

Review

Comprehensive Protection of Aluminium Alloys Against Corrosion in Aggressive Oil Production and Oil Refining Environments

Viktor Yuryevich Piirainen ¹, Vladimir Nikolaevich Starovoytov ², Vladimir Vladimirovich Khachinikolaev ^{1,*} 
and Andrei Romanovich Bezprozvannyi ¹

¹ Department of Materials Science and Technology of Artistic Products, Empress Catherine II Saint Petersburg Mining University, St. Petersburg 199106, Russia; piraynen@gmail.com (V.Y.P.); andrey.bezprozvannyi@gmail.com (A.R.B.)

² Department of Metallurgy, Empress Catherine II Saint Petersburg Mining University, St. Petersburg 199106, Russia; bob.star2016@yandex.ru

* Correspondence: vladimr.vladimrov@gmail.com

Abstract

Aluminum alloys are attractive for oil production, refining, and hydrocarbon-processing equipment because of their low density, high specific strength, and heat-transfer properties; however, their use is limited by localized corrosion in chloride-, sulfur-, and water-containing environments. This review analyzes combined anodic oxide/polymer and anodic oxide/fluoropolymer coating systems as surface-engineering approaches for improving corrosion resistance, adhesion, and durability of aluminum alloys under such conditions. The reviewed data show that coating performance is governed by anodic oxide morphology, pore sealing or polymer impregnation, and oxide/polymer interfacial stability. Quantitative results indicate that anodizing and pore widening can increase aluminum/polyamide lap-shear strength from 5.0 to 17.4 MPa, while optimized interfacial treatment can provide 22.5 ± 0.5 MPa before aging and 18.1 ± 0.2 MPa after humid aging. Corrosion data show that anodizing can increase the polarization resistance of aluminum alloy 6061 in seawater from $17.2 \text{ k}\Omega \cdot \text{cm}^2$ to $2.24 \text{ M}\Omega \cdot \text{cm}^2$. For wear-related durability, optimized anodizing can increase the critical scratch load from 37.3 to 118.9 N. These values provide practical benchmarks for designing anodic oxide/polymer systems for complex oilfield and hydrocarbon-processing environments.

Keywords: anodizing; aluminum; protective coatings; fluoropolymer; corrosion; corrosion resistance; oilfield environments



Academic Editor: Cecilia Bartuli

Received: 11 May 2026

Revised: 19 June 2026

Accepted: 24 June 2026

Published: 28 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Due to their low density and high specific strength, aluminum alloys are increasingly being used in pipelines, storage tanks, and equipment for oil production, transportation, and storage. Steels traditionally used for these purposes have a number of shortcomings, most notably their susceptibility to difficult-to-detect intergranular corrosion [1,2]. However, the large-scale adoption of aluminum structures is constrained by their poor corrosion resistance in the aggressive media encountered in oil production and refining (e.g., sulfur- and chloride-containing environments), which reduces operational reliability.

To enhance the service life of equipment and pipeline systems in the oil and gas industry, an integrated set of approaches is employed, combining the selection of corrosion-resistant materials, the application of protective coatings, and chemical conditioning of

the transported fluid using corrosion and deposit inhibitors [3,4]. However, the effectiveness of many organic inhibitors, particularly at elevated temperatures, is limited by their thermal degradation and deposit formation [5]. Therefore, the search for alternative or supplementary methods of metal corrosion protection remains highly relevant.

Despite the corrosion challenges, aluminum alloys have found successful applications in several oil and gas and petrochemical sectors, where their unique combination of properties provides distinct advantages.

For downhole applications, aluminum alloy drill pipes have been successfully used in deep and ultra-deep wells. Comprehensive studies of aluminum alloy drill pipes, particularly those made from 1953T1 series alloy (Russian Grade), have demonstrated their effectiveness in drilling ultra-deep and extended-reach wells, especially in corrosive environments [6]. The low weight of these pipes reduces hook loads and allows for the use of smaller drilling rigs, while maintaining sufficient strength for demanding well trajectories [7]. Furthermore, structural aluminum alloys (SAAs) are used for tubing and casing in well construction. Their overall corrosion resistance, including resistance to dissolved hydrogen sulfide (H_2S) and carbon dioxide (CO_2), coupled with the absence of a cold-shortness effect, makes them suitable for sour service conditions where conventional steel tubulars are prone to failure [8]. The feasibility of using aluminum alloy pipes (e.g., alloys 2024 and 1953) in petrochemical applications has also been verified, with studies confirming their corrosion stability under real operating conditions, even at elevated temperatures [9].

For surface and offshore equipment, aluminum alloys are used in heat exchangers. Aluminum's high thermal conductivity, typically around $205\text{ W/(m}\cdot\text{K)}$, allows for rapid heat transfer, while its corrosion resistance can be enhanced through proper surface treatments [10]. In marine and offshore environments, aluminum alloys (e.g., 5xxx and 6xxx series) are widely used to construct lightweight, corrosion-resistant structures, including helidecks, accommodation modules, and various deck structures. These applications benefit from significant weight savings (typically 50–65% compared to steel equivalents) and reduced maintenance costs [11–13].

In addition, aluminum alloys have been successfully employed in geothermal well construction [14]. The geothermal drilling industry, which faces extreme thermal and mechanical stresses, has explored aluminum alloy drill pipes to reduce rig loads and achieve greater drilling depths. A key example is the Kola Superdeep Borehole project, where depths of over 12 km were reached, in part, through the use of aluminum drill pipes [15]. The advantages of aluminum alloy pipes in geothermal applications include reduced weight, improved buoyancy, and the ability to drill longer and more deviated wells, although challenges such as performance at high temperatures must be addressed [15].

One promising approach to overcome the corrosion limitations of aluminum alloys in these harsh environments is specialized surface treatment aimed at forming a protective coating with high adhesion strength. In this context, the present review critically examines modern aluminum anodizing technologies followed by the application of polymer and nanocomposite coatings.

Anodizing is an electrochemical process that generates a protective oxide layer on the aluminum surface, providing primary corrosion protection and serving as an adhesion-promoting substrate for the subsequent application of a polymer coating. It is well established that the morphology, porosity, and thickness of the aluminum oxide layer critically influence both the barrier protection efficiency and the adhesion properties of polymer coatings applied to the metal surface [16].

Polymer coatings, particularly fluoropolymer-based systems, exhibit high chemical inertness and a low coefficient of friction, enabling further improvement in surface resis-

tance in aggressive and abrasive environments. However, the strength of their adhesion to the oxide layer depends to a considerable extent on the surface modification method and deposition conditions [17,18].

Despite a growing body of literature on anodized aluminum combined with polymer coatings, several significant gaps remain that hinder the rational design and industrial implementation of such protective systems for oil and gas environments. First, quantitative adhesion data for many polymer systems (e.g., PTFE, fluorosilanes, epoxy) are scarce; most studies report only qualitative assessments such as “good adhesion”, and systematic comparisons under identical test conditions are lacking. Second, the long-term corrosion performance of combined anodized/polymer coatings in realistic oilfield environments—especially at elevated temperatures, in the presence of H_2S , and under abrasive conditions—is rarely documented, as available studies are typically limited to short-term salt spray or electrochemical tests spanning days to a few months. Third, the influence of aluminum alloy composition (e.g., high-copper 2xxx or Al-Si 6xxx series) on the quality of anodic oxide films and subsequent polymer adhesion remains poorly understood, leading to reproducibility issues and unexpected failures. Fourth, standardized testing protocols and performance benchmarks for combined coatings in sulfur- and chloride-containing media are absent, making cross-study comparison and technology selection difficult. These gaps are not merely academic; they directly impede the adoption of aluminum alloys in critical oil production and refining equipment where corrosion-resistant, lightweight materials are urgently needed.

The objective of this review is to summarize and critically discuss published data on the protection of aluminum alloys by anodizing combined with polymer and nanocomposite coatings in aggressive environments characteristic of oil production and refining. In pursuing this objective, the review considers how anodizing parameters (electrolyte composition, temperature, current and voltage regimes) influence the structure and properties of the anodic oxide layer, how the resulting oxide morphology is reported to affect the adhesion and durability of polymer coatings, and which types of surface pretreatments and polymer formulations are currently used to improve bonding at the oxide–polymer interface. Particular attention is given to corrosion behaviour in chloride-containing media and other service conditions typical of oilfield and refinery practice, so that the main unsolved problems and directions for further development of anodized aluminum/polymer coating systems can be identified.

2. Physicochemical Fundamentals of Aluminum Anodizing

2.1. Mechanism of Oxide Layer Formation

Anodizing is a conversion coating method for metal surfaces, in which aluminum atoms at the surface (Figure 1) react with electrolyte anions (oxygen), forming a porous aluminum oxide (Al_2O_3) film. Unlike electrodeposition, where the workpiece serves as the cathode, anodizing promotes oxidation reactions that lead to film growth.

The anodic oxide layer is commonly described as a two-layer system consisting of a compact barrier layer adjacent to the metal and an outer porous layer. An idealized model of anodic aluminum oxide is represented by hexagonally packed cells with central pores (Figure 1a). During anodizing under an applied electric field, two main stages can be distinguished [19]:

- Barrier-layer formation. At the initial stage of electrolysis, a thin, compact, and continuous oxide layer forms on the aluminum surface. This barrier layer is typically only a few nanometers thick, commonly about 2–3 nm (Figure 1b).
- Porous-layer growth. As anodizing proceeds, oxide growth at the metal/oxide interface and field-assisted oxide dissolution at the oxide/electrolyte interface occur

simultaneously. This results in pore nucleation and subsequent growth of a porous oxide layer. Depending on the anodizing parameters, pore diameters typically range from 10 to 100 nm, while pore depths may vary from approximately 1 to 20 μm (Figure 1c).

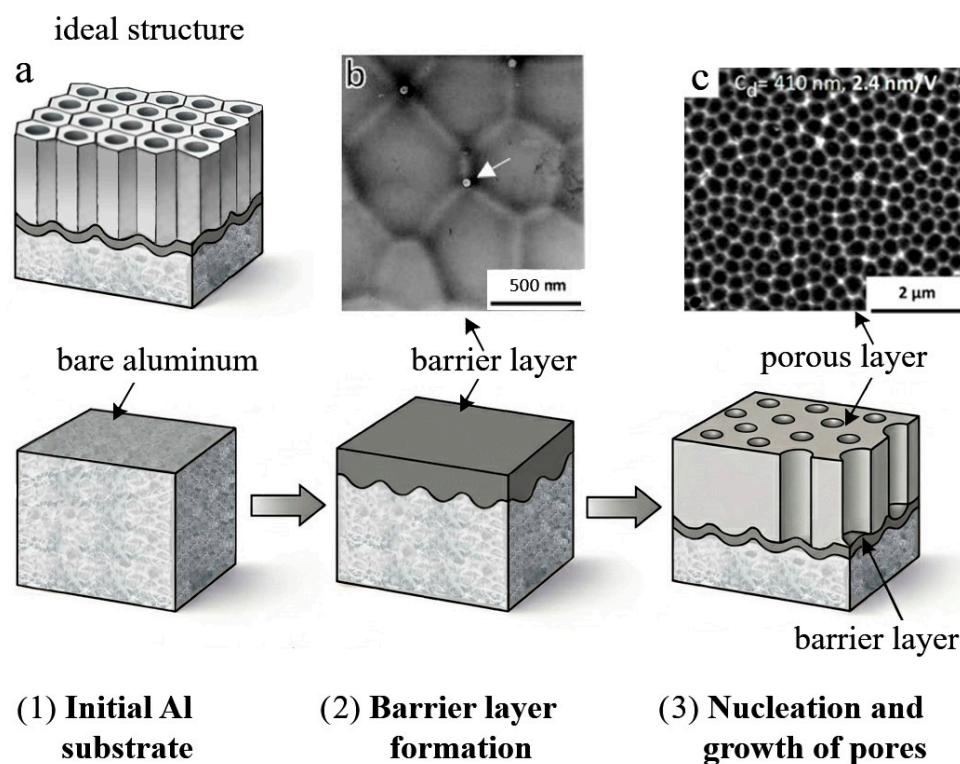


Figure 1. Structure of anodic aluminum oxide: (a) idealized porous-cell structure; (b) barrier layer, with the arrow indicating a pore-nucleation depression; (c) porous layer; (1) initial aluminum substrate; (2) barrier-layer formation; (3) nucleation and growth of pores. Compiled and adapted by the authors based on [20].

The key parameters influencing the characteristics of the oxide layer are:

- Electrolyte composition (sulfuric, chromic, or oxalic acid, concentration, presence of additives) [21,22];
- Bath temperature (typically 0–10 $^{\circ}\text{C}$ for hard anodizing and 18–25 $^{\circ}\text{C}$ for the standard sulfuric acid process) [23];
- Current density and voltage (increasing voltage increases film thickness and porosity) [24,25];
- Surface pretreatment: degreasing and etching (typically in an alkaline solution) remove organic contaminants and the native oxide, which is critical for uniform film growth [24,26].

The three most widely used anodizing processes are chromic, sulfuric acid, and hard anodizing, each producing a film of different thickness (from 5 to 18 μm for the standard sulfuric acid process and up to 100 μm for hard anodizing) and pore morphology [27].

Thus, anodizing is a multi-step process of converting the aluminum surface into a porous oxide film. Its final properties are determined by the interplay of electrolytic and electrochemical parameters, as well as the quality of surface pretreatment.

2.2. Effect of Electrolyte Composition and Temperature

Electrolyte composition and process temperature govern the morphology, structure, and protective properties of anodic aluminum oxide. The choice of acidic electrolyte, including sulfuric, oxalic, chromic, or phosphoric acid, determines pore diameter, barrier-layer

thickness, oxide dissolution rate, and the degree of ordering of the porous structure [28]. Sulfuric acid, the most widely used electrolyte, usually produces oxide films with high pore density and pore diameters of approximately 10–20 nm. Oxalic acid generally forms larger pores, up to approximately 40 nm at a forming voltage of about 40 V, and is often used when enhanced corrosion resistance is required [20,29].

Temperature controls ion-transport kinetics and the balance between oxide growth and oxide dissolution. During anodizing in oxalic acid, increasing the temperature in the range of 35–50 °C significantly changes the nanostructure and pore ordering [23]. For aluminum alloy 6061, anodizing at 5 °C produces a uniform fine-porous structure, whereas treatment at 25 °C results in a looser, coral-like morphology and greater film thickness [30].

Substrate temperature also affects electrochemical oxidation and the ordering of the porous oxide structure [31]. At a constant electrolyte temperature, an increase in electrode temperature may reduce oxide-film thickness because of intensified oxide dissolution and changes in heat dissipation within the specimen.

Overall, the reviewed studies indicate that electrolyte composition and temperature are the main parameters used to adjust pore size, film thickness, compactness, and surface morphology of anodic aluminum oxide.

2.3. Current and Voltage Regimes

Current density and applied voltage are fundamental parameters that govern the thickness, microstructure, and service properties of the anodic oxide layer on aluminum [32,33]. Using alloy 6061 as an example, it has been established that increasing the voltage in the range of 20–28 V at a constant current of 2 A leads to a decrease in surface microhardness from 59.117 to 57.718 HV 0.3. This decline is attributed to enhanced dissolution of the oxide layer and changes in pore morphology at higher voltages [34].

In industrial anodizing practice, an empirical relationship is widely used, according to which the oxide layer thickness is approximately 0.3–0.4 times the product of current density (A/dm^2) and anodizing time (minutes). The specific value of the coefficient depends on the electrolyte composition. This relationship enables preliminary estimation of the film thickness and ensures process reproducibility. For example, at a current density of $1.3 \text{ A}/\text{dm}^2$, a film thickness of 25 μm requires 60 min, whereas at $4.3 \text{ A}/\text{dm}^2$ the same thickness is achieved in 18 min [32].

Hard anodizing is characterized by higher current densities of 2.5–4 A/dm^2 at reduced electrolyte temperatures from 0 to -5°C , which ensures the formation of a dense oxide layer 25–150 μm thick with a microhardness of up to 500 HV 0.05. It has been shown that the anodizing parameters for alloy EN AW-5251 determine the thickness and roughness of the Al_2O_3 layers formed, and also influence their tribological characteristics [35].

A mathematical description of the dependence of anodic potential on current density under steady-state aluminum anodizing conditions adequately characterizes the current–voltage parameters of the process. The use of such a computational approach makes it possible to select process regimes for obtaining oxide layers with the required service properties [36].

Taken together, these data show that current density and voltage are practical parameters for controlling oxide thickness, pore morphology, roughness, and mechanical properties of anodic aluminum oxide.

2.4. Morphology, Porosity, and Film Thickness

A native oxide film forms spontaneously on aluminum upon exposure to air; however, this film is thin, non-uniform, and insufficient for reliable protection in aggressive environments. As a result, non-anodized aluminum alloys may undergo localized corrosion under humid, chloride-containing, or industrial service conditions. Examples of such

damage are shown and schematically illustrated in Figure 2. Cast tunnel fan blades made of EN AC-48000 alloy (AlSi12CuMgNi) suffered stress-corrosion cracking, with cracks up to 13 mm deep in the mounting area, due to wedging stresses generated by corrosion products in the gap between the blade root and the mounting blocks under a humid road-tunnel atmosphere with chloride-containing deposits [37]. Aluminum tubes in heat exchangers used for electric motors at a hydrocarbon gas-processing terminal experienced intense pitting and intergranular corrosion at the protruding tube ends. This degradation was attributed to cyclic wetting and drying caused by salt-containing inlet air from a marine environment, which led to the formation of a concentrated aluminum chloride solution with a pH of approximately 3.5 [38].

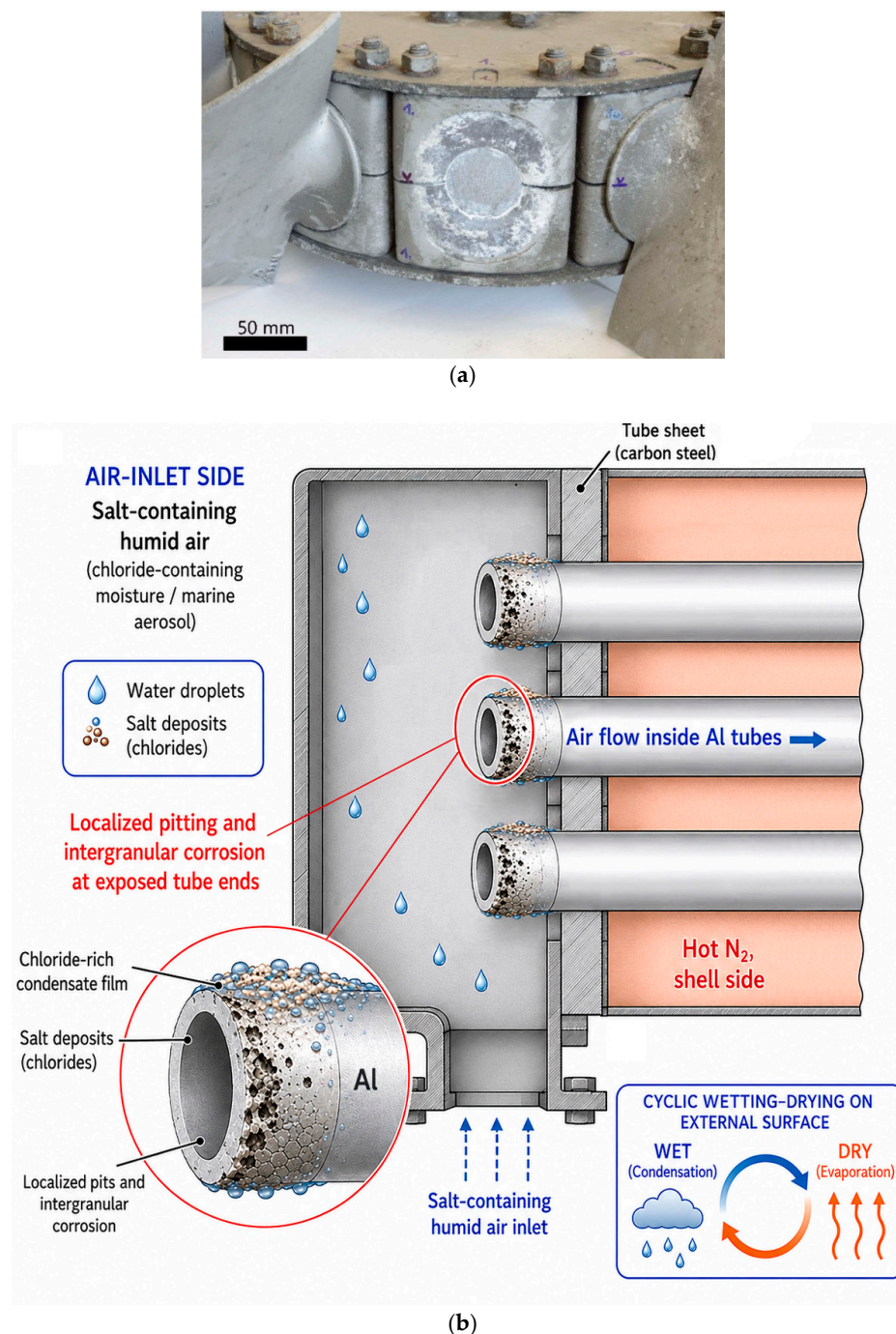


Figure 2. Examples of corrosion damage in aluminum alloy components exposed to humid industrial environments: (a) damaged section of a tunnel ventilation fan blade [37]; (b) schematic illustration of

corrosion damage at tube ends of an industrial aluminum heat exchanger used at a hydrocarbon gas-processing terminal, based on the case reported in [38]. Note: Figure 2b was created with the assistance of OpenAI 4o Image Generation. The AI tool was used to improve the visual presentation of the authors' schematic; the final figure was checked and revised by the authors.

The morphology of anodic aluminum oxide (AAO) films is characterized by a porous structure with cylindrical pores oriented approximately perpendicular to the substrate surface. The structural parameters of this porous layer are mainly governed by electrolyte composition, applied voltage, and process temperature [39]. At the same anodizing voltage of 20 V, sulfuric acid electrolyte produces pores with an average diameter of 12.3 ± 0.1 nm, whereas oxalate electrolyte increases the pore diameter to 14.8 ± 0.1 nm [40].

Atomic force microscopy studies of anodizing in phosphoric acid show a stepwise transformation of the aluminum surface. At the initial stage, surface ridges are formed; at an intermediate stage, they develop into a continuous phosphate-containing layer; and under steady-state conditions, this layer evolves into a developed porous structure [41]. These observations confirm that the final oxide morphology is the result of simultaneous oxide growth, dissolution, and structural reorganization at the oxide/electrolyte interface.

Film thickness varies over a wide range depending on process conditions. At current densities of 1–2 A/dm², coating thickness typically ranges from 5 to 18 µm for conventional anodizing and may reach approximately 100 µm for hard anodizing. Increasing current density generally increases film thickness, whereas lowering the bath temperature promotes the formation of a denser oxide layer [42].

Porosity is one of the most important structural parameters controlling the adhesion of subsequent polymer coatings. Studies on Fe–Al system alloys have shown that porosity may vary from 42 to 72%, depending on electrolyte composition and applied voltage. Anodizing in aqueous electrolytes at 10–15 V produces self-ordered morphologies with pore diameters of 9–16 nm, which provide favorable conditions for polymer penetration and mechanical interlocking within the oxide layer [43].

This factor is particularly important for low-surface-energy polymers such as PTFE, for which strong chemical bonding to oxide surfaces is generally weak. In such systems, adhesion is largely governed by physical penetration of the polymer or polymer particles into the porous anodic layer, followed by mechanical interlocking after curing or consolidation. Therefore, controlled pore morphology is especially important for fluoropolymer-containing coatings, where the anodic oxide layer acts not only as a corrosion-resistant barrier, but also as a mechanical anchoring framework.

Two-step anodizing provides additional control over pore diameter, periodicity, and distribution density. A more ordered porous architecture is favorable for uniform polymer penetration, stable mechanical anchoring, and reproducible protective performance of combined anodic oxide/polymer coating systems.

Taken together, the reviewed studies show that morphology, porosity, and film thickness are not only structural characteristics of anodic aluminum oxide, but also key parameters determining its suitability as an adhesion-promoting substrate for subsequent polymer and nanocomposite coatings.

3. Characteristics of Polymer Coatings

3.1. Types of Polymers

A wide range of polymer and polymer-based coatings are employed to improve the hydrophobicity, chemical stability, tribological performance, and barrier protection of anodized aluminum. The most widely used polymer materials include polytetrafluoroethylene (PTFE), polydimethylsiloxane (PDMS), epoxy resins, and various types of fluorosilanes. These coatings should not be considered as stand-alone organic barriers;

their effectiveness depends on the combination of polymer chemistry, the morphology and mechanical integrity of the anodic oxide layer, and, where necessary, adhesion-promoting surface modifiers [44].

Changes in the anodizing regime and subsequent surface modification with polymeric and nanocomposite formulations significantly affect the wettability of anodized aluminum, as clearly shown in Figure 3.

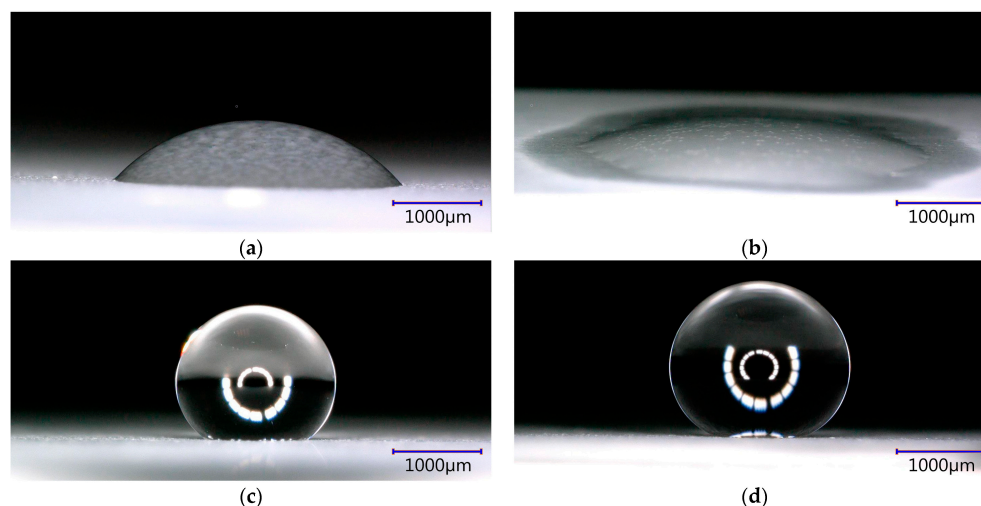


Figure 3. Wettability of specimen obtained during: (a) basic anodization process—Series Hydrophilic; (b) anodization at an increased voltage and extended time; (c) anodization at an increased voltage and extended time, and after impregnation by PDMS—Series Hydrophobic; and (d) anodization at an increased voltage and extended time, and after coating with epoxy resin, SiO₂ nanopowder and PDMS—Series Superhydrophobic [44].

PTFE coatings are relevant because they combine high chemical inertness, low surface energy, and a low coefficient of friction, which is important for surfaces exposed to corrosive media and abrasive or sliding contact. However, PTFE is not an intrinsically strongly adhesive polymer; strong chemical bonding to oxide surfaces is generally weak. Therefore, in anodized aluminum systems, its retention is mainly associated with penetration of PTFE particles or polymer into the porous oxide layer and subsequent mechanical interlocking. The incorporation of PTFE particles into anodic aluminum oxide has been reported to improve wear resistance. Two-step anodizing in oxalic acid followed by electrophoretic deposition of PTFE yields a contact angle of 139°, whereas PTFE spraying onto a hard-anodized surface produces coatings with a contact angle of up to 165° [44,45]. Recent data on fluoroplastic coatings used in hydrocarbon transportation systems also support the practical relevance of fluoropolymer coatings under demanding service conditions: such coatings require special substrate preparation because of their low intrinsic adhesion, but they can provide high elasticity, impact resistance at negative temperatures, and low surface roughness compared with epoxy coatings [46].

The use of hard-anodized aluminum as a substrate for polymer antifouling coatings based on non-toxic and environmentally safe materials provides high operational reliability in marine environments. Such composite systems are characterized by a pronounced ability to suppress biofouling while maintaining environmental safety [47].

Fluorosilanes are of particular interest for the development of superhydrophobic coatings. It has been shown that coatings based on 1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane (PFODA), after additional etching in phosphoric acid, achieve a contact angle of 161.5°, while the use of perfluorodecyltrimethoxysilane (FDTS) yields a value of 146°, confirming

the high effectiveness of fluorine-containing organosilanes for surface modification of anodized aluminum [44].

A technology exists for synthesizing a polypyrrole–aluminum oxide nanocomposite film on the aluminum surface. A protective composite film with improved barrier properties was obtained by electrochemical synthesis under galvanostatic oxidation conditions on top of a porous aluminum oxide film. IR spectroscopy confirmed the presence of characteristic stretching vibration bands of polypyrrole: peaks at 772, 811, and 920 cm^{-1} correspond to C–H vibrations, peaks at 1558 and 1487 cm^{-1} to C=C vibrations, and peaks at 1686 and 1315 cm^{-1} to C=N and C–N vibrations, respectively [48].

3.2. Methods of Polymer Coating Application

The choice of method for applying a polymer coating to anodized aluminum determines the adhesion quality, uniformity of distribution, and service characteristics of the final system. The principal technologies for applying polymers to a porous anodized surface include impregnation, spin coating, spraying, and electrophoretic deposition [44].

Impregnation is the most widely used industrial method for introducing polymers into the porous structure of anodized aluminum. In this method, parts are immersed in a polymer solution or melt, which penetrates the pores of the oxide film under capillary forces. The effectiveness of impregnation depends on pore size, pore density, and the depth of polymer penetration. Typical solvents include ethanol for silanes, toluene for PDMS, and specialized suspensions for PTFE [49].

Electrophoretic deposition (EPD) is a promising method for applying polymer coatings under the action of an electric field. Pulsed cathodic electrophoretic deposition (Pulsed-CEPD) has been developed for sealing and silanization of unsealed anodized aluminum alloy AA2024 from a silane–ethanol–water suspension [50]. The different mechanisms of cathodic and anodic EPD of charged biopolymers can be adapted for the application of functional polymer coatings onto anodized surfaces [51].

Spin coating yields uniform thin polymer films on a pre-modified anodized surface. Two-step anodizing in oxalic acid followed by spin coating of a PTFE solution achieves a contact angle of 139° [44].

Polymer spraying onto anodized surfaces can be carried out by various methods. Spraying of PTFE onto hard-anodized aluminum produces coatings with a contact angle of up to 165°. Electrostatic spraying is widely used in industry due to its high material transfer efficiency and ability to form a uniform layer. Powder coating is also employed, in which electrostatically charged polymer powder is applied to the anodized surface followed by thermal curing [44].

Dip coating is used for complete coverage of complex-profile parts, including hard-to-reach areas. It is particularly convenient for mass production of small articles, as it allows batch processing and ensures uniform coating of the entire part surface. The coating thickness is controlled by adjusting the withdrawal speed of the specimen [52].

In addition to individual technologies, combined approaches are also used, notably TUFRAM® and LECTROFLUOR®. In the TUFRAM® process, polymer particles are incorporated into the ceramic oxide layer, imparting self-lubricating properties to the surface while maintaining high hardness and wear resistance. The LECTROFLUOR® technology combines anodizing with controlled introduction of polymers into the porous oxide structure, thereby enhancing corrosion resistance and reducing the coefficient of friction [53].

3.3. Adhesion to the Oxide Layer and Surface Modification

The adhesion quality of polymer coatings to anodized aluminum is governed by a combination of mechanical anchoring within the porous oxide structure and chemical

interactions at the oxide–polymer interface. Therefore, adhesion cannot be attributed to the polymer deposition method alone. It depends on the complete interfacial system, including pore diameter, pore density, oxide thickness, surface hydroxylation, polymer viscosity, curing conditions, and the testing protocol used.

Mechanical anchoring occurs when a polymer, adhesive, or polymer-containing formulation penetrates into the pores of the anodic oxide layer and is subsequently fixed after curing, cooling, or consolidation. Phosphoric acid anodizing is particularly relevant in this respect because it can produce relatively large pores and a porous morphology suitable for polymer penetration. The depth and completeness of polymer penetration are controlled by pore size, pore geometry, pore connectivity, and the rheological properties of the polymer phase [54].

Chemical interactions at the interface are provided by functional groups present on the oxide surface and in the polymer. A modified anodizing process with an electroactive polymer added to the electrolyte enables the formation of composite polymer–oxide films. The retention within the oxide structure of organic moieties capable of undergoing electrophilic addition reactions with subsequent polymer layers allows the formation of stable intermediate bonds [55]. Surface modification with silanes is also a widely used method for improving adhesion. Organosilane coupling agents containing methoxy, ethoxy, or hydroxyl groups can adsorb onto the metal oxide surface through hydrogen bonding. Upon curing, metal–siloxane bonds (Al–O–Si) are formed, which are significantly stronger than hydrogen bonds [56].

To provide a clearer quantitative comparison, representative adhesion and bonding-strength data for metal–polymer systems relevant to anodized-aluminum/polymer coating design are summarized in Table 1. These values should be compared cautiously because they were obtained for different substrates, polymers, application routes, and test protocols. The example involving a steel/fluoroplastic system is included only to illustrate the general principle that fluoroplastic coatings require a mechanically developed or chemically prepared surface, which is also relevant to the design of fluoropolymer-containing coatings on porous anodic aluminum oxide. Nevertheless, the data demonstrate the same general trend: adhesion improves when a smooth metal surface is transformed into a porous or chemically modified interface capable of polymer penetration and stronger interfacial bonding.

The data in Table 1 show that anodizing and pore widening can increase adhesion from 5.0 MPa to 17.4 MPa, while chemical treatment of aluminum can provide lap-shear strength above 20 MPa and retain most of this value after humid aging. These results support the view that the adhesion of polymer coatings to aluminum is controlled by both oxide morphology and interfacial chemistry.

For PTFE and related fluoropolymer-containing coatings, comparable pull-off, peel, or lap-shear data for systems based on anodized aluminum are rarely reported in a standardized manner. This is mainly associated with the low surface energy and weak chemical affinity of PTFE to oxide surfaces. Therefore, fluoropolymer retention on anodized aluminum should be associated primarily with mechanical anchoring inside the porous oxide layer rather than with intrinsically strong chemical bonding. Available studies on fluoroplastic coatings for metal substrates confirm that reliable performance requires a mechanically developed or chemically prepared surface, which supports the use of hard porous anodic oxide as an anchoring framework for fluoropolymer-containing coatings. This lack of systematic adhesion data for fluoropolymer/anodic oxide systems remains a research gap that should be addressed in future work.

Table 1. Representative quantitative adhesion and bonding-strength data for metal–polymer systems.

System/Deposition Route	Surface Modification	Test/Indicator	Reported Value	Ref.
A6063–polyamide/hot-press bonding	No anodizing	Lap-shear strength	5.0 MPa	[57]
A6063–polyamide/hot-press bonding	H ₃ PO ₄ anodizing at 60 V	Lap-shear strength	10.1 MPa	[57]
A6063–polyamide/hot-press bonding	H ₃ PO ₄ anodizing at 60 V + pore widening to $\approx$ 166 nm	Lap-shear strength	17.4 MPa	[57]
AlMg3–epoxy/adhesive bonding	H ₂ O ₂ -assisted cerium-based chemical treatment	Single lap-shear strength	22.5 $\pm$ 0.5 MPa before aging; 18.1 $\pm$ 0.2 MPa after aging at 70 °C and 100% RH for 4 weeks	[56]
Anodized Al–PBT/injection molding	H ₃ PO ₄ –H ₂ O ₂ anodizing with enlarged nanopores and 3D-channeling morphology	Bonding strength	up to 40.34 MPa	[58]
Anodized Al–polymer resin/3D printing	H ₃ PO ₄ –H ₂ O ₂ anodizing with enlarged nanopores	Bonding strength	4.90 $\rightarrow$ 8.50 MPa	[58]
Steel–fluoroplastic coating/pneumatic spraying	Laser texturing + cold phosphatizing	Pull-off adhesion	4.65 MPa for untreated steel; 7.45–8.32 MPa after treatment	[46]
PTFE- or fluoropolymer-containing systems on anodized Al	Porous anodic oxide; pore filling or mechanical anchoring	Standardized pull-off, peel, or lap-shear data	Not consistently available	[44,45]

Note: The steel/fluoroplastic example is included only to illustrate the general principle that fluoroplastic coatings require a mechanically developed or chemically prepared surface because of their low intrinsic adhesion to metals. For PTFE- or fluoropolymer-containing systems on anodized aluminum, most studies report wettability, friction, wear, or coating retention rather than comparable standardized adhesion values. The arrow indicates an increase in bonding strength after surface modification.

Thus, surface modification of anodized aluminum should be designed to combine two functions: formation of a mechanically stable porous oxide layer for polymer anchoring and creation of chemically active interfacial sites for stronger bonding. The available quantitative data indicate that controlled pore morphology can increase adhesion by a factor of approximately 3–4, while optimized chemical treatment or polymer penetration into a developed anodic structure can produce adhesion or bonding strengths above 20 MPa. These values provide practical benchmarks for the design of combined anodic oxide/polymer coatings intended for aggressive environments.

3.4. Corrosion Protection Mechanisms

The protective performance of polymer coatings on anodized aluminum is ensured by a combination of barrier effects, controlled permeability to aggressive ions, and, in some cases, active protection provided by functional additives.

Barrier protection is the primary mechanism of corrosion resistance for polymer coatings. The anodized layer forms a primary barrier, while the polymer coating provides an additional protective layer that hinders the diffusion of aggressive ions to the metal surface [59]. Studies indicate that the main reason for the anticorrosion properties of polymer coatings on aluminum is the obstruction of chloride-ion diffusion to the surface, which is often the rate-limiting step of the corrosion reaction [60–62].

Active anticorrosion protection can be achieved by incorporating functional electrically conducting polymers into the coating. Despite the natural tendency of aluminum to passivate, its protective characteristics can be significantly enhanced. In particular, polyani-

line (PANI), due to its high redox potential, induces anodic polarization of the aluminum substrate, shifting its steady-state potential into the region of stable passivation [63].

However, this active protection mechanism is effective only if a dense, continuous passive layer at the phase boundary is maintained. In media with extreme pH values or high concentrations of aggressive ions (e.g., chlorides), the oxide film becomes destabilized. Under such conditions, the high electrical conductivity and cathodic character of PANI relative to aluminum lead to the formation of galvanic macro-couples, which accelerates localized corrosion of exposed metal [63].

These risks can be mitigated by introducing specialized additives and inhibitors, justifying the use of PANI for the development of adaptive, stimulus-responsive (“smart”) protective systems operated in aggressive environments. Active protection can also be achieved in PANI-free polymer matrices by forming a percolating conductive network from other electroactive components. Nevertheless, during long-term exposure under harsh conditions (e.g., in 1 M NaCl solution), the oxidative capacity of the conductive components is gradually depleted, and the protection mechanism reverts to a purely barrier one [60].

Utilizing nanopores in the anodic aluminum oxide film as reservoirs for a corrosion inhibitor provides self-healing of protective properties in the event of local coating damage [64].

Superhydrophobic coatings on anodized aluminum maintain high corrosion inhibition efficiency even after the loss of superhydrophobic behavior. In this case, the porous structure remains covered by a protective layer of epoxy resin and SiO₂ nanoparticles, which hinders electrolyte penetration into the porous coating [44].

Long-term natural-exposure tests show that hydrophobic coatings obtained by impregnating porous anodized aluminum with silicone do not possess sufficient durability, in contrast to superhydrophobic coatings. Prolonged environmental exposure leads to leaching of the impregnation from the pores of the hydrophobic coating, after which all types of contaminants adhere more readily to the porous structure [44].

4. Behavior of Combined Coatings in Aggressive Environments

4.1. Corrosion Testing Under Standardized Conditions

Standardized corrosion testing methods, including salt spray testing, electrochemical impedance spectroscopy (EIS), and potentiodynamic polarization, are widely used to evaluate the protective properties of combined polymer–oxide systems on aluminum.

Salt spray testing according to ASTM B117 is the most common method of accelerated corrosion testing. Anodizing in a mixed tartrate–sulfate electrolyte increases the resistance of the anodic oxide to galvanic stress and aggressive environments compared with sulfate anodizing. Under these conditions, anodized aluminum panels with a coating thickness of 20 µm (Class I—highest architectural class according to the Aluminum Association) show virtually no damage after 1000 h of salt spray exposure, whereas coatings 6 µm thick exhibit pronounced pitting corrosion [33].

Combined coatings (hard anodizing + hard coating and hard anodizing + sealing) with thicknesses of 25–100 µm demonstrate high corrosion resistance, with no pitting corrosion observed after 336 h of salt spray testing [64]. The latter system is the most corrosion-resistant owing to the synergistic effect of the anodic oxide and the polymer layer. Such coatings comply with the U.S. military standard MIL-PRF-8625 [65] and meet the requirements of GOST 9.031-74 [66].

Electrochemical impedance spectroscopy provides a quantitative assessment of coating corrosion resistance. It is known that an anodic oxide layer formed in a sulfuric acid electrolyte significantly improves the corrosion resistance of alloy 6061 in seawater. According to Nyquist plots [67], the polarization resistance of the alloy after anodizing increases by roughly two orders of magnitude—from 17.2 kΩ·cm² to 2.24 MΩ·cm².

Comprehensive evaluation of the corrosion resistance of anodic oxide coatings on aluminum alloys using standardized climatic chambers, immersion tests, and electrochemical methods shows that impedance testing is a fast and convenient way to verify the quality of the anodic oxide layer [68]. Impedance spectra make it possible to quantify the protective properties of anodized coatings on alloys 1163, V96Ts3pch, and V-1461 in 3% NaCl solution over 24 h and to predict the time to onset of corrosion damage [69]. Analysis of the impedance spectra of anodic oxide coatings using an equivalent-circuit model shows that changes in the capacitive parameter of a constant phase element associated with the porous layer, i.e., its pseudo-capacitance, can be used to evaluate the protective state of the coating during corrosion testing [68].

Study of the electrochemical behavior and corrosion mechanisms of anodized aluminum alloy 7B04 during immersion in an acidic NaCl solution ($\text{pH} = 3.5$) and salt spray testing confirms that anodizing significantly increases corrosion resistance in acidic chloride environments [70].

Bubble testing is an accelerated method for evaluating coating resistance in acidic media. In this test, a 5% HCl solution is placed in a tube on the anodized specimen, and the time from the start of the test to the moment the acid reaches the base aluminum (indicated by bubble formation) serves as a measure of corrosion resistance. Typical results for standard anodized coatings are around 30 min, which confirms their limited protective capacity [71].

4.2. Long-Term Testing and Wear Resistance

The durability of polymer coatings applied to anodized aluminum is evaluated in terms of their wear resistance, resistance to abrasive action, and ability to retain protective properties under service conditions. Standardized methods are used for quantitative assessment of wear resistance, including Taber abrasion tests, the Ball-on-Flat scheme, and macro- and micro-scratch testing under controlled load [72,73].

Taber abrasion testing is the principal method for quantitative evaluation of the wear resistance of anodized coatings. According to MIL-PRF-8625, the maximum Taber wear index for hard-anodized coatings must not exceed 1.5 mg/1000 cycles, and for alloys with Cu content greater than 2% it must not exceed 3.5 mg/1000 cycles. Tests are carried out using a Taber abraser, which generates a combination of rolling and sliding that causes wear of the specimen surface. The microhardness of hard-anodized coatings has a pronounced effect on the test results and the Taber index [73].

Mechanical property studies show that hard-anodized coatings significantly outperform conventional anodic films in terms of hardness and wear resistance. For hard anodizing of aluminum alloys in sulfuric electrolytes at reduced temperature, typical microhardness values are on the order of 250–400 HV, whereas for conventional anodic coatings they are much lower, in the range of 60–96 HV. On alloys 6061-T6 and 7075-T6, the hard-anodized layer is formed more densely, which provides markedly higher resistance to abrasive and sliding wear [74]. For alloy 6061-T6, wear after 50,000 cycles is half that of cyanide-hardened steel [65].

Macro-scratch testing under controlled load makes it possible to quantify the adhesive and cohesive strength of coatings. Optimization of the anodizing regime plays a critical role in improving the mechanical characteristics and scratch resistance of the oxide layer. Appropriate selection of process parameters allows the critical load to be increased from 37.3 N for a baseline regime to 118.9 N. Scratch testing makes it possible to detect adhesion and cohesion defects in the coating system before the components are put into actual service [75].

The long-term stability of polymer coatings under natural conditions depends on their type and method of application. Hydrophobic coatings obtained by impregnating porous anodized aluminum with silicone do not possess sufficient durability, in contrast to superhydrophobic coatings. Prolonged exposure to natural environments leads to leaching of the impregnation from the pores, after which contaminants adhere more readily to the exposed porous structure [44].

A hard-anodized surface with high abrasion resistance can serve as an optimal sublayer for a polymer film, providing the mechanical properties required for use as an antifouling coating in marine environments. The combination of an anodized layer and a polymer coating produces a synergistic protective effect [47].

A two-step anodizing can be used to form nanoporous anodic aluminum oxide (AAO) layers on aluminum substrates with controlled surface morphology, hardness, and abrasion resistance [72]. The use of oxalic acid in anodizing allows the production of membranes with higher flexibility, hardness, and abrasion resistance compared with membranes formed in sulfuric acid [49].

Hard-anodized layers 25–60 μm thick provide high resistance to abrasion [74]. Hard-anodized layers on alloys 6061 and 7075 show substantially lower mass loss than unanodized substrates and, in some cases, even outperform traditional protective systems, including hard chrome [76]. However, as coating thickness increases for certain aluminum alloys (notably those in the 2000 series and especially the 7000 series), the wear index also increases, indicating the need to optimize anodizing conditions for each specific alloy [77]. In combination with polymer impregnations and silane-based sealing systems, such coatings exhibit enhanced resistance to mechanical and chemical stresses in service, as confirmed by long-term testing [44,78].

At the same time, an increase in applied load, as well as an unfavorable microstructure of the oxide layer, can cause a transition from moderate abrasive wear to accelerated coating failure. This highlights the need to consider not only the thickness and microhardness of the layer, but also its porosity, defectiveness, and ability to retain lubricating or modifying additives.

The durability of hard protective layers is also influenced by the distribution of residual and service-related thermomechanical stresses in the coating–substrate system. Finite-element modeling of a TiN coating on a steel substrate has shown that a combination of differing thermal expansion coefficients and elastic moduli leads to high radial and circumferential stresses in the layer during thermal cycling, which significantly affects the risk of cracking and delamination [79]. A similar approach can be used for quantitative assessment of the stress state in anodic aluminum oxide/polymer systems.

In this context, long-term testing should be regarded not as a purely formal verification of wear resistance but as a tool for identifying the operating limits of the “anodic layer–polymer coating” system under realistic mechanical and tribological loads.

5. Alternative Protection Methods

Combined anodized aluminum–polymer coatings offer a distinctive combination of corrosion resistance, wear performance, and adhesion that is not matched by any single alternative method. A comparative analysis with alternative protection methods makes it possible to evaluate more clearly the advantages and limitations of this approach under conditions typical of oil production and oil refining. For convenience of comparison, the main characteristics of the most relevant alternative methods are summarized in Table 2.

Table 2. Comparison of alternative protection methods with the “anodized aluminum + polymer coating” system.

Alternative Method	Protection Mechanism and Key Properties	Main Limitations	Performance in Oil Production/Refining Environments	Comparison with the “Anodizing + Polymer” System	Ref.
Chromating (Cr6+)	Passivation with partial self-healing; benchmark corrosion protection	Toxicity, legislative restrictions, limited wear resistance, disposal costs	Use in hot chloride–sulfide media requires additional evaluation	Less environmentally acceptable; weaker corrosion–wear balance	[80]
Powder coatings	Thick organic barrier layer, chemical resistance, decorative finish	Chipping, delamination without pretreatment, dimensional change	May degrade under thermal cycling, mechanical damage, and abrasive wear	Lower adhesion reliability and dimensional precision	[81]
Plasma electrolytic oxidation (PEO)	Ceramic-like layer with high hardness, wear and corrosion resistance	High roughness, open porosity, high energy consumption, sealing required	Open porosity may promote electrolyte penetration if unsealed	Harder, but less suitable for uniform polymer impregnation	[82]
Lithium conversion coatings	Active protection; environmentally safer chromate alternative	Limited long-term data, low wear resistance, developing technology	Data for H ₂ S, cyclic temperature, and abrasive media remain scarce	Promising, but less proven for combined corrosion–wear protection	[83]
Zinc or zinc–polymer coatings for steel	Cathodic/barrier protection and self-healing for steel	Not directly applicable to aluminum; galvanic compatibility issues	Produced water may increase galvanic risk in steel–Al assemblies	Not a direct alternative for aluminum components	[84]

As follows from the data summarized in Table 2, no single alternative method provides the same balance of corrosion resistance, wear resistance, adhesion, dimensional stability, and environmental acceptability as the anodizing + polymer system. Chromate-based treatments remain effective in terms of passivation, but are constrained by toxicity and regulatory pressure, whereas powder coatings and plasma electrolytic oxidation each exhibit important technological limitations in aggressive oilfield service. Lithium conversion coatings are promising from an environmental standpoint, but still do not provide a comparable level of long-term durability. At the same time, comparative studies of sealed anodic aluminum layers produced with different electrocoloring methods indicate that combined systems outperform single-layer coatings in long-term tests [85–87].

Thus, the best protection of aluminum alloys is achieved by systems that integrate several complementary mechanisms, in which the barrier function of the anodic oxide layer is combined with the chemical resistance of the polymer and its mechanical anchoring within the porous structure.

6. Critical Analysis and Identification of Gaps

Analysis of current studies on aluminum anodizing with polymer coatings reveals a number of significant limitations and gaps that hinder process optimization and large-scale industrial implementation in aggressive environments of the oil industry [60].

One of the main features of existing research is the lack of data on the long-term service behavior of combined polymer coatings on aluminum. For example, waterborne acrylic coatings provide good barrier protection at the initial stage of immersion in 3.5% (0.62 M) NaCl but over time lose adhesion and protective properties due to electrolyte penetration and underfilm corrosion [60]. Similar results have been obtained for waterborne epoxy coatings, where a gradual deterioration of barrier performance in 1 M NaCl is observed, accompanied by blister formation and loss of adhesion to the metallic substrate [88]. Most

studies are limited to short-term tests ranging from several days to a few months, which is insufficient for predicting coating behavior over many years of service under oil production and refining conditions.

Conflicting data regarding the mechanisms of porous structure formation introduce additional challenges for process optimization. The exact mechanism of pore formation has been debated in the scientific community for decades. It has been established that the field-assisted dissolution hypothesis is not universal and does not fully describe pore initiation in most inorganic acids under the conditions typically used for AAO formation. According to current views, plastic flow of the material under the stresses arising in the growing oxide layer (the field-assisted flow theory) plays the dominant role in pore formation. Nevertheless, the dependence of this mechanism on the type of electrolyte used complicates the development of unified approaches to controlling coating morphology.

Existing standardized evaluation methods do not adequately account for the complex interactions between pore structure, oxide morphology, and polymer coating properties. Quality control of anodized coatings is considerably more challenging than for traditional protection methods. Moderate variations in pore structure lead to property changes that are not always captured by standard tests but affect polymer adhesion and the long-term durability of the system as a whole.

Insufficient understanding of the influence of aluminum alloy composition on the quality of combined coatings poses a serious problem for practical applications. For Al–Si alloys or aluminum alloys with high copper content, the oxide film is difficult to form, and the resulting film is dark and exhibits poor adhesion. At the same time, the chemical composition, structure, and homogeneity of the metallic phase have a critical impact on oxide film formation, yet systematic studies of these dependencies for various alloys used in the oil industry are lacking.

Reproducibility issues in anodizing results create additional barriers to industrial adoption. Various process failures during sulfuric acid anodizing can lead to areas without oxide film, visible surface defects, and the formation of a non-uniform porous structure. These issues are particularly critical when polymer coatings are applied, since defects in the oxide layer act as stress concentrators and initiation sites for corrosion processes.

7. Prospects and Future Research Directions

Current trends in the development of combined anodized aluminum/polymer coatings highlight several promising directions that could significantly expand the application of these systems in oil, gas, hydrogen, and other aggressive environments.

One such direction is the use of the porous structure of anodic aluminum oxide as a platform for forming functional polymer layers. Figure 4 shows an example of a composite system of the DA+PSBMA-AAO type, in which polymer retention on the pore surface is ensured by a combination of specific intermolecular interactions. This approach illustrates the general principle of constructing multilayer systems of the “anodic oxide + functional polymer layer with controlled adhesion” type, which can be adapted for combined protection of aluminum structures in aggressive oil production and refining environments [89].

Promising research avenues are associated with the development of economically efficient and scalable coating technologies, assessment of their environmental impact, and creation of multifunctional nanocomposite systems [90]. Of particular interest is the formation of multifunctional coatings, including triphasic systems on pretreated metallic substrates, which could potentially be adapted for aluminum materials as well [91].

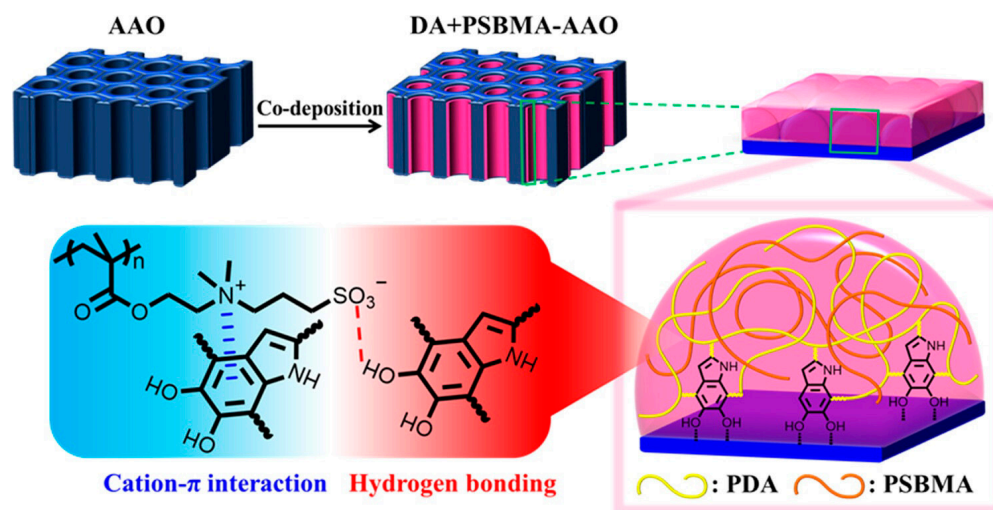


Figure 4. Surface modification of AAO membranes using PSBMA [89]. The blue and red shading schematically denotes the positively charged quaternary ammonium and negatively charged sulfonate groups of PSBMA, respectively.

Further development of “anodized aluminum/polymer” systems may be linked to the application of mathematical modeling and machine learning methods to predict service life of combined coatings and to select optimal anodizing regimes. A promising direction is the integration of existing models describing the relationship between voltage and current density during aluminum anodizing with neural-network approaches, which could potentially be used to predict oxide layer thickness and optimize process parameters. Additional opportunities arise from calculating the interpore spacing in anodic films based on porous oxide growth models, which in the future will allow more targeted tailoring of the oxide architecture for specific protection systems [36].

Integration of anodized coatings with intelligent polymer systems may provide the basis for adaptive protective coatings. In particular, the use of “smart” AAO membranes bearing grafted thermoresponsive polymer brushes, for example based on PNIPAM, potentially enables temperature-dependent control of permeability and ionic conductivity. Such systems are of interest for developing self-diagnosing coatings capable not only of adjusting their protective characteristics in response to external conditions, but also of indicating the onset of corrosion processes at an early stage [38]. Beyond material design, this direction also requires diagnostic tools capable of tracking corrosion kinetics in real time. Optical monitoring combined with computer-assisted image analysis can provide early indicators for predicting the onset and propagation of corrosion damage [92].

In biomedicine, biocompatible and antibacterial surfaces based on anodized coatings are already being developed. In the future, similar solutions may be adapted for the oil industry, for example to protect equipment against biofouling and deposits in water treatment systems [93].

The environmental focus of modern anodizing technologies implies a gradual phase-out of toxic components in favor of sustainable solutions. In particular, hybrid sol–gel coatings on anodized AA2024-T3 aluminum alloy are being considered as an effective alternative to traditional chromium-containing systems. Such combined layers provide enhanced corrosion resistance while fully eliminating the environmental risks associated with the use of hexavalent chromium compounds [43].

Another promising direction involves accounting for the degradation of mechanical and protective properties of polymer and combined coatings under extremely low temperatures, freeze–thaw cycling, and marine aerosol exposure—effects already demonstrated for polymer composite structures operated in Arctic and sub-Arctic conditions [94].

The industrial prospects of the technology are supported by market forecasts: the global aluminum anodizing market is expected to grow from 6.61 billion USD in 2025 to 9.12 billion USD by 2034, with a compound annual growth rate of 3.60%.

The development of nanotechnology and composite materials will contribute to the creation of more efficient and durable protection systems for extreme service conditions in the oil industry.

8. Conclusions

- a. A comprehensive consideration of the physicochemical fundamentals of oxide-layer formation, the characteristics of polymer coatings, and their behavior under corrosive conditions has made it possible to identify both the achievements and the current limitations of this technology.
- b. Analysis of the mechanisms of anodic oxide layer formation has shown that controlled adjustment of coating morphology, porosity, and thickness can be achieved by optimizing electrolysis parameters, including electrolyte composition and temperature, current density, and voltage. In this context, two-step anodizing provides the highest structural ordering and reproducibility of results.
- c. Characterization of polymer coatings has demonstrated the broad applicability of various polymer systems, ranging from simple silicone impregnations to complex nanocomposite materials based on PTFE and functional silanes. The most promising approaches are combined schemes involving surface modification of the oxide layer with organosilanes, which provide both mechanical anchoring and chemical interaction at the phase boundary.
- d. Corrosion tests of combined coatings under standardized conditions have shown their superiority over single-layer systems.
- e. Comparative analysis with alternative protection methods has revealed that combined “anodizing/polymer” systems possess a number of competitive advantages, including environmental safety compared with chromate coatings, higher dimensional accuracy relative to powder coatings, and improved long-term stability in aggressive environments. Their economic efficiency is due to an extended service life that compensates for higher initial costs.
- f. Critical analysis has revealed significant gaps in current research, including a lack of data on long-term performance under real service conditions, conflicting data on pore-formation mechanisms, and the limited capability of standardized evaluation methods. A particularly important issue is the insufficient understanding of how the chemical composition of aluminum alloys affects the quality of combined coatings, which is crucial for practical applications in the oil industry.

To facilitate the rational design of combined protective coatings, the key relationships identified in this review are summarized in a conceptual model (Figure 5) that links process parameters, coating structure, and performance with degradation-driven optimization, targeting aluminum alloys operating in aggressive oil production and refining environments.

Based on the systematic analysis and synthesis of the results obtained in this study, combined anodized aluminum/polymer coatings can be regarded as a promising and effective alternative to traditional protection systems, which in turn highlights the need for further fundamental and applied research in this area.

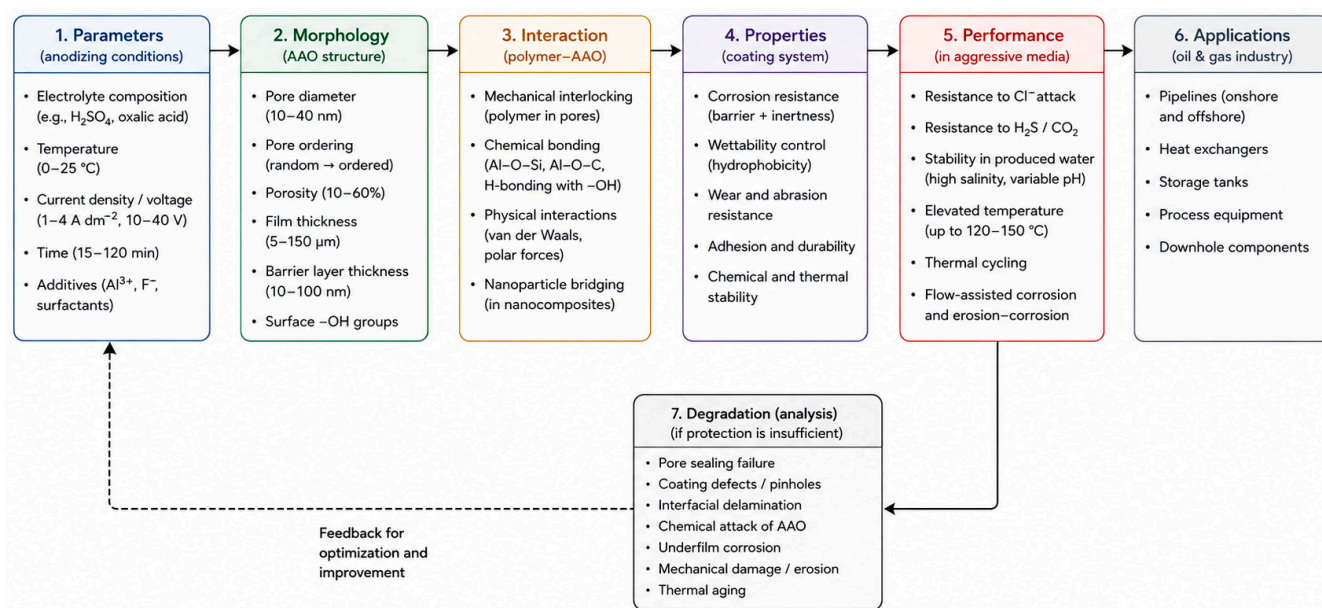


Figure 5. A conceptual design model for combined anodized aluminum/polymer nanocomposite coatings incorporating degradation-driven optimization for aggressive oil production and refining environments. Solid arrows indicate the main design sequence, whereas dashed arrows indicate feedback for optimization and improvement.

Promising directions for future work include the development of nanocomposite polymer coatings with controlled functional properties, mathematical modeling of coating formation and degradation processes, and the creation of intelligent polymer systems with adaptive protective behavior. The advancement of these areas, together with increasing demands for environmental safety and energy efficiency, opens up broad opportunities for the industrial implementation of advanced anodizing technologies with polymer coatings under the aggressive conditions of oil production and refining.

Author Contributions: Conceptualization, V.Y.P.; methodology, V.N.S. and V.V.K.; formal analysis, V.N.S. and V.V.K.; writing—original draft preparation, V.V.K.; writing—review and editing, V.Y.P., V.N.S., V.V.K. and A.R.B.; visualization, A.R.B.; supervision, V.Y.P.; project administration, V.N.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data used in this analysis are available in the cited sources.

Acknowledgments: The authors express their gratitude to the Department of Materials Science and Technology of Artistic Products, Empress Catherine II Saint Petersburg Mining University, for organizational and academic support. The work was carried out with the support of the International Competence Centre in Mining Engineering Education under the auspices of UNESCO, within the framework of the project “Nauka” (St. Petersburg, Russian Federation).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AAO	Anodic aluminum oxide
AFM	Atomic force microscopy
ASTM	American Society for Testing and Materials
DA	Dopamine
EIS	Electrochemical impedance spectroscopy

EPD	Electrophoretic deposition
FDTS	Perfluorodecyltrimethoxysilane
PANI	Polyaniline
PDMS	Polydimethylsiloxane
PFODA	1H,1H,2H,2H-Perfluorooctyltriethoxysilane
PNIPAM	Poly(N-isopropylacrylamide)
PSBMA	Poly(sulfobetaine methacrylate)
PTFE	Polytetrafluoroethylene
Pulsed-CEPD	Pulsed cathodic electrophoretic deposition

References

1. Ermakov, B.S.; Ermakov, S.B.; Vologzhanina, S.A.; Khuznakhmetov, R.M. Relationship between operating conditions and the emergence of nano- and ultradispersed grain boundary defects in weld joints. *Tsvetnye Met.* **2023**, *8*, 80–85. (In Russian) [[CrossRef](#)]
2. Popov, G.; Bolobov, V.; Zhuikov, I.; Zlotin, V. Development of the kinetic equation of the groove corrosion process for predicting the residual life of oil-field pipelines. *Energies* **2023**, *16*, 7067. [[CrossRef](#)]
3. Petrova, T.A.; Epishina, A.D. Anti-corrosion protection of pipelines at mining and processing enterprises. *Obogashchenie Rud* **2023**, *6*, 52–58. (In Russian) [[CrossRef](#)]
4. Buslaev, G.; Lavrik, A. Comparative Study of Efficiency of Hydrate Inhibitors Based on Ammonium Salts and Polyvinylpyrrolidone. *Int. J. Eng.* **2026**, *39*, 898–905. [[CrossRef](#)]
5. Piirainen, V.Y.; Perina, A.I.; Khachinikolaev, V.V.; Guseva, M.S. Thermal Degradation of Corrosion Inhibitors in Oil and Gas Refining Conditions: Mechanisms, Consequences, and Strategies for Deposit Minimization. *Int. J. Eng.* **2026**, *39*, 3044–3054. [[CrossRef](#)]
6. Tikhonov, V.S.; Gelfgat, M.Y.; Cheatham, C.; Adelman, A. Comprehensive Studies of Aluminum Drillpipe. In Proceedings of the IADC/SPE Drilling Conference and Exhibition, New Orleans, LA, USA, 2–4 February 2010. [[CrossRef](#)]
7. Gelfgat, M.Y.; Alkhimenko, A.; Kolesov, S. Corrosion and the role of structural aluminum alloys in the construction of oil and gas wells. *E3S Web Conf.* **2019**, *121*, 4003. [[CrossRef](#)]
8. Basovich, V.; Gelfgat, M.; Basovich, D.; Buyanovskiy, I.; Vakhrushev, A.; Alikin, R.; Sledkov, V.; Loparev, D.S.; Sapunzhi, V. Aluminum Alloys for Casing and Tubing. In Proceedings of the International Petroleum Technology Conference, Bangkok, Thailand, 7–9 February 2012. [[CrossRef](#)]
9. Kondrat'ev, S.; Shvetsov, O. Real and imaginary obstacles of aluminum alloys application in petrochemical industry. In Proceedings of the 26th International Conference on Metallurgy and Materials, Brno, Czech Republic, 24–26 May 2017; pp. 1481–1488.
10. Factors Affecting Heat Transfer Efficiency in Aluminium Finned Tube Heat Exchangers. *CHAL*, 5 February 2025. Available online: <https://www.chaluminium.com/factors-affecting-heat-transfer-efficiency-in-aluminium-finned-tube-heat-exchangers> (accessed on 12 June 2026).
11. Aluminium Helidecks for Offshore Platforms. Northsea Offshore Technology. Available online: <https://www.offshore-technology.com/contractors/transport/northsea/> (accessed on 12 June 2026).
12. Marine Aluminium Products. Marine Aluminium A/S. Available online: <https://www.goltens.com> (accessed on 12 June 2026).
13. Enhancing Access with Aluminium Helidecks. *Aluminium Offshore*, 7 October 2024. Available online: <https://www.aluminium-offshore.com/2024/10/07/aluminium-offshores-role-in-oil-gas-innovations-for-offshore-aluminium-structures/> (accessed on 12 June 2026).
14. ISO 13085:2014; Petroleum and Natural Gas Industries—Aluminium Alloy Pipe for Use as Tubing for Wells. International Organization for Standardization (ISO): Geneva, Switzerland, 2014.
15. Anderson, E.R. Aluminum Alloy Drill Pipe in Geothermal Drilling. Master's Thesis, Reykjavík University, Reykjavík, Iceland, 2010.
16. Kim, Y.; Kim, W.-B. Enhancing the Surface Hydrophilicity of an Aluminum Alloy Using Two-Step Anodizing and the Effect of Inkjet Printing Characteristics. *Coatings* **2023**, *13*, 232. [[CrossRef](#)]
17. Pryakhin, E.I.; Pribytkova, D.A. Application of polymer coatings to protect the external surface of municipal hot water supply pipes against corrosion. *Chernye Met.* **2025**, *5*, 68–72. (In Russian) [[CrossRef](#)]
18. Pryakhin, E.I.; Azarov, V.A. Comparative analysis of the use of epoxy and fluoroplastic polymer compositions as internal smooth coatings of the inner cavity of steel main gas pipelines. *CIS Iron Steel Rev.* **2024**, *28*, 93–98. [[CrossRef](#)]
19. Lee, W.; Park, S.J. Porous Anodic Aluminum Oxide: Anodization and Templated Synthesis of Functional Nanostructures. *Chem. Rev.* **2014**, *114*, 7487–7556. [[CrossRef](#)] [[PubMed](#)]
20. Ono, S. Nanostructure Analysis of Anodic Films Formed on Aluminum-Focusing on the Effects of Electric Field Strength and Electrolyte Anions. *Molecules* **2021**, *26*, 7270. [[CrossRef](#)] [[PubMed](#)]

21. Domagalski, J.T.; Xifre-Perez, E.; Marsal, L.F. Recent Advances in Nanoporous Anodic Alumina: Principles, Engineering, and Applications. *Nanomaterials* **2021**, *11*, 430. [[CrossRef](#)] [[PubMed](#)]
22. Zhou, W.-Y.; Li, Y.-B.; Liu, Z.-Q.; Tang, D.-S.; Zou, X.-P.; Wang, G. Self-organized formation of hexagonal nanopore arrays in anodic alumina. *Chin. Phys.* **2001**, *10*, 218–222. [[CrossRef](#)]
23. Stepniowski, W.J.; Nowak-Stepniowska, A.; Presz, A.; Czujko, T.; Varin, R.A. The effects of time and temperature on the arrangement of anodic aluminum oxide nanopores. *Mater. Charact.* **2014**, *91*, 1–9. [[CrossRef](#)]
24. Balkan, S.; Yurddaskal, M. Anodization Parameter-Driven Control of Nucleation, Pore Formation and Hydrophobic Behavior in Anodic Aluminum Oxide Nanostructures. *Crystals* **2026**, *16*, 227. [[CrossRef](#)]
25. Ono, S.; Masuko, N. Electron microscopic study of the structure and dissolution behavior of porous anodic films formed on aluminum. *J. Jpn. Inst. Light Met.* **1993**, *43*, 453–458. (In Japanese) [[CrossRef](#)]
26. Abd-El-Naby, B.A.; Abdullatef, O.A.; El-Kshlan, H.M.; Khamis, E.; Abd-El-Fatah, M.A. Effect of Alkaline Etching on the Inhibition of the Acidic Corrosion of Aluminum by Lupine Extract. *Port. Electrochim. Acta* **2015**, *33*, 1–11. [[CrossRef](#)]
27. Prasad, A.R.; Prakash, S. A Review on Anodizing Process of Aluminum and Non-Aluminium Alloys. In Proceedings of the National conference on Recent Advances in Mechanical, Robotics & Technology, Mukka, Mangalore, India, 28–29 June 2022.
28. Schneider, M.; Fürbeth, W. Anodizing—The pore makes the difference. *Mater. Corros.* **2022**, *73*, 1752–1765. [[CrossRef](#)]
29. Chang, J.-K.; Liao, C.-M.; Chen, C.-H.; Tsai, W.-T. Effect of electrolyte composition on hydration resistance of anodized aluminum oxide. *J. Power Sources* **2004**, *138*, 301–308. [[CrossRef](#)]
30. Guo, F.; Cao, Y.; Wang, K.; Zhang, P.; Cui, Y.; Hu, Z.; Xie, Z. Effect of the Anodizing Temperature on Microstructure and Tribological Properties of 6061 Aluminum Alloy Anodic Oxide Films. *Coatings* **2022**, *12*, 314. [[CrossRef](#)]
31. Ayalew, A.A.; Han, X.; Sakairi, M. Effect of substrate temperature and electrolyte composition on the fabrication of through-hole porous AAO membrane with SF-MDC. *Mater. Chem. Phys.* **2024**, *323*, 129658. [[CrossRef](#)]
32. Grubbs, C.A. Anodizing by current density—An update. *Met. Finish.* **1999**, *97*, 71–73. [[CrossRef](#)]
33. Paz Martinez-Viademonte, M.; Abrahami, S.T.; Havigh, M.D.; Marcoen, K.; Hack, T.; Burchardt, M.; Terryn, H. The Role of Anodising Parameters in the Performance of Bare and Coated Aerospace Anodic Oxide Films. *Coatings* **2022**, *12*, 908. [[CrossRef](#)]
34. Wisnujati, A.; Wijayanto, H.; Widodo, A.M.; Mudjijana; Rahaman, M. Characterization of Anodizing Process on Aluminum Series 6 with Variable Voltage. In *Proceedings of the First Mandalika International Multi-Conference on Science and Engineering 2022, MIMSE 2022 (Mechanical and Electrical) (MIMSE-M-E-I-2022)*; Atlantis Press International BV: Dordrecht, The Netherlands, 2022; Volume 2, pp. 46–56. [[CrossRef](#)] [[PubMed](#)]
35. Niedźwiedź, M.; Bara, M.; Skoneczny, W.; Kaptacz, S.; Dercz, G. Influence of Anodizing Parameters on Tribological Properties and Wettability of Al₂O₃ Layers Produced on the EN AW-5251 Aluminum Alloy. *Materials* **2022**, *15*, 7732. [[CrossRef](#)] [[PubMed](#)]
36. Mirzoev, R.A.; Davydov, A.D.; Vystupov, S.I.; Kabanova, T.B. Mathematical model of current-voltage characteristic of steady-state aluminum anodization. *Electrochim. Acta* **2021**, *371*, 137823. [[CrossRef](#)]
37. Michel, S.; Tuchschild, M.; Sauder, M.; Frey, S. Stress Corrosion Cracking of Tunnel Ventilation Fan Blades: A Case Study. *Metals* **2022**, *15*, 2065. [[CrossRef](#)]
38. Ifezue, D.; Tobins, F.H. Corrosion Failure of Aluminum Heat Exchanger Tubes. *Fail. Anal. Prev.* **2015**, *15*, 229. [[CrossRef](#)]
39. Rozhdestvenska, L.; Kudelko, K.; Ogenko, V.; Chang, M. Membrane materials based on porous anodic aluminium oxide. *Ukr. Chem. J.* **2021**, *86*, 67–102. [[CrossRef](#)]
40. Lushpa, N.V.; Dinh, H.T.; Chernyakova, K.V.; Vrublevsky, I.A. Morphology investigation of nanoporous anodic alumina films with image analysis. *Mater. Phys. Mech.* **2019**, *41*, 74–77. [[CrossRef](#)] [[PubMed](#)]
41. De Lima, L.C.; De Macedo, M.M.G.; De Albuquerque, M.P.; De Albuquerque, M.P.; Simão, R.A. Morphological characterization of the surface of nanoporous aluminum oxide by AFM and laws of scale. *Nano* **2009**, *4*, 157–164. [[CrossRef](#)]
42. El-Hameed, A.M.A.; Abdel-Aziz, Y.A.; El-Tokhy, F.S. Anodic Coating Characteristics of Different Aluminum Alloys for Spacecraft Materials Applications. *Mater. Sci. Appl.* **2017**, *08*, 197–208. [[CrossRef](#)]
43. del Olmo, R.; Łazińska, M.; Czerwiński, M.; Durejko, T.; Michalska-Domańska, M. Morphological and semiconductive properties of the anodic oxide layers made on Fe3Al alloy by anodizing in tartaric-sulfuric acid mixture. *Sci. Rep.* **2023**, *13*, 15135. [[CrossRef](#)] [[PubMed](#)]
44. Olkowicz, K.; Kowalczyk, K.; Buczek, Z.; Czwartos, J.; Nasiłowska, B. Durability and Additional Properties of Anodized Aluminum-Based Coatings with Different Wettability under Natural Conditions. *Materials* **2023**, *16*, 3729. [[CrossRef](#)] [[PubMed](#)]
45. Remešová, M.; Tkachenko, S.; Kvarda, D.; Ročňáková, I.; Gollas, B.; Menelaou, M.; Čelko, L.; Kaiser, J. Effects of anodizing conditions and the addition of Al₂O₃/PTFE particles on the microstructure and the mechanical properties of porous anodic coatings on the AA1050 aluminium alloy. *Appl. Surf. Sci.* **2020**, *513*, 145780. [[CrossRef](#)]
46. Pryakhin, E.I.; Azarov, V.A. Increasing adhesion of fluoroplastic coatings to steel surfaces of pipes with a view to their use in gas transportation systems. *Chernye Met.* **2024**, *3*, 69–74. [[CrossRef](#)]
47. Bakhti, H.; Weyrich, T.; Es-Souni, M.; Laghrissi, A.; Es-Souni, M. Non-fouling polymer films on hard-anodized aluminum substrates: Nanomechanical properties and modelling. *Prog. Org. Coat.* **2021**, *161*, 106553. [[CrossRef](#)]

48. Tomaev, V.V.; Levin, K.L.; Stoyanova, T.V.; Syrkov, A.G. Synthesis and Study of a Polypyrrole-Aluminum Oxide Nanocomposite Film on an Aluminum Surface. *Glas. Phys. Chem.* **2019**, *45*, 291–297. [CrossRef]
49. Poinern, G.E.J.; Ali, N.; Fawcett, D. Progress in Nano-Engineered Anodic Aluminum Oxide Membrane Development. *Materials* **2011**, *4*, 487–526. [CrossRef] [PubMed]
50. Gonçalves, I.L.M.; Vinhos, R.A.; de Freitas, D.S.; Brasil, S.L.D.C. Pulsed electrophoretic deposition for surface silanization of anodized aluminum from a silane-ethanol-water suspension. *Surf. Coat. Technol.* **2024**, *478*, 130456. [CrossRef]
51. Sikkema, R.; Baker, K.; Zhitomirsky, I. Electrophoretic deposition of polymers and proteins for biomedical applications. *Adv. Colloid Interface Sci.* **2020**, *284*, 102272. [CrossRef] [PubMed]
52. Sakaue, H.; Ishii, K. A Dipping Duration Study for Optimization of Anodized-Aluminum Pressure-Sensitive Paint. *Sensors* **2010**, *2*, 9799–9807. [CrossRef] [PubMed]
53. Timmermans, F. Polymer Layers: Protection and Style in One Coating. MIFA. Available online: <https://mifa.eu/en/techniques/polymer-layers/?cmplz-force-reload=1773225633997> (accessed on 12 June 2026).
54. Chen, J.; Huang, J.; Wu, Y.; Du, K.; Xiang, H.; Li, Y.; Yang, C.; Xia, X. Effect of surface anodizing on the bonding properties of aluminum alloy/glass-fiber reinforced polypropylene random copolymer hybrid joints. *Int. J. Adhes. Adhes.* **2023**, *123*, 103361. [CrossRef]
55. Runge, J.M.; Pornis, A.J.; Nussbaum, T. Insights Regarding the Adhesion Mechanism for Supplementary Organic Coatings on Porous Anodic Films. In Proceedings of the Aluminium 2002, Cambridge, UK, 22–26 September 2002.
56. Fan, C.; Yang, B.; Wang, X.; Zhan, X.; Yin, X.; Shi, J.; Liu, Y.; Dilger, K. A Simple Surface Treatment for Improving the Adhesive Bonding Properties and Durability of an AlMg3 Alloy. *Molecules* **2024**, *29*, 5856. [CrossRef] [PubMed]
57. Sato, K.; Asoh, H.; Yamamoto, H. Effects of nanoporous structure of anodic films on adhesive strength between aluminum alloys and polyamide resin. *J. Jpn. Inst. Light Met.* **2021**, *71*, 234–240. (In Japanese) [CrossRef]
58. Ryu, S.W.; Kim, D.H.; Lee, W.; Hong, J.-Y.; Jeon, Y.-P.; Lee, J.U. Improvement of Polymer/Metal Adhesion Using Anodizing Treatment and 3D Printing Process. *Polymers* **2025**, *17*, 299. [CrossRef] [PubMed]
59. Wen, Y.; Li, J.; Wang, Q.; Cao, Y.; Shang, W.; Peng, N. Corrosion Resistance and Formation Mechanism of Anodic Oxidation–Organic Structure Super-Hydrophobic Self-Assembled Film. *Adv. Mater. Interfaces* **2021**, *8*, 2100383. [CrossRef]
60. Wan, H.; Song, D.; Li, X.; Zhang, D.; Gao, J.; Du, C. A new understanding of the failure of waterborne acrylic coatings. *RSC Adv.* **2017**, *7*, 38135–38148. [CrossRef]
61. Jothi, V.; Adesina, A.Y.; Kumar, A.M.; Al-Aqeeli, N.; Ram, J.S.N. Influence of an anodized layer on the adhesion and surface protective performance of organic coatings on AA2024 aerospace Al alloy. *Prog. Org. Coat.* **2020**, *138*, 105396. [CrossRef]
62. Wang, F.; Tong, L.; Li, D.; Wei, X.; Mao, J. Effective chloride ion resistance of aluminum powder through interface electric field designing. *Heliyon* **2023**, *9*, e21521. [CrossRef] [PubMed]
63. Kumar, A. Role of conducting polymers in corrosion protection. *World J. Adv. Res. Rev.* **2023**, *17*, 45–47. [CrossRef]
64. Yabuki, A.; Nagayama, Y.; Fathona, I.W. Porous anodic oxide film with self-healing ability for corrosion protection of aluminum. *Electrochim. Acta* **2019**, *296*, 662–668. [CrossRef]
65. U.S. Department of Defense. *Anodic Coatings for Aluminum and Aluminum Alloys; MIL-PRF-8625F*; U.S. Department of Defense: Washington, DC, USA, 2020. Available online: <https://quicksearch.dla.mil/> (accessed on 12 June 2026).
66. GOST 9.031-74; Unified System of Corrosion and Ageing Protection Coatings. Anodic Oxide on Aluminium and its Alloys. General Technical Requirements. Euro-Asian Council for Standardization, Metrology and Certification: Moscow, Russia, 1974.
67. Dumitrascu, V.M.; Benea, L. Improving the Corrosion Behaviour of 6061 Aluminum Alloy by Controlled Anodic Formed Oxide Layer. *Rev. Chim.* **2017**, *68*, 77–80. [CrossRef]
68. Medvedev, I.M.; Kutyrev, A.E.; Volkov, I.A. Investigation of the influence of corrosion damage on impedance spectra of anodic oxide coatings. *Elektrokhimiya* **2022**, *58*, 261–272. Available online: <https://sciencejournals.ru/view-article/?a=ElKhim2206007Medvedev&j=elkhim&n=6&v=58&y=2022> (accessed on 12 June 2026). (In Russian) [CrossRef]
69. Karimova, S.A.; Kutyrev, A.E.; Pavlovskaya, T.G.; Zakharov, K.E. Low-temperature sealing of anodic oxide coatings on aluminum alloy parts. *Aviatsionnye Mater. Tekhnologii* **2014**, *4*, 9–17. (In Russian) [CrossRef]
70. Zhang, Y.; Chen, Y.; Bian, G.; Zhang, Y. Electrochemical behavior and corrosion mechanism of anodized 7B04 aluminum alloy in acid NaCl environments. *J. Alloys Compd.* **2021**, *886*, 161231. [CrossRef]
71. Wang, Y.; Zhao, Y.; Wang, S.; Chen, J.; Zhang, T.; Wang, F. Thermodynamics-based sealing method for anodized aluminum used in semiconductor processing apparatuses. *J. Mater. Sci. Technol.* **2025**, *216*, 241–259. [CrossRef]
72. Sundararajan, M.; Devarajan, M.; Jaafar, M. Investigation of surface and mechanical properties of Anodic Aluminium Oxide (AAO) developed on Al substrate for an electronic package enclosure. *Surf. Coat. Technol.* **2020**, *401*, 126273. [CrossRef]
73. Jaenecke, A. Proper Testing of Wear Resistant Anodized Coatings. *Finishing & Coating*, 22 March 2023. Available online: <https://finishingandcoating.com/index.php/anodizingcat/1522-proper-testing-wear-of-resistant-anodized-coatings> (accessed on 12 June 2026).

74. Behzadifar, J.; Najafi, Y.; Nazarizade, B. Synergistic effects of hard anodizing parameters on the microstructural, mechanical, and tribological properties of 6061 aluminum alloy. *Sci. Rep.* **2026**, *16*, 5021. [CrossRef] [PubMed]
75. Li, D.; Herrmann, A. Macro Scratch Testing of Anodized Coatings. Available online: <https://nanovea.com/App-Notes/macro-scratch-anodized.pdf> (accessed on 12 June 2026).
76. Mohitfar, S.H.; Mahdavi, S.; Etmianfar, M.; Khalil-Allafi, J. Characteristics and tribological behavior of the hard anodized 6061-T6 Al alloy. *J. Alloys Compd.* **2020**, *842*, 155988. [CrossRef]
77. Bordiga, G. Hardness and Wear Resistance of Hard Anodizing. Available online: <https://www.microncoatings.it/en/anodizing/hardness-resistance-wear-anodization/> (accessed on 12 June 2026).
78. Telmenbayar, L.; Ramu, A.G.; Yang, D.; Song, M.; Erdenebat, T.-O.; Choi, D. Corrosion resistance of the anodization/glycidoxypolytrimethoxysilane composite coating on 6061 aluminum alloy. *Surf. Coat. Technol.* **2020**, *403*, 126433. [CrossRef]
79. Riyadi, T.W.B.; Setiadhi, D.; Anggono, A.D.; Siswanto, W.A.; Al-Kayiem, H.H. Analysis of mechanical and thermal stresses due to TiN coating of Fe substrate by physical vapor deposition. *Forces Mech.* **2021**, *4*, 100042. [CrossRef]
80. Campestrini, P.; Terryn, H.; Vereecken, J.; de Wit, J.H.W. Chromate Conversion Coating on Aluminum Alloys. *J. Electrochem. Soc.* **2004**, *151*, B370–B377. [CrossRef]
81. Lutz, A.; Halseid, M.C.; De Graeve, I. Corrosion performance of powder-coated aluminum profiles with increased trace element content. *Mater. Corros.* **2022**, *73*, 1575–1585. [CrossRef]
82. Lucas, R.R.; Sales-Contini, R.C.M.; da Silva, F.J.G.; Botelho, E.C.; Mota, R.P. Plasma electrolytic oxidation (PEO): An alternative to conventional anodization process. *AIMS Mater. Sci.* **2024**, *11*, 684–711. [CrossRef]
83. Minhas, B.; Dino, S.; Huang, L.; Wu, D. Active Corrosion Protection by Epoxy Coating on Li₂CO₃-Pretreated Anodized Aluminum Alloy 2024-T3. *Front. Mater.* **2022**, *8*, 804328. [CrossRef]
84. Sharma, S.; Girish, S.; Nayaka, G.P.; Samhitha, S.S.; Pilliadugula, R.; Shivamurthy, B.P.; Gurumurthy, S.C.; Ruiz-Robles, M.A.; Rojas, D.; Surabhi, S. Advanced zinc-polymer composites for marine corrosion protection and self-healing. *npj Mater. Degrad.* **2025**, *9*, 150. [CrossRef]
85. Zhao, J.; Yang, Z.; Shi, M.; La, L.; Bukovetskiy, N.A.; Mustafaev, A.S.; Qin, L. Oxidation behavior of TaNbHfTiZr coatings prepared by double glow plasma surface alloying technique. *J. Vac. Sci. Technol. Vac. Surf. Film* **2025**, *43*, 043107. [CrossRef]
86. Li, Z.; Visser, P.; Hughes, A.E.; Homborg, A.; Gonzalez-Garcia, Y.; Mol, A. Review of the state of art of Li-based inhibitors and coating technology for the corrosion protection of aluminium alloys. *Surf. Coat. Technol.* **2024**, *478*, 130441. [CrossRef]
87. Hakimizad, A.; Raeissi, K.; Ashrafizadeh, F. A comparative study of corrosion performance of sealed anodized layers of conventionally colored and interference-colored aluminium. *Surf. Coat. Technol.* **2012**, *206*, 4628–4633. [CrossRef]
88. Roselli, S.N.; Romagnoli, R.; Deyá, C. The anti-corrosion performance of water-borne paints in long term tests. *Prog. Org. Coat.* **2017**, *109*, 172–178. [CrossRef]
89. Chu, C.-W.; Tsai, C.-H. Surface Modification of Nanopores in an Anodic Aluminum Oxide Membrane through Dopamine-Assisted Codeposition with a Zwitterionic Polymer. *Langmuir* **2024**, *40*, 5245–5254. [CrossRef] [PubMed]
90. Syrkov, A.G.; Kushchenko, A.N.; Maslennikov, A.A. Professor P.P. Weimarn, founder of the science of nanotechnology: Development of works in the field of nanodispersed metals production. *Non-Ferr. Met.* **2024**, *56*, 63–71. [CrossRef]
91. Chai, X.; Lin, J.; Xu, C.; Sun, D.; Liu, H.H. Engineering Triphasic Nanocomposite Coatings on Pretreated Mg Substrates for Biomedical Applications. *ACS Appl. Mater. Interfaces* **2024**, *16*, 54716–54730. [CrossRef] [PubMed]
92. Perina, A.I.; Piirainen, V.Y.; Khachinikolaev, V.V.; Guseva, M.S. Comprehensive assessment of the efficiency of hydrogen sulfide corrosion inhibition of carbon steels in oil and gas processing. *Chernye Met.* **2026**, *5*, 75–82. [CrossRef]
93. Korobov, G.Y.; Vorontsov, A.A.; Buslaev, G.V. Influence of Inhibitors Based on Surfactants on Processes of Hydrates and Asphalt-Resin-Paraffin Deposits Formation: Experimental Studies. *Int. J. Eng. Trans. B Appl.* **2025**, *38*, 2220–2230. [CrossRef]
94. Ermakov, B.S.; Shvetsov, O.V.; Vologzhanina, S.A.; Nechaev, D.V.; Karpov, I.D. The influence of water-repellent coating on the performance of structures made of polymer composite materials in conditions of extremely low temperatures. *Gorn. Promyshlennost* **2024**, *55*, 198–203. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.