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REVIEWARTICLE – MATERIAL SCIENCE (MISCELLANEOUS)

Multifunctional Superhydrophobic Coatings for Aluminum and Magnesium Alloys: Applications and Performance - Review

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Abstract

The manufacturing of aerospace, automotive, and defense systems depends on aluminum and magnesium alloys because they provide low density, a high strength-to-weight ratio, and easy machining capabilities, which result in better fuel efficiency, increased payload capacity, and enhanced maneuverability in aerospace and ground-based military platforms. Despite these advantages, both alloys suffer from poor corrosion and wear resistance, which restricts their use in harsh environments and poses risks to the performance and reliability of military systems. Surface modification technologies provide immediate solutions to these problems through superhydrophobic coatings emerging as a promising approach. The coatings deliver water repellency while simultaneously improving self-cleaning capabilities, antifouling properties, drag reduction, anti-icing features, corrosion protection, and wear resistance. Recent studies have made substantial advancements in designing and manufacturing superhydrophobic surfaces. The current methods for preparing superhydrophobic surfaces require complicated procedures, expensive equipment, and strict processing conditions, which create challenges for industrial-scale implementation. This review presents two representative studies for aluminum and two for magnesium alloys, with emphasis on preparation methods, surface morphology, and performance outcomes. The aim is to clarify the strengths and limitations of these coatings and support their development in practical applications that require durability, corrosion resistance, and multifunctionality. It compares their performance across different substrates while considering their effectiveness for corrosion resistance, anti-bacterial, anti-icing, and friction resistance with self-cleaning performance.

Publisher: Middle Technical University

Keywords: Aluminum/Magnesium Alloys; Superhydrophobic Surface; Corrosion Resistance; Wear Resistance.

1. Introduction

The aerospace, automotive, and defense industries rely on aluminum and magnesium alloys because these materials offer low density, a high strength-to-weight ratio, and excellent machinability [1-5]. The alloys demonstrate suitable performance for weight-sensitive applications because their properties decrease system weight and boost energy efficiency. The alloys face restrictions in use because they lack sufficient protection against corrosion and mechanical wear when exposed to harsh environments. Magnesium shows strong chemical reactivity that causes it to corrode swiftly when exposed to humid or chloride-rich environments. The natural oxide layer protects aluminum from corrosion but the metal develops pitting and crevice attack in marine or industrial environments. Additionally, repeated surface contact between the alloys leads to low resistance to both adhesive and abrasive wear. This reduces functionality, increases maintenance requirements, and shortens service life [6, 7], (Fig. 1).

Nomenclature & Symbols			
SHP	Superhydrophobic	CA	Contact Angle (°).
Mg	Magnesium	SA	Sliding Angle (°).
AA	Aluminum Alloy	wt.%	Weight Percent
WCA	Water Contact Angle (°).	i_{corr}	Corrosion Current Density (A/cm^2).

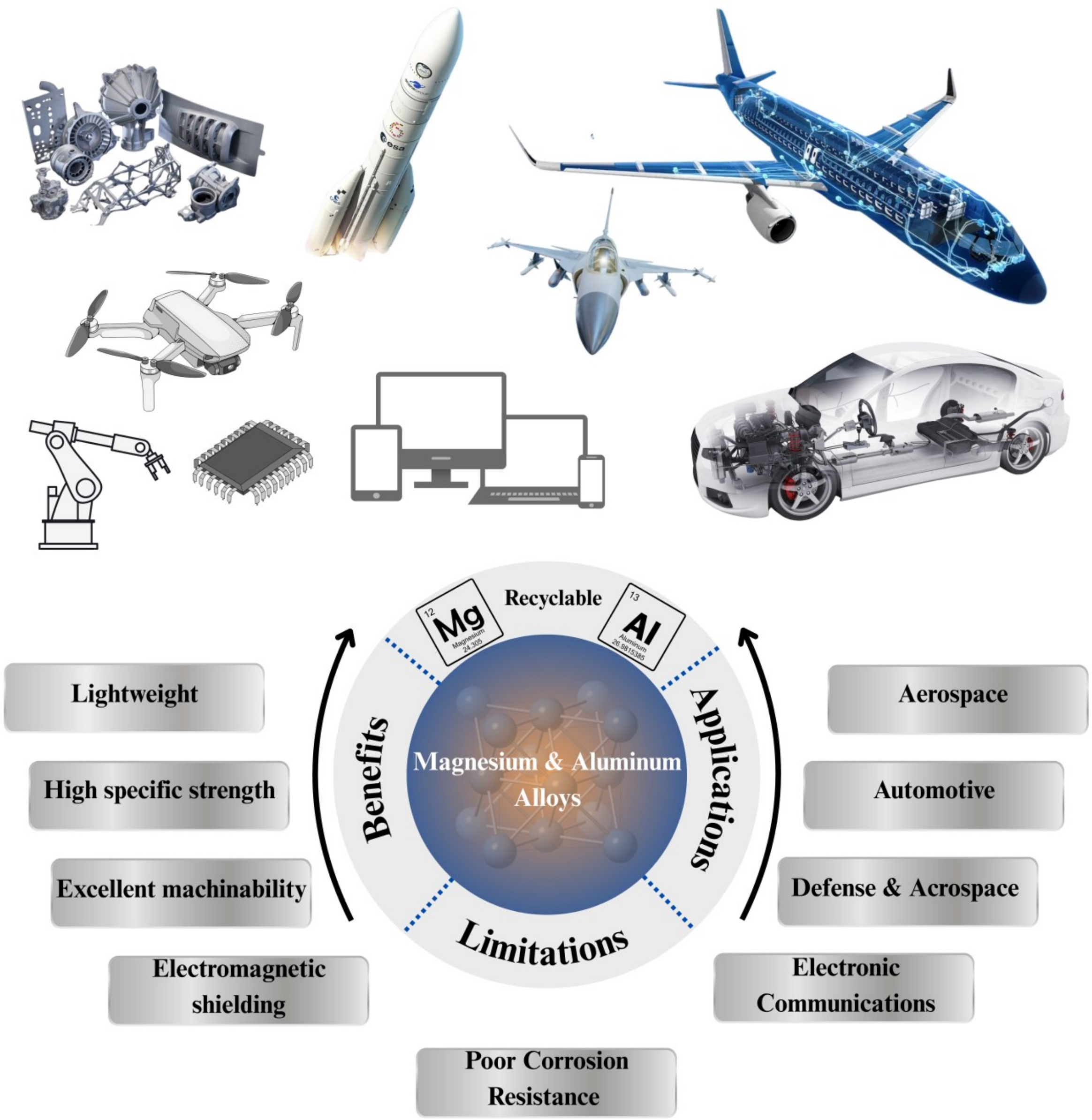

Fig. 1. Key benefits, limitations, and applications of aluminum and magnesium alloys [6, 7]

Multiple surface modification techniques exist to address these limitations through chemical methods such as anodizing [8, 9], micro-arc oxidation [10-13], metallic or organic coatings [14-17], physical methods including vapor phase deposition [18, 19], and laser surface treatment [18, 20]. These methods enhance corrosion and wear resistancebut their effectiveness varies, and they typically come with high costs, complex procedures, and environmental concerns. The industrial implementation of these methods faces challenges because they need hazardous chemicals, specialized equipment, and high energy consumption, which restricts their scalability and sustainability.

Multifunctional superhydrophobic coatings have received growing attention because of their potential applications. The development of these coatings stems from observing natural surfaces like lotus leaves that show both self-cleaning capabilities and water-repellency characteristics [21, 22] (Fig. 2). Superhydrophobic artificial surfaces display water contact angles exceeding 150° while showing sliding angles less than 10° which enables water droplets to roll off effortlessly while removing surface contaminants [23, 24]. Over the last two decades, researchers have worked to create these surfaces both for natural mimicry and functional enhancement which includes self-cleaning capabilities [25-29], anti-icing functionality [30-33], friction reduction and wear resistance improvements [34-37], oil-water separation [38-40], and antibacterial features [41, 42], (Fig. 3).

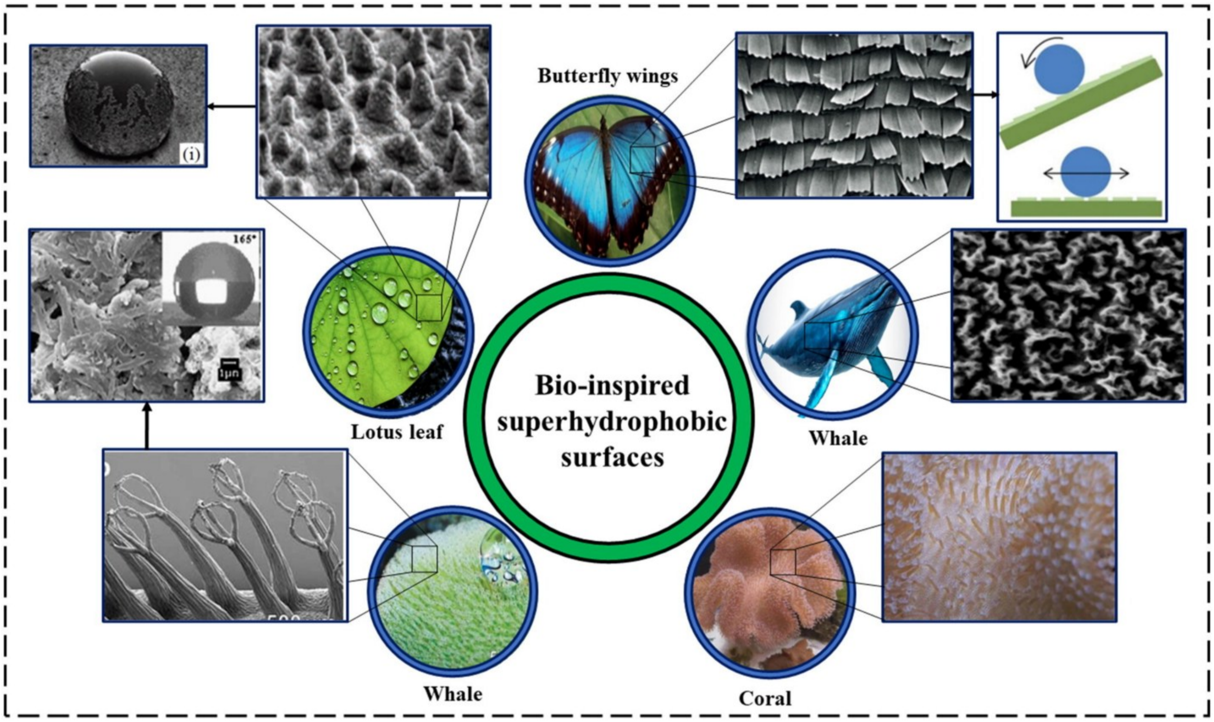

Fig. 2. Superhydrophobic property found in nature [21, 22]

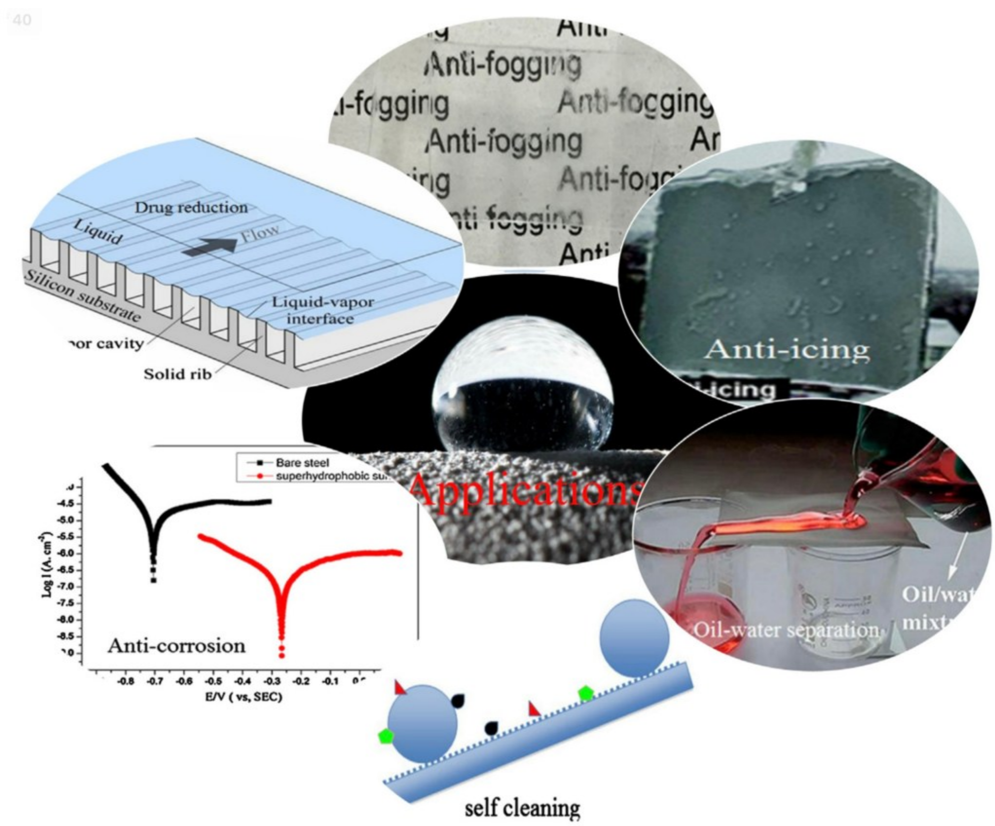

Fig. 3. Schematic of important applications of superhydrophobic surfaces [41, 42]

The structural elements of natural biological surfaces develop specific features to solve environmental problems such as corrosion protection and self-cleaning requirements[43]. These functional properties are duplicated through a combination of surface roughness with low surface energy [44]. The contact angle (CA) is a key parameter used to evaluate how a liquid interacts with a solid surface. It reflects the degree of wettability and helps classify surfaces as hydrophilic or hydrophobic. The contact angle is measured using Young's equation, which describes the balance of surface tensions at the solid-liquid-vapor interface [45]. The two primary models used to study the wetting effects of surface roughness are the Wenzel and Cassie-Baxter models [45]. Wenzel's model shows how increased surface roughness leads to higher hydrophobicity or hydrophilicity through an increased surface area [45]. In contrast, the Cassie-Baxter model explains how liquid air pockets underneath reduce solid–liquid contact and produce better water repellency [45] (Fig. 4). The dynamic wetting behavior includes contact angle hysteresis, which measures the difference between advancing and receding contact angles, along with the roll angle, which defines the minimum tilt angle needed for droplet movement, and wetted contact area, where smaller areas indicate easier droplet mobility [46, 47]. The efficiency of droplet shedding depends on the roll angle so applications require minimal roll angles for effective droplet removal.

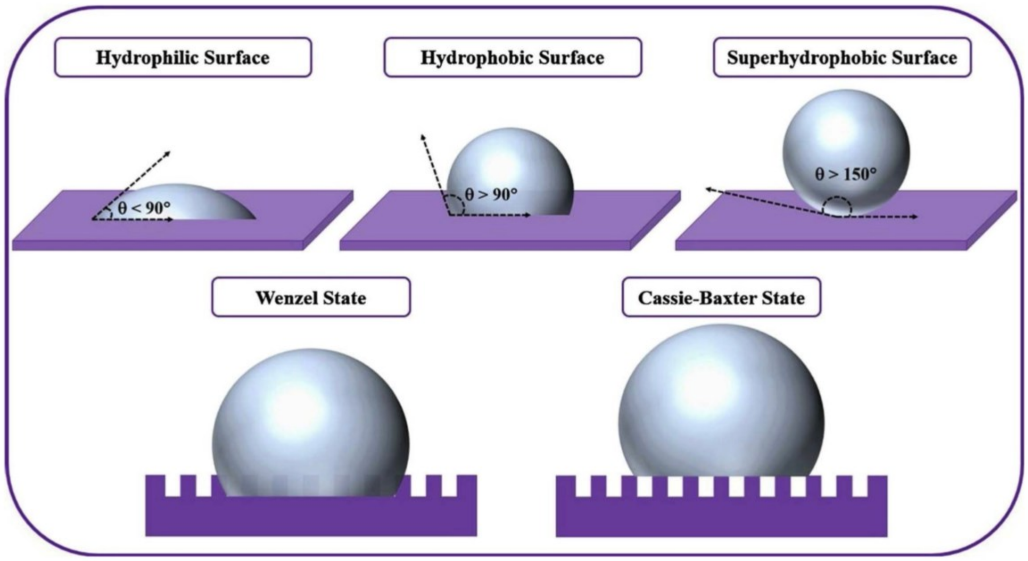

Fig. 4. Representation of water droplet on hydrophilic surface, hydrophobic surface, superhydrophobic surface, water droplet in Wenzel state and water droplet in Cassie-Baxter state, respectively [45]

These principles guide the design of superhydrophobic coatings that protect aluminum and magnesium alloys from corrosion and wear. The interaction between each coating and alloy depends on electrochemical properties and oxide layer stability, which influence overall performance. Applying such coatings improves the durability and reliability of these metals under harsh environmental conditions. Aluminum forms a passive and stable oxide layer that offers moderate protection. In contrast, magnesium develops unstable oxides, making it more vulnerable to corrosion [48-50]. These differences, along with each alloy's microstructural characteristics, affect how effective the coatings are. Developing optimal coating strategies requires understanding the unique surface chemistry and behavior of each alloy.

This review focuses on the development and application of multifunctional superhydrophobic coatings on aluminum and magnesium alloys. It highlights their functional properties, including corrosion resistance, wear resistance, oil–water separation, and self-cleaning. The review also compares coating behavior across different substrates. Each property is discussed with reference to relevant studies to demonstrate coating effectiveness. Current limitations and future research directions are outlined to improve durability and enable large-scale industrial use.

2. Superhydrophobic Functional Surfaces

]By mimicking natural surfaces like lotus leaves (self-cleaning), mosquito eyes (anti-fog), desert beetle elytra (water collection), and pitcher plant rims (liquid manipulation), researchers have successfully prepared various superhydrophobic surfaces with excellent functions such as anti-corrosion, anti-icing, friction-wear, oil-water separation, and antibacterial properties. The surfaces have been applied to different materials, including polymers, fabrics, glass, and metals. Among these metals, aluminum and magnesium alloys have been gaining more attention because of their use in lightweight and high-performance applications.

2.1. Anti-corrosion

The use of magnesium and aluminum alloys in various industries faces significant lifespan reduction and performance degradation because of corrosion. The metals experience fast degradation because they show high chemical reactivity. The application of superhydrophobic coatings on these alloys creates protective barriers which effectively repel water and corrosive agents. Surface treatments, such as plasma electrolytic oxidation, micro-arc oxidation, chemical etching, and other methods. When combined with superhydrophobic coatings, they improve corrosion resistance. This results in longer service life and lower maintenance costs in harsh operating environments. [49-54], (Table 1).

Joo J et al. [55] conducted research which demonstrated how multiple surface treatment steps improve magnesium alloy corrosion resistance. The first step involved plasma electrolytic oxidation (PEO) to generate an oxide layer which was followed by hydrothermal treatment to produce nanoporous magnesium hydroxide structures. The surface received a perfluorodecyltrichlorosilane (FDTS) self-assembled monolayer to achieve superhydrophobic properties. The protection was enhanced by adding immiscible oil to the nanoporous oxide layer. The combination resulted in a maximum water contact angle of 172.8° and a sliding angle of less than 2.4° which confirmed excellent water repellency. The corrosion current density decreased dramatically from 4.23×10^{-6} A/cm² to 2.74×10^{-10} A/cm² which demonstrated more than a two-order magnitude decrease compared to the untreated surface. The oil-impregnated layer functioned as an extra protective barrier which blocked corrosive liquids from entering and resulted in better long-term durability than surfaces treated with either hydrophobic or superhydrophobic coatings alone. The results show that integrating hydrothermal treatment with FDTS surface modification and oil impregnation produces a robust and durable superhydrophobic coating. The protection method delivers exceptional corrosion resistance which makes it appropriate for safeguarding magnesium alloys in harsh environmental conditions, as shown in Fig. 5, which explains the preparation process with the most important results.

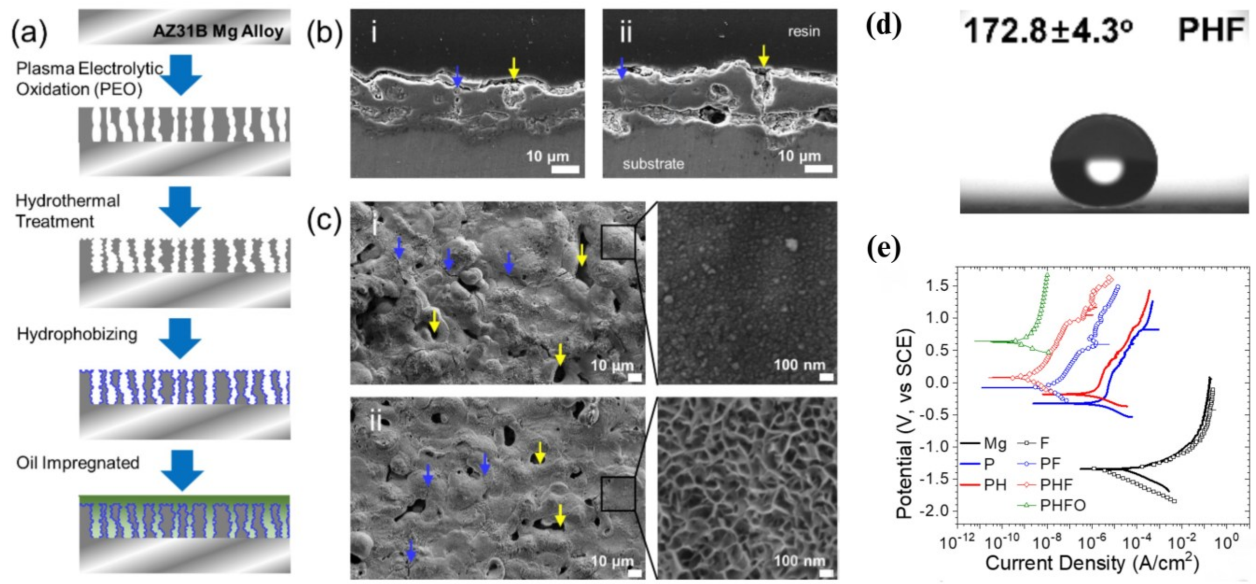

Fig. 5. Fabrication of porous oxide layer on Mg alloy; (a) Schematic representation of the preparation procedure based on plasma electrolytic oxidation (PEO) and hydrothermal treatment of Mg alloy AZ31B, (b-c) Cross-sectional and surface SEM images of the porous oxide layer by PEO, (d) Contact angle (CA), (e) Potentiodynamic polarization curves, Reprinted with permission from Ref. [55], Copyright

Jiang D et al. [56] used micro-arc oxidation (MAO) technology to prepare a superhydrophobic surface. In the MAO process, the magnesium alloy substrate was used as the anode and the stainless steel was used as the cathode. The MAO samples were prepared by placing them in an alkaline silicate solution containing 15 g/L Na_2SiO_3 and 10 g/L NaOH. The samples were immersed in 20 mL of phytic acid solution (0.01 mol/L) for 60 s, and then the MAO samples were immersed in 20 mL of $Ce(NO_3)_3$ The magnesium alloy samples were immersed in a 1wt.% stearic acid ethanol solution for 1h and then heated at 80℃. After keeping the temperature in the oven for 2 hours, this process resulted in a superhydrophobic surface with a water contact angle of 159°, formed by constructing a micro-nano hierarchical structure after three assembly cycles. The electrochemical tests showed that the corrosion current density was reduced from 2.1×10^{-5} A/cm² to 3.5×10^{-8} A/cm² in 3.5 wt.% NaCl solution, indicating an improvement in corrosion resistance by three orders of magnitude. The MAO-$(PA@Ce)_3$-FAS coated sample maintained a low corrosion current of 4.8×10^{-8} A/cm² after 72 hours of immersion whereas the uncoated magnesium alloy showed a corrosion current of 2.8×10^{-4} A/cm². The results confirmed The MAO pre-treatment process protected the surface from cracking due to hydrogen evolution and the cyclic assembly process fixed the pores in the MAO layer. The integrated method created durable corrosion-resistant superhydrophobic coatings on magnesium alloys through a reliable process, as shown in Fig. 6, which explains the preparation process along with the most important results.

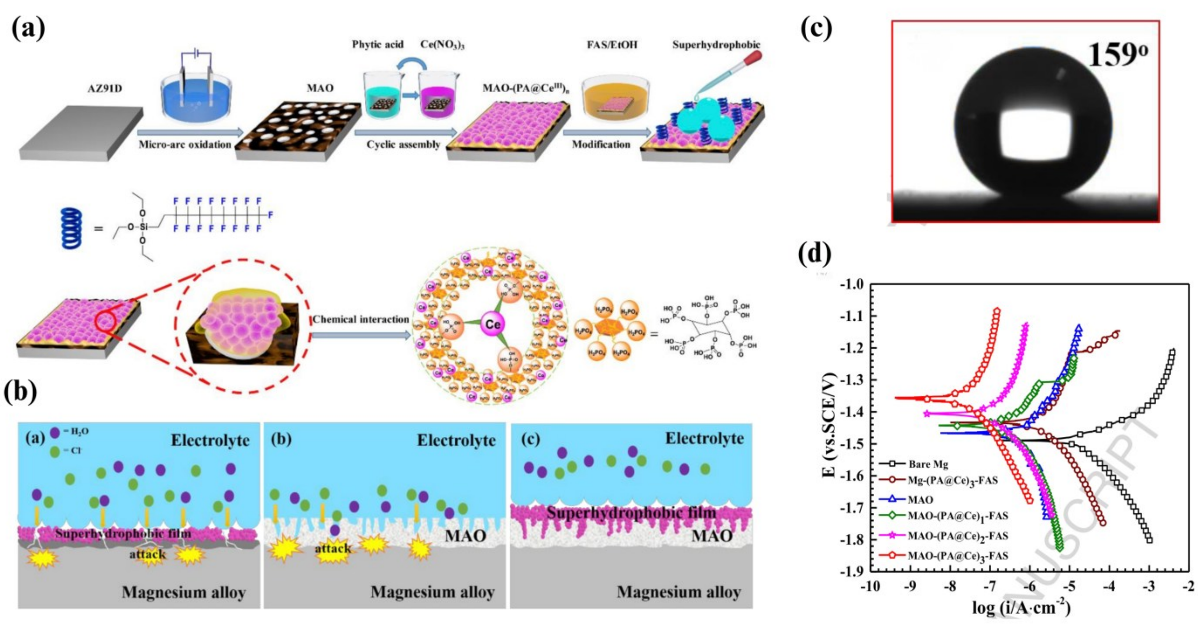

Fig. 6. (a) Schematic preparation of superhydrophobic coating, (b) Contact angle (CA), (b) Polarization curves of the samples, (c) Polarization curves of the samples after 72 h immersion in 3.5 wt.% NaCl solution, (d) Schematic representation of the corrosion and protection mechanisms of Mg (PA@Ce)3-FAS coating, MAO layer, and MAO-(PA@Ce)3-FAS coating on Mg alloy, Reprinted with permission from Ref. [56], Copyright

In order to obtain an aluminum alloy super-hydrophobic surface with excellent corrosion resistance, Khodaei M et al. [57] Developed a superhydrophobic aluminum alloy surface through a two-stage process. They achieved micron-scale roughness through rapid chemical etching with $CuCl_2$ solution. The researchers achieved nano-scale roughness by applying a silane-based nanocomposite coating that contained tetraethyl orthosilicate (TEOS) and (3-glycidyloxypropyl) trimethoxysilane (GPTMS) combined with functionalized Al_2O_3 nanoparticles. The silane layer served as a structural base for nanoparticles while simultaneously protecting the surface. Surface functionalization was completed using a fluorinated silane (FAS) solution. The final surface achieved a water contact angle of 164° and a rolling angle of 2.5°, and the corrosion tests show that the surface protection had been enhanced. The untreated aluminum sample demonstrated a current density of 3.17×10^{-6} A/cm² after both 10 minutes and 90 minutes of immersion. The treated sample (F-TGNf-EAl) reached 3.04×10^{-9} A/cm² at 10 minutes and 1.91×10^{-8} A/cm² at 90 minutes. The results demonstrate a more than three order of magnitude decrease proving the strong barrier function against ion penetration. The results revealed that the incorporation of functionalized Al_2O_3 nanoparticles within the silane layer created a stable nano/micro hierarchical surface structure. This led to the formation of a dense protective coating that simultaneously enhanced superhydrophobicity and corrosion protection comparison to the pure silane layer and the coatings containing non-functionalized particles displayed weak hydrophobic performance because they failed to achieve proper dispersion, as shown in Fig. 7, which explains the preparation process along with the most important results.

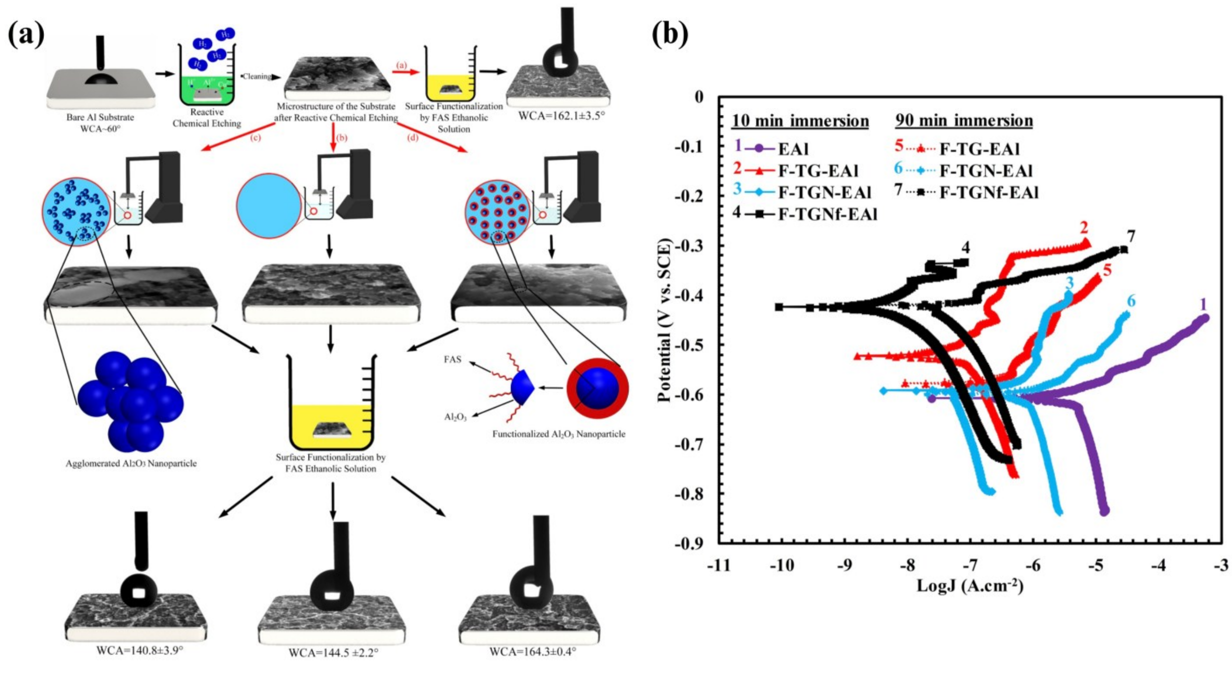

Fig. 7. Schematics of sample preparation routes in this work, (a) etching of Al and functionalization by FAS solution, etching of Al, coating by TEOS-GPTMS hybrid sol, and functionalization by FAS solution, etching of Al, coating by nano-Al_2O_3, (b) Potentiodynamic polarization curves of the samples after immersion time of 10 and 90 min in 3.5 wt.% NaCl solution, Reprinted with permission from Ref. [57] copyright

Wei ZB et al. [58] fabricated a superhydrophobic aluminum surface using a two-step method. First, the aluminum alloy (AA1050) was etched in a solution of 1.5 mol/L HCl and 1.5 mol/L H_2O_2. The micro-structured surface was obtained by etching in the solution for 5 min, and then the micro-structured aluminum plate was vertically immersed in the suspension containing Al nanoparticles. A 10V DC power supply was applied for electrophoretic deposition for 3 min, and the prepared sample was immersed in 2wt.% stearic acid ethanol. The mixture was then placed in the solution for 1.5 h and finally dried at 100 °C for 1.5 h. The resulting surface exhibited a water contact angle of 169.6° and a sliding angle of approximately 1°, indicating excellent superhydrophobicity. Mechanical durability was evaluated by subjecting the surface to abrasion on 400# sandpaper under 8 kPa pressure. After a 60 cm sliding distance, the contact angle remained at 154°, demonstrating that the multiscale roughness structure was retained in the lower layer despite partial damage to the upper surface. The surface retained its superhydrophobic properties after 70 days of air exposure and 48 hours of water immersion because contact angles remained above 163° in both conditions. The electrochemical corrosion testing revealed that the treated pure aluminum alloy (AA1050) exhibited the best corrosion resistance because it achieved a Jcorr value of 5.71×10^{-9} A/cm² which demonstrated an excellent protective barrier against corrosive environments, as shown in Fig. 8, which explains the preparation process with the most important results.

The application of superhydrophobic coatings protects aluminum and magnesium alloys from corrosion but encounters major implementation difficulties. The protective coating provides strong protection yet mechanical abrasion causes its degradation throughout the passage of time. The scalability of these coatings faces challenges because their preparation methods are complex and their manufacturing conditions are harsh despite their proven effectiveness. The performance of these materials decreases when they experience long-term exposure to acidic or alkaline environments. The industrial-scale production of uniform and reproducible coatings faces significant challenges which restrict their widespread adoption. The practical and durable application of these coatings requires solving their existing issues.

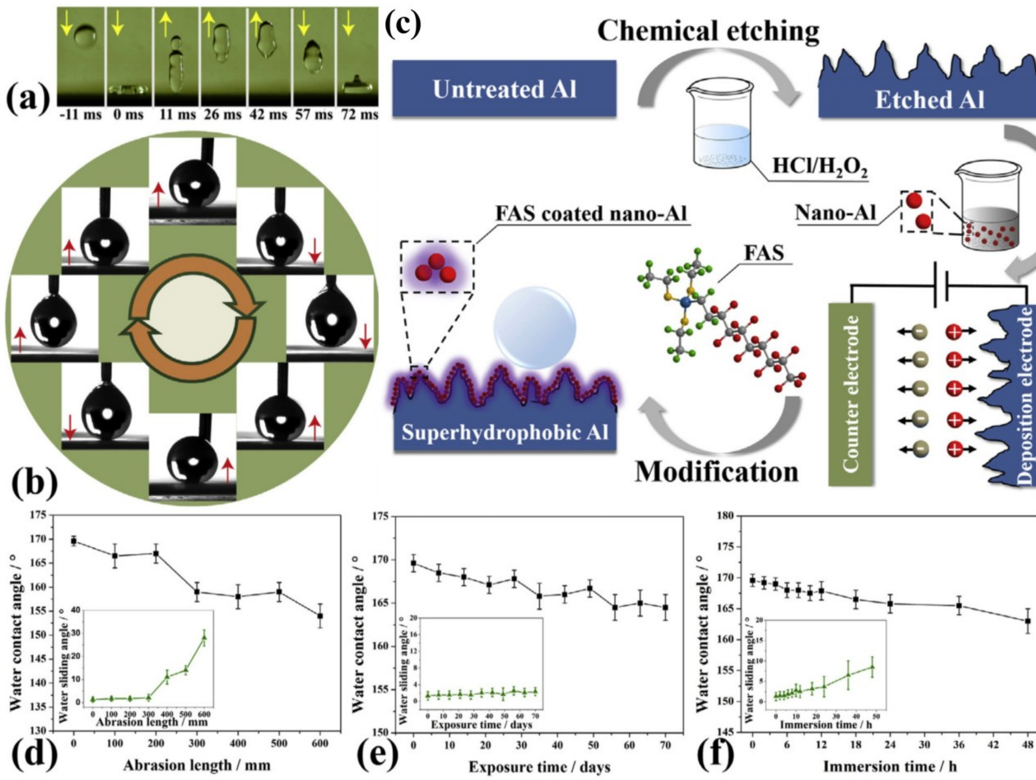

Fig. 8. (a) Snapshots of water droplet bouncing behavior, (b) The approach, contact, deformation, and departure cycle processes of water droplet on superhydrophobic surfaces, (c) Schematic illustration of the fabrication process, (d) abrasion distance, (e) exposure time to air, and (f) immersion time in water, Reprinted with permission from Ref. [58], Copyright

Table 1. Summary of the anti-corrosion performance of superhydrophobic (SHP) coatings

Substrate	Method	WCA°	Results	Re
Mg alloy	PEO + Hydrothermal + FDTS + Oil impregnation	172	Current density reduced from 4.23×10^{-6} to 2.74×10^{-10} A/cm²	[55]
Mg alloy	MAO + Phytic acid + $Ce(NO_3)_3$ + Stearic acid	159	Freezing time increased by 250% at −40 °C, Stable after 7 abrasion and tape tests	[56]
Al alloy	Chemical etching + Silane-nanocomposite with FAS	164	Current reduced from 3.17×10^{-6} to 3.04×10^{-9} A/cm² (10 min)	[57]
Al alloy	Acid etching +Electrophoretic deposition + Stearic acid	169	Current reduced to 5.71×10^{-9} A/cm²; CA stayed above 154° after 60 s of abrasion	[58]

2.2. Anti-icing

The formation of ice and frost on cryogenic surfaces leads to operational breakdowns which include blocked pipes, faulty sensors, structural damage and heat dissipation problems. The formation of ice on wings disrupts aerodynamic performance while simultaneously decreasing lift. The presence of ice leads to power outages and causes cables to collapse. The current deicing approaches through mechanical and chemical methods create environmental pollution while requiring significant energy consumption and delivering poor results. As global economic activities grow, it has become necessary to develop effective solutions to anti-icing. Through recent advancements, the development of superhydrophobic coatings has become a key focus in recent research to combat icing. The coatings achieve their anti-icing properties through the combination of micro-nano textures with low-surface-energy materials, which decrease water adhesion and extend the freezing time. The improved anti-icing performance together with corrosion resistance and durability makes lightweight Al and Mg alloys suitable for reliable operation in cold environments including aerospace applications, power systems and refrigeration systems [59-62], (Table 2).

Kang Liang et al. [63] developed a novel photothermal superhydrophobic hybrid multifunctional deicing, protective, and self-healing coating system (MDPCS) on magnesium (Mg) alloy, combining anti-icing/deicing, corrosion resistance, and self-healing. The coating consists of a micro-arc oxidation (MAO) layer, an ionic liquid (DMIm), (NTf2), and a photothermal superhydrophobic top layer made of H-CNTs@SiO_2 and Polydimethylsiloxane (PDMS). The MAO layer acts as a corrosion barrier, thermal insulator, and a reservoir for the ionic liquid, which enables self-healing. Compared to bare Mg alloy, the MDPCS coating extends the freezing time from 21 s to 670 s and reduces the deicing time to 48 s under 1 W/cm² NIR irradiation .In addition, the coating resists corrosion after 60 days of immersion in a 3.5% sodium chloride solution by weight. After 10 freeze/thaw cycles, the coating maintains superior hydrophobicity with a water CA of 156.9 and a SA of 4.8, demonstrating stability and durability. It also shows no deterioration after 21 days in a salt spray test, as shown in Fig. 9, which explains the preparation process with the most important results.

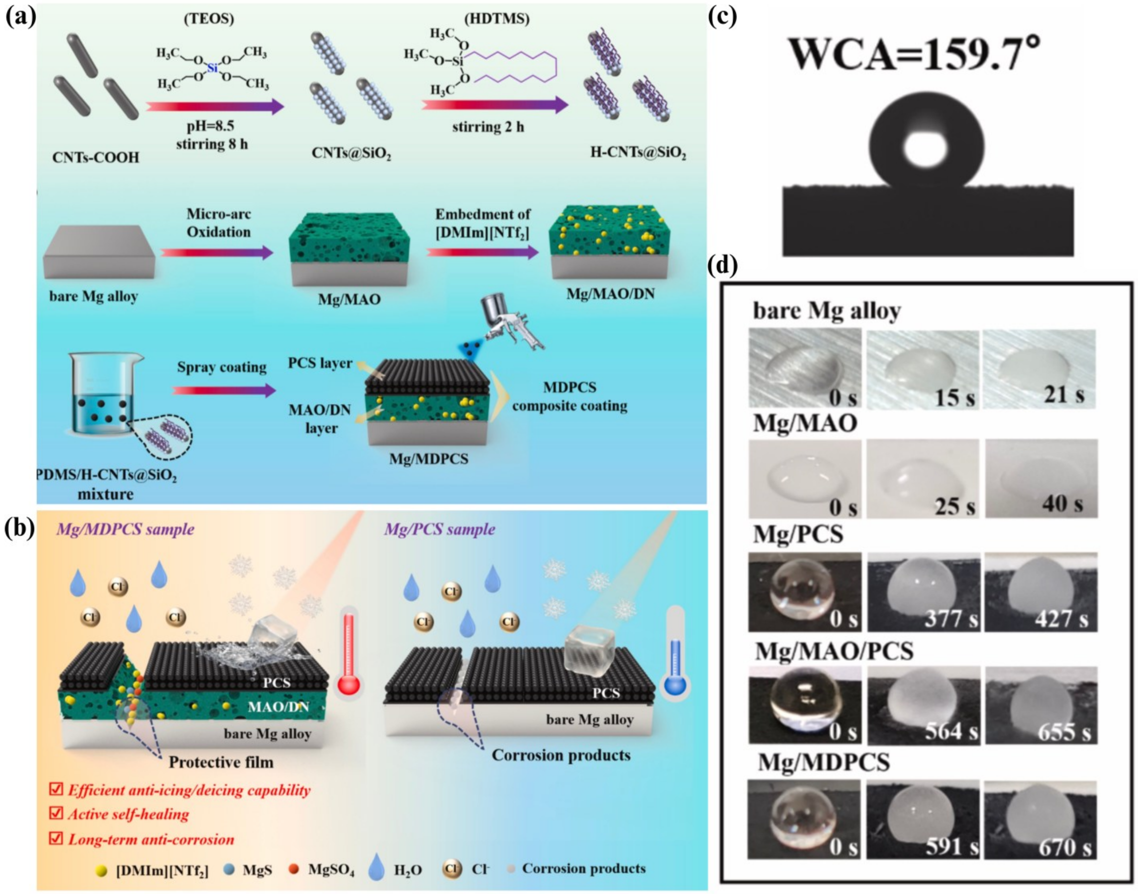

Fig. 9. (a) Schematic diagram of preparation, (b) Schematic diagrams of the synergistic mechanism of the composite coating, (c) Contact angle (CA), (d) Images of water droplets before and after freezing on different samples, Reprinted with permission from Ref. [63], Copyright

Lin Dai et al. [64] fabricated a coating by applying femtosecond pulsed laser treatment to a magnesium alloy, followed by the in situ growth of layered double hydroxide (LDH) layers composed of magnesium and aluminum. Finally, they modified it with low-surface-energy materials to prepare a superhydrophobic composite coating. The superhydrophobic coating consists of dense Mg-Al LDH nanosheets, features complex micro/nano-scale morphology, and provides a layer of air film. This achieves a high contact angle (CA) of 154.60°, exceptional corrosion resistance, and a fivefold reduction in corrosion current density compared to untreated AZ91D alloy. In addition, the ice-forming time on the coated surface is extended by 250% at -40 °C compared to the bare magnesium alloy, highlighting its potential for applications in cold environments where delayed icing is crucial. It also shows excellent self-cleaning, anti-fouling, and mechanical durability properties. It performs effectively in dye immersion and dust contamination experiments and retains its superhydrophobicity after 7 cycles of sandpaper abrasion and 8 tape-peeling tests, as shown in Fig. 10. This explains the preparation process with the most important results.

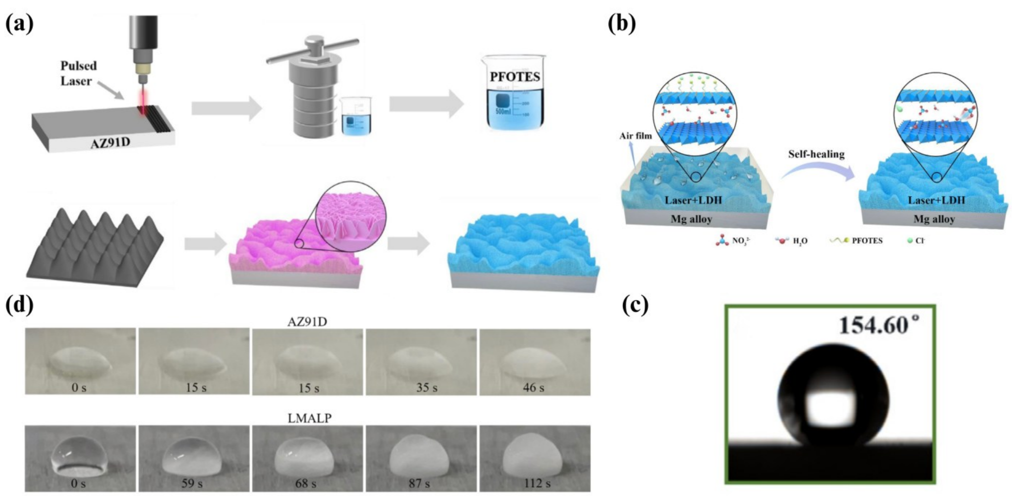

Fig. 10. (a) Schematic diagram of the preparation of the LMALP film layer, (b) The protection mechanism of bionic surface, (c) WCA, (d) Static anti-icing performance of a single droplet on AZ91D and LMALP, Reprinted with permission from Ref. [64] copyright

In this study, Ruoyu Sun et al. [65] Developed an efficient method to fabricate superhydrophobic surfaces on aluminum alloy substrates. The process involved three main steps: high-speed wire electrical discharge machining (HS-WEDM), short-duration chemical etching, and surface modification using a low-surface-energy material. The HS-WEDM step was used to generate micro-scale surface textures on the alloy. This was followed by chemical etching, which further refined the roughness and contributed to the creation of a hierarchical micro/nano structure. Finally, a surface modification step was applied to lower the surface energy, resulting in a superhydrophobic surface. The treated samples exhibited a high contact angle of 158.6 ± 1.3° and a sliding angle of less than 1°, confirming excellent water repellency. Freeze-delay tests were conducted to evaluate anti-icing performance. At temperatures between −12 °C and −24 °C, the coated samples demonstrated significantly longer freezing times. For example, at −12 °C, the average freezing delay was 552 seconds compared to 287 seconds for untreated smooth samples. The superhydrophobic performance remained stable for up to 92 hours at −20 °C and for 28 hours at −24 °C, indicating strong durability at low temperatures. In addition, the coatings showed high thermal stability and mechanical robustness under physical stress, as shown in Fig. 11, which explains the preparation process with the most important results.

In the study, by Libang Feng et al. [66] a simple one-step immersion method was developed to fabricate superhydrophobic surfaces on aluminum alloys. The process involved immersing the alloy in a DMF–H_2O solution containing stearic acid (STA) at 70 °C for 35 hours. This treatment produced a rough surface with micro- and nano-scale structures grafted with hydrophobic alkyl chains. These structures trap air beneath water droplets, reducing the contact area between water and the solid surface-air accounted for 92.0% of the total interface area. As a result, the treated surface exhibited a contact angle of 155.5° ± 1.0° and a rolling angle below 4°. The superhydrophobic aluminum surface also showed excellent anti-icing and anti-frosting performance. Freezing was delayed by 5 to 9 minutes, and the freezing temperature was reduced by 2 to 4 °C compared to untreated samples. The surface prevented the formation and growth of frost crystals, allowing melted frost to roll off easily. In addition, the coating demonstrated strong self-cleaning ability, effectively removing simulated contaminant particles. This method offers an efficient and practical approach to enhancing the anti-icing, anti-frosting, and self-cleaning properties of aluminum alloys in cold environments, as shown in Fig. 12, which explains the preparation process with the most important results.

However, the anti-icing capabilities remain restricted by a short lifespan and poor stability under harsh conditions and reduced effectiveness after wear or contamination. The majority of coatings fail to sustain their performance when temperatures reach very low levels. The current limitations in their use for real-world long-term applications necessitate additional research to overcome these issues.

Table 2. The summary of Anti-icing performance of superhydrophobic (SHP) coatings

Substrate	Method	WCA°	Results	Re
Mg alloy	MAO + Photothermal layer	156	Freezing time from 21 s to 670 s under 1 W/cm² NIR, stable after 10 freeze/thaw cycles	[63]
Mg alloy	laser treatment +Surface modification	154	Freezing time increased by 250% at −40 °C, stable after 7 abrasion and tape tests	[64]
Al alloy	High-speed EDM +Chemical etching +Surface modification	158	Freezing time average 552 s at −12 °C (vs 287 s smooth surface), Stable for 92 hours at −20 °C	[65]
Al alloy	Immersion in DMF–H2O + STA	155	Freezing delayed 5-9 minutes; freezing temp lowered 2-4 °C	[66]

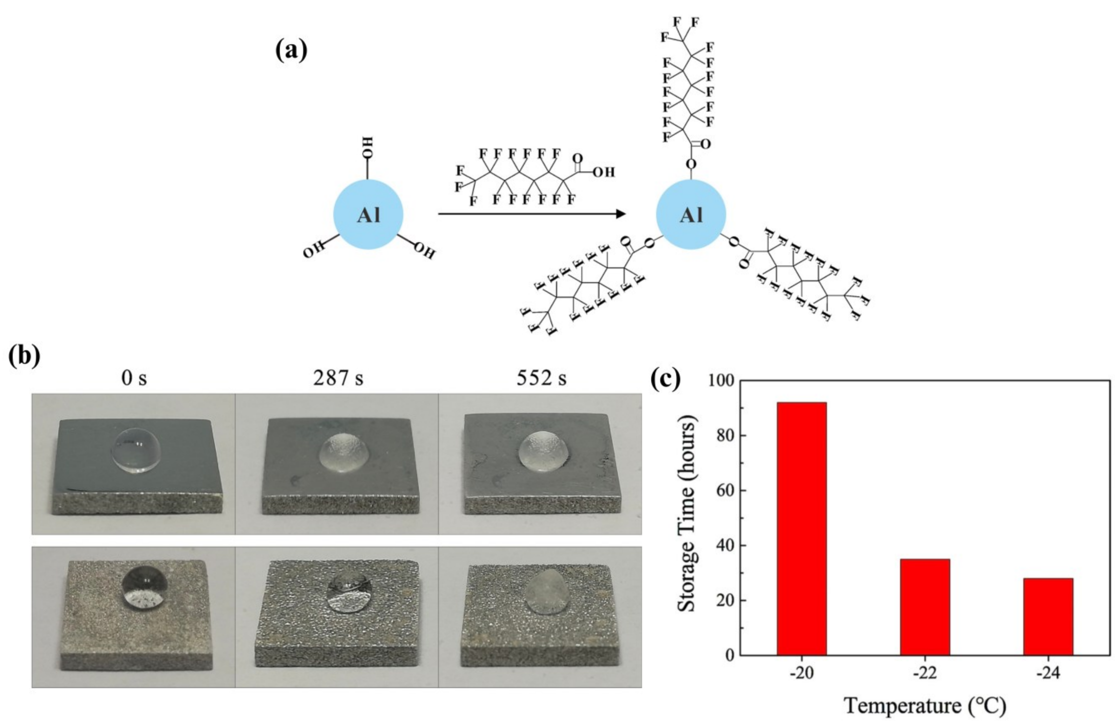

Fig. 11. (a) Chemical reaction of PFOA and $Al(OH)_3$. (b) Digital images of the freezing process of the water droplet on the smooth Al alloy sample and 2m-8h-Al alloy sample at−12 °C for different times. (c) The low temperature durability of the 2m-8h-Al alloy samples at -20~ −24 °C, Reprinted with permission from Ref. [65], Copyright

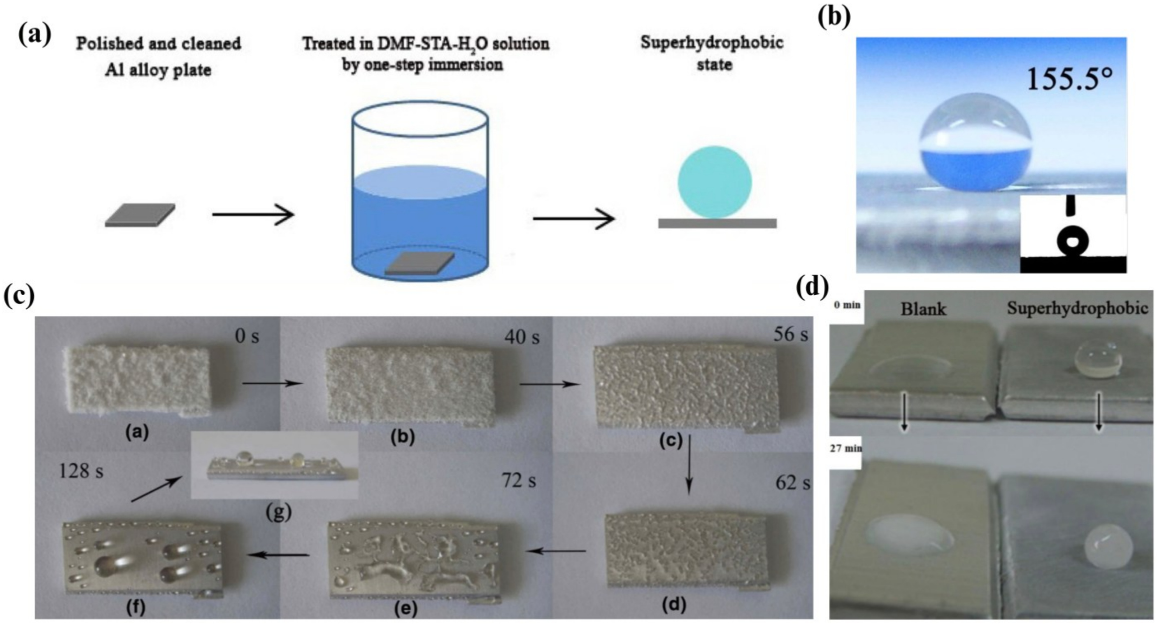

Fig. 12. (a) Fabrication procedure of superhydrophobic aluminum alloys, (b) Contact angle (CA), (c) Melting process of frost accumulated on superhydrophobic aluminum alloy surface, (d) Digital images of water freezing process on blank (L) and superhydrophobic (R) aluminum alloys at ⁻8 °C for different time periods, Reprinted with permission from Ref. [66] Copyright

2.3. Anti-bacterial

The development of superhydrophobic surfaces with antibacterial properties shows great promise for improving magnesium and aluminum alloy performance. The surfaces effectively decrease bacterial attachment and biofilm development which leads to better corrosion protection and extended durability in demanding conditions. These advancements represent a crucial development toward decreasing antibiotic and chemical agent reliance while enhancing both hygiene and mechanical properties of lightweight metal alloys used in medical applications, aerospace and industrial sectors [67-71], (Table 3).

In this study, Wei Xiong et al. [72] created a surface treatment process for Mg alloy to enhance its antibacterial and corrosion protection properties. The method consists of two steps, which include laser surface structuring for dual-scale micro/nanostructure formation followed by stearic acid immersion for chemical treatment. The dual treatment process transformed surface physical and chemical properties which enhanced biological performance during exposure to physiological environments. The antibacterial property assessment involved counting E. coli and S. aureus colonies that formed on different surfaces after 24 hours of incubation. The surface achieved superhydrophobic properties through modification which resulted in a water contact angle of 160.1° ± 0.5°. The modified surface structure produced substantial antibacterial effects that reached 74.43% against E. coli and 82.05% against S. aureus, compared with untreated alloy, which showed a high density of bacterial colonies. The superhydrophobic nanostructured surface developed air pockets that blocked bacterial fluid entry and minimized bacterial cell adhesion to the surface, as shown in Fig. 13, which explains the preparation process with the most important results.

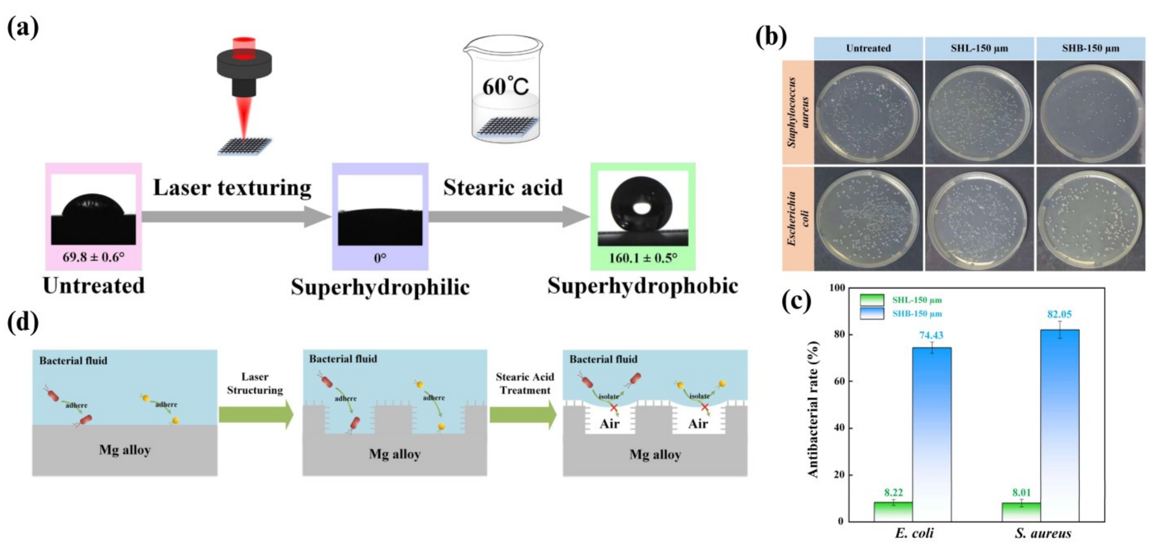

Fig. 13. (a) Evolution of surface wettability of a specimen after each treatment, (b) Images of bacteria on tested specimens, (c) Antibacterial rates of tested specimens, (d) Schematic illustration of the underlying mechanism of bacterial adhesion on different types of Mg alloy surfaces, Reprinted with permission from Ref. [72], Copyright

Qianqian Li et al. [73] the researchers developed a superhydrophobic composite coating through hydrothermal processing of hydroxyapatite (HA) and stearic acid on AZ31B magnesium alloy followed by stearic acid surface modification. The coating showed superior wetting characteristics because it maintained a water contact angle of 152.5° and a sliding angle of 2° which demonstrated high liquid repellency efficiency. In addition, the S100 surface demonstrated the best performance in bacterial tests because no bacteria adhered to its surface during 4 and 8 hours of incubation, while the hydrophilic (HA) surface and untreated alloy showed substantial bacterial adhesion. The S100 surface achieves its effectiveness through its ability to create an air layer that minimizes bacterial contact with the surface. The results show that the HA/stearic acid coating on AZ31B alloy through hydrolysis provides an effective medical solution for orthopedic and dental implants because it offers antibacterial and corrosion resistance properties, as shown in (Fig. 14), which explains the preparation process with the most important results.

In this study by Henry Agbe et al. [74], a superhydrophobic coating was fabricated using a two-step process. First, aluminum substrates underwent chemical etching to create a micro-nano surface, followed by passivation with OTES-QUATs molecules to reduce surface energy. The resulting coating of the OTES-QUATs sample exhibited a high-water contact angle of 160° and excellent antibacterial activity against Staphylococcus aureus, Pseudomonas aeruginosa, and Escherichia coli. The coating demonstrated outstanding anti-biofouling performance with bacterial adhesion reduction rates of 99.9% for Staphylococcus aureus, 99% for Pseudomonas aeruginosa, and 99% for E. coli bacteria. coli bacteria, these results were attributed to the combined superhydrophobic properties provided by the OTES layer and the antibacterial characteristics of the QUATs molecules, as shown in (Fig. 15), which explains the preparation process with the most important results.

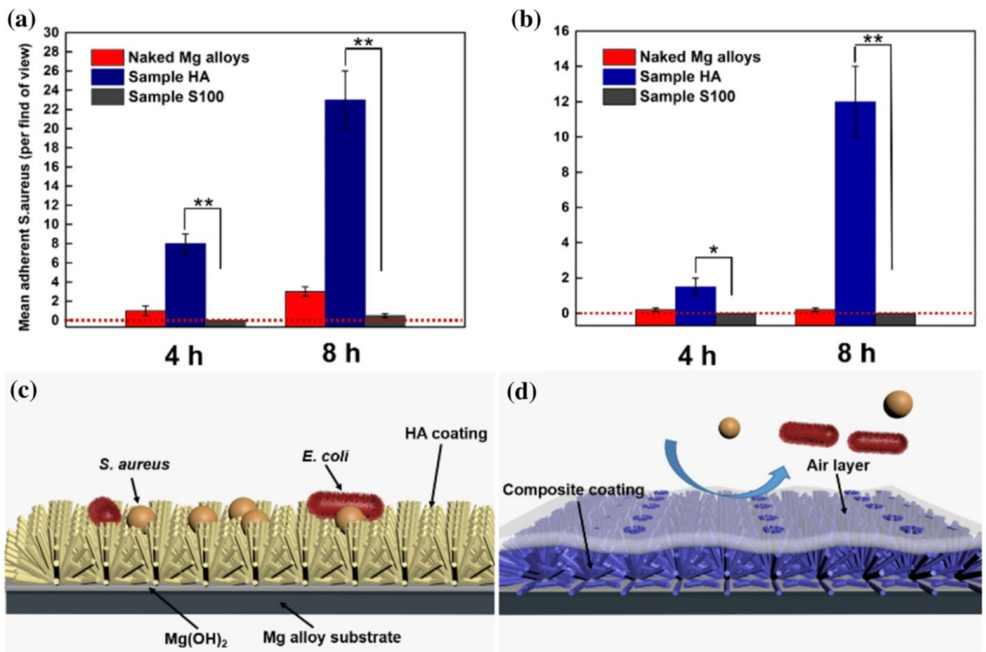

Fig. 14. The statistical results of (a) S. aureus, (b) E. coli adhesion on different samples, statistically significant differences between sample HA and sample S100 ($p^* < 0.05$, $p^{**} < 0.001$). The illustrations of bacterial adhesion on (c) sample HA. (d) sample S100, Reprinted with permission from Ref. [73], Copyright

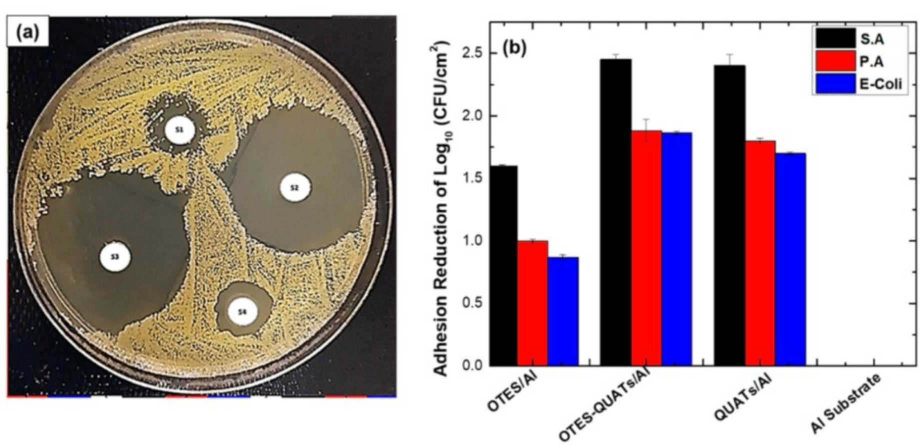

Fig. 15. (a) Disk diffusion assay of ethanoic solution of: OTES (Region S1); OTES-QUATs (region S2); (QUATs) (region S3) and Ethanol (region S4), treated against Staphylococcus aureus bacterium, (b) Graphical representation of adhesion reduction of Staphylococcus aureus, Pseudomonas aeruginosa and Escherichia coli on OTES/Al, OTES-QUATs/Al, QUATs/Al and etched Al substrate, Reprinted with permission from Ref. [74], Copyright

In the study by Asia Sultana et al. [75] a superhydrophobic coating was fabricated on aluminum alloy using a three-step process: by etching in a NaOH solution, immersing in a $Zn(NO_3)_2$ aqueous solution, and annealing. The resulting $ZnO/Zn–Al/Al_2O_3$ (ZnSHS) surface exhibited a high-water CA of 161° and a SA of 2°, and high corrosion resistance. The corrosion current density (I_{corr}) of the ZnSHS sample was 3.97 times lower than that of the untreated aluminum. In addition, the coating demonstrated strong antibacterial performance, with a bacteriostatic efficiency of approximately 99.99% after 24 hours. Even after 19 consecutive reuse cycles in antibacterial testing, the ZnSHS sample maintained a bacteriostatic rate of 94.85%. This work presents a practical method for developing superhydrophobic materials with combined antibacterial and anticorrosive properties for advanced engineering applications on aluminum and its alloys, as shown in Fig. 16, which explains the preparation process with the most important results.

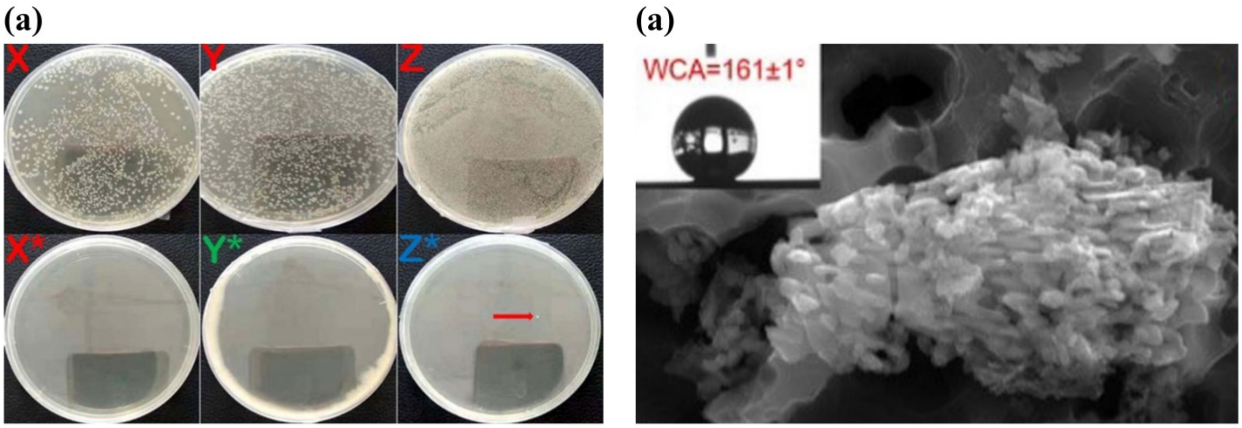

Fig. 16. (a) image of non-coated Al plates (X, Y, Z) and ZnSHS plates (X^*, Y^*, Z^*) for 24 h, (b) ZnSHS and the insets of SEM images are the Contact angle (CA) of samples, Reprinted with permission from Ref. [75], Copyright

However, the development of superhydrophobic antibacterial surfaces has shown progress, but essential challenges continue to exist. The majority of coatings experience a decline in their protective capabilities because of surface degradation and environmental factors. Many research studies rely on specific bacterial strains, which restricts their practical use. The complete safety profile and long-term biocompatibility remain unclear. Industrial adoption faces challenges because of scalability issues and high costs. The development of stable, broad spectrum, and clinically safe coatings for real-world applications requires additional research.

Table 3. The summary for anti-bacterial performance of superhydrophobic (SHP) coatings

Substrate	Method	WCA°	Results	Re
Mg alloy	Laser structuring + stearic acid	160	74.43% reduction in E. coli, 82.05% reduction in S. aureus colonies after 24 hours	[72]
Mg alloy	Hydrothermal + stearic acid	152	No bacterial adhesion after 4 and 8 hours incubation	[73]
Al alloy	Chemical etching + OTES-QUATs	160	99.9% reduction S. aureus, 99% P. aeruginosa, 99% E. coli bacterial adhesion	[74]
Al alloy	NaOH etching + Zn(NO3)2 immersion	161	99.99% bacteriostatic resistance after 24 hours; 94.85% resistance after 19 reuse cycles	[75]

2.4. Friction resistance and self-cleaning performance

Superhydrophobic surfaces have friction resistance with self-cleaning properties through their ability to repel water and prevent contaminants from adhering to the surface, which enables easy particle rolling off. The technology enhances operational performance in applications that require surface cleanliness and reduced drag and wear resistance including biomedical devices aerospace structures and outdoor equipment. Research indicates that superhydrophobic surfaces reduce friction and mechanical wear by minimizing direct contact between materials, which helps extend their service life [76-80], (Table 4).

In this study, Tingting Zhao et al. [81] a one-step coating was fabricated using electrodeposition to produce a multifunctional hydrophobic layer on magnesium surfaces. The process was carried out in an ethanol solution with magnesium nitrate and myristic acid. The formation of magnesium myristate on the surface during electrodeposition resulted in hierarchical micro/nanostructures and a low surface energy. The surface properties resulted in excellent wetting properties, with water contact angles exceeding 150°, while sliding angles remained below 6°. The coatings exhibited superior corrosion resistance. The corrosion potential was increased and the corrosion current density decreased by twofold when pure magnesium was immersed in a 3.5 wt% sodium chloride solution. The coating also showed strong mechanical and chemical durability. After 48 chloride solution. The coating also showed strong mechanical and chemical durability. After 48 hours of immersion in salt water and pure water, only a slight decrease in mass and contact/ sliding angles was observed. Oil absorption tests confirmed that ASSC and CSSC samples retained stable oil uptake capacities of 4.65 g/g and 7.62 g/g, respectively, even after ten absorption-release cycles. In muddy water tests, the surface remained clean over 20 cycles, with water droplets effectively removing contaminants such as Al_2O_3 particles and algae. The coating preserved its superhydrophobic performance even after eight months of storage and exposure to wear at a distance of 600 mm. These findings demonstrate that electrodeposition in magnesium nitrate and myristic acid solution provides a robust method for developing coatings with corrosion resistance, oil absorption, and self-cleaning functions, as shown in Fig. 17, which explains the preparation process with the most important results.

Huimin Zhou et al. [82] a superhydrophobic coating was fabricated on AZ31 magnesium alloy using a spraying and hydrothermal process. First, ZnO nanoparticles were mixed with epoxy resin and sprayed onto the alloy surface from a 10 cm distance, then cured at 80 °C. A ZnO layer was grown by immersing the coated sample in a solution of $Zn(NO_3)_2 \cdot 6H_2O$ and hexamethylenetetramine at 100 °C for 5 hours. After washing and drying, the surface was modified with stearic acid in ethanol to enhance hydrophobicity, which reached contact angles of 163°. The superhydrophobic coating showed excellent mechanical strength because it maintained its water-repelling properties after undergoing 100 strip-peeling cycles and after exposure to #2000 sandpaper wear for distances up to 210 cm. The CA remained at 162° throughout the first 30 cm of wear but decreased to 132° at 210 cm while maintaining surface functionality. In addition, the coating demonstrated improved corrosion resistance through its good performance in a 3.5% solution. The contact angle showed minimal variation between 158° and 163° when exposed to droplets of different pH levels. The air gap between the coating and the liquid droplets prevented penetration, which improved chemical resistance. The self-cleaning capability was shown through experiments with dust particles as contaminants. The coated surface allowed water droplets to roll off while removing dust particles without leaving any residue, whereas uncoated magnesium alloys showed both water and dust sticking to their surfaces. The superhydrophobic zinc oxide/ epoxy coating with stearic acid modification achieved high contact angle values and strong corrosion protection and durable mechanical resistance and excellent self-cleaning properties, and chemical stability, which makes it suitable for harsh environment applications, as shown in Fig. 18, which explains the preparation process with the most important results.

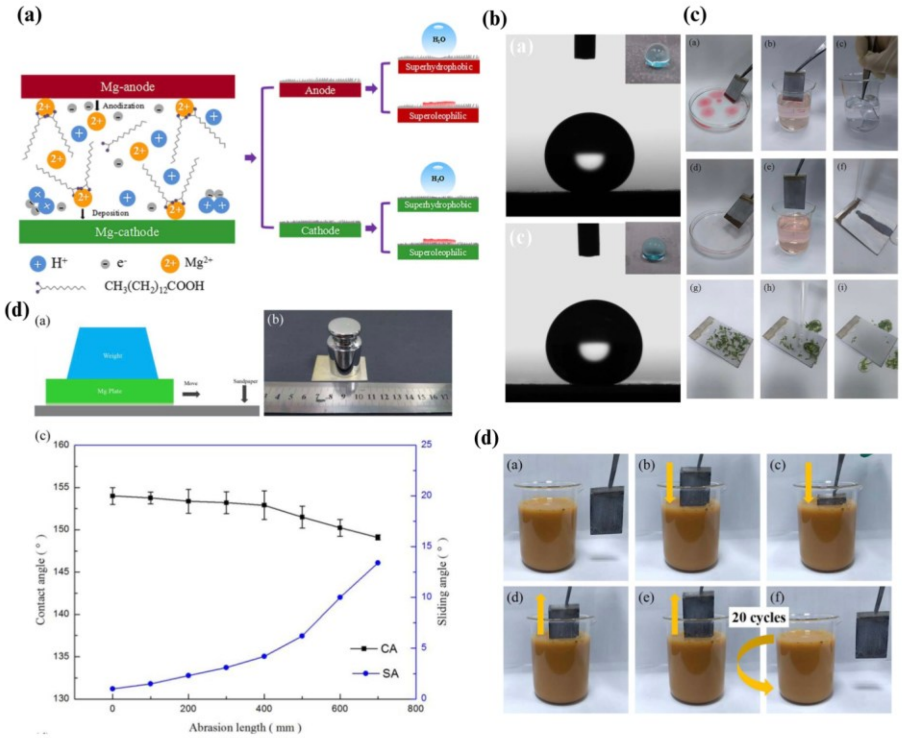

Fig. 17. (a) Schematic illustration of the electrodeposition process on the AS and CS, (b) Contact angle (CA) of ASSC and CSSC, (c) Oil absorption, Surface deoiling, Silver mirror phenomenon, Self-cleaning effect, (d) Self-cleaning and anti-fouling effect experiments, (e) the abrasion test, Reprinted with permission from Ref. [81], Copyright

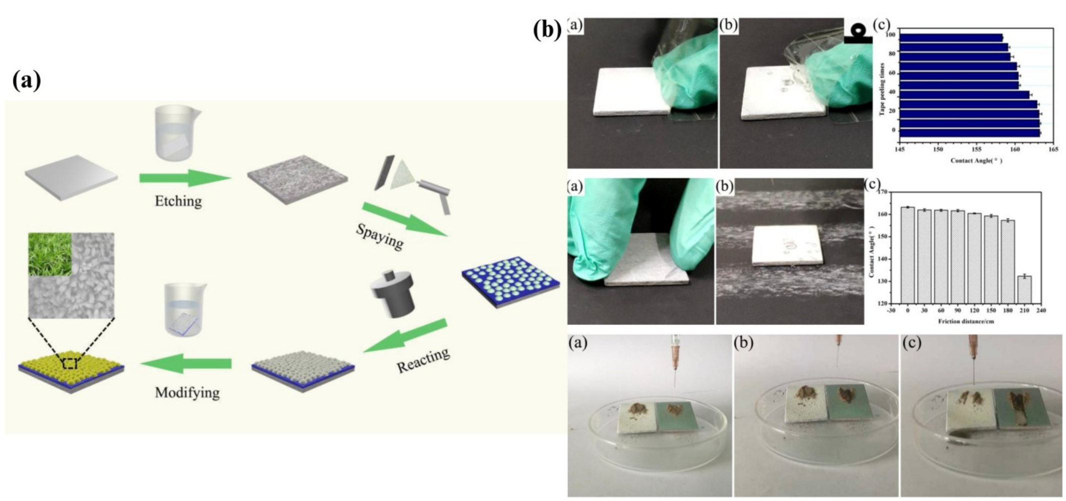

Fig. 18. (a) Schematic illustration of the preparation process of the cluster-like ZnO coating, (b) tape peeling test, Sandpaper abrasion test, and Self-cleaning properties, Reprinted with permission from Ref. [82], Copyright

Wenbo Su et al. [83] developed a two-step procedure for creating superhydrophobic aluminum surfaces that exhibit both self-cleaning capabilities and mechanical durability. The first step utilizes femtosecond laser etching before surface treatment with 1H,1H,2H,2H perfluorooctanetriethoxysilane (PFOTES). The surface treatment produced a contact angle of 152.8° and a sliding angle of 0.6°. The treated surface demonstrated high self-cleaning ability in coal dust particle spray tests (20-40 µm), effectively removing dust, and the treated surface retained only 30% of the dust weight of the untreated surface. Furthermore, mechanical durability was evaluated by a 1000-grit sandpaper abrasion test under a load of 200 g at a distance of 150 cm. Vickers hardness measurement showed that the treated surface outperformed the untreated surface by one and a half times. Based on these results, the surface treated using this method demonstrated promising application potential and long-term durability, as corrosion did not affect its hydrophobic properties. Furthermore, it demonstrated cost effectiveness, processing efficiency, and mechanical stability with effective dust removal for industrial applications, as shown in Fig. 19, which explains the preparation process with the most important results.

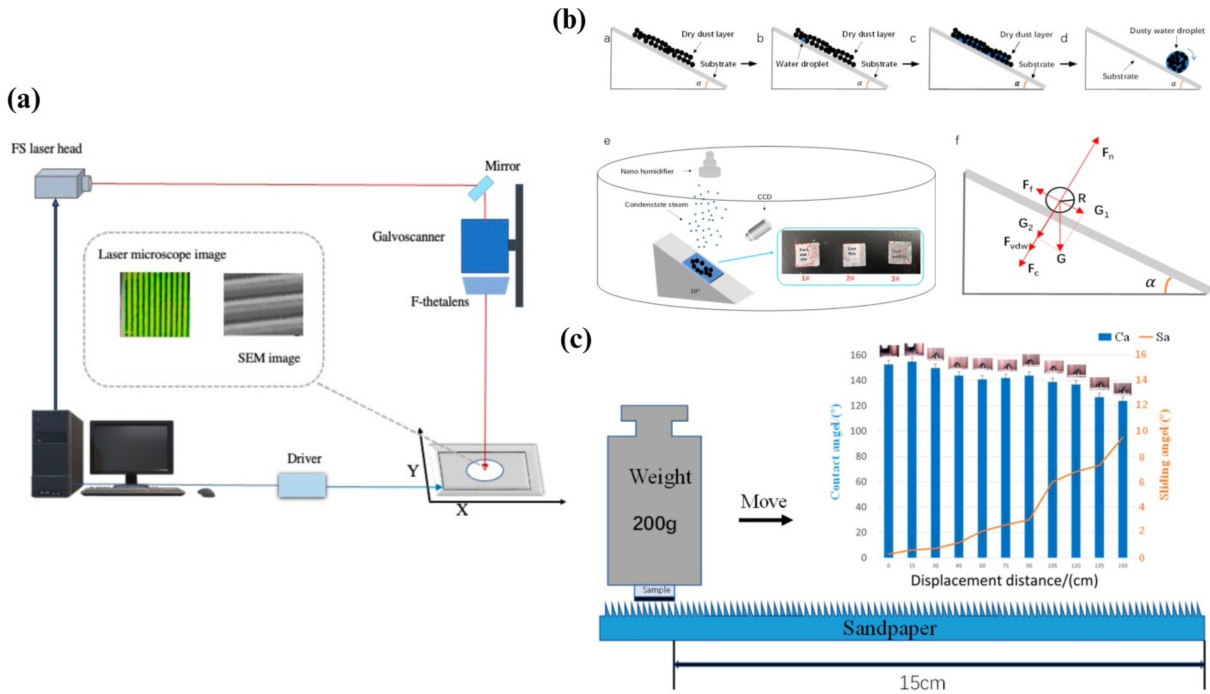

Fig. 19. (a) Schematic diagram of the femtosecond laser processing system, (b) self-cleaning process, dust removal experiment, (c) surface wear test, Reprinted with permission from Ref. [83], Copyright

Zihao He et al. [84] a simple technique was developed to create superhydrophobic surfaces on aluminum alloys. Using an electrodeposition method, an ethanol-based electrolyte solution containing aluminum chloride hexahydrate with N-dodecyltrimethoxysilane (DTMS) was used. The results demonstrated a water contact angle of 155°, along with high corrosion resistance, with an inhibition efficiency of 98% protection after 30 days of immersion in a 3.5 wt% solution. Furthermore, the mechanical durability of the coating was demonstrated using a reciprocating friction test system. The contact angle decreased with increasing distance, and after reaching 150 cm, the angle decreased to 135°. The surface also exhibited self-cleaning properties and anti-adhesion properties, as sand and sewage particles did not adhere to it. The surface easily shed water droplets, allowing the particles to drift away. The aluminum surface remained clean after immersion in muddy water, thanks to the formation of an air cushion underneath. This observation, combined with the low surface energy and air-trapping properties of SHAl, confirmed that this manufacturing technique produces long-lasting, superhydrophobic aluminum surfaces that can be used in marine environments, as shown in Fig. 20. It explains the preparation process with the most important results.

Despite these advantages, the properties of most coatings deteriorate after multiple uses and when exposed to high pressure or harsh environmental conditions. The physical stress and chemical exposure of these materials reduces their ability to function over time, and it is also challenging to achieve both low friction and strong mechanical strength. Research efforts currently aim to enhance mechanical strength while maintaining self-cleaning properties and friction reduction capabilities throughout extended periods on different surfaces.

Table 4. The summary for friction resistance and self-cleaning performance of superhydrophobic (SHP) coatings

Substrate	Method	WCA°	Results	Re
Mg alloy	Electrodeposition + myristic acid	>150	Maintained properties after 48h saltwater immersion; stable after 8 months wear. Removed Al_2O_3 particles and algae after 20 muddy water cycles.	[81]
Mg alloy	Hydrothermal + stearic acid	163	Maintained CA after 100 strip-peeling cycles; dropped to 132° after 210 cm sandpaper wear. Water droplets removed dust completely; no residue left.	[82]
Al alloy	Femtosecond laser etching + PFOTES	152	Passed 1000-grit sandpaper abrasion (200g load, 150 cm); hardness 1.5×higher than untreated. Removed 70% dust compared to untreated surface in coal dust spray.	[83]
Al alloy	Electrodeposition + Al chloride hexahydrate with (DTMS)	155	The contact angle (CA) decreased to 135° after a 150 cm friction test. Sand and sewage particles did not adhere, and the surface stayed clean in muddy water.	[84]

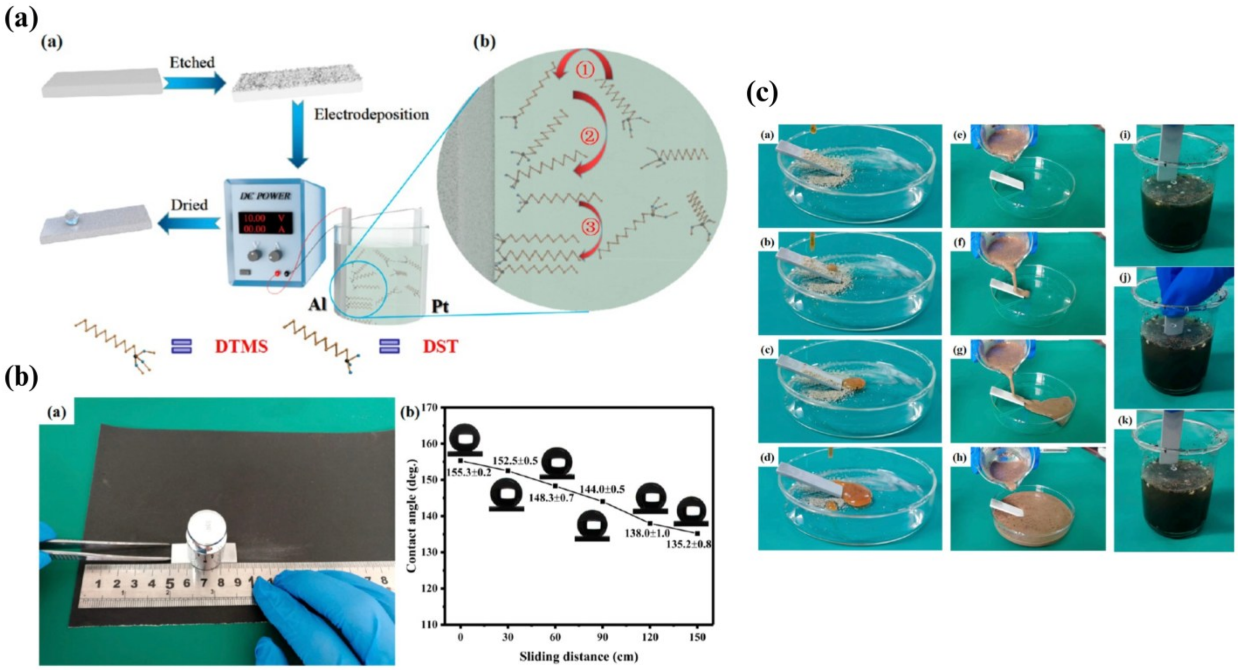

Fig. 20 (a) Schematic illustration of the fabrication process and the formation mechanism of the superhydrophobic film, (b) friction test, and the contact angle (CA) with the sliding distance, (c) Self-cleaning and antiadhesion tests of SH Al, Reprinted with permission from Ref. [84], Copyright

3. Conclusion

Superhydrophobic coatings demonstrate excellent potential to improve the corrosion resistance of aluminum and magnesium alloy materials. The surface properties of these coatings enable water repellence and minimize corrosive agent contact, and extend the time before corrosion starts, which makes them useful for industrial and environmental applications. The protective properties of these coatings extend beyond corrosion resistance because they also deliver self-cleaning capabilities and anti-icing properties, and fouling resistance, which enhance their practical applications. The widespread adoption of these materials remains limited due to various constraints. The majority of superhydrophobic coatings experience poor mechanical durability and show restricted long-term stability when exposed to harsh conditions, including high humidity and abrasion, and UV radiation. The environmental compatibility of materials and the adhesion strength between the coating and metal substrate require additional optimization efforts. Future research should concentrate on enhancing the durability of these coatings while making them more resistant to environmental factors. The development of industrial-scale fabrication methods together with environmentally friendly formulations represents essential requirements for commercial applications. Standardized testing protocols need development to ensure fair performance assessments between different studies. Research into multifunctional coatings which unite superhydrophobic properties with protective and responsive features will enable expanded application possibilities. The resolution of these challenges will create a pathway to transform laboratory-developed superhydrophobic metal surface technology into practical applications.

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