nanocomposite coating with graphene content at 1.0 wt% (sample C3) is drastically different from that of sample C2 in the SEM photograph. The texture of the coating is inhomogeneous with particles or particle agglomerates ranging from small to large, providing an uneven surface for the coating.

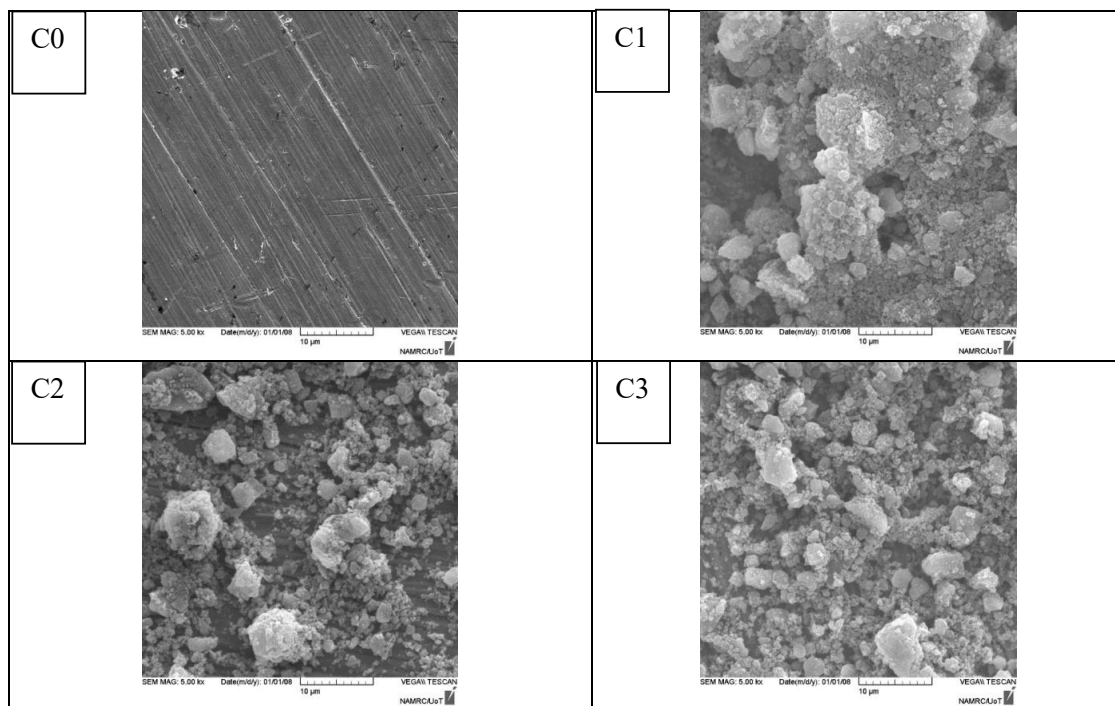


Fig. 2. SEM for SS316L Coated Samples.

The surface of sample C3 with a larger amount of graphene content (C3) is rough and hard to spread the particles uniformly on the coating surface. The polished substrate grooves are still covered by the coating, but the non-compactness of the coating is fragile and could be an indication of a lower barrier efficiency of the coating.

The particle agglomeration has a great influence on the electrochemical properties of sample C3 (high graphene load content); it shows a higher corrosion rate than sample C2 (nominal graphene loading). The experimental data of sample C3 further validate the predictions made by the Random Forest model, which suggests a lower amount of graphene is present in the case of dense and non-defective coating.

Such residual stresses may arise in dense coatings due to the differences in thermal expansion coefficients between graphene sheets and the alumina matrix, and from densification during heat treatment. Such stresses can appear in SEM images as microcracks, slight delaminations, or localized wrinkling at the load concentration region. These properties can have an impact on the mechanical integrity of the coating, as well as affect corrosion behaviour where microcracked areas act as preferred routes for electrolyte encapsulation.

Corrosion Behavior Analysis of 316L Stainless Steel Before and After Coating

The corrosion behavior of hybrid graphene–alumina coatings on stainless steel 316L in SBF (37 °C) has been studied by potentiodynamic Tafel polarization analysis, and I_{corr} , E_{corr} , and CR have been obtained to analyze the protective performance of different contents of graphene (contents as C0–3), comparing it with that for the control sample (C0) [18].

As shown in Table 1, the pure Al_2O_3 -coated sample (sample C1) had the best corrosion protection behavior with the lowest I_{corr} ($1.117 \times 10^{-7} \text{ A cm}^{-2}$), E_{corr} (-0.15788 V), and quite low corrosion rate of about $0.00131 \text{ mm year}^{-1}$. The small discrepancy between the experimental polarization curve and the Tafel fitting residual further demonstrates the reliability of the electrochemical testing, reflecting a highly uniform and dense coating. These results indicate that the Al_2O_3 layer serves as an efficient physical barrier, which effectively blocks aggressive ion migration to the stainless steel surface and

metal dissolution. The compact and continuous microstructure in SEM also confirms the excellent barrier characteristics of C1.

A significant increase of the corrosion current density ($8.275 \times 10^{-6} \text{ A cm}^{-2}$), a more negative corrosion potential (-0.17664 V), and a high corrosion rate, equal to $0.09707 \text{ mm year}^{-1}$, were obtained once the graphene was incorporated into the matrix (C2, at 0.5% wt). This degradation in corrosion protection is indicative that, at this graphene content, the agglomerated partial formation of stacked flakes and/or inhomogeneous dispersion took place inside the alumina matrix, resulting in microdefects and localised discontinuities within the coating. Furthermore, these defects might work as preferred routes for penetration of electrolyte, which facilitates local corrosion processes. This interpretation is consistent with SEM images that revealed the occurrence of clustered formations and the presence of heterogeneous surface features in C2. However, the graphene–alumina composite coating still shows reasonable protection ability compared with uncoated stainless steel in literatures [19].

An intermediary behavior is noted for C3 (1.0 Graphene wt%). The corrosion current density dropped to $3.438 \times 10^{-6} \text{ A cm}^{-2}$, and the corrosion potential was -0.16757 V . The corrosion rate was $0.04034 \text{ mm year}^{-1}$, indicating that O1 has partial restoration of corrosion resistance compared with C2. This enhancement indicates that the defect-filling and coating continuity of the composite film may also be further promoted with reinforcing nanofiller loading up to 0.5 wt%, which is attributed to improved interparticle connection within the poorly organized nanocomposite layer. Furthermore, the small residual of Tafel fitting indicates that the electrochemical data quality is high. Nevertheless, even with the improvement, the corrosion resistance of C3 is less than that of pure alumina coating (C1), indicating that too much graphene can break up coating compactness by agglomeration and a large amount of structural heterogeneity, as shown in Fig. 3.

Generally, the Tafel polarization curves show non-linear improvement of the corrosion resistance with increasing graphene content. Both alumina and graphene have beneficial effects on barrier properties of the matrix: either low defect density for AE or high tortuosity effect for GP. Poor dispersion at intermediate graphene loadings

leads to degraded corrosion resistance, and higher levels of graphene addition only mitigate this effect partially, with no cases out performing pure alumina. These changes in electrochemical behavior are well supported by SEM and XRD data analysis, i.e., at lower Gnp concentrations, the structure preservation is exhibited, while high loading resulted in peak broadening and lattice strain that matches their decline in corrosion performance [20].

It also could be attributed to the competition between defect formation and barrier enhancement mechanism upon increment of graphene content. At low graphene content (0.5 wt%, C2), it is shown that the incomplete dispersion of partially agglomerated graphene nanosheets gives rise to microstructural defects характерные for inhomogeneous structures, including discontinuity at interfaces and voids

formed within the alumina matrix. These defects serve as preferred paths for electrolyte ingress, which results in localized corrosion acceleration and higher levels of corrosion current density.

Upon increasing graphene content to 1.0 wt% (C3) the corrosion resistance partially regains. This is due to the formation of a more interlinked graphene framework in the coating, thus making diffusion pathways for corrosive agents more tortuous. Higher graphene loading is also consistent with possible partial defect filling progressively reducing the effective permeability of the coating,²⁹ as well as increased particle–particle connectivity reducing pathway tortuosities within the composite,³⁰ further contributing to reduced permeation throughout.

However, an excess of graphene still causes aggregation along with structural non-uniformity that results in the coating not reaching the

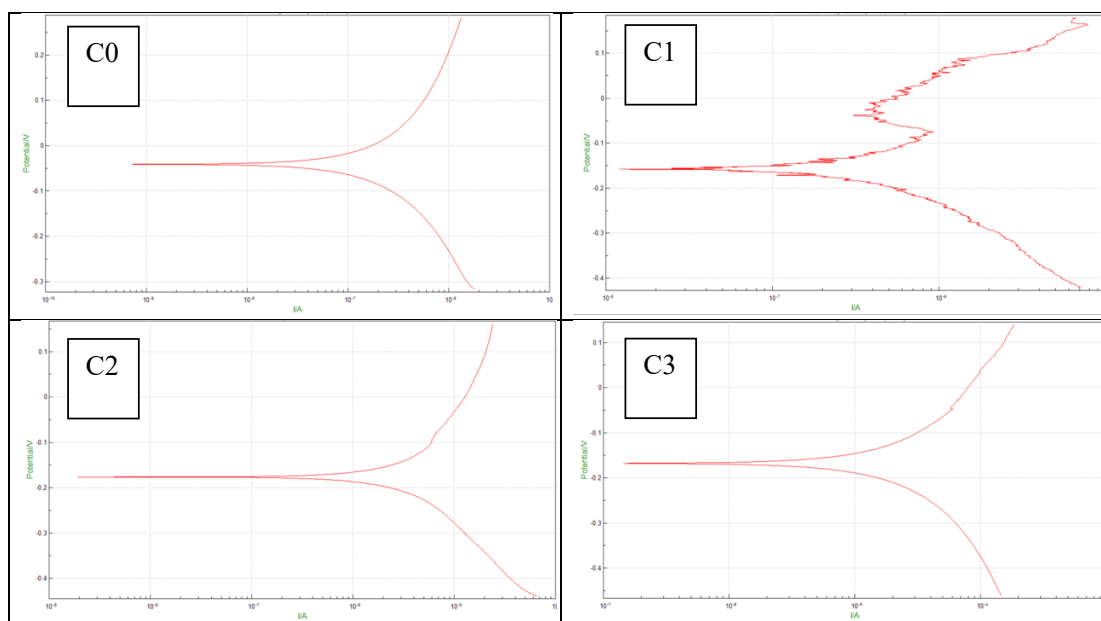


Fig. 3. Electrochemical behavior of SS316L and SS316L – Coated.

Table 1. Corrosion Parameters of 316L Stainless Steel.

#	-E _{corr} (mV)	I _{corr} (A.cm ⁻²)	b _c	Ba ⁺	CR
C0	41.121	7.1147×10 ⁻⁶	37.594	32.529	0.083515
C1	157.88	1.117×10 ⁻⁷	26.346	64.207	0.001310
C2	176.64	8.2747×10 ⁻⁶	333.31	673.27	0.097073
C3	167.57	3.4383×10 ⁻⁶	25.614	42.216	0.040336

compactness and uniformity of pure alumina coatings (Guan et al., 2019). This accounts for the continued inferior corrosion resistance of C3 compared to that of C1 despite some improvement.

While this study only reached graphene loadings of up to 1.0 wt% in the graphene–alumina coating system, it is likely that too high contents would have an adverse effect on both coating stability and corrosion resistance. High loading levels of graphene nanosheets usually cause intense agglomeration as a result of strong van der Waals forces, which further leads to enhanced surface roughness and pore formations in the coating, as well as structural heterogeneity.

High graphene content can also lead to discontinuities in the alumina matrix, impairing interfacial bonding and resulting in decreased coating adhesion with the substrate. Moreover, after a specific distance, a conductive path development may promote local electrochemical processes that could hasten corrosion rather than inhibit it.

Thus, an ideal graphene content value, above which the adverse consequences of agglomeration and structural instability become greater than the advantages due to its enhanced barrier properties.

Antibacterial activity of the bare and coated 316L stainless steel

The antibacterial efficacy of the uncoated and coated 316L stainless steel specimens were tested against *Staphylococcus* spp. using the agar diffusion method by incubating for 24 h at 37 °C, according to standard microbiological testing. Triplicate measurements were made and the inhibition zone diameters presented as mean $\pm$ standard deviation for reproducibility and reliability. For every sample, the same method was used to record the inhibition-zone measurements. [The entire inhibition-zone diameter, including the specimen diameter and the clear halo outside the specimen boundary] is represented by the stated values. The slight variation between the C2 and C3 values should be viewed with caution and does not imply a statistically significant increase in antibacterial activity on its own.

The inhibition zone of the uncoated sample (C0) was found to be relatively small (12 ± 0.5 mm) revealing weak antibacterial activity due probably to lack of proper surface plan and low metal ions release from the surface. It was observed

that the alumina-coated sample (C1) had a small improvement in the inhabitation zone (14 ± 0.6 mm), confirming that the ceramic coating can minimally decrease bacterial adhesion due to changes in surface energy and topography, even though ceramics are considered bioinert materials [21].

The graphene–alumina hybrid coatings were found to exhibit a marked improvement in antibacterial performance. The inhibition zone for the C2 (0.5 wt% graphene) sample was found to be 18 ± 0.8 mm while for C3 sample with 1.0 wt% graphene it was slightly increased up to 19 ± 0.7 mm. Such enhancement can be rationalized by the known antibacterial mechanisms previously reported for graphene-based materials, including physical rupture of bacterial cell membranes, generation of oxidative stress from reactive oxygen species (ROS), and increased surface contact between bacterial cells onto the coating. Nevertheless, the current study did not specifically look into these mechanisms. Therefore, rather than being mechanisms that the current studies experimentally prove, they are suggested as potential explanations based on earlier literature.

An increase of graphene content leads to increased antibacterial activity, but the small difference between C2 and C3 indicates a non-linear dependence. This behavior can be related to the agglomeration phenomenon of graphene in high concentrations which decreases effective surface area to interact with bacterial cells. Saturation effects inside the coating matrix may also play a role in this trend.

The bottom line is that inclusion of graphene into alumina coatings give a remarkable impact on antibacterial activity of 316L stainless steel. These findings point to the possibility of graphene–alumina nanocomposite coatings for multipurpose uses that call for antibacterial and corrosion resistance. However, further assessment of cytocompatibility, coating adherence, wear resistance, and long-term stability is necessary before they may be used in biomedical and clinical contexts [22].

AI-Based Simulation of Corrosion Rate Random Forest Analysis

Screening approach - Random Forest. The experimental results and the predictive physico-chemical framework for HYGC-A were screened based on an RF regression model. An

ensemble machine-learning technique, in the form of Random Forest (RF), based on the aggregation of decision trees, is particularly useful for modeling non-linear and complex relationships between input parameters and output responses.

In the present study, the RF model was fitted with the measured corrosion rates of samples C1–C3 as target output, and graphene- and alumina component masses as features. In this way, the model works favoring small-scale interactions between graphene dispersion, particle agglomeration, and alumina concentration that cannot easily be predicted by conventional analytics.

Optimization was accomplished with respect to the hyperparameters of predictive performance, whereupon the number of trees, maximum depth per tree, and minimum samples per leaf were tuned. The Random Forest analysis was regarded

as an exploratory computational evaluation because to the extremely small dataset, which only included three coated compositions (C1–C3). Any interpolation between the measured formulations should be taken cautiously because there is not enough data to create trustworthy generalization to untested mixes. For predictive optimization, the model was therefore not regarded as independently validated. The developed model was then used to predict corrosion rate over a continuously varying range of graphene (0–0.04 g) and alumina (1.96–2.00 g), which resulted in a three-dimensional (3-D) corrosion response surface that represents the impact of compositional variations on corrosion behavior.

The RF analysis is regarded as exploratory and should not be viewed as a fully verified machine-learning prediction model because the current experimental dataset only includes three

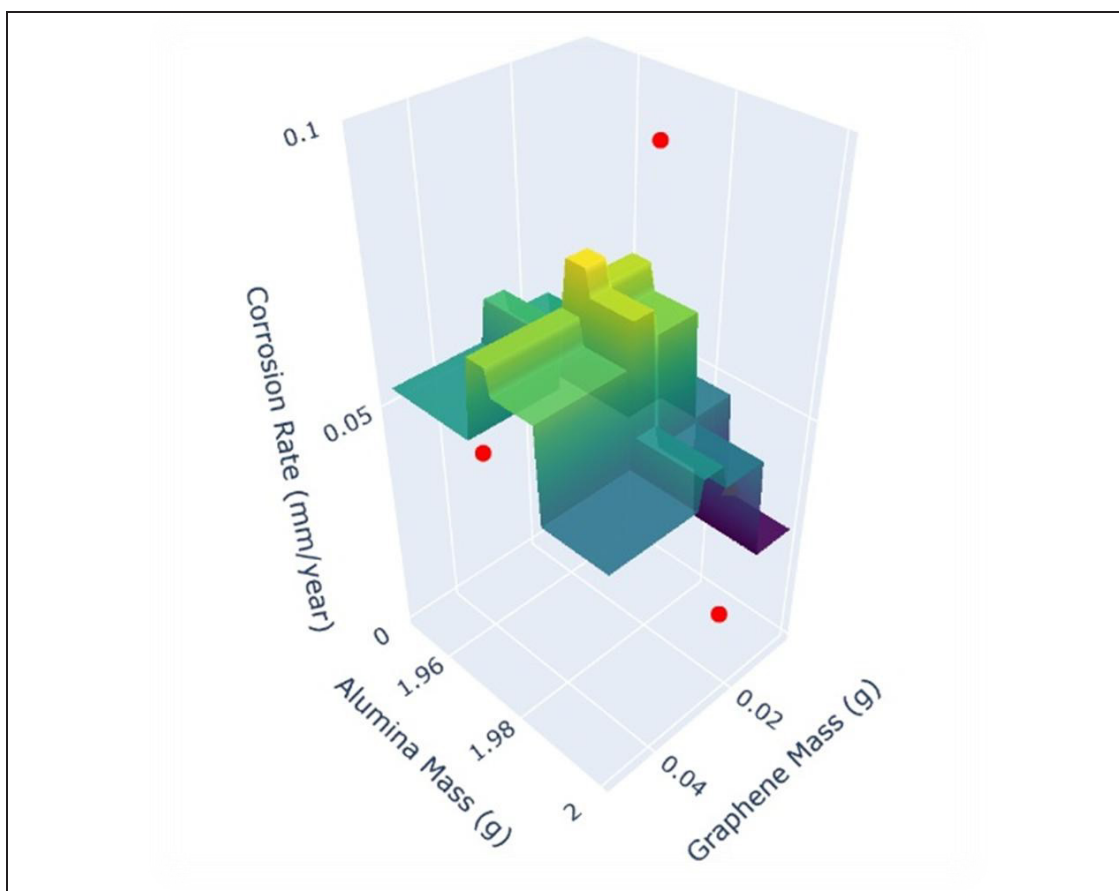


Fig. 4. 3D corrosion rate surface predicted by Random Forest showing the effect of graphene and alumina content. Experimental points are in red; optimal composition in gold.

coated formulations. Specifically, the reliability of model training, hyperparameter optimization, cross-validation, and prediction of untested compositions is constrained by the small number of experimental data. Therefore, rather than serving as proof of broad model generalizability, the RF results are merely offered as a preliminary computational evaluation of the reported composition–corrosion association.

Some important observations relative to the corrosion performance of hybrid coatings were obtained from simulation results. Interestingly, the AI model based on Random Forest determined C1 (100% alumina) where the predicted corrosion rate was minimized (0.00131 mm/year), whereas C2 (0.5 wt% graphene and 99.5 wt% alumina) exhibited a substantially higher corrosion rate of 0.097073 mm/year. Experimental results indicate that the corrosion response was not directly proportional to the graphene content; Sample C1 (pure alumina) exhibited the lowest corrosion rate (0.001310 mm/year), whereas Sample C2 (containing 0.5 wt% graphene) showed the highest rate (0.097073 mm/year), and Sample C3 (containing 1.0 wt% graphene) recorded an intermediate rate of 0.040336 mm/year. Consequently, the incorporation of graphene did not result in a consistent improvement in corrosion resistance under the conditions studied. Accordingly, Random Forest analysis was employed solely as an exploratory computational assessment of these composition-related trends, and its outputs were not deemed sufficient to determine the experimentally validated optimal composition. With these predictions model is well corroborated with experimental results obtained on one of the sample such as C2, which confirmed its good capacity to describe these complex interactions between dispersion of graphene, alumina matrix, and barrier performance. The simulation's major findings were:

Small amounts of graphene greatly improve the performance of protective barriers by increasing surface coverage with no defect or agglomeration and reducing porosity.

Retention of more graphene than the optimum concentration, leading to higher corrosion rates at longer exposure times because of phase agglomeration, non-uniform distribution, and possible microvoid formation.

Mass differences in alumina have relatively little effect on corrosion rate, revealing that alumina

functions mainly as a structural matrix, with the extent and distribution of graphene controlling barrier efficacy.

The 3D surface plots are also a clear visual image of the landscape of corrosion, where experimental parameters (red) and the ideal point (gold) predicted are shown.

This method has the potential of quickly screening unproven formulations, thereby minimizing experimental load, material expense, and development time.

The model offers some mechanistic insights that are in good agreement with SEM and XRD observations:

The spin-coated graphene–alumina coatings (graphene content: 0.5 wt%) retain structural integrity and uniform particle distribution for maximum barrier performance, while corrosion is minimal.

With the increase in the graphene loadings, there is lattice distortion, peak broadening in XRD, and partial agglomeration, which all lead to enhanced corrosion rates.

Along with the prediction of corrosion rates, SEM image processing can be synergistically combined along AI/ML techniques for automated defect identification in coatings. Fragments are assessed through image processing algorithms and machine-learning models that extract correlation and classifications of parameters such as cracks, pores, particle agglomerates, among others in terms of performance in application. Such an approach can allow for fast, objective, and high-throughput analysis of microstructural quality while permitting guided optimization of the graphene–alumina coatings independent from purely SEM-based manual interpretations.

In summary, the combination of AI-based simulation and experimental characterization gives a comprehensive elucidation of the structure–property–performance correlation in hybrid nanocomposite coatings, as shown in Fig. 4.

Even if the total mass of powder was maintained throughout the coating preparation process, this does not guaranty that the samples will have the same coating thickness or adherence. The current investigation did not use quantitative adhesion tests or direct thickness measurements. As a result, it is impossible to totally rule out the impact of potential variations in coating thickness and adherence, and future research should examine these characteristics.

Although the graphene–alumina coatings demonstrated measurable corrosion and antibacterial performance under the conditions investigated, these findings alone do not establish their suitability for biomedical implants. Cytocompatibility, coating adhesion, wear resistance, ion or particle release, and long-term stability were not evaluated in the present study. Accordingly, the biomedical relevance of these coatings should be considered preliminary, and further biological and mechanical assessments are required before specific implant applications can be recommended.

Practical Implications

The AI approach towards materials design has several practical advantages:

Aids the optimization of predictive coating while minimizing the need for many experiments.

Supports sustainable and resource-efficient development consistent with the principles of green nanotechnology.

The coatings may find use in corrosion-resistant systems, such as marine environments and chemical processing machinery. Their potential use in biomedical implants still needs more biological, mechanical, and long-term stability evaluations.

Aids in the making of intelligent decisions when it comes to coating composition, thickness, and process parameters for next-generation defense nanocoatings.

CONCLUSION

In this AI-facilitated experimental work, the corrosion behaviour of spin-coated hybrid graphene–alumina nanostructured films prepared over stainless steel 316L substrates was thoroughly studied. The influence of graphene amount on morphology, structure, and electrochemical performance of the coating was studied by using SEM, XRD, and Tafel polarization measurements, as well as Random Forest numerical simulated assembly. From the results of this work, the following conclusions may be obtained:

The corrosion resistance of 316L stainless steel was not uniformly affected by the composition of the coating; the pure alumina coating (C1) showed the lowest corrosion rate (0.001310 mm/year), while the graphene–alumina coating containing 0.5 wt% graphene (C2) showed a higher corrosion rate than the uncoated substrate (C0). Increasing the graphene content to 1.0 wt% (C3) decreased

the corrosion rate in comparison to C2 under the conditions examined.

- The pure alumina layer (C1) showed superior corrosion resistance, evidenced by its lowest icorr and corrosion rate values, which is attributed to its dense, homogeneous, and defect-strained microstructure that prevents ions from reaching the substrate.

- Non-linear effect of corrosion behavior was observed due to the addition of graphene into alumina matrix. Partial agglomeration and heterogeneous coating were detected at 0.5 wt% graphene (C2) with the generation of micro-defects, thus decreasing corrosion protection efficiency.

When the graphene content was raised to 1.0 wt% (C3), the corrosion resistance was partially restored because there was improved defect filling and inter-particle connectivity; however, the protective performance was still inferior to that of the pure alumina coating, suggesting that too much graphene load would impair the compactness of the coating.

An initial computational representation of the correlation between composition and corrosion rate was given by the Random Forest analysis. However, neither the identification of a validated optimum nor a trustworthy evaluation of model generalizability are made possible by the small number of experimental formulations. To assess the model's predictive ability, more experimental data encompassing a wider variety of compositions is needed.

The initial evaluation of composition–corrosion relationships in graphene–alumina coatings may be supported by the combination of experimental characterisation and exploratory AI-based modeling. The coatings' suitability for biomedical implants has not been determined, despite the fact that they demonstrated quantifiable corrosion and antibacterial performance under the examined conditions. Before recommending certain biomedical uses, more research on cytocompatibility, coating adherence, wear resistance, ion or particle release, and long-term stability is required. Additional validation under pertinent operating circumstances is also necessary for potential applications in industrial, marine, and chemical processing settings.

Integrating real-time monitoring data into adaptive predictive models can further advance our understanding of the coatings behavior and

improve forecasting capabilities. The models can be updated with new measurements of the electrochemical and environmental data using Kalman filters, recurrent neural networks, or Bayesian algorithms. By combining analytics with operational data, corrosion and mechanical behavior predictions can be continuously refined allowing for proactive decision making and optimization of coating application/maintenance.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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