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Recent Advances in Superhydrophobic Anti-corrosive Coatings

Athira Suresh and Biji Pullithadathil*

Department of Chemistry and Nanoscience and Technology, Nanosensors and Clean Energy Laboratory, PSG Institute of Advanced Studies, Coimbatore - 641004, India

Abstract

Corrosion is a chronic and costly issue that affects a wide range of industries, leading to material deterioration, safety risks, and significant economic losses. Traditional anti-corrosion strategies, even though effective to some extent, often suffer from environmental limitations and lack of long-term durability. Recently, superhydrophobic coatings have emerged as a highly promising solution due to their unique ability to repel water by limiting the interaction between corrosive agents and metal surfaces. These coatings create a high-water contact angle and low surface energy, forming an effective barrier against moisture, oxygen, and electrolytes. The basics of the anti-corrosive behaviour of superhydrophobic coatings, different materials, fabrication methods and latest technological breakthroughs have been discussed. This review explores the development and properties of superhydrophobic surfaces as a novel and sustainable approach to corrosion protection, while highlighting the need for further research to improve their durability and industrial scalability.

Keywords: Anti-corrosion, Durability, Electrochemical Studies, Superhydrophobic Coatings, Water Repellence

1. Introduction

Corrosion is a spontaneous electrochemical process where the material loses electrons and deteriorates, especially when exposed to moisture, air, or due to chemical reactions with their environment[1]. The corrosion process weakens materials, causing structural damage and reducing their lifespan, thus creating a need for effective corrosion prevention strategies. Corrosion mechanisms can vary widely based on the type of metal, the environment, and the conditions to which the material is exposed. Several common methods are used to prevent corrosion, each targeting different aspects of the process. These methods are widely applied in industries such as construction, automotive, marine, and manufacturing to extend material lifespan and reduce maintenance costs[2]. Paints, varnishes, and other coatings include pigments or corrosion inhibitors that counteract corrosive substances (like moisture, oxygen, and chemicals) in the environment and offer sacrificial protection, increasing the metal's resistance to deterioration. These coatings can be organic (*e.g.*, epoxy, polyurethane) or inorganic (*e.g.*, zinc coatings, ceramic coatings)[3]. The coatings also provide aesthetic benefits and can enhance the material's resistance to UV radiation. This method is typically used for large structures like pipelines, storage tanks, as they are frequently subjected to environmental factors such as moisture, temperature changes, and chemical vapour that can cause deterioration. Moreover, offshore platforms installed in ocean for extraction of oil and natural gas must withstand harsh marine environmental conditions like saltwater, varying temperature which may accelerate corrosion. Corrosion inhibitors are commonly used in closed-loop water systems, such as cooling towers, and in industrial equipment like boilers, pipelines, and heat exchangers. Inhibitors can be organic (*e.g.*, amines, phosphates) or inorganic (*e.g.*, chromates, molybdates). They work by forming a protective film on the metal surface, reducing the metal's exposure to corrosive elements[4]. Conventional methods for

*Email: bijuja123@yahoo.co.in

preventing corrosion, while widely used, have several notable disadvantages that can impact their effectiveness and sustainability. These limitations include high costs, environmental concerns, and the need for continuous maintenance. Conventional techniques for preventing corrosion, like cathodic protection and protective coatings, can require high upfront expenses and regular maintenance. By interfering with electrochemical reactions, corrosion inhibitors provide a more affordable option; yet, their efficacy is frequently constrained by elements like toxicity, short service life, environmental sensitivity, and decreased performance in harsh environments. They may not always provide reliable long-term protection, necessitating the exploration of alternative technologies that can offer improved performance at potentially lower life cycle costs. Their limitations prompt a need for innovative approaches that balance effectiveness, cost, and environmental safety. This shift towards alternative technologies may enhance corrosion management and reduce ecological impacts.

As the impact of corrosion is one of the most important problems which requires a solution, one promising approach is superhydrophobic coatings. Superhydrophobicity refers to the extreme water-repellent properties of a surface, where water droplets form high contact angles (> 150°), causing them to bead up and roll off the surface[5]. The application of superhydrophobic coatings to materials is a revolutionary way to mitigate corrosion, especially in environments prone to moisture and exposure to corrosive agents. These coatings create a barrier that prevents water from adhering to the surface, thus limiting its ability to interact with the material underneath. In addition to preventing water ingress, the coating also reduces the adhesion of salts, acids, and other pollutants that may accelerate the corrosion process. Recently, superhydrophobic anti-corrosive coatings are trending with improved durability, insulation, and thermal properties, non-fluorinated composites,coatings based on silica nanoparticles and over the last 5 years, superhydrophobic coatings have increased charge transfer resistance by more than 5 orders of magnitude and achieved corrosion inhibition efficacy of up to 99.99%. This review focuses on corrosion-related challenges and how superhydrophobicity helps to mitigate them, as it highlights emerging trends and performance benchmarks, providing a clearer roadmap for future research and industrial application

2. Corrosion: Mechanisms and Challenges

Corrosion typically involves electrochemical surface reactions, such as anodic dissolution and the formation of oxide films on metals. Passivity, pitting, and stress-corrosion cracking are key processes, especially in stainless steels and reinforced concrete structures[6]. Electrochemical surface reactions like formation of oxide films and anodic dissolution are some of the major issues related to surface corrosion. Many factors, such as chlorides, moisture, harsh environmental conditions, and carbonation, accelerate the rate of corrosion. In oil refineries, due to contact with aggressive substances, high flow rates, and elevated operating temperatures, most processing units are vulnerable to common corrosion problems. Electrochemical corrosion is the most common form and happens when a metal is exposed to an electrolyte (such as water, salt, or acids). It typically involves a redox (reduction-oxidation) reaction at the metal's surface. The metal ions at the anode combine with the hydroxide ions at the cathode to form corrosion products like rust (iron oxide) or other compounds depending on the metal. Iron (Fe) makes up the majority of steel, an alloy that is especially prone to corrosion when exposed to oxygen, moisture, and electrolytes (such salts). Rusting is the most prevalent type of corrosion in steel and is caused by an electrochemical process that combines reduction and oxidation processes. Over time, this process weakens the material's structural integrity by forming iron hydroxides and oxides, which are usually referred to as rust.

Oxidation at anode: $Fe \rightarrow Fe^{2+} + 2e^-$

Reduction at cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

Overall reaction: $4Fe + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3$

$Fe(OH)_3 \rightarrow Fe_2O_3 \cdot xH_2O$(Rust)

Galvanic corrosion occurs when two different metals are electrically connected in a conductive environment (like water), creating an electrochemical cel[7]. One metal acts as the anode (the one that corrodes), while the other acts as the cathode. The metal with a more negative electrochemical potential corrodes faster. Under gaskets, washers, or seals, for example, if the electrolyte (such as water) remains stagnant, crevice corrosion takes place. The corrosion process is accelerated by the difference in electrochemical potential caused by the absence of oxygen in these regions[8]. Pitting corrosion is a type of

corrosion that occurs locally and causes tiny holes or pits to emerge in the material. Stainless steel, aluminum, and other alloys are frequently linked to it, particularly in situations that are high in chloride. A pit usually becomes self-sustaining once it has formed. Deep pitting may result from the metal dissolving more quickly due to the acidic environment inside the pit. Stress corrosion cracking occurs when a material experiences both tensile stress and a corrosive environment, which leads to crack formation and propagation. This is particularly dangerous because the cracks can cause catastrophic failures in materials under stress. The corrosive environment accelerates crack initiation and propagation along the stressed regions of the material. Microorganisms such as bacteria, fungi, or algae can produce corrosion that is influenced by microbiology. Metal degradation can be accelerated by the confined corrosive conditions that these organisms might provide. On the metal's surface, microorganisms create biofilms that can cause localized acidity, oxygen depletion, or the creation of caustic compounds like sulfuric acid. Sulfate-reducing bacteria have the ability to produce severe localized corrosion in water pipes, which can result in pitting and pipe failure.

3. Mechanism of Corrosion Resistance in Superhydrophobic Coatings

The ability of superhydrophobic surfaces to repel water is one of its fundamental properties. Water, particularly when it contains electrolytes like salts or acids, is essential to electrochemical reactions that lead to the oxidation of metals in conventional corrosion processes. Water droplets on a superhydrophobic surface take on a virtually spherical shape and do not disperse over the surface due to a contact angle greater than 150°. The amount of water that can come into direct contact with the metal substrate is significantly thus decreased. As oxygen and water cannot readily enter a substance, there is minimal chance for the metal to oxidise when water does not spread across the surface. This lessens the corrosion-causing electrochemical processes. When superhydrophobic coatings are applied onto steel, water droplets bead up and roll off, minimizing the risk of rust formation and prolonged moisture exposure. Superhydrophobic coatings frequently produce a rough surface at the nano or microscale that traps air beneath the water droplet. Between the water droplet and the substrate, the roughness produces tiny air pockets[9]. By reducing direct water contact with the metal surface, the air cushion effectively blocks electrolytes from reaching the substrate and inhibits electrochemical corrosion. Another crucial component of corrosion resistance is the ability of superhydrophobic surfaces to clean themselves. As they roll off, water droplets can remove impurities, salts, and contaminants that would otherwise adhere to the surface and promote corrosion. By acting as an electrolyte that promotes electrochemical processes, salt build-up in coastal environments or highly polluted places can dramatically speed up corrosion. Superhydrophobic coatings self-cleaning properties lessen the chance of corrosion by preventing such types of salt build-up. On a superhydrophobic-coated car or ship, rainwater would naturally carry away road salts or sea salts before they can corrode the surface. Some metals, such as aluminum or stainless steel, naturally form a protective oxide layer that prevents further corrosion. The superhydrophobic coating acts as a physical barrier, minimizing the metal's exposure to water and corrosive agents and helping preserve the integrity of the protective oxide layer (Fig. 1). This is particularly important for metals like aluminium and stainless steel, which rely on the oxide layer to protect the material from further corrosion. Chloride ions (from saltwater, for instance) are particularly aggressive at breaking down oxide layers,by reducing direct contact with water. While superhydrophobic coatings can offer excellent corrosion protection, their durability is a key factor affecting their long-term performance. In some cases, the mechanical strength of the coating may degrade over time due to abrasion, weathering, or environmental exposure. Since many superhydrophobic coatings rely on nano/micro-structural roughness, they are often more resistant to physical damage that could expose the material underneath to corrosion. Since water beads up and rolls off, it cannot collect in crevices or gaps, which is a common starting point for crevice corrosion. This helps in maintaining the integrity of the metal in such regions. In addition to providing physical water-repellence effect, some superhydrophobic coatings may also have chemically protective properties. These coatings can be made from materials that resist oxidation and chemical degradation. Such materials not only repel water, but also offer chemical inertness, thereby preventing corrosion due to oxygen, acids, or bases. Some superhydrophobic coatings also enhance durability through crosslinking

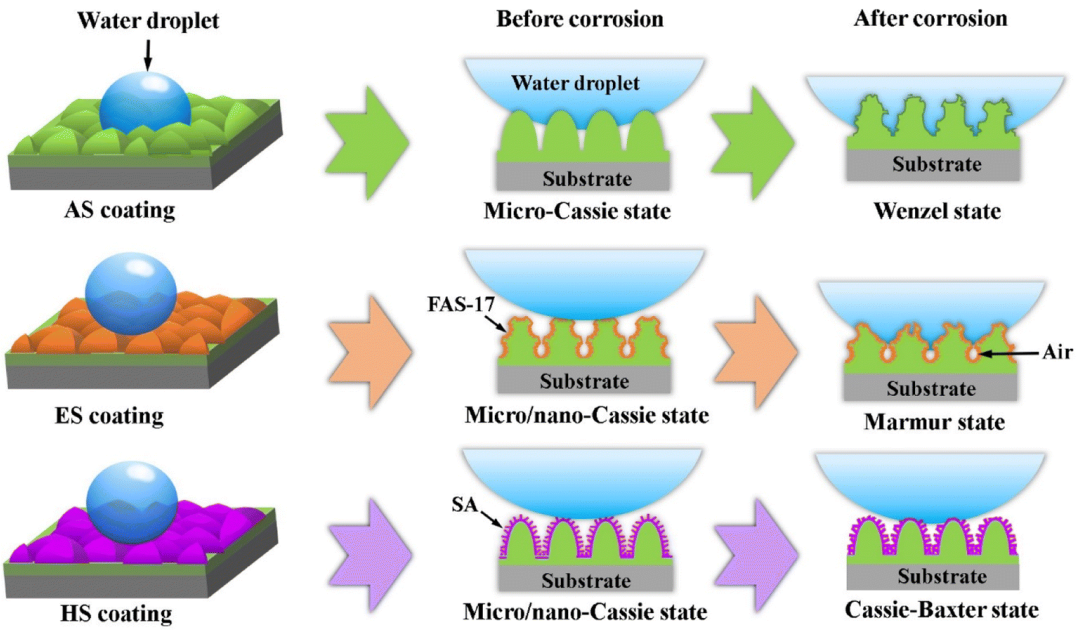


Figure 1. Mechanism of corrosion resistance with superhydrophobic coating. Durability and corrosion behaviours of superhydrophobic amorphous coatings: a contrastive investigation[10]. Reproduced from Ref[10], Copyright {2022}*RSC*.

or incorporating corrosion-resistant compounds into the material, making them more resistant to wear and environmental degradation.

4. Materials Used in Anti-corrosive Superhydrophobic Coatings

Anti-corrosive superhydrophobic coatings are made from a wide variety of materials that combine both hydrophobic properties (water-repellent) and corrosion resistance to provide durable protection against environmental factors such as moisture, salt, and air. These coatings typically feature nano- or micro-structured surfaces that help form a superhydrophobic layer, which effectively repels water and prevents corrosion.

4.1. Silicon-based Materials

Silicon-based materials are one of the most used types of materials in anti-corrosive superhydrophobic coatings. They are widely used to create rough, textured surfaces that enhance hydrophobicity. These nanoparticles form micro/nano-scale roughness on the substrate, increasing water contact angle and improving the corrosion resistance of the underlying material. Their ability to form highly effective hydrophobic surfaces and provide corrosion resistance makes them a popular choice in various applications. Kovac *et al.* developed superhydrophobic coatings for aluminium alloy 2024-T3 to protect the surface from corrosion and to improve its longevity using SiO_2 nanoparticles, synthesised *via* the Stober method and modified with Alkyl Silane (AS) or perfluoroalkylsilane (FAS).

4.2. Metal Oxide/Nanocomposite Based Materials

In order to enhance particle adhesion to the alloy substrate, nanoparticles were incorporated into a hybrid sol-gel coating composed of tetraethyl orthosilicate, methyl methacrylate, and 3-methacryloxypropyl trimethoxysilane[11]. These compounds self-assemble into a monolayer that bonds chemically with the surface, offering both water resistance and corrosion protection. Silane coatings offer excellent adhesion to metal substrates, protecting them from oxidative corrosion by forming a thin yet effective barrier layer. These are chemical compounds containing Silicon-Oxygen bonds (Si-O), often used in superhydrophobic coatings because of their stability and water-repellence effect. Huang *et al.* synthesized a self-curing, solvent-free, and recyclable polyester polyol polymer material combined with (5 and 6.5 μm) micro- and nanosized SiO_2 (μ-SiO_2

and n-SiO_2) particles to create superhydrophobic coatings with contact angles above 170° also. The electrochemical tests confirmed that the superhydrophobic coatings possess robust corrosion resistance, making them suitable for use in marine environments and other applications[12]. Zhang *et al.* have used fluorine-modified SiC (F-SiC) nanoparticles were added to the Epoxy resin (EP) matrix to develop anti-corrosive superhydrophobic coatings[13]. Because of their exceptional resistance to chemical and water degradation, fluorinated siloxane compounds aid in preventing the development of rust and other corrosion products on metal surfaces.

4.3. Polymer Based Materials

Huang *et al.* produced an anti-corrosive superhydrophobic coating using natural rubber, nano-silicon dioxide sol modified by a silane coupling agent, nanoscale titania, and SBS resin (a Styrene-Butadiene-Styrene triblock copolymer). Even after ten days of immersion in saline solution (3.5% NaCl), the coating retains its super-hydrophobic qualities[14]. This flexibility lowers the coating's chance of peeling or breaking over time by assisting it in maintaining its integrity under a variety of circumstances. Leon *et al.* demonstrated for the first time the use of electrodeposited superhydrophobic conducting polythiophene coating to effectively protect the underlying steel substrate from corrosion attack which was immersed in chloride solution of different pH and temperature for up to 7 days, is very well protected from corrosion evidenced by protection efficiency of greater than 95%[15]. Chen *et al.* synthesized bilayer Polyethylene Glycol Diacrylate (PEGDA)-co-EGDA *via* a single-step vapour deposition method. By reducing the diffusion of water and ions as well as oxygen permeation, the bilayer coating structure has a synergistic effect that significantly lowers the corrosion rate to 2.19×10^{-7} mm $year^{-1}$, which is more than 104 times lower than that of bare copper[16]. Because of their adaptability, simplicity of usage, and potent corrosion protection, polymer-based superhydrophobic coatings are frequently employed in a variety of sectors.

4.4. Hybrid Coatings

Hybrid coatings that combine metal oxides and polymer/silane have become a viable option because they effectively prevent corrosion by utilising the benefits of polymer-mixed metal oxides. Zinc-enriched superhydrophobic composite anti-corrosive coating layer provides improved corrosion protection, is economical to manufacture, and has a wide range of uses in various industries[17]. The superhydrophobic component of zinc-rich coatings keeps moisture out while the sacrificial layer corrodes in place of the metal substrate to prevent oxidation. ZnO can improve the coating's ability to withstand corrosion and water while maintaining its self-healing qualities. By using the electrodeposition approach, Benea *et al.* developed Zn/nano-TiO_2 composite coatings on low-carbon steel with different concentrations of TiO_2 nanoparticles (diameter size of 10 nm). In comparison to pure zinc coatings produced under comparable circumstances, the incorporation of TiO_2 nanoparticles into the zinc matrix results in an enhanced corrosion resistance[18]. Superhydrophobic coatings may incorporate carbon-based nanomaterials, such as graphene and Carbon Nanotubes (CNTs), to increase corrosion resistance and mechanical qualities. Li *et al.* successfully created a novel kind of anti-corrosive and electrically conductive composite coating filled with GO/CNT/PANI nanocomposites. It has a greater electrochemical impedance of $3.84 \times 106\ \Omega \cdot cm^3$ and a lower corrosion current density of $4.53 \times 10^{-8}\ A \cdot cm^{-2}$ [19].

5. Fabrication Methods of Superhydrophobic Anti-corrosive Coatings

Either the "top-down" method, which involves placing the micro-nano structure on the hydrophobic material surface, or the "bottom-up" method, which involves grading the micro-nano structure surface using low surface energy, can be used to create a superhydrophobic surface. The surface design and coating composition, affect the coating's hydrophobicity and anti-corrosion efficacy throughout the electrochemical deposition process. The bath composition, electrodeposition duration, and current density are the three essential elements. Many electrodeposition methods, such as pulse, jet, magnetic field-induced, and ultrasound-assisted electrodeposition, are used to produce superhydrophobic coatings. Tang *et al.* employed a simple one-step electrodeposition procedure to create the superhydrophobic Cu/Mn coatings on steel substrates. With this method, copper

and manganese can be deposited onto the substrate simultaneously, producing a coating with the required qualities[20]. Another popular method is Chemical Vapour Deposition (CVD), which involves introducing precursor gases into a vacuum chamber. These gases react on the substrate's surface to deposit a thin, hydrophobic layer. Zhang *et al.* created a simple CVD technique for creating a superhydrophobic coating on aluminium alloy. Cerium oxide hydrothermal deposition made it simple to achieve the rough surface structure[21]. Guo *et al.* used a straightforward spraying technique to create a strong anti-corrosive superhydrophobic coating made of Polyphenylene Sulphide (PPS), Polyvinylidene Difluoride (PVDF), and modified titanium dioxide (SA-TiO_2) with a water contact angle of over 140° following 1000 Taber friction tests and a corrosion protection duration of up to 200 hours in a neutral salt spray test using 3.5% NaCl, the produced coatings exhibit exceptional mechanical stability[22]. Wu *et al.* adopted a one-step dipping technique to produce a composite coating of PTFE and aluminium phosphate, which increased endurance against corrosive conditions and produced a water contact angle of 155.7°[23]. A straightforward technique for roughening the surface of materials like metals, polymers, or ceramics is etching, chemical or plasma-based. By etching nickel surfaces in a neutral electrolyte with a controlled wire cathode, this technique improves processing efficiency and achieves a contact angle of 153° with notable corrosion protection[24]. Depending on variables like material type, desired coating qualities, and scalability, each of these fabrication techniques has unique benefits. As shown in Fig. 2, superhydrophobicity and corrosion resistance are achieved by combining low surface energy agents (often fluorinated chemicals) with surface roughness[25]. These coatings are becoming more and more significant in fields including construction, automotive, aerospace, and marine where surface protection is essential.

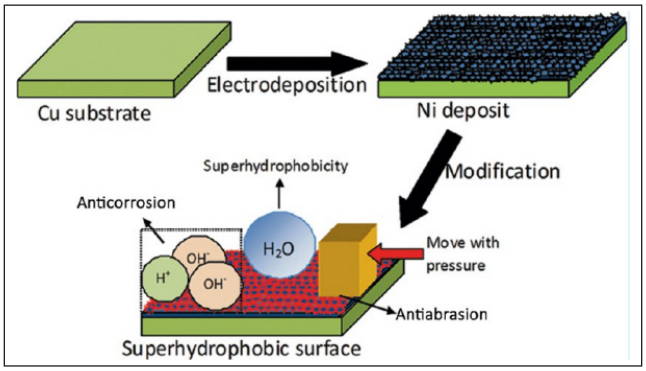


Figure 2. Anti-corrosive superhydrophobic coating fabricated with electrode position method illustrating electrode position of a layer of nickel onto a copper substrate superhydrophobic surface. The resultant surface exhibits exceptional anticorrosion and anti-abrasion performance by successfully repelling water and corrosive ions[25].
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6. Performance Evaluation

6.1. Contact Angle Measurement

For anti-corrosive superhydrophobic coatings to be successful and long-lasting in real-world applications, performance evaluation is crucial. Water contact angle measurement is the most straightforward way to evaluate water repellence characteristics. The measurement of Water Contact Angles (WCA), a commonly used technique for describing hydrophilic and hydrophobic surfaces, is frequently used to evaluate surface wettability. Usually, a 1 µL or 5 µL water droplet is placed on the surface of a contact angle goniometer to measure the contact angle. Variations in WCA measurements might happen due to the variations in topography and chemical composition. Even though this evaluates the water-repelling properties, it can also be used to monitor the stability of the coating over time[26]. A coating that maintains a high contact angle even after prolonged exposure to various conditions is considered more durable. The measurement of the sliding angle is an additional crucial evaluation technique in addition to the contact angle. This test gauges how easily water droplets can be removed from the surface, which is a crucial sign of the coating's capacity for self-cleaning. A water droplet is placed on the surface, and the substrate is gradually tilted until the droplet starts to slide off in order to calculate the sliding angle, also known as the roll off angle. It is preferred for superhydrophobic surfaces to have a low sliding angle (less than 10°). In addition to being rejected, this guarantees that water droplets will roll off the surface with ease, carrying dirt and debris with them.

6.2. Salt Spray Testing

The corrosion resistance of anti-corrosive superhydrophobic coatings is crucial because they are frequently utilized in severe settings. A controlled saline mist atmosphere is used in salt spray testing, an

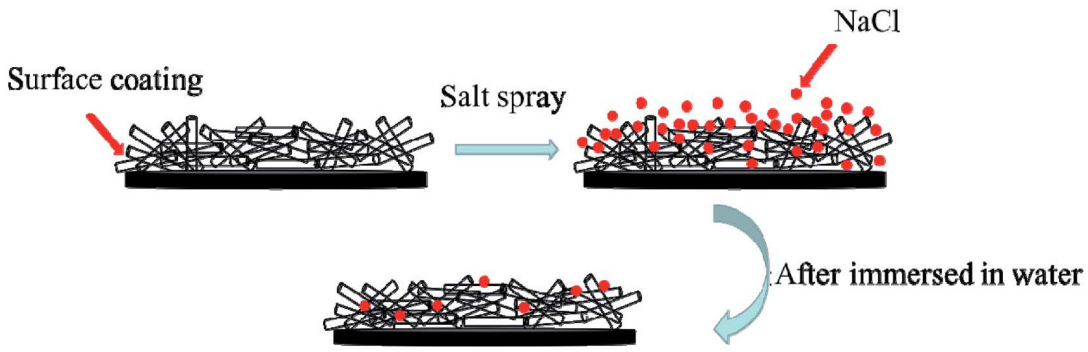


Figure 3. Mechanism of corrosion inhibition property and restorability of surface after salt spray test[29]. Reprinted with permission from Ref[29] Copyright {2017} *RSC*.

accelerated corrosion test, to evaluate the corrosion resistance of metals and protective coatings[27]. A 5% Sodium chloride (NaCl) solution sprayed as a fine mist is continually applied to specimens in a sealed chamber at approximately 35°C. The test is usually carried out in accordance with standards such as ASTM B117 or ISO 9227. The test length might vary from 24 to more than 1000 hours, contingent on the necessary performance standards, and the pH of the solution is kept close to neutral (6.5-7.2). Specimens are examined for corrosion symptoms like rust, blistering, or coating deterioration following testing[28]. By using mesoporous material (SBA-15), imidazole, and bisphenol A-aniline benzoxazine (BA-a), which has a low surface energy, Wang *et al.* were able to create a super-hydrophobic surface through spray coating, providing unique density gradient structure, organic-inorganic interpenetrating networks, and self-similar structures. The specified materials can prevent corrosion on the glass surface and prevent other materials from coming into contact with it. NaCl can adhere to the micro-nano surface following a salt spray, changing the surface's overall characteristics from superhydrophobic to hydrophilic. As depicted in Fig. 3, after being submerged in water, the micro-nano surface's shape remained unchanged due to the coated surface's exceptional wear resistance[29]. Although salt spray testing is frequently employed for quality assurance and evaluating corrosion prevention techniques, it is not a reliable way to simulate natural environmental conditions and should not be used independently to forecast long-term service performance.

6.3. Potentiodynamic Polarization Tests

By monitoring the current response to a linearly changed applied potential, the potentiodynamic polarization test is an electrochemical method used to assess the corrosion properties of metals. The test involves submerging the metal sample (working electrode) in a corrosive electrolyte and performing a controlled potential scan, usually beginning anodically and sweeping a few hundred millivolts below the Open Circuit Potential (OCP). Tafel extrapolation can be used to obtain significant characteristics from the resulting polarization curve, including the corrosion potential and corrosion current density[30]. The Tafel formula, which is given by $\eta = a + b \log (i)$ where, a is a constant, η is the over potential, b is the Tafel slope, and i is the current density, describing the relationship between current and potential in the activation-controlled region. Corrosion efficiency of the superhydrophobic coating is given by,

$$\eta = \left(1 - \frac{I_{SS}}{I_{BS}}\right) \times 100$$

I_{SS} and I_{BS} corrosion current density of the superhydrophobic coated surface. The electrochemical results exhibiting a high Z modulus at low frequency and low corrosion current density, it can prevent the copper substrate from corroding and shows excellent superhydrophobic anticorrosive property as shown in Fig. 4c.

7. Electrochemical Impedance Spectroscopy (EIS)

Other electrochemical techniques, such as Electrochemical Impedance Spectroscopy (EIS) can also be employed to evaluate the coating's ability to protect the substrate from corrosion by measuring resistance

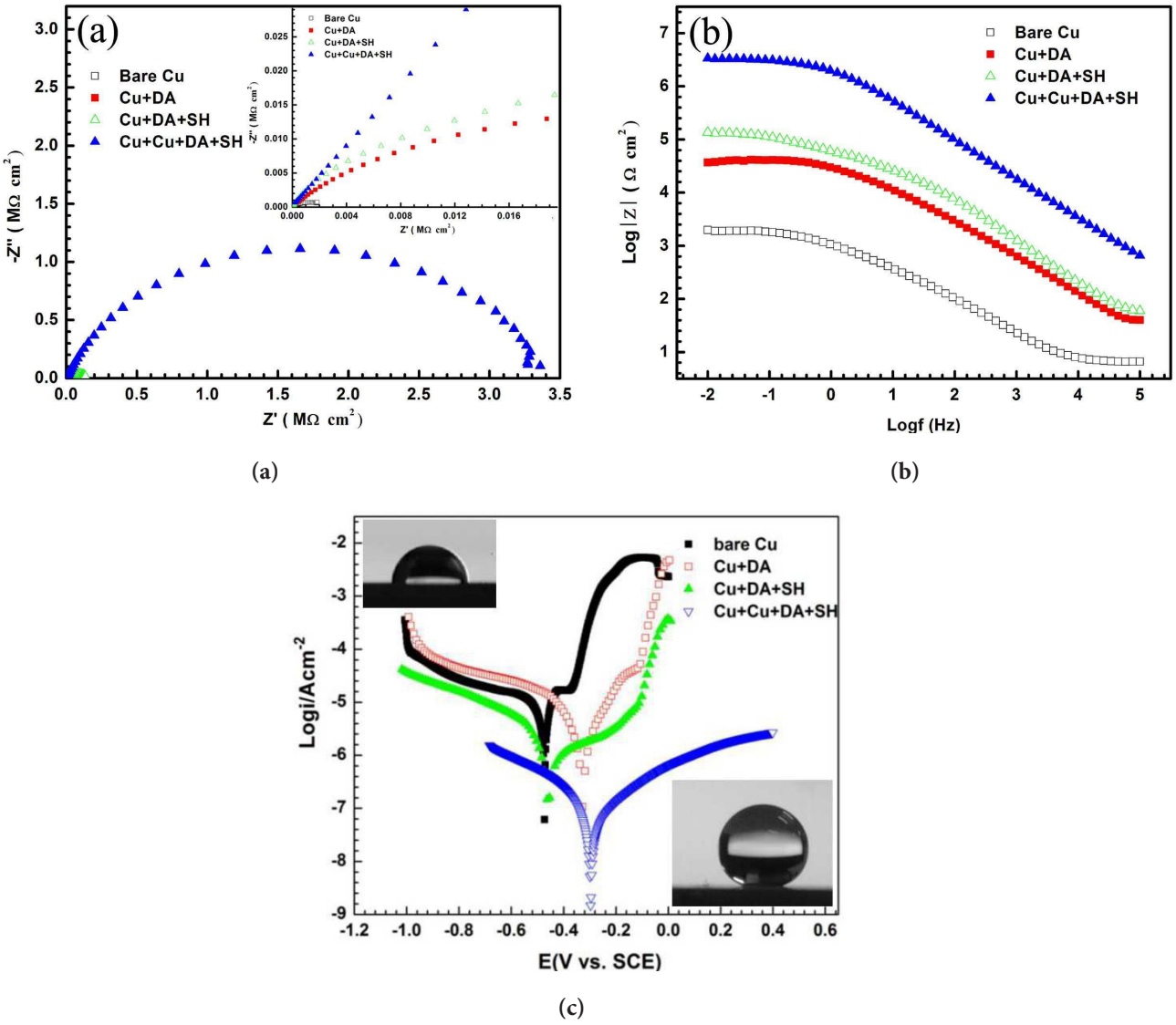


Figure 4. **(a)** Nyquist plot **(b)** Bode plots showing the super-hydrophobic film has good corrosion resistance in 3.5 wt% NaCl solution **(c)** Potentiodynamic polarization curves for various copper surfaces in an aqueous solution containing 3.5 wt%[32]. Reprinted with permission from Ref[32] Copyright {2017} *RSC.*

to electrical currents or corrosion potential. In order to extract fundamental electrochemical parameters like charge transfer resistance and double-layer capacitance, the Nyquist plot displays the complex impedance with the real component on the x-axis and the negative imaginary component on the y-axis. Understanding the frequency-dependent electrochemical activity and temporal constants of the sensor system is possible through the Bode plot, which shows the phase angle and impedance magnitude as a function of frequency. EIS sheds light on the integrity of the protective layer and its barrier qualities in corrosive conditions. Because they demonstrate the coating's capacity to prevent electrolyte penetration and lessen ionic transport, high impedance values especially at low frequencies generally signify exceptional corrosion resistance. The development of a persistent, non-conductive coating that restricts electrochemical reactions at the substrate contact is further suggested by the existence of capacitive behaviour in the EIS spectrum. A thorough grasp of the protective performance of the coating can be obtained by quantifying important factors such as coating resistance, pore resistance, and charge

transfer resistance by modelling the impedance data using analogous electrical circuits[31]. A straightforward electrodeposition technique was used to create micro and nano rough cube copper crystals on a smooth copper substrate. On a modified rough copper surface, 1-dodecanethiol/polydopamine multilayer films self-assembled layer by layer. Modified multilayer films had surface contact angles that were stable in air and could reach a maximum of roughly 154°. The results of electrochemical impedance spectroscopy demonstrated that the modified functional surface had corrosion resistance ability, and excellent corrosion resistance and chemical stability of super-hydrophobic coatings[32].

8. Applications of Superhydrophobic Anti-corrosive Coatings

The marine industry, where metal constructions like ships, oil rigs, and underwater pipelines are continuously exposed to hostile saltwater environments, benefits greatly from anti-corrosive superhydrophobic coatings. Because saltwater is so corrosive, steel and metal deteriorate more quickly. Superhydrophobic coatings minimize corrosion by acting as a barrier that keeps water from coming into direct contact with the surface and self-cleaning qualities also aid in preventing the build up of marine life, such as barnacles and algae, which can worsen corrosion and drag. This increases the overall effectiveness of marine operations and lowers the need for maintenance. Anti-corrosive superhydrophobic coatings are used on vital parts such as engine parts, wings, and aircraft bodies in the aerospace industry. These coatings aid in shielding materials from the damaging elementssuch as moisture, ice, and chemicals that are present during flight and lower the risk of corrosion by forming a hydrophobic surface that stops water and other corrosive chemicals from adhering to the metal. Superhydrophobic coatings are used in infrastructure and construction to shield steel, concrete, and other materials from environmental stresses including pollution, rain, and humidity. These structures can withstand the effects of weathering and corrosion and retain their integrity over time by adding anti-corrosive superhydrophobic coatings. Anti-corrosive superhydrophobic coatings are used in the electronics sector to prevent corrosion and water damage to circuit boards and other delicate components. Similarly, these coatings are used on drilling equipment, pipes, and valves in the oil and gas sector that are subjected to moisture, high temperatures, and harsh chemicals. In harsh conditions, the superhydrophobic qualities not only prevent corrosion, but also lessen the accumulation of muck and impurities, guaranteeing smoother performance and lowering the frequency of cleaning and maintenance.

9. Limitations and Challenges

As corrosion usually occurs internally and is invisible, diagnosis can be challenging. Electrical approaches (*e.g.*, resistivity tomography, half-cell potential), optical, acoustic, and X-ray methods, as well as real-time

Table 1. Superhydrophobic coatings for corrosion prevention: a comparative study of their components, techniques, and electrochemical performance

Author	Material Used	Fabrication Method	Anti corrosive Efficiency	CA(°)	Ref
Gong *et al.*	Fluorinated polyurethane SiO_2 nanoparticles	Spray coating	Corrosion Potential= 0.54 V Corrosion Current Density= 5.26×10^{-8} A cm^{-2}	161.35°	33
Heidari *et al.*	Fe_2O_3 and Fe $(CH_3(CH_2)_{12}$-COO)	Electrodeposition	Corrosion Potential$_=$ 87.8mV	160^0	34
Daneshnia *et al.*	nickel and nickel myristate	Electrodeposition	Charge transfer resistance (2370 kΩ·cm^2) at 37V	171.3°	35
Vilaro *et al.*	1H, 1H, 2H, 2H-perfluorodecyl acrylate ethylene glycol diacrylate	Solventless CVD Method	Corrosion rate decreased to 0.077 μm/year	163°	36

and unmanned monitoring platforms, are examples of advancements in monitoring. It is still difficult to accurately forecast when corrosion would start and spread, particularly in complicated settings and heterogeneous materials. Advanced modelling and numerical simulations are being developed, but they still need to be improved. The creation of universal solutions is complicated by the variety of materials (such as silicon, steel, and aluminium) and exposure conditions[37]. Moreover, the structural integrity of the superhydrophobic surface is also one of the most important features for accomplishing durability for a long period of time.

1. The majority of superhydrophobic coatings are mechanically delicate and readily destroyed under impact or abrasion.
2. Performance of the coating can gradually deteriorate due to prolonged UV exposure, severe temperatures, and chemical attacks.
3. Harmful solvents and toxic chemicals can raise environmental and health concerns.
4. Scalable and economically feasible coatings remain a major challenge.

10. Conclusion and Future Directions

In conclusion, the superhydrophobic coatings under evaluation show great promise for preventing corrosion owing to their hierarchical architectures and tailored surface chemistry. Electrodeposited metal-organic composites and fluorinated polymers reinforced with nanoparticles are excellent choices for industrial use considering their high durability and resistance to corrosion. Because of their consistency, convenience of use, and scalability for large-area substrates, scalable methods like as solventless CVD and spray coating stand out as the most promising among them. Across many industries, corrosion is still a complicated, expensive, and enduring issue. Understanding various corrosion mechanisms, enhancing detection and monitoring, and creating long-lasting, successful prevention techniques are some of the main challenges. To overcome these barriers and guarantee the robustness and security of machinery and infrastructure, developments in materials science, monitoring technologies, and predictive modelling are essential. In many industries, the longevity and functionality of infrastructure, machinery, and gadgets depend on the efficient management of corrosion, whether by coatings, material selection, cathodic protection, or environmental control. In a nutshell, the combination of superhydrophobicity and corrosion prevention is a major breakthrough in material research. By forming a barrier that repels water and impurities, superhydrophobic coatings not only offer an efficient means to mitigate corrosion but also increase material longevity and improve economical standards. Superhydrophobic coatings are anticipated to become increasingly significant in the research and development in this area progresses, providing sustainable solutions for industries all over the world. Because of their remarkable capacity to eliminate water and reduce the contact between corrosive elements and metal surfaces, superhydrophobic coatings have become extremely efficient anti-corrosive agents. These coatings greatly inhibit the onset of corrosion and increase the longevity of materials in challenging conditions by forming a barrier that reduces moisture adhesion and ion transport. They are a potential option for a range of industrial and maritime applications because to their multipurpose qualities, like durability, chemical resistance, and self-cleaning. Researchers are developing mitigating measures to solve durability difficulties, such as employing multilayered or hierarchical designs, adding resilient nanomaterials (like graphene or silica), and creating self-healing systems that regain functionality after damage. Furthermore, surface binders, hybrid organic-inorganic coatings, and UV-resistant polymers can improve mechanical and environmental stability. These tactics intend to increase the coating's longevity and make it more practically and economically viable for crucial applications in the infrastructure, aerospace, and marine industries. In order to ensure widespread use of superhydrophobic coatings in corrosion prevention measures, more research and development is necessary to improve their mechanical robustness and scalability. Intelligent monitoring systems and smart nanomaterial coatings are still being developed. To improve diagnosis and prediction, more data must be gathered and combined with data from computational or experimental methods.

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