

Review Article

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Advancements in surface treatments for aluminum alloys in sports equipment

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Abstract: This review examines recent advancements in surface treatment technologies for aluminum alloys used in sports equipment. We discuss conventional methods like chemical conversion coatings and anodizing, as well as emerging techniques such as plasma electrolytic oxidation, physical vapor deposition, and laser surface modification. The replacement of toxic hexavalent chromium with eco-friendly alternatives is highlighted as a key development. We also explore the potential of smart, self-healing coatings to extend equipment lifespan. Our analysis reveals that while significant progress has been made in enhancing corrosion resistance and mechanical properties, challenges remain in scaling up advanced treatments for industrial implementation. The review concludes that continued innovation in surface treatments will be crucial for improving the performance, safety, and sustainability of aluminum alloys in sports applications, ultimately benefiting athletes and manufacturers alike.

Keywords: surface modification, corrosion protection, eco-friendly coatings, microstructural refinement, mechanical performance

1 Introduction

Aluminum alloys have emerged as the material of choice for a wide range of sports equipment due to their exceptional properties, such as a high strength-to-weight ratio, good formability, and excellent corrosion resistance [1,2]. The low density of aluminum alloys enables the manufacturing of lightweight equipment, which is crucial for enhancing athletic performance and user comfort [3]. Aluminum alloys have revolutionized sports equipment,

providing high-performance gear like baseball bats, tennis rackets, bicycle frames, and golf clubs [4]. While aluminum alloys offer excellent properties for sports equipment, their surfaces are subject to various forms of deterioration depending on the specific application and usage conditions [5–7]. Understanding these factors is crucial for developing effective surface treatments and protective coatings. Table 1 systematically explores the main factors contributing to surface deterioration of aluminum alloy parts in sports equipment.

To address these challenges, surface treatment technologies have been developed and continuously improved to enhance the corrosion resistance and overall performance of aluminum alloys used in sports equipment. These surface treatments aim to create a protective barrier layer on the aluminum surface, preventing direct contact with corrosive environments and inhibiting the onset and propagation of corrosion. Some of the most commonly used surface treatment methods for aluminum alloys include chemical conversion coatings, anodizing, physical vapor deposition (PVD) coatings, and sol-gel coatings [8–11]. Among these surface treatment technologies, chemical conversion coatings have been widely used in the sports equipment industry due to their cost-effectiveness, ease of application, and ability to provide excellent corrosion protection. The sports equipment industry widely uses chromate conversion coatings (CCCs) due to their cost-effectiveness, ease of application, and ability to provide excellent corrosion protection [12]. However, the use of hexavalent chromium in CCCs has raised environmental and health concerns due to its toxic and carcinogenic nature. Stringent regulations have been imposed on the use of hexavalent chromium, driving the development of eco-friendly alternatives such as trivalent chromium conversion (TCC) coatings and other chromium-free conversion coatings based on molybdenum, zirconium, titanium, and rare-earth elements [13].

Addressing these challenges requires a multidisciplinary approach, combining materials science, engineering, and manufacturing expertise. Recent studies have shown promising results in developing nano-engineered coatings that offer superior performance across

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Table 1: Main factors contributing to surface deterioration of aluminum alloy parts in sports equipment

Factor	Deterioration of aluminum alloy parts in sports equipment
Mechanical wear and abrasion	• Cycling equipment: Exposure to sand, gravel, and road debris can cause abrasive wear on bicycle frames, wheels, and components. This is particularly significant in off-road cycling disciplines, such as mountain biking and gravel riding • Skiing and snowboarding: Contact with snow, ice, and rocky surfaces can lead to scratches and abrasion on ski and snowboard edges, bindings, and other aluminum components • Ball sports: Repeated impacts with balls, bats, or other equipment can cause localized wear and surface deformation in aluminum alloy parts
Impact damage	• Cycling: Falls, collisions, and transportation-related impacts can lead to dents, deformation, and cracking of bicycle frames and components • Climbing and mountaineering equipment: Carabiners, ice axes, and other aluminum alloy tools are subject to impact forces during falls or when striking rock surfaces • Team sports: Hockey sticks, baseball bats, and other equipment made from aluminum alloys can experience impact damage during normal use or collisions
Environmental exposure	• Moisture and humidity: Prolonged exposure to damp environments can accelerate corrosion processes, particularly in coastal areas or during storage • Temperature fluctuations: Extreme temperature changes, such as those experienced in winter sports, can lead to thermal stress and potential microcracking of protective coatings • UV radiation: Long-term exposure to sunlight can degrade surface coatings and potentially affect the underlying aluminum alloy structure
Chemical exposure	• Sweat and body oils: Contact with athletes' skin can introduce corrosive substances, particularly in equipment like handlebars, grips, and handles • Cleaning agents: Improper use of harsh cleaning chemicals can damage protective coatings and expose the underlying aluminum surface • Sports-specific chemicals: Exposure to chlorine in swimming pools or salt water in marine sports can accelerate corrosion processes
Cyclic loading and fatigue	• Repeated elastic deformations: Cyclic stresses experienced in activities like cycling, skiing, and racquet sports can lead to fatigue and potential microcracking of both the aluminum alloy and its protective coatings • Vibration: Continuous vibration in equipment such as bicycle frames or tennis rackets can contribute to surface degradation over time
Manufacturing and assembly stresses	• Welding and joining: Heat-affected zones near welds or mechanical joints can create areas of increased susceptibility to corrosion and fatigue • Forming processes: Residual stresses from manufacturing processes like bending or hydroforming can influence long-term surface integrity
User-induced damage	• Improper maintenance: Neglecting regular cleaning and maintenance can lead to accumulation of corrosive substances and accelerated surface deterioration • Misuse: Using equipment outside its intended purpose or beyond design limits can cause unexpected surface damage and structural issues

multiple, and in optimizing plasma electrolytic oxidation (PEO) processes for complex geometries. These advancements pave the way for the next generation of surface treatments for aluminum alloys in sports equipment.

Anodizing is another well-established surface treatment method for aluminum alloys, which involves the electrochemical growth of a thick, stable oxide layer on the aluminum surface [14]. Conventional anodizing processes, such as sulfuric acid anodizing (SAA) and hard anodizing, have been extensively used to improve the corrosion resistance, wear resistance, and surface hardness of aluminum sports equipment. In recent years, advanced anodizing

techniques like PEO have gained attention due to their ability to produce thick, dense, and highly adherent oxide coatings with excellent corrosion protection and mechanical properties [15]. Other surface treatment technologies, such as PVD coatings, sol-gel coatings, and laser surface modification, have also shown promising results in enhancing the corrosion resistance and performance of aluminum alloys used in sports equipment [2,16]. PVD coatings, which involve the deposition of a thin, dense, and uniform coating on the aluminum surface, offer excellent barrier protection against corrosion. Sol-gel coatings, derived from organic-inorganic hybrid materials, provide a versatile and eco-friendly approach to corrosion protection, with the ability

to incorporate corrosion inhibitors and self-healing functionalities. Laser surface modification techniques, such as laser surface melting (LSM) and laser surface alloying (LSA), have been explored to create corrosion-resistant surface layers on aluminum alloys through microstructural refinement and the incorporation of corrosion-resistant elements.

The advancements in surface treatment technologies for aluminum alloys used in sports equipment have not only focused on improving corrosion resistance but also on developing eco-friendly and sustainable solutions. The replacement of toxic hexavalent chromium with safer alternatives, such as trivalent chromium and chromium-free conversion coatings, has been a major focus of research and development efforts. Additionally, the development of smart, self-healing coatings that can autonomously repair damage and prevent the onset of corrosion has gained significant attention in recent years [17]. These coatings incorporate corrosion inhibitors, pH-sensitive materials, or self-healing agents that are released upon damage, enabling the coating to heal and restore its protective function. Despite these advancements, several challenges persist in the development and implementation of surface treatments for aluminum alloys in sports equipment. One major hurdle is achieving uniform coating thickness on complex geometries, which is crucial for maintaining consistent performance across the entire surface of sports equipment components [18]. Additionally, surface treatments must withstand the dynamic stresses experienced by sports equipment during use, including impacts, vibrations, and cyclic loading, which can lead to coating degradation over time [19]. Another significant challenge lies in balancing functional improvements with aesthetic appeal, as sports equipment often serves both performance and marketing purposes. Coatings that enhance corrosion resistance and mechanical properties while maintaining or improving the visual appearance of the equipment are in high demand [20]. The development of multifunctional coatings represents a frontier in surface treatment technologies. These advanced coatings aim to simultaneously provide corrosion protection, wear resistance, improved impact strength, and even self-healing capabilities [21]. However, achieving this combination of properties while ensuring cost-effectiveness and ease of application remains a significant technical challenge. Furthermore, the industrial implementation of advanced surface treatments poses economic challenges. Many novel techniques developed in laboratory settings are difficult to scale up for large-scale production or integrate into existing manufacturing processes without significant capital investment.

This review assesses and evaluates the advancements in surface treatment technologies for aluminum alloys used in sports equipment. It discusses the types of aluminum alloys commonly used in sports applications, their microstructural features, and the corrosion mechanisms they are susceptible to. This review then delves into the various surface treatment methods, including chemical conversion coatings, anodizing, PVD coatings, sol-gel coatings, and laser surface modification, highlighting their working principles, corrosion protection mechanisms, and recent developments. The environmental and health aspects of these surface treatments will also be addressed, focusing on the replacement of toxic hexavalent chromium and the development of eco-friendly alternatives. Finally, it will discuss the future directions and challenges in the field, emphasizing the need for smart, self-healing coatings, improved corrosion resistance and durability, and the industrial implementation of advanced surface treatment technologies. To provide a comprehensive overview of the topics covered in this review, Figure 1 presents a visual summary of the key aspects of surface treatment technologies for aluminum alloys in sports equipment.

2 Types of aluminum alloys used in sports equipment

2.1 Types of aluminum alloys commonly used

Due to their high strength-to-weight ratio, good formability, and excellent corrosion resistance, aluminum alloys are widely used in sports equipment. The choice of aluminum alloy for a specific sports equipment depends on the desired performance characteristics, such as strength, stiffness, durability, and weight. The most commonly used aluminum alloys in sports equipment belong to the 2xxx, 6xxx, and 7xxx series, each offering distinct advantages and tailored properties.

The 2xxx series aluminum alloys, particularly AA2014 and AA2024, are known for their high strength-to-weight ratio and good fatigue resistance. These alloys are widely used in applications that require high strength and durability, such as baseball bats, and bicycle frames [22,23]. The primary alloying element in the 2xxx series is copper, which contributes to the alloy's high strength through precipitation hardening. However, the presence of copper also makes these alloys more susceptible to corrosion, necessitating the use of appropriate surface treatments to

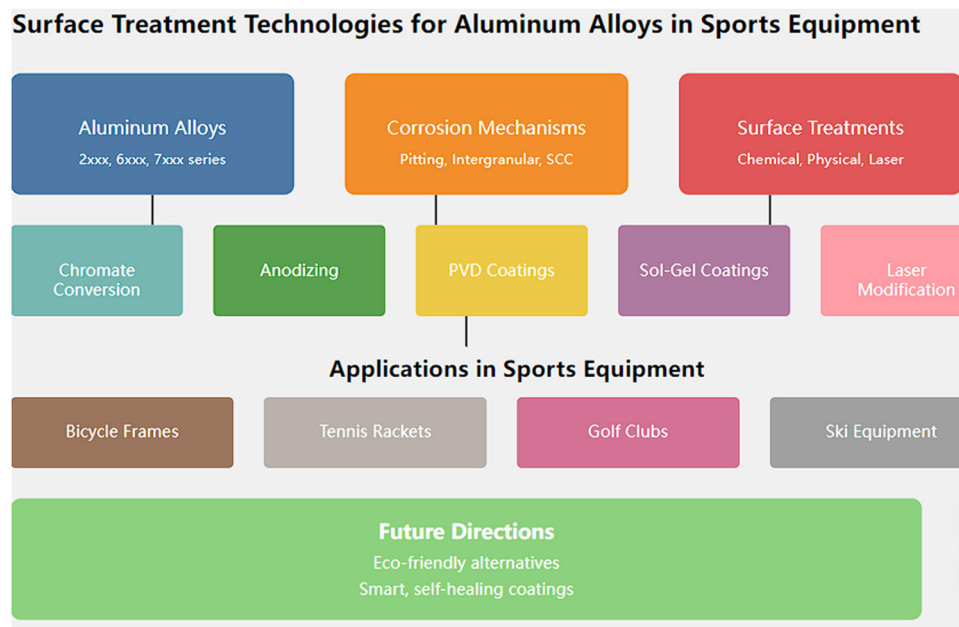


Figure 1: Overview of surface treatment technologies for aluminum alloys in sports equipment.

enhance their corrosion resistance. AA2014 is commonly used in the manufacture of high-performance bicycle frames, while AA2024 finds applications in lightweight and durable sports equipment components. Fan [24] recently reviewed the aging and application of composite materials, focusing on the superplasticity and application of AA2024. It reviews the plastic deformation of AA2024 in sports equipment, emphasizing the importance of excellent mechanical properties and the potential for engineering applications.

The 6xxx series aluminum alloys, particularly AA6061 and AA6082, are renowned for their excellent combination of strength, formability, and corrosion resistance. These alloys are widely used in the production of various sports equipment, including tennis rackets, golf clubs, ski poles, and mountaineering equipment [25]. The main alloying elements in the 6xxx series are magnesium and silicon, which form the strengthening precipitate Mg_2Si upon heat treatment. AA6061 is a versatile alloy that offers good strength, excellent corrosion resistance, and ease of fabrication, making it a popular choice for sports equipment components. AA6082, with its higher strength and improved corrosion resistance compared to AA6061, is commonly used in the manufacture of high-performance sports equipment, such as ski poles and mountaineering gear [26].

The 7xxx series aluminum alloys, particularly AA7075, are extensively used in high-performance sports equipment due to their exceptional strength-to-weight ratio

and excellent fatigue resistance. AA7075, with zinc as its primary alloying element (5.1–6.1%), along with magnesium (2.1–2.9%) and copper (1.2–2.0%), offers one of the highest strengths among aluminum alloys. This makes it ideal for applications requiring high stress tolerance, such as tennis rackets, golf club shafts, and high-end bicycle frames. For instance, in a study by Iskandar *et al.* [27], AA7075 bicycle frames demonstrated mechanical fatigue of 1.5×10^7 cycles compared to frames made from AISI 1020 steel (1,000 cycles) under identical loading conditions. However, the high copper content in 7075 also makes it more susceptible to stress corrosion cracking (SCC) and exfoliation corrosion, especially in marine environments. To mitigate these issues, surface treatments such as anodizing or conversion coatings are often applied. Harvey [28] summarized that a novel cerium-based conversion coating on AA7075 improved its corrosion resistance, making it more suitable for water sports equipment.

In addition to the wrought aluminum alloys mentioned above, cast aluminum alloys also play a significant role in the production of sports equipment components. The most commonly used cast aluminum alloys in sports equipment are A356, A357, and ADC12 [29–32]. These alloys offer good castability, strength, and corrosion resistance, making them suitable for the production of complex-shaped components, such as golf club heads, bicycle frame joints, and other intricate parts. The presence of silicon as the main alloying element in these cast alloys improves their fluidity and castability, enabling the

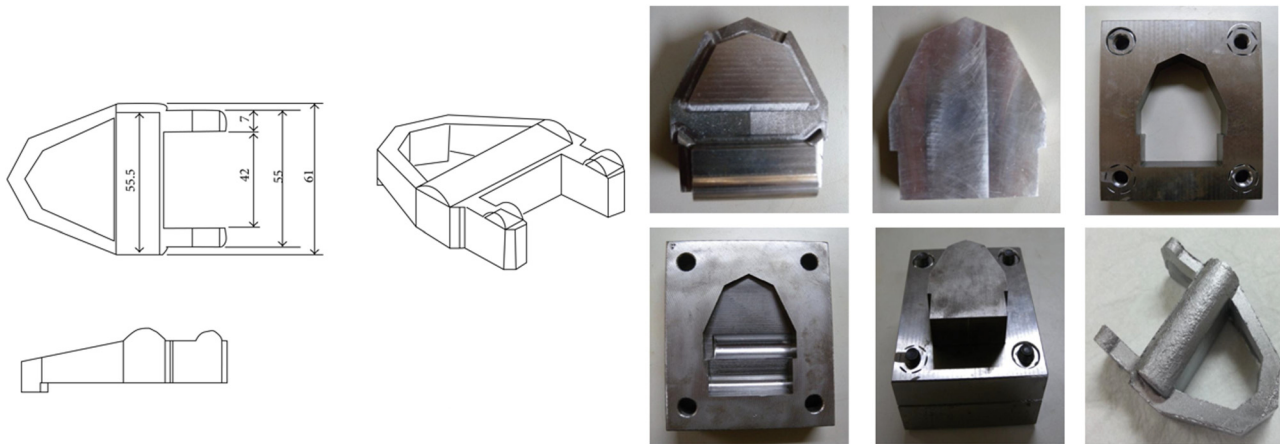


Figure 2: Die dimension design of bicycle pedal forming and the final product [34].

creation of near-net-shape components with high dimensional accuracy.

The selection of the appropriate aluminum alloy for a specific sports equipment application involves a careful consideration of the desired performance characteristics, manufacturing processes, and cost implications. In a comprehensive exploration of materials for mountain bike frames [33], a literature review delved into the comparison between traditional aluminum, A6013, and BioMid Fiber™ composite. The study concluded that A6013 emerged as a superior choice in terms of strength and environmental sustainability when compared to traditional aluminum alloys. Specifically, A6013 showcased a remarkable ultimate tensile strength of 370 MPa and an impressive fatigue strength at 50,000 cycles, significantly outperforming A6061 in durability and longevity. This enhanced performance was attributed to specific design modifications, such as geometry adjustments that predicted a fatigue life using finite element analysis of nearly six times longer than that of A6061. Additionally, the environmental impact of A6013 was scrutinized, revealing that despite its advantages, it shares similar ecological drawbacks with other aluminum alloys due to the mining processes involved. However, the potential for recycling presents a pathway to mitigate these environmental concerns. The review also touched upon the innovative use of BioMid Fiber™ composite, highlighting its lightweight and environmentally friendly properties, though it fell short in strength when used alone for bike frames. By integrating this composite with aluminum elements and enlarging the frame tubes, researchers were able to achieve a balance of strength and lightness, suggesting a promising direction for future sustainable bike manufacturing practices. In a recent study, researchers explored the innovative use of A6061 and A7075, in the

forging process of bicycle pedals, highlighting the material's significant benefits in enhancing product quality and manufacturing efficiency (Figure 2) [34]. The study meticulously employed simulation analyses alongside the Taguchi method and a genetic algorithm to pinpoint the optimal forging conditions, focusing on variables such as workpiece and mold temperatures, forging speed, friction factor, and mold size. The findings underscored aluminum alloys' capacity to reduce deformation behavior in bicycle pedals, showcasing a marked improvement in structural integrity and durability. For instance, the optimal settings identified for A6061 alloy included a workpiece temperature of 20°C, a die temperature of 20°C, and a forging speed of 50 mm·s⁻¹, among others. Such meticulous optimization efforts not only underscored aluminum alloys' suitability for precision forging applications but also paved the way for more sustainable and cost-effective manufacturing practices. By leveraging advanced simulation tools and optimization techniques, the study effectively demonstrated how aluminum alloys could revolutionize the bicycle pedal manufacturing process, offering insights that could extend to other components and industries seeking lightweight and high-strength materials.

Table 2 summarizes the examples aluminum material used for sports equipment.

2.2 Food-contact coatings for sports equipment

While discussing aluminum alloys used in sports equipment, it is crucial to consider the specialized alloys and treatments used for items that come into direct contact

Table 2: Examples of aluminum material used for sports equipment [35]

Category	Part name	Aluminum alloy
Baseball	Hard baseball bat; soft baseball bat; baseball box; pitching position	7001; 7178; 6061; 6063; 1050A
Tennis	Racket box (tennis); racket handle rivets (tennis); tennis racket frame hoop, badminton racket box; badminton racket joint	6061; 2A12; 7046; 2A11; 1100; 6061; ADC12
Badminton	Forced parts; ski side rear board; inclined plate; bottom plate belt buckle and shell; belt structural parts	7A09; 7178; 6061; 5A02; ADC6; ADC12
Snowboard rod	Stick body; buckle ring	6061; 7001; 7178; 6063
Arrow	Pole; bow	2A12; 7A09
Track and field	Bolt; strut; bar and rail javelin; baton starter; signal gun	6063; 7A09; 5A02; 2A12; 1050A; 5A02; ADC12
Hiking trip	Cookware; food utensils; kettle backpack rack; chairs	1060; 3003; 5A02; 6063; 7A09
Golf	Ball bat; umbrella; post ball; bat head; frame	7A09; 5A02; ADC10; 1050A
Fencing	Mask	2A11
Ice hockey	Rapping bur	7A04; 7178
Shoes	Running shoes nuts; ski shoes; rivets ski shoes; belt buckle; olive shoe bolts	2A11; 6063; ADC12
Bike	All kinds of parts	2A14; 2A11; 6061; 7075
Swimming pool	Pipe reinforcement; side plate; bottom plate	5A02; 6006; 6A02; 6063
Football, water ball, ice hockey, rugby	Door, column	6061; 6063
Other facilities	Seats; scaffolding; locker rooms	6063
Rowing	Mast; boat body	7A19; 5083
Diving	Board; frame	6070

with food and beverages. These applications, such as water bottles, food containers, and thermal flasks, are essential for athletes during training and competitions. For food-contact applications, aluminum alloys must not only meet mechanical and durability requirements but also ensure food safety. The 3xxx series alloys, particularly AA3003 and AA3004, are commonly used for these purposes due to their excellent formability, corrosion resistance, and relatively low cost [36,37]. These alloys contain manganese as the primary alloying element, which enhances strength without significantly affecting the alloy's corrosion resistance.

To make these alloys suitable for food contact, manufacturers often apply specialized surface treatments. A common approach is to use a two-step process: first, the aluminum surface is treated to enhance its corrosion resistance, often through anodization [38]. This creates a hard, non-reactive surface layer. Following this, a food-grade coating is applied to further ensure safety and prevent any potential metal leaching. Food-grade epoxy resin coatings are frequently used for this purpose. These coatings provide excellent chemical resistance and adhere well to the anodized aluminum surface [39]. They create an effective barrier between the aluminum alloy and the food or beverage, significantly reducing the risk of any metal transfer. In some high-end sports bottles and containers,

manufacturers may opt for more advanced coatings [40]. Ceramic coatings, for instance, can be applied through plasma spraying techniques. These coatings offer superior durability and are non-reactive with food and beverages, making them suitable for both cold and hot contents.

The development of these food-safe aluminum alloys and their associated coatings represents an important area where materials science intersects with public health and athletic performance. By carefully selecting and treating these alloys, manufacturers can produce lightweight, durable, and safe equipment that meets the unique needs of athletes for hydration and nutrition during sports activities.

2.3 Microstructural features and alloying elements

The microstructural features and alloying elements play a crucial role in determining the properties and performance of aluminum alloys used in sports equipment. The specific combination of alloying elements and the resulting microstructure contribute to the alloy's strength, ductility, corrosion resistance, and other desired characteristics [41,42]. Understanding the relationship between microstructure, alloying elements, and material properties is

essential for selecting the appropriate aluminum alloy for a given sports equipment application. Aluminum alloys used in sports equipment typically contain various alloying elements, such as copper, magnesium, silicon, zinc, and manganese, each contributing to specific microstructural features and properties [43,44]. These alloying elements can be present in solid solution, form intermetallic compounds, or precipitate as second-phase particles, depending on the alloy composition and thermal history.

In the 7xxx series aluminum alloys, such as AA7075, zinc is the primary alloying element, often combined with magnesium and copper. For example, Zhao [45] explored the potential of $\text{Ni@Al}_2\text{O}_3$ coated powders to enhance the properties of A7075 composites for sports equipment applications. By employing electroless plating, uniformly distributed $\text{Ni@Al}_2\text{O}_3$ coated powders were synthesized and subsequently used to fabricate $\text{Ni@Al}_2\text{O}_3(\text{p})/7075$ composite materials. The findings revealed that the inclusion of $\text{Ni@Al}_2\text{O}_3$ coated powders significantly improved the wettability between the Al_2O_3 particles and the aluminum matrix, effectively mitigating the agglomeration of Al_2O_3 particles and reducing defect formation. Notably, when the content of $\text{Ni@Al}_2\text{O}_3(\text{p})$ reached 1.5%, the composite material exhibited optimal microstructural refinement,

characterized by the smallest average grain size and a uniform distribution of Al_2O_3 particles within the matrix (Figure 3). This microstructural enhancement translated into superior physical properties, with the composite demonstrating the highest average hardness, density, tensile strength, and elongation compared to other formulations. Specifically, the composite material's density, tensile strength, and elongation increased by 11.7, 19.4, and 28.4%, respectively, relative to the base alloy.

There are many other studies using different aluminum alloys. Lu and Liu [46] explored the application of ultrasonic vibration in the preparation of semi-solid aluminum alloy slurry, specifically A356, for use in sports equipment manufacturing. The findings revealed that ultrasonic vibration significantly refined the microstructure of the semi-solid aluminum alloy slurry (Figure 4). More notably, the primary $\alpha\text{-Al}$ particles became smaller and more rounded, which directly contributed to the enhanced mechanical properties of the material. Specifically, the application of ultrasonic vibration resulted in a 25.3% increase in tensile strength, a 69.4% increase in elongation, and an 11.4% increase in hardness. Furthermore, it was observed that a decrease in ultrasonic temperature led to an increase in the size of the primary $\alpha\text{-Al}$ particles, with

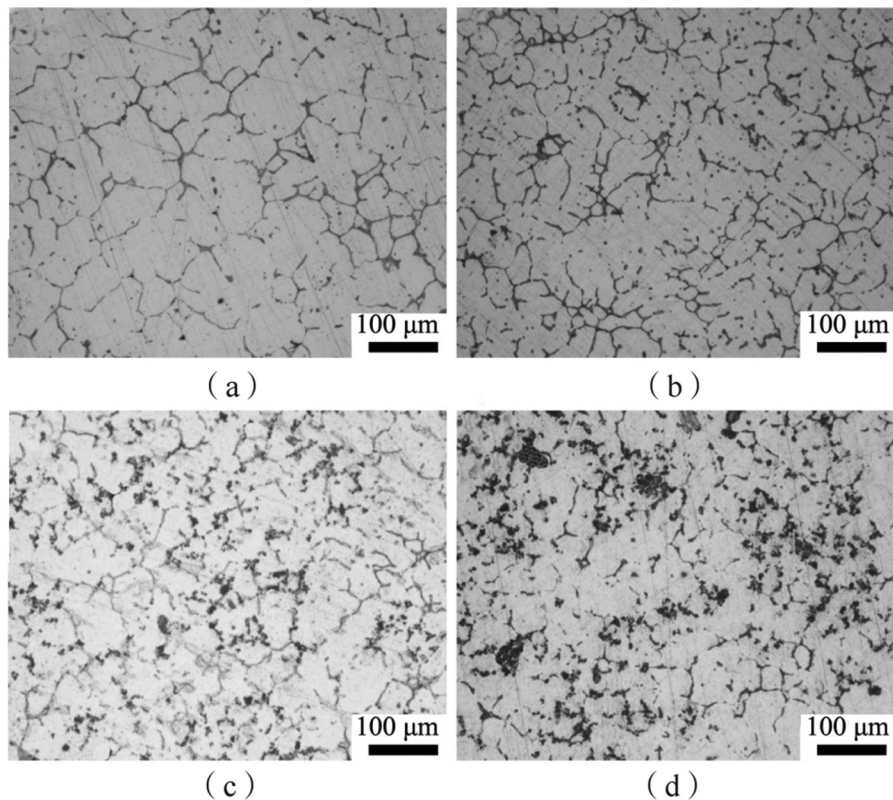


Figure 3: Microstructures of A7075 composites with different $\text{Ni@Al}_2\text{O}_3(\text{p})$ contents [45]. (a) 0 wt%, (b) 0.5 wt%, (c) 1.5 wt%, and (d) 2.5 wt%.

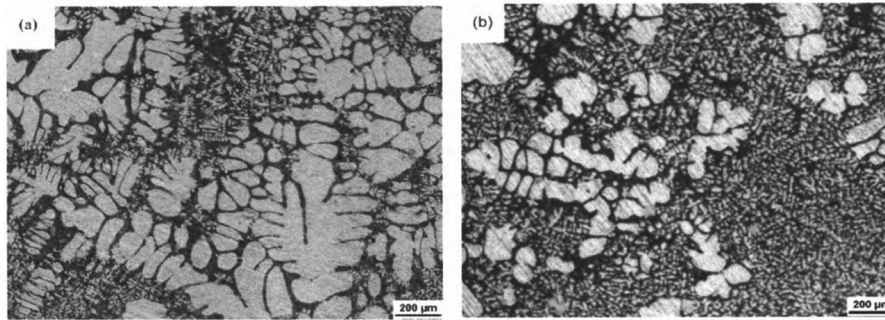


Figure 4: Microstructure of semi-solid A356 (a) before and (b) after ultrasonic vibration [46].

the shape coefficient initially increasing before decreasing. This refinement effect introduced by ultrasonic vibration was attributed to cavitation effects and acoustic streaming, underscoring the potential of this technique in improving the quality and performance of materials used in sports equipment manufacturing. In a study conducted to evaluate the effects of Mg content on the microstructure and mechanical properties of $\text{Al}_6\text{Zn}_x\text{Mg}_{0.5}\text{Cu}_{0.1}\text{Zr}$ casting aluminum alloy [47], researchers discovered that the granularity of the alloy's structure was significantly refined with an increase in Mg content. Specifically, as Mg content rose from 1.4 to 2.6%, the alloy experienced a reduction in grain size, with the smallest grain size observed at a Mg content of 2.6%. The microstructural analysis revealed that the alloy's second phase was predominantly composed of continuous meshy MgZn_2 phase and dispersed, circular Al_2MgCu phase. Following heat treatment, most of these second phases dissolved into the matrix, leaving behind only a few aging precipitated phases in fine strips. However, when the Mg content reached 2.6%, a considerable amount of residual precipitated phases remained within the matrix. Mechanical testing showed that both tensile strength and yield strength of the alloy first increased and then decreased with rising Mg content, peaking at 2.0% Mg with tensile strength and yield strength reaching 470.8 and 218.9 MPa, respectively. This represented a significant improvement of 21.2 and 13.3% over the alloy with 2.6% Mg content. The study concluded that adjusting the Mg content in $\text{Al}_6\text{Zn}_x\text{Mg}_{0.5}\text{Cu}_{0.1}\text{Zr}$ alloys offers a viable pathway to optimize their microstructure and mechanical properties for applications in sports equipment manufacturing.

In a study conducted by Xusheng [48], the effects of Yttrium (Y) element addition on the microstructures and mechanical properties of aluminum alloy A356, tailored for sports equipment, were meticulously analyzed. The research revealed that incorporating varying amounts of Y into the alloy led to significant modifications in its microstructural and mechanical characteristics post-heat

treatment. As the Y content increased, the alloy's grain structure became finer, and the morphology of the eutectic silicon phase transitioned from elongated strips to a more spherical shape. This alteration in microstructure was accompanied by an initial increase in both tensile and yield strengths, followed by a decrease as Y content continued to rise, with the alloy achieving optimal strength at a Y addition of 0.7%. Additionally, the elongation rate gradually decreased with increasing Y content. The study underscored the importance of optimizing Y element addition to enhance the alloy's performance for sports equipment applications. It demonstrated that a Y content of approximately 0.7% yielded the highest tensile and yield strengths, indicating a critical balance between enhancing mechanical properties and maintaining the alloy's structural integrity.

3 Corrosion mechanisms of aluminum alloys

3.1 Sport-specific corrosion factors of aluminum alloys

The corrosion of aluminum alloys used in sports equipment is heavily influenced by the specific environmental conditions and usage patterns associated with different sports. Table 3 provides a systematic overview of sport-specific corrosion factors and their effects on aluminum alloys.

In cycling applications, the effect of mud on aluminum alloy components is particularly significant. Acidic mud ($\text{pH} < 7$) can accelerate pitting corrosion by breaking down the protective oxide layer on the aluminum surface [7]. Conversely, alkaline mud ($\text{pH} > 7$) may promote more

Table 3: Sport-specific corrosion factors and their effects on aluminum alloys in sports equipment

Sport	Corrosion factors	Effects on aluminum alloys
Cycling	• Mud (acidic or alkaline) • Road salt • Human sweat • Mechanical wear	• Acidic mud (pH < 7) accelerates pitting corrosion • Alkaline mud (pH > 7) promotes uniform corrosion • Road salt induces crevice corrosion in joints • Sweat causes localized corrosion and surface etching • Mechanical wear damages protective oxide layer
Swimming	• Chlorinated water • Salt water (ocean)	• Chloride ions initiate pitting corrosion • Salt water accelerates general and pitting corrosion
Winter sports (Skiing, snowboarding)	• Snow • De-icing salts • Temperature fluctuations	• Melted snow in crevices leads to crevice corrosion • De-icing salts promote pitting and crevice corrosion • Thermal cycling can cause coating degradation
Water sports (Kayaking, canoeing)	• Fresh water • Salt water	• Fresh water may cause mild general corrosion • Salt water accelerates pitting and crevice corrosion
Tennis/Badminton	• UV radiation • Human sweat	• UV exposure can degrade protective coatings • Sweat causes localized corrosion on grip areas
Golf	• Abrasion from court surfaces • Soil chemistry • Grass stains • UV radiation	• Abrasion damages protective oxide layer • Acidic soils accelerate corrosion • Grass stains may trap moisture, promoting corrosion • UV exposure can degrade protective coatings

uniform corrosion by dissolving the oxide layer [49]. The presence of road salt, especially in winter conditions, can lead to severe crevice corrosion in joints and connections of bicycle frames. Human sweat is a common corrosion factor across many sports, but its effects are particularly noticeable in cycling due to prolonged contact with handlebars, seat posts, and other components. Sweat typically has a pH range of 4.5–6.5 and contains chloride ions, which can cause localized corrosion and surface etching of aluminum alloys [50–53]. For example, AA6061 alloy, commonly used in bicycle frames, may experience accelerated corrosion in areas of frequent sweat contact, such as the handlebars and seat tube junction [26]. In swimming applications, the chlorinated water of pools and the salt water of oceans present significant corrosion challenges for aluminum alloy equipment [54–56]. Chloride ions in both environments can rapidly initiate pitting corrosion, particularly in alloys with high copper content, such as the 2xxx series [57]. The constant exposure to water also increases the risk of crevice corrosion in joints and fasteners. For winter sports equipment, the combination of snow [58], de-icing salts [59,60], and temperature fluctuations [61] creates a complex corrosion environment. Melted snow trapped in crevices of aluminum components can lead to severe crevice corrosion, especially when combined with de-icing salts. The thermal cycling experienced by equipment used in winter sports can also cause degradation of protective coatings, exposing the underlying aluminum alloy to corrosive elements [62].

One of the most common forms of corrosion in aluminum alloys is pitting corrosion [63]. Pitting corrosion occurs when localized areas of the alloy surface break down, leading to the formation of small, deep pits. This type of corrosion is often associated with the presence of aggressive anions, such as chloride ions, which can penetrate the passive oxide layer on the aluminum surface and initiate localized corrosion [64]. Pitting corrosion is particularly dangerous because the pits can grow rapidly and lead to significant material loss, compromising the structural integrity of the sports equipment. Aluminum alloys with higher contents of alloying elements, such as copper and iron, are more susceptible to pitting corrosion due to the formation of galvanic couples between the intermetallic phases and the aluminum matrix [65].

3.2 General corrosion mechanisms in aluminum alloys

Intergranular corrosion is another form of corrosion that can affect aluminum alloys used in sports equipment. This type of corrosion occurs when the grain boundaries of the alloy are preferentially attacked, leading to the loss of material and a reduction in mechanical properties [66]. Intergranular corrosion is often associated with the precipitation of intermetallic phases at the grain boundaries, which can create localized galvanic cells and promote

corrosion. In aluminum alloys containing copper, such as 2A12, the formation of Al_2Cu precipitates at the grain boundaries can lead to intergranular corrosion [67]. Similarly, in alloys containing magnesium and silicon, such as AA6061, the precipitation of Mg_2Si phases at the grain boundaries can increase the susceptibility to intergranular corrosion [68].

SCC is a form of corrosion that occurs when aluminum alloys are subjected to both a corrosive environment and sustained tensile stress. SCC is characterized by the formation and propagation of cracks, which can lead to sudden and catastrophic failure of the sports equipment. The susceptibility of aluminum alloys to SCC depends on various factors, including the alloy composition, microstructure, and the specific corrosive environment [69]. Alloys with higher strength, such as the 7xxx series (*e.g.*, AA7075), are particularly prone to SCC due to their high levels of alloying elements and the presence of residual stresses from manufacturing processes [70]. The presence of chloride ions and other aggressive species in the environment can accelerate the SCC process by promoting crack initiation and growth.

The role of alloying elements and intermetallic phases in the corrosion of aluminum alloys is significant [71–74]. Alloying elements, such as copper, magnesium, silicon, and zinc, are added to aluminum to enhance its mechanical

properties, but they can also influence the alloy's corrosion behavior. These elements can form intermetallic phases, which have different electrochemical potentials compared to the aluminum matrix. The difference in electrochemical potential between the intermetallic phases and the matrix can create micro-galvanic cells, leading to localized corrosion [75]. For example, in alloys containing copper, such as 2A12, the Al_2Cu intermetallic phase is cathodic compared to the aluminum matrix, which can lead to the preferential corrosion of the matrix around the intermetallic particles [76]. Similarly, in alloys containing magnesium and silicon, such as AA6061, the Mg_2Si intermetallic phase can act as a cathode, promoting localized corrosion of the surrounding aluminum matrix [77].

To effectively evaluate the corrosion behavior of aluminum alloys used in sports equipment, a range of measurement techniques and testing methods are employed. These characterization methods provide crucial data on corrosion rates, mechanisms, and the effectiveness of various surface treatments. Table 4 lists the key measurement approaches used in aluminum alloy corrosion testing.

By employing a combination of these measurement techniques, researchers and manufacturers can comprehensively characterize the corrosion behavior of aluminum alloys and evaluate the effectiveness of various surface treatments for sports equipment applications. This multi-

Table 4: Key measurement approaches used in aluminum alloy corrosion testing

Measurements	Key features
Electrochemical measurements	These include potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and linear polarization resistance. These techniques provide quantitative data on corrosion rates, passivation behavior, and the electrochemical properties of protective coatings
Weight loss measurements	This traditional method involves measuring the weight of aluminum samples before and after exposure to corrosive environments. It provides a direct measure of material loss due to corrosion
Surface analysis techniques	Methods such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy, and X-ray photoelectron spectroscopy are used to characterize surface morphology, composition, and the nature of corrosion products
Salt spray testing	This accelerated corrosion test, typically following ASTM B117 standards, involves exposing aluminum alloy samples to a fine mist of salt solution (usually 5% NaCl) at elevated temperatures. The time to the onset of visible corrosion, or “survival time,” serves as a key indicator of corrosion resistance. Salt spray tests are particularly valuable for simulating marine or coastal environments
Immersion tests	These tests involve submerging aluminum samples in corrosive solutions for extended periods. They can be conducted under various conditions (<i>e.g.</i> , different pH levels, temperatures) to simulate specific environmental exposures
Atmospheric exposure tests	Long-term tests conducted in real outdoor environments provide data on the corrosion behavior of aluminum alloys under actual service conditions
Localized corrosion measurements	Techniques such as the scanning vibrating electrode technique and localized EIS are used to study localized corrosion phenomena like pitting and intergranular corrosion
SCC tests	These tests evaluate the susceptibility of aluminum alloys to SCC under combined mechanical stress and corrosive environments

faceted approach ensures that the selected materials and protective measures can withstand the diverse and often challenging environments encountered in sports use.

3.3 Vibration-induced fatigue and microstructural changes

Long-term exposure to vibrations, a common occurrence in many sports applications, can lead to significant changes in the microstructure of aluminum alloys. This phenomenon, known as vibration-induced fatigue, is well-studied in the aviation industry and has important implications for sports equipment performance and longevity. Research by Zhao *et al.* [78] on aircraft-grade aluminum alloys demonstrated that prolonged exposure to high-frequency vibrations can lead to the formation of persistent slip bands (PSBs) in the microstructure. These PSBs act as preferential sites for crack initiation and can accelerate fatigue failure. In the context of sports equipment, similar effects could be observed in components subjected to repetitive impacts or vibrations, such as bicycle frames, tennis rackets, or golf club shafts. Furthermore, Zhang *et al.* [79] found that vibration-induced microstructural changes can affect the corrosion behavior of aluminum alloys. Their study on 2319 showed that cyclic loading representative of typical usage patterns led to the redistribution of alloying elements at grain boundaries. This redistribution resulted in the formation of micro-galvanic cells, potentially increasing susceptibility to intergranular corrosion.

The interplay between vibration-induced fatigue and corrosion is particularly relevant for sports equipment used in harsh environments. For example, Pathak *et al.* [80] investigated the combined effects of vibration and salt spray exposure on aluminum. They observed that the synergistic effect of mechanical stress and corrosive environment led to accelerated degradation compared to either factor alone. To mitigate these effects, some manufacturers have adopted technologies from the aerospace industry. For instance, the use of damping materials or composite layering techniques can help reduce the transmission of vibrations through the equipment structure [81]. Additionally, advanced surface treatments, such as shot peening or laser shock peening, can induce compressive residual stresses in the surface layers, potentially improving resistance to both fatigue and corrosion [82].

4 Surface treatment methods

4.1 CCCs

Chemical conversion coatings are widely used surface treatments for aluminum alloys in sports equipment applications. These coatings are formed through a chemical reaction between the aluminum substrate and the coating solution, resulting in the formation of a protective layer that enhances corrosion resistance, wear resistance, and adhesion properties. CCCs have been the most widely used and effective surface treatments for aluminum alloys in sports equipment for several decades. CCCs are formed by immersing the aluminum substrate in an acidic solution containing hexavalent chromium (Cr(VI)) compounds, such as sodium dichromate or potassium dichromate. The coating formation involves the reduction of Cr(VI) to trivalent chromium (Cr(III)), which precipitates as a hydrated chromium oxide layer on the aluminum surface [83]. The formation mechanism of CCCs involves several steps. First, the aluminum substrate is cleaned and deoxidized to remove any surface contaminants and the native oxide layer. The substrate is then immersed in the CCC solution, where the Cr(VI) species are reduced to Cr(III) at the aluminum surface, forming a thin, amorphous layer of hydrated chromium oxide. This layer acts as a barrier against corrosive species and provides a reservoir of Cr(VI) ions that can be released to heal any defects or damage to the coating [84]. CCCs offer excellent corrosion protection for aluminum alloys through several mechanisms. The hydrated chromium oxide layer acts as a physical barrier, preventing the penetration of corrosive species to the aluminum substrate [85]. Additionally, the Cr(VI) ions present in the coating can be released and migrate to any defects or damaged areas, where they can be reduced to Cr(III) and form a new protective layer, effectively “self-healing” the coating.

The thickness of CCCs is a critical factor that influences their protective properties and overall performance. Typically, CCCs form very thin layers on aluminum surfaces, with thicknesses ranging from 200 to 1,000 nm, or 0.2 to 1 μm . The exact thickness can vary depending on several factors, including the specific composition of the conversion bath, the immersion time, the temperature of the process and the aluminum alloy substrate [86]. For example, traditional hexavalent chromium-based CCCs tend to form slightly thicker coatings, often in the range of 400–800 nm. In contrast, more environmentally friendly

TCC coatings may form slightly thinner layers, typically in the 200–600 nm range. It is important to note that despite their relatively thin nature, CCCs provide excellent corrosion protection due to their unique structure and chemistry [87]. The thickness of these coatings strikes a balance between providing adequate protection and maintaining the dimensional tolerances of the treated components, which is particularly crucial for precision parts in sports equipment.

4.2 Anodizing surface treatments

4.2.1 Conventional anodizing processes

Conventional anodizing processes for aluminum alloys involve the electrochemical growth of an oxide layer on the substrate surface in an acidic electrolyte solution. The most common anodizing processes are SAA and chromic acid anodizing (CAA). In these processes, the aluminum substrate is immersed in the electrolyte solution and connected to the positive terminal of a power supply, while a cathode (usually made of lead or stainless steel) is connected to the negative terminal [88]. When an electric current is applied, the aluminum surface is oxidized, forming a thick, porous oxide layer.

SAA is widely used for aluminum alloys in sports equipment applications due to its low cost, simplicity, and versatility [89]. In this process, the aluminum substrate is anodized in a solution containing 10–20% sulfuric acid at a temperature of 18–25°C. The resulting oxide layer is typically 5–25 µm thick and has a porous structure with a high surface area [14]. The pores in the oxide layer can be further sealed using hot water or steam to improve the corrosion resistance and surface properties of the anodized coating. For example, Veys-Renaux *et al.* [90] conducted a study focusing on the anodizing process of aluminum alloys, researchers explored the impact of alloy microstructure on the formation and properties of anodic films in sulfuric acid. Analyzing three different aluminum alloys – A1050, A7175, and A2618 – through a combination of *in situ* electrochemical methods and *ex situ* characterization techniques, the study revealed significant insights into the anodizing behavior and the resulting anodic films (Figure 5). One of the most commercially significant aspects of the anodizing process, particularly for sports equipment, is its ability to produce a wide range of vibrant and durable colors. This color-changing capability is achieved through a process called electrolytic coloring, which occurs after the initial anodizing step [91]. In this process, metal salts

are deposited into the pores of the anodic oxide layer, creating different color effects depending on the type of metal salt used and the depth of deposition. For example, cobalt acetate can produce rich blue hues [92], while nickel sulfate creates shades of brown and black [93]. Gold tones can be achieved using ferric ammonium oxalate [94], while tin sulfate produces a range of yellows and bronzes [95]. The thickness of the anodic layer and the voltage used during the coloring process also influence the final color, allowing for precise control and repeatability in production.

CAA is another conventional anodizing process that has been widely used for aluminum alloys in sports equipment applications. In this process, the aluminum substrate is anodized in a solution containing chromic acid (CrO_3) at a temperature of 40–50°C. The resulting oxide layer is typically 2–5 µm thick and has a dense, non-porous structure with excellent corrosion resistance and paint adhesion properties [96]. For example, Elabar *et al.* [97] examined the impact of sulfate impurities on the anodizing process of aluminum and AA2024-T3 alloy, researchers discovered significant findings related to film growth rate, morphology, and corrosion protection. The study meticulously analyzed the effect of varying sulfate concentrations, particularly focusing on higher levels. For aluminum specimens anodized in electrolytes with 3,000 ppm sulfate, film thickness ranged between 1,737 and 2,058 nm, averaging at 1,942 nm, which indicated a growth rate of approximately 3.2 nm. This detailed exploration employed the Bengough–Stuart anodizing process on AA2024-T3 alloy, prepared through electropolishing and etching, to understand the sulfate concentration's impact. Scanning electron micrographs revealed that at lower sulfate concentrations (~38–300 ppm), the film growth rate on aluminum anodized at 100 V was reduced compared to electrolytes with ≤ 1.5 ppm sulfate. However, at concentrations around 1,500–3,000 ppm, the pore stability within the anodic film became compromised, leading to unstable pore diameters. Intriguingly, films formed in electrolytes with 38 ppm sulfate exhibited abnormal pore orientations, causing a cusped interface between the aluminum and the film. Conversely, films anodized in electrolytes containing 1,500 ppm sulfate showed linear pores with distinct ribs and striations along the fractured cell walls.

4.2.2 PEO

PEO, also known as micro-arc oxidation, is an advanced anodizing technique that has gained increasing attention for aluminum alloys in sports equipment applications. PEO involves the growth of a thick, dense, and highly adherent

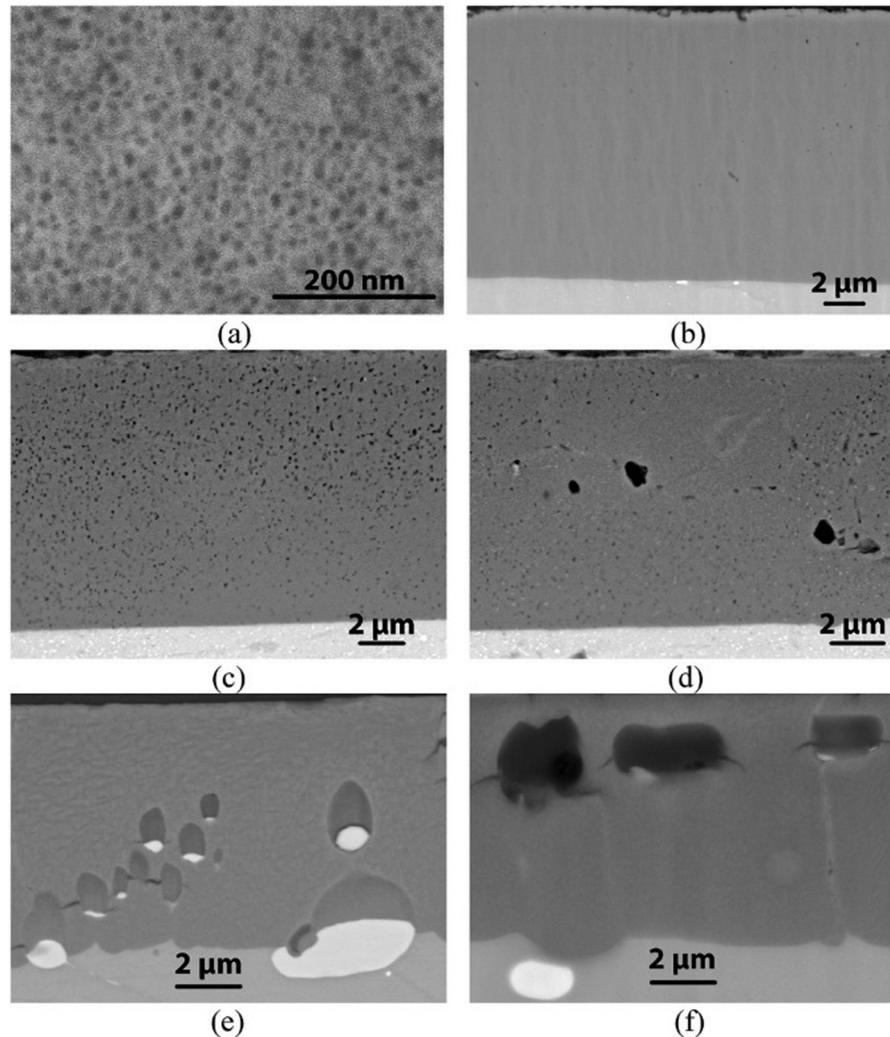


Figure 5: Typical morphologies of anodized layers grown in H_2SO_4 (a), cross-section observations for aluminum alloys 1050 (b), 7175 (c) and (d), and 2618 (e) and (f) [90].

oxide layer on the aluminum surface using high voltages (typically hundreds of volts) in an alkaline electrolyte solution containing silicates, phosphates, or aluminates [98]. During the PEO process, localized plasma discharges occur on the aluminum surface, resulting in the formation of a complex oxide layer with a mixture of crystalline and amorphous phases [99]. The oxide layer produced by PEO is typically 10–100 μm thick and has a highly porous structure with excellent mechanical properties, such as high hardness, wear resistance, and thermal stability. For example, Sobolev *et al.* [100] explored the effectiveness of PEO for enhancing the corrosion resistance of aluminum alloy surfaces. The investigation delved into how the PEO technique, applied in a molten salt medium, impacts the kinetics and mechanisms underlying the corrosion of oxide coatings. A notable focus was placed on understanding the

role of oxygen and chloride ion concentrations in the corrosion process, alongside observing morphological changes in the coatings. Through meticulous experimentation, it was observed that the thickness of the oxide coatings increased with the duration of the PEO treatment, which in turn significantly influenced their corrosion resistance properties. Specifically, coatings developed under optimized PEO conditions demonstrated a marked improvement in corrosion resistance, attributed to a denser and more uniform microstructure, as well as enhanced adhesion to the aluminum substrate. The study provided quantitative data showcasing this improvement; for instance, corrosion rates were substantially reduced in treated samples compared to untreated ones, as evidenced by electrochemical testing. Moreover, the research proposed a detailed mechanism for the corrosion process,

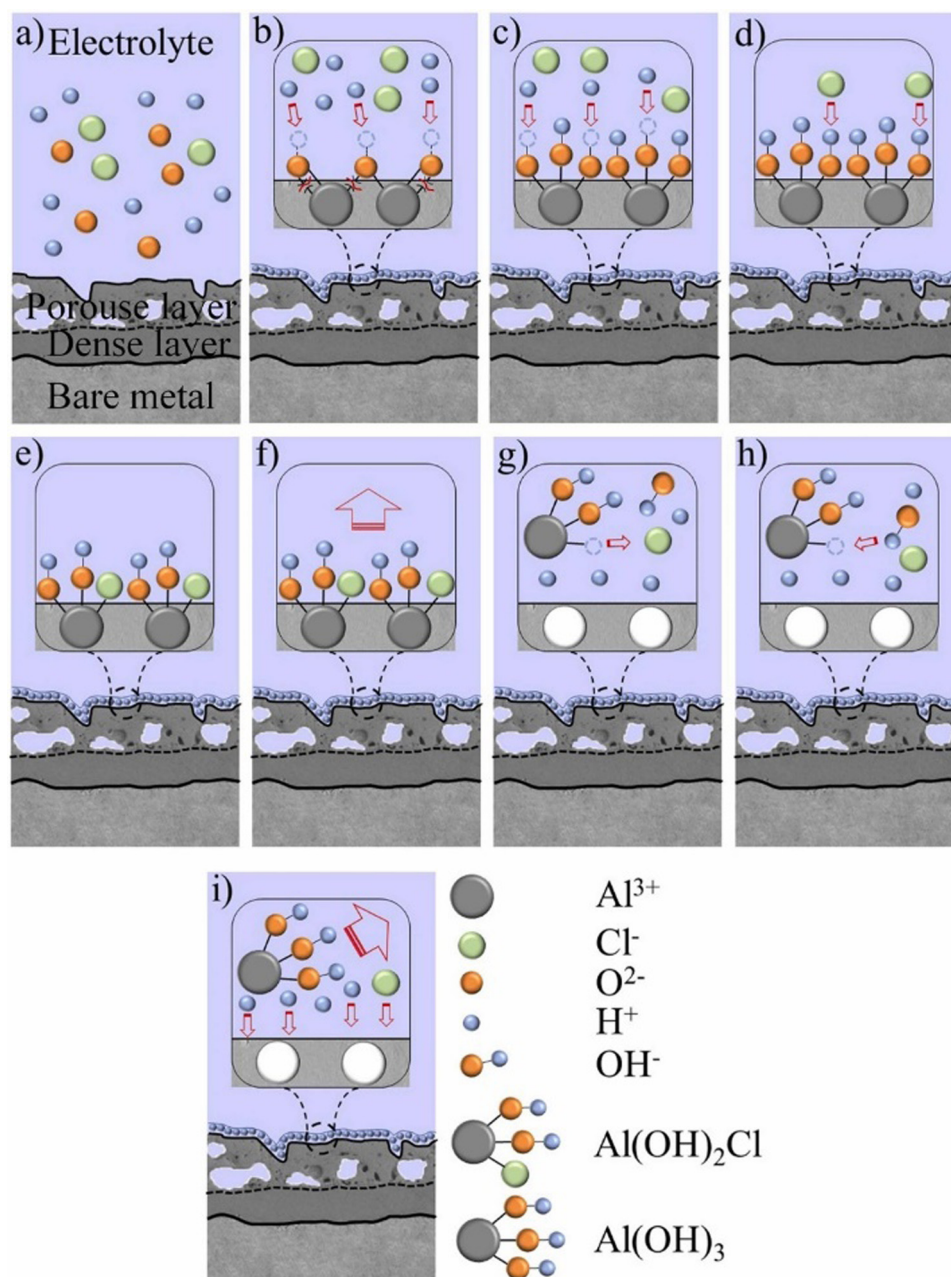


Figure 6: Scheme for the corrosion mechanism of the coating [100].

integrating both the physical changes observed in the coating's morphology and the chemical dynamics at play in the corrosive environment (Figure 6). This mechanism highlighted the protective role of the PEO-generated oxide layer in mitigating the penetration of corrosive agents, thereby extending the lifespan of the aluminum alloy. In another work [101], they explored the application of PEO on an aluminum alloy using a nitrate molten salt electrolyte at 280°C , aiming to synthesize high-performance oxide coatings. This method stands out as it

permits the treatment of larger surfaces than traditional aqueous solutions, which are limited by heating issues. Results unveiled a dual-layered coating structure consisting of an outer layer rich in $\alpha\text{-Al}_2\text{O}_3$ phase and an inner dense layer, both devoid of contaminants from the electrolyte – a common drawback in aqueous-based PEO treatments. Notably, the coatings exhibited remarkable integrity, free from the usual cracks or pores. Micro-hardness evaluations revealed a significant enhancement in the treated surfaces' durability. The innovative approach of using nitrate

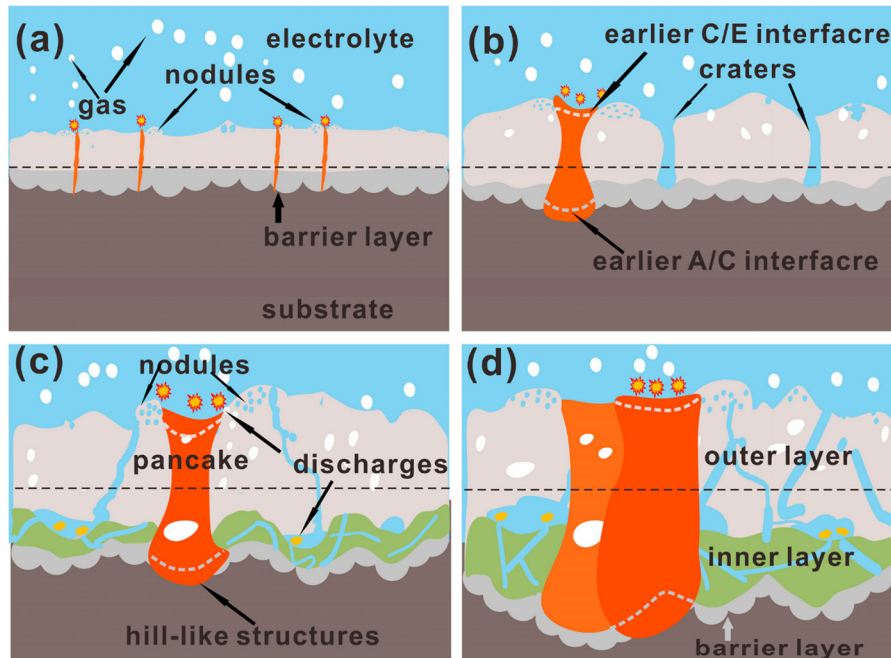


Figure 7: A growth and 3D structure model of the PEO coating at different stages: (a) breakdown of dielectric film under plasma discharges; (b) formation of PEO coating with open pores; (c) initial formation of three-layer structure; and (d) further evolution of three-layer structure [102].

molten salt for PEO processes not only overcomes the size limitation of parts that can be treated but also improves the quality of the oxide layers formed on aluminum alloys, promising extended applications in industries requiring high corrosion and wear resistance.

In a recent study on PEO coatings on A1060 [102], researchers embarked on an in-depth analysis of the coatings' three-dimensional structure and growth model during various stages of the oxidation process. Initial observations revealed that the surface of the PEO coatings featured a unique combination of crater- or pancake-like alumina structures surrounded by silicon-rich nodules. The interface between the aluminum substrate and the coating was characterized by a dense barrier layer, approximately 1 μm thick, composed of clustered cells. As the oxidation time increased, the coatings evolved into a three-layered structure: a barrier layer, an internal structure filled with numerous closed holes, and an outer layer marked by a rough surface texture. The study meticulously documented the morphological transformations of the PEO coatings over time, noting significant changes in the surface and internal structures as well as at the aluminum/coating interface. With oxidation times extending to 45 and 60 min, the coatings developed large cavities within a three-layered architecture, and discontinuous nodules dotted the outer surface. The internal structure was replete with micropores, some of which spanned the entire

thickness of the outer layer. The culmination of these observations led to the development of a growth and discharge model for PEO coatings. This model elucidates the correlation between molten zones and structural evolution within the coatings, providing a comprehensive understanding of the PEO process's impact on A1060 (Figure 7). The study's findings not only advance our knowledge of PEO coatings but also offer valuable insights into optimizing their properties for various industrial applications.

4.3 Other surface treatment technologies

In addition to chemical conversion coatings and anodizing surface treatments, several other surface treatment technologies have been developed and applied to aluminum alloys used in sports equipment. These technologies aim to enhance the corrosion resistance, wear resistance, and surface properties of aluminum components, while also providing unique functionalities and aesthetic appeal.

4.3.1 PVD coatings

PVD is a versatile surface coating technology that involves the deposition of thin, dense, and uniform coatings on the

aluminum substrate through the condensation of a vaporized material [103]. PVD coatings offer excellent barrier protection against corrosion, as well as enhanced wear resistance, hardness, and surface lubricity. The most common PVD techniques used for aluminum alloys in sports equipment applications are magnetron sputtering and arc evaporation. Magnetron sputtering involves the bombardment of a target material (*e.g.*, titanium, chromium, or zirconium) with energetic ions, resulting in the ejection of atoms from the target surface [16]. These atoms then condense on the aluminum substrate, forming a thin, dense coating. Magnetron sputtering can produce a wide range of coating compositions and structures, including monolithic, multilayered, and nanocomposite coatings, with thicknesses ranging from a few nanometers to several micrometers.

PVD coatings have been successfully applied to various aluminum alloys used in sports equipment, including 2xxx, 6xxx, and 7xxx series alloys. For example, Paiva *et al.* [104] delved into the performance of various PVD coatings applied to aluminum die casting molds, with a particular focus on AlCrN, AlTiN/Si₃N₄, and AlCrN/Si₃N₄ nanocomposite coatings (Figure 8). The findings revealed that the AlCrN/Si₃N₄ nanocomposite coating stood out for its superior wear resistance and durability, attributing these characteristics to its unique structural composition and the synergistic effect of its constituents. Specifically, this coating demonstrated a significant reduction in surface roughness and enhanced adhesion properties, leading to a notable decrease in friction coefficients compared to the other tested coatings. Quantitative data showed that the AlCrN/Si₃N₄ coated molds experienced a 40% improvement in tool life under rigorous operational conditions, underscoring the material's potential to substantially increase the longevity and efficiency of aluminum die casting molds. Campos Neto *et al.* [105] explored the impact of various factors on the

performance of AlCrN-based PVD coatings in lube-free aluminum die casting environments. The study focused on the effects of the Al/(Al + Cr) ratio, the incorporation of TiCN-doped layers, surface roughness, and the presence of coating defects. A notable finding was that coatings with a higher Al/(Al + Cr) ratio exhibited superior resistance to wear and attack from molten aluminum. Specifically, when the Al content was increased, the coatings showed enhanced protective qualities against the corrosive and erosive actions of molten aluminum. The introduction of TiCN-doped layers into the AlCrN coatings further improved their performance by significantly enhancing their resistance to molten aluminum attack and reducing friction, which is critical in die casting applications.

4.3.2 Sol-gel coatings

Sol-gel coatings are another promising surface treatment technology for aluminum alloys used in sports equipment. Sol-gel coatings are derived from organic-inorganic hybrid materials, which are formed through the hydrolysis and condensation of metal alkoxide precursors [106]. The resulting coatings are typically thin (<1 μm), transparent, and highly adherent to the aluminum substrate. Sol-gel coatings offer several advantages over traditional surface treatment technologies, including low processing temperatures, eco-friendliness, and the ability to incorporate various functional materials, such as corrosion inhibitors, UV absorbers, and self-healing agents [107]. Sol-gel coatings can also provide excellent barrier protection against corrosion, as well as improved scratch resistance and surface hydrophobicity.

The most common sol-gel coatings used for aluminum alloys in sports equipment applications are based on silica (SiO₂), zirconia (ZrO₂), and titania (TiO₂). These coatings

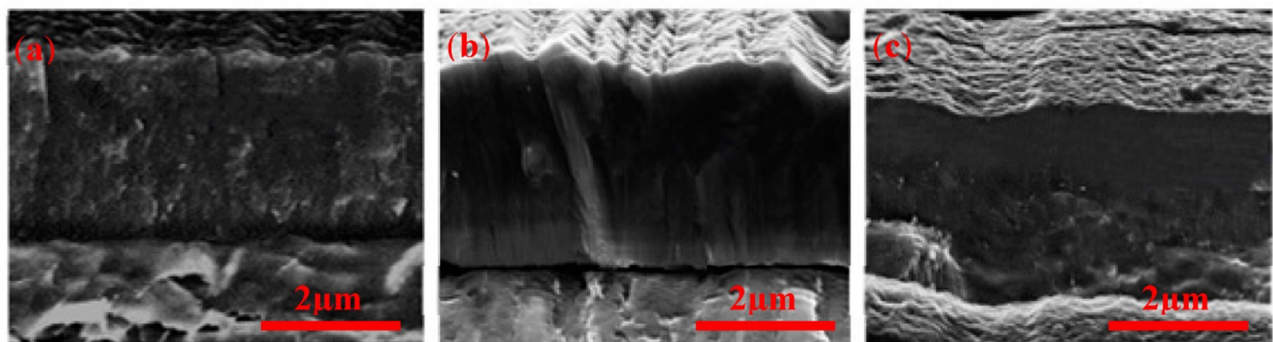


Figure 8: SEM images of coatings cross-section for coating chemical composition: (a) AlCrN PVD coating; (b) AlTiN/Si₃N₄ PVD nanocomposite; and (c) AlCrN/Si₃N₄ PVD nanocomposite coating [104].

can be applied using various methods, such as dip coating, spin coating, or spray coating, depending on the size and shape of the aluminum components and the desired coating thickness and uniformity. For example, Tarzanagh *et al.* [108] developed a novel approach to enhance the corrosion resistance of A2024 by incorporating MIL-53 (Al) nanoparticles into a sol-gel coating. This innovative method aimed to leverage the unique properties of Metal-Organic Frameworks (MOFs) to improve the protective capabilities of conventional sol-gel coatings. The sol-gel process, known for its ability to form uniform and dense coatings, was optimized with the addition of synthesized MIL-53 (Al) nanoparticles. The primary outcome of this research was a significant enhancement in the thermal stability and corrosion resistance of the coated A2024 alloy. Specifically, the addition of MIL-53 (Al) nanoparticles to the sol-gel coating resulted in a notable improvement in the coating's uniformity and a reduction in surface roughness. EIS tests demonstrated that the nanocomposite coating exhibited superior corrosion resistance compared to the neat sol-gel coating. The polarization resistance of the nanocomposite coating was significantly higher, indicating a more effective barrier against corrosion processes. In another work [109], they embarked on enhancing the corrosion resistance

of AA2024 through innovative sol-gel coatings. Central to their approach was the incorporation of diclofenac sodium (DFS)-loaded mesoporous SBA-15 particles, aimed at leveraging the pH-sensitive release of DFS for active corrosion protection. The synthesis involved creating a sol-gel matrix using 3-Glycidoxypyltrimethoxysilane and tetraethyl orthosilicate, into which aminated and DFS-encapsulated SBA-15 particles were integrated (Figure 9). This concoction was meticulously applied to pre-treated AA2024 substrates *via* dip-coating, ensuring uniform distribution and adherence. The resultant coatings were subjected to rigorous characterization and corrosion resistance testing. Notably, the sol-gel coatings augmented with encapsulated SBA-15@DFS exhibited remarkable corrosion resistance, evidenced by EIS tests conducted over 150 days in a simulated acidic rain environment. These coatings significantly outperformed their neat counterparts, demonstrating the efficacy of the encapsulated DFS in mitigating corrosion processes. The SEM analysis further revealed that the inclusion of SBA-15-NH₂ and SBA-15@DFS not only filled the micro-defects inherent to neat sol-gel coatings but also fostered a more robust chemical interaction within the matrix, enhancing the overall integrity and protective capabilities of the coating.

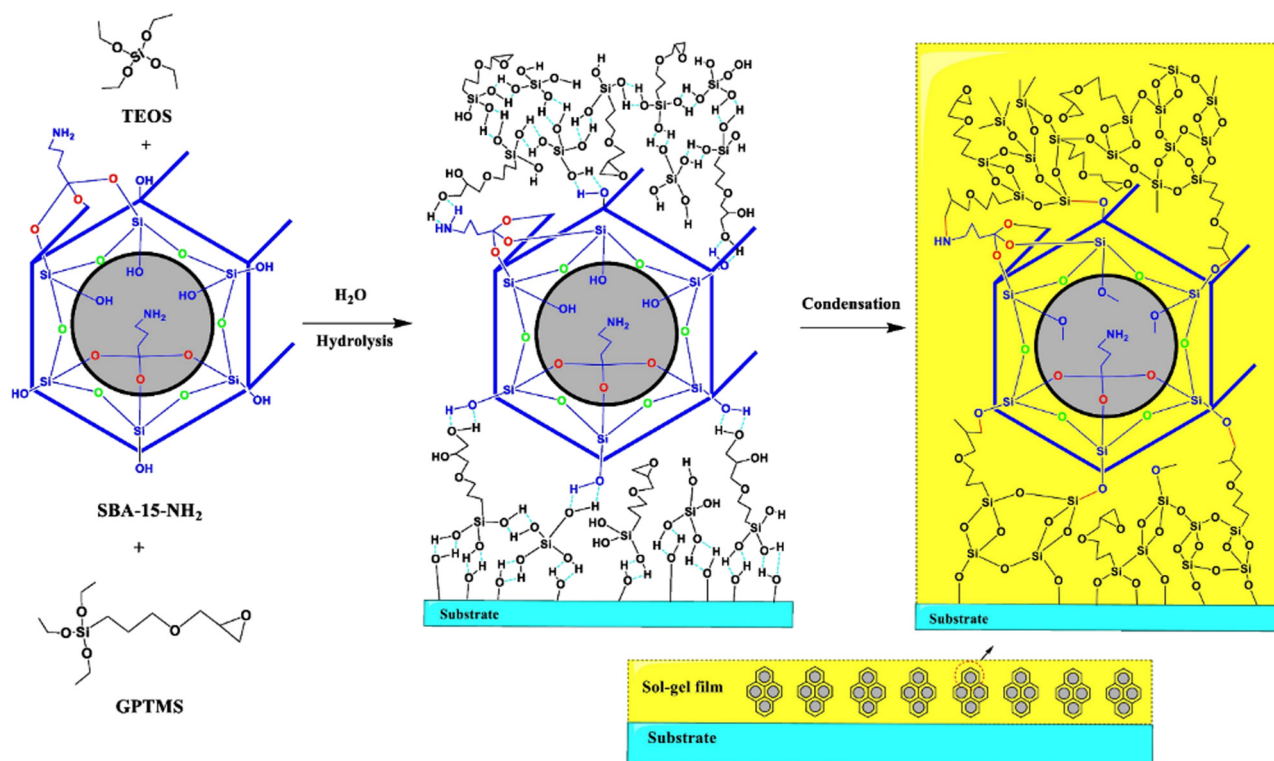


Figure 9: Chemical interaction of the sol-gel coating and SBA-15-NH₂ nanostructure [109].

4.3.3 Sublimation coating technology

Sublimation coating is a surface treatment technology that has recently gained attention for its potential applications in enhancing the performance and aesthetics of aluminum alloys. This process involves the direct transition of a solid coating material into a gaseous state, which then condenses onto the aluminum substrate, forming a thin, uniform, and highly adherent coating. The sublimation coating process typically consists of several key steps. Initially, the aluminum substrate surface is carefully prepared to ensure optimal adhesion. Next a specially formulated sublimation coating powder or film is applied onto a transfer medium. This transfer medium is then positioned in close proximity to the aluminum substrate. The assembly is heated to a specific temperature, causing the coating material to sublime. As the vaporized coating condenses onto the aluminum surface, it forms a strong bond. Finally, cooling and post-treatment processes are employed to enhance the durability of the coating.

One of the primary advantages of sublimation coating for sports equipment applications is its ability to create complex, multi-color designs and patterns with high resolution and durability. This capability makes it particularly suitable for creating visually appealing and customized finishes on aluminum components such as bicycle frames and tennis racket frames [110]. The aesthetic versatility of sublimation coating allows manufacturers to produce unique, eye-catching designs that can set their products apart in a competitive market. In terms of performance benefits, sublimation coatings offer several advantages for aluminum alloys used in sports equipment. These coatings can provide enhanced wear resistance, improving the longevity of equipment subjected to frequent use and harsh conditions. The corrosion protection offered by sublimation coatings is another crucial benefit, especially for equipment exposed to diverse environmental conditions, such as moisture, sweat, and salt water. Furthermore, the increased UV stability of these coatings helps maintain the appearance and integrity of the equipment over time, even when used extensively outdoors.

4.3.4 Laser surface modification

Laser surface modification is an advanced surface treatment technology that involves the use of high-energy laser beams to alter the surface microstructure and properties of aluminum alloys (Figure 10). Laser surface modification techniques, such as LSM and LSA, can significantly

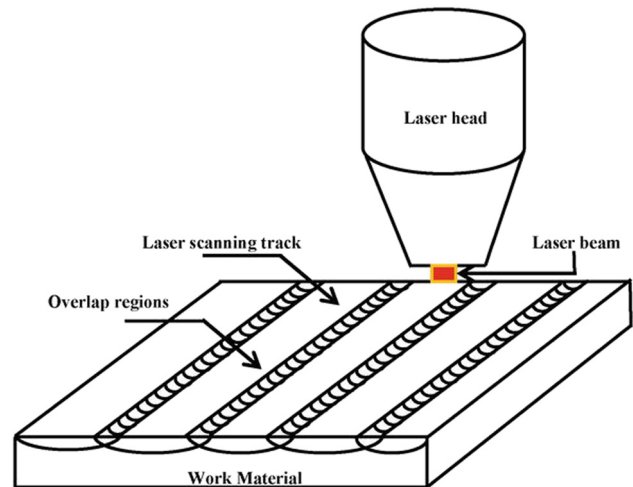


Figure 10: Schematic of laser transformation hardening [111].

improve the corrosion resistance, wear resistance, and surface hardness of aluminum components, without affecting their bulk properties.

LSM involves the rapid heating and melting of the aluminum surface using a focused laser beam, followed by rapid solidification. The rapid melting and solidification process can refine the surface microstructure, reduce surface porosity, and redistribute alloying elements, resulting in improved surface properties. LSA, on the other hand, involves the simultaneous melting of the aluminum surface and the addition of alloying elements, such as silicon, nickel, or chromium, using a laser beam. The alloying elements can react with the molten aluminum to form hard, wear-resistant intermetallic phases, such as Al_3Ni or $\text{Al}_{13}\text{Cr}_4\text{Si}_4$.

Liu *et al.* [112] presents an approach for enhancing the surface strength of aluminum alloys used in sports equipment through laser shock processing, employing a sophisticated numerical simulation method. By integrating the finite element method for dynamic load analysis, this research offers a detailed examination of the laser strengthening process, including temperature field changes and deformation. Specifically, the study revealed that optimal laser processing parameters could significantly improve the surface hardness and wear resistance of aluminum alloys, making them more suitable for high-performance sports equipment. The simulation results indicated a notable increase in surface hardness by up to 70% compared to untreated samples, without compromising the material's integrity. This enhancement is attributed to the laser's ability to induce rapid thermal cycles and severe plastic deformation on the surface, leading to grain refinement and dislocation density increase. Furthermore, wear tests showed a reduction in wear rate by over

50% for laser-treated samples, underscoring the effectiveness of this technique in extending the lifespan of sports equipment. This research not only advances our understanding of laser material processing but also sets the stage for further exploration into optimizing laser parameters for various applications, promising significant advancements in materials science and engineering. Kandavalli *et al.* [113] reviewed the advancements in laser surface treatment of aluminum alloys and composites, a detailed exploration was conducted on how these methods revolutionize the enhancement of surface properties. A significant outcome highlighted was the improvement in wear and corrosion resistance, crucial for extending the lifespan of components in aerospace and automotive applications. For instance, LSM on A7075 demonstrated a remarkable increase in SCC resistance – up to five times higher than untreated specimens. Similarly, the application of an excimer laser for surface melting resulted in a six-fold decrease in corrosion current, indicating a superior corrosion resistance. These enhancements were attributed to the refined microstructure and the formation of protective layers or phases on the aluminum surfaces. The review underscored the pivotal role of laser treatment parameters in achieving desired material characteristics, pointing towards a future where precise control over these processes can lead to even more significant improvements in metal and composite performance.

Laser surface modification techniques offer several advantages over traditional surface treatment technologies, including high precision, localized treatment, and minimal heat-affected zones. Laser surface modification

can also be easily automated and integrated into existing manufacturing processes, making it suitable for high-volume production of sports equipment components. However, laser surface modification also has some limitations, such as high equipment costs and the need for skilled operators. The surface properties achieved by laser surface modification may also depend on the specific aluminum alloy composition and the laser processing parameters, such as laser power, scanning speed, and spot size.

4.4 Commercial surface treatments for sports equipment

In addition to the laboratory-scale and emerging surface treatment technologies discussed earlier, several commercial processes have gained widespread adoption in the sports equipment industry. These treatments offer proven performance, scalability, and cost-effectiveness for large-scale manufacturing. Table 5 shows some of the most notable commercial treatments.

The adoption of these commercial processes has significantly contributed to the advancement of aluminum alloys in sports equipment, enabling manufacturers to produce lighter, more durable, and higher-performing products. As these technologies continue to evolve, we can expect further improvements in the performance and lifespan of aluminum sports equipment.

Table 5: Most notable commercial treatments for sports equipment

Treatment method	Features
Keronite PEO coatings	Keronite is a proprietary PEO process that has found significant application in sports equipment, particularly for bicycle components and golf club shafts. The Keronite process produces a ceramic-like coating on aluminum alloys, offering exceptional wear resistance and corrosion protection
Bonderite conversions	Henkel's Bonderite line includes a range of conversion coatings specifically formulated for aluminum alloys used in sports equipment. These include both traditional chromate and modern chromium-free formulations
Tagnite anodizing	Developed by Tagnite LLC, this advanced anodizing process creates a hard, ceramic-like surface on aluminum alloys. It has gained popularity in high-end sports equipment, such as archery components and lightweight camping gear. Tagnite-treated surfaces exhibit superior wear resistance compared to traditional anodizing
Coloring by AaCron	This electrolytic coloring process for anodized aluminum has become a staple in the sports industry for creating durable, vibrant finishes on equipment. Ionicolor treatments are particularly popular for snowboarding and skiing equipment, where they provide both aesthetic appeal and additional surface protection. The process allows for a wide range of colors while maintaining the corrosion resistance of the underlying anodic layer
Nituff by Nimet Industries	This proprietary hard anodizing process incorporates polytetrafluoroethylene into the anodic coating, resulting in a surface with both high hardness and low friction. Nituff coatings have found applications in high-stress areas of sports equipment, such as bicycle suspension components and fishing reels, where they provide both wear resistance and smooth operation



Figure 11: Manufacturing sequence of aluminum extrusions for sports applications.

4.5 Full protection systems

While individual surface treatments offer significant protection, many sports equipment manufacturers employ comprehensive protection systems that combine multiple layers for enhanced performance and durability. A common and highly effective approach is the use of conversion coatings as a base layer, followed by organic layers such as primers and topcoats. These multi-layer systems provide synergistic protection, addressing various environmental challenges faced by sports equipment. The conversion coating enhances adhesion and provides initial corrosion resistance, the primer further improves adhesion and barrier properties, while the topcoat offers final environmental protection and desired aesthetics. Studies have consistently shown that such full protection systems significantly outperform single-layer treatments in terms of corrosion resistance, durability, and overall equipment lifespan. The combination of inorganic conversion coatings with organic layers allows for optimized protection against a wide range of environmental factors, including moisture, UV radiation, and chemical exposure. This multi-layer approach has become increasingly prevalent in high-end sports equipment, allowing manufacturers to meet the demanding requirements of both performance and longevity for aluminum components used in various sporting applications.

4.6 Painting methods and types of paint for aluminum sports equipment

In addition to the various surface treatments discussed earlier, painting is a crucial final step in the production of many aluminum sports equipment items. Painting not only provides aesthetic appeal but also offers an additional layer of protection against corrosion and wear [114]. Figure 11 shows a typical manufacturing sequence of aluminum extrusions for sports applications. Table 6 shows the several painting methods employed in the sports equipment industry for aluminum components.

The choice of paint type depends on the specific requirements of the sports equipment and the intended use environment. Epoxy paints is known for their excellent adhesion and chemical resistance, epoxy paints are often used as a primer or base coat for aluminum sports equipment. They provide a strong foundation for subsequent paint layers and enhance corrosion resistance [118]. Polyurethane paints offer superior UV resistance, color retention, and gloss, making them ideal for outdoor sports equipment. Polyurethane paints are commonly used as topcoats for bicycle frames, golf clubs, and tennis rackets [119]. Acrylic paints offering good weather resistance and color stability are used for both indoor and outdoor sports equipment. They are particularly popular for their quick drying times and ease of application [120]. Fluoropolymer

Table 6: Painting methods are employed in the sports equipment industry for aluminum components

Painting methods	Applications in sports equipment
Powder coating	This method involves electrostatically charging dry paint particles and spraying them onto the aluminum surface. The coated item is then heated, allowing the powder to melt and form a uniform, durable finish. Powder coating is widely used for bicycle frames, golf clubs, and other sports equipment due to its durability and resistance to chipping [115]
Wet painting	Traditional wet painting techniques, including spray painting and electrostatic spray painting, are also common. These methods allow for a wide range of colors and finishes but may require multiple coats and longer curing times compared to powder coating [116]
Anodized coloring	While not strictly a painting method, anodized coloring involves adding dyes to the porous anodic oxide layer during the anodizing process. This technique is popular for items like carabiners, ski poles, and lightweight bicycle components, offering excellent color retention and wear resistance [117]

paints such as polyvinylidene fluoride, offer exceptional durability, chemical resistance, and color retention [121]. While more expensive, they are used in high-end sports equipment where long-term performance is critical.

4.7 Comparative analysis of surface treatment categories

To provide a more comprehensive and structured overview of the surface treatment methods discussed, we can categorize these techniques into three broad groups: chemical, electrochemical, and physical treatments [122]. This classification allows for a systematic comparison of their mechanisms, advantages, and limitations in the context of aluminum alloys used in sports equipment.

Chemical treatments primarily involve the formation of protective layers through chemical reactions on the aluminum surface. This category includes CCCs, such as traditional CCCs and chromium-free alternatives, as well as sol-gel coatings [123]. These methods offer relatively simple application processes and are cost-effective for large-scale production. They also have the ability to form uniform coatings on complex geometries [124]. However, chemical treatments face limitations such as environmental concerns with certain formulations, particularly those involving hexavalent chromium. Additionally, they typically produce coatings with limited thickness compared to other methods and may have reduced durability in harsh environments.

Electrochemical treatments utilize electrical current to modify the aluminum surface, typically forming oxide layers. Key techniques in this category include conventional anodizing (e.g., SAA), hard anodizing, and PEO. These methods are capable of producing thick, durable oxide layers with excellent corrosion and wear resistance. They also offer the potential for decorative finishes, such as colored anodizing. However, electrochemical treatments generally require more complex processing equipment and have higher energy consumption compared to chemical treatments. There is also a potential for coating non-uniformity on complex shapes.

Physical treatments involve the deposition of materials or modification of the surface structure through physical processes. This category includes PVD coatings, laser surface modification, and sublimation coating. These techniques offer precise control over coating composition and structure, enabling the creation of unique surface properties such as superhydrophobicity. They also tend to have

minimal environmental impact compared to some chemical processes. However, physical treatments often require specialized, costly equipment and may have limitations in coating large or complex-shaped components. There is also a potential for thermal effects on substrate properties.

To visually summarize these comparisons, Table 7 outlines the key characteristics, advantages, and limitations of each surface treatment category.

This categorization and comparative analysis provide a framework for understanding the relative merits of different surface treatment approaches. The choice of treatment method for a specific sports equipment application depends on various factors, including the desired performance characteristics, manufacturing constraints, environmental considerations, and cost-effectiveness. For instance, chemical treatments like chromium-free conversion coatings might be preferred for large-scale production of affordable sports equipment where moderate corrosion protection is sufficient. Electrochemical treatments, particularly advanced techniques like PEO, could be ideal for high-performance equipment requiring superior wear and corrosion resistance, such as professional-grade bicycle components or marine sports equipment [125]. Physical treatments might find their niche in specialized, high-value equipment where unique surface properties or precise control over coating characteristics justify the higher processing costs.

As the sports equipment industry continues to evolve, manufacturers must carefully weigh these factors to select the most appropriate surface treatment method, balancing performance requirements with production feasibility and environmental responsibility. The ongoing development of these surface treatment technologies promises to further enhance the performance, durability, and sustainability of aluminum alloys in sports equipment applications.

4.8 Recent advancements and emerging trends in surface treatment technologies

A prominent trend is the development of eco-friendly alternatives to hexavalent chromium-based conversion coatings. TCC coatings and chromium-free formulations based on molybdenum, zirconium, titanium, and rare-earth elements have shown promise in providing comparable corrosion protection while addressing environmental and health concerns [126]. Advanced anodizing techniques, particularly PEO, have progressed significantly. Recent research by Almajidi *et al.* [127] explored PEO in molten salt mediums, demonstrating potential for high-performance oxide

Table 7: Comparison of surface treatment categories for aluminum alloys in sports equipment

Treatment category	Key techniques	Advantages	Limitations	Typical applications
Chemical	CCCs, sol-gel	Cost-effective, simple application	Environmental concerns, limited thickness	Bicycle frames, golf clubs
Electrochemical	Anodizing, PEO	Thick, durable coatings, corrosion resistant	Energy-intensive, complex equipment	Ski poles, tennis rackets
Physical	PVD, laser modification	Precise control, unique properties	High equipment costs, scalability challenges	High-end components, specialized equipment

coatings with improved corrosion resistance and mechanical properties on larger surfaces.

Smart, self-healing coatings represent another frontier, incorporating reactive materials or reversible chemical bonds to autonomously repair damage and extend equipment lifespan. In PVD, recent advancements have focused on nanocomposite structures. Work by Paiva *et al.* [104] highlighted the superior wear resistance and durability of AlCrN/Si₃N₄ nanocomposite coatings, indicating potential for improving component longevity in high-stress applications.

Sol-gel coating technology has seen innovations such as the incorporation of MOFs. Tarzanagh *et al.* [108] explored adding MIL-53 (Al) nanoparticles to sol-gel coatings, showing promising results in enhancing corrosion resistance and thermal stability. The integration of nanotechnology across various surface treatment methods is an overarching trend, enabling unprecedented control over coating properties and performance [128]. These advancements underscore the field's dynamic nature and continuous efforts to enhance performance, durability, and sustainability of surface treatments for aluminum alloys in sports equipment. Ongoing research promises further innovations in developing high-performance, environmentally friendly, and cost-effective solutions.

5 Environmental and health aspects

Environmental and health considerations have become increasingly important in the development and application of surface treatments for aluminum alloys used in sports equipment. One of the most significant challenges in this field has been the replacement of hexavalent chromium (Cr(vi)) compounds, which have been widely used in CCCs due to their excellent corrosion protection properties. However, Cr(vi) is known to be highly toxic and carcinogenic, posing serious risks to both human health and the environment. Stringent regulations, such as the European Union's Restriction of Hazardous Substances directive and the Registration, Evaluation, Authorization, and Restriction of Chemicals regulation, have pushed the industry to develop alternative surface treatments that are more environmentally friendly and less hazardous to human health.

The shift towards more sustainable surface treatments has also focused on reducing the environmental impact of the treatment processes themselves [129]. Traditional anodizing and chemical conversion coating processes often

Table 8: Comparison of eco-friendly surface treatment alternatives for aluminum alloys

Treatment	Advantages	Disadvantages
TCC coatings	– Less toxic than Cr(vi) – Comparable corrosion protection to CCCs – Relatively easy implementation	– Still contains chromium – May have slightly inferior self-healing properties compared to CCCs
Zirconium-based conversion coatings	– Chromium-free – Good corrosion protection – Suitable for various Al alloys	– May have lower corrosion resistance in highly aggressive environments – Process optimization can be challenging
Rare earth-based conversion coatings	– Environmentally benign – Excellent corrosion protection – Self-healing properties	– Higher cost of rare earth compounds – Process sensitivity to pH and temperature
Sol-gel coatings	– Versatile and customizable – Excellent barrier properties – Can incorporate additional functionalities	– May have lower mechanical durability – Often require thermal curing, increasing energy consumption
Low-temperature anodizing	– Reduced energy consumption – Similar performance to conventional anodizing	– May require longer processing times – Limited to certain alloy types
PEO	– Superior wear resistance – Thick, hard coatings – Uses more environmentally friendly electrolytes	– Higher equipment costs – Can be energy-intensive – May have rougher surface finish
Water-based conversion coatings	– Reduced use of organic solvents – Environmentally friendly ingredients	– May have lower corrosion resistance compared to solvent-based systems – Can be sensitive to application conditions

involve the use of strong acids, alkaline solutions, and other potentially harmful chemicals. These processes can generate significant amounts of hazardous waste and consume large quantities of water and energy. Table 8 summarizes the advantages and disadvantages of these eco-friendly alternatives.

As the industry continues to evolve, there is a growing emphasis on developing surface treatments that not only provide excellent protection for aluminum alloys but also contribute to the overall sustainability and safety of sports equipment throughout its lifecycle. Future research should focus on further improving the performance of these eco-friendly alternatives while optimizing their production processes for large-scale industrial implementation.

6 Future directions and challenges

The development of advanced surface treatment technologies for aluminum alloys used in sports equipment has made significant progress in recent years. However, several challenges remain to be addressed, and new research directions are emerging to meet the ever-increasing demands for

high-performance, eco-friendly, and cost-effective surface treatments. This section will discuss the future directions and challenges in the field, focusing on the replacement of toxic hexavalent chromium, the development of smart and self-healing coatings, the need for improved corrosion resistance and durability, and the industrial implementation and cost considerations.

One of the major challenges in the surface treatment of aluminum alloys for sports equipment is the replacement of toxic hexavalent chromium (Cr(vi)) compounds, which have been widely used in CCCs due to their excellent corrosion protection and self-healing properties. However, the use of Cr(vi) has been increasingly restricted due to its carcinogenic nature and environmental concerns. Therefore, the development of eco-friendly alternatives to CCCs that can provide comparable or superior corrosion protection has become a key focus for researchers and manufacturers. Another promising research direction in the field of surface treatments for aluminum alloys in sports equipment is the development of smart and self-healing coatings. These coatings can autonomously detect and repair damage, such as scratches and cracks, thereby extending the service life and maintaining the performance of the equipment. Self-healing coatings typically

incorporate reactive materials, such as microcapsules or reversible chemical bonds, which can be triggered by external stimuli, such as pH changes, mechanical damage, or light irradiation.

Examples of smart and self-healing coatings for aluminum alloys in sports equipment include pH-sensitive polyelectrolyte multilayers, which can release corrosion inhibitors in response to pH changes caused by corrosion reactions, and UV-responsive microcapsules containing healing agents, which can be released upon UV irradiation to repair damaged areas. However, the development of smart and self-healing coatings still faces challenges in terms of the long-term stability, mechanical durability, and scalability of the coating systems. The need for improved corrosion resistance and durability of surface treatments for aluminum alloys in sports equipment is another key challenge and research direction. While various surface treatment technologies, such as anodizing, PVD coatings, and laser surface modification, have been developed to enhance the corrosion resistance and mechanical properties of aluminum components, their performance in harsh environments and under high mechanical stresses still needs to be further improved.

Finally, the industrial implementation and cost considerations of advanced surface treatment technologies for aluminum alloys in sports equipment remain significant challenges. While various surface treatment techniques have shown promising results in laboratory-scale studies, their scalability, reproducibility, and cost-effectiveness in industrial-scale production need to be carefully evaluated. For example, the implementation of PVD coatings and laser surface modification techniques in high-volume production of sports equipment components may be limited by the high equipment costs, long processing times, and the need for skilled operators. The development of cost-effective and eco-friendly surface treatment processes, such as low-temperature and low-pressure PVD techniques, high-throughput laser processing, and energy-efficient anodizing and conversion coating processes, will be crucial for the widespread adoption of these technologies in the sports equipment industry.

7 Conclusion

Based on the comprehensive review of advancements in surface treatment technologies for aluminum alloys used in sports equipment, it is evident that significant progress

has been made in enhancing the corrosion resistance, mechanical properties, and overall performance of these materials. The development of eco-friendly alternatives to toxic hexavalent chromium-based conversion coatings, such as trivalent chromium and chromium-free formulations, has been a major focus of research efforts. Advanced anodizing techniques, including PEO, have shown promising results in producing thick, dense, and highly adherent oxide coatings with excellent corrosion protection and mechanical properties. Other surface treatment technologies, such as PVD coatings, sol-gel coatings, and laser surface modification, have also demonstrated their potential in improving the surface properties of aluminum alloys for sports applications. However, challenges remain in terms of the long-term durability, scalability, and cost-effectiveness of these advanced surface treatments. Future research directions should focus on the development of smart and self-healing coatings, further optimization of surface treatment processes for improved corrosion resistance and mechanical properties, and the industrial implementation of these technologies in a cost-effective and sustainable manner. By addressing these challenges and continuing to innovate in the field of surface treatment technologies, the performance, safety, and longevity of aluminum alloys in sports equipment can be further enhanced, ultimately benefiting athletes and sports enthusiasts worldwide.

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