Protection of aluminum and aluminum alloys from corrosion

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Abstract: *This paper examines corrosion protection techniques for aluminum alloys, focusing on traditional and innovative surface treatment methods. Aluminum alloys are applicable in many industries due to their advantages derived from the good combination of chemical, physical, and mechanical properties. However, they are susceptible to various forms of corrosion, which can critically compromise the structure of the component and lead to damage that does not ensure safe operation. Coatings are necessary for the durability and effective protection of aluminum and its alloys from corrosion, ensuring safe and long-term operation of components in aggressive environments.*
KEYWORDS*: ALUMINUM, ALUMINUM ALLOYS, CORROSION, CORROSION PROTECTION*

1. Introduction

Aluminum and aluminum alloys are utilized as primary structural components in the aerospace industry, marine and rail transportation, automotive manufacturing, architecture, biomedicine, and other fields, owing to their advantageous combination of chemical, physical, and mechanical properties [1-3]. Aluminum alloys have low density, making them lightweight and ideal for applications where weight is a critical factor. Despite their low mass, they exhibit durability, making them suitable for various industries where strength and weight need to be carefully balanced. Additionally, they can be easily processed and shaped, offering flexibility in manufacturing processes, regardless of significant differences in the characteristics of a given alloy [4-5].

Pure aluminum, compared to aluminum alloys, is more resistant to corrosion and requires less protection than most metals. However, various industries primarily use alloys, which are more susceptible to corrosion. On the surfaces of products made from aluminum alloys, a natural oxide film forms, providing protection against corrosion in many environments, including aggressive ones. Often, the natural anti-corrosion abilities of aluminum and its alloys are insufficient to protect the products from degradation. The film can be disrupted by acids or bases, leading to surface or structural damage to the material. Common mechanical damages can also cause film disruption and subsequent corrosion due to the created defect. This, in turn, leads to malfunctions and poses a significant problem for the safe long-term operation of the products. Depending on the application environment and various external factors, different types of corrosion damage can be distinguished: general (uniform) corrosion, galvanic corrosion, crevice corrosion, intergranular corrosion, filiform corrosion, and stress corrosion [6]. To prevent or minimize the occurrence of corrosion, manufacturers in the industry use several techniques to protect aluminum products. They choose a specific type or combination of techniques depending on the working conditions of the products (the aggressiveness of the environment) [7-8].

2. Techniques used for protecting aluminum and aluminum alloys from corrosion

The primary techniques used to combat corrosion aim to artificially reduce the corrosion rate of aluminum and its alloys, namely:

• by anodizing

This technique is used even at the stage of production of aluminum products, thanks to which a natural protection against corrosion is formed on the surface. It is an electrochemical process aimed at creating a thin oxide film that strongly adheres to the aluminum surface and protects it from oxidation. The thickness of the anode film (oxide), its morphology and structure depend on the temperature and composition of the electrolyte and the deposition time. The surface has a pleasant gray, olive, brown or black shade (depending on the density of the electrolyte). This film (layer) does not dissolve under the influence of aggressive chemical compounds, and if mechanically damaged, it is able to self-repair. The material acquires high anti-corrosion properties during long-term operation in various aggressive environments [9]. Some aluminum alloys are more suitable to be anodized than others. For example, with 1XXX series aluminum, the resulting aluminum oxide layer (film) is clear and somewhat shiny, but these anodized aluminum alloys can be easily damaged because the underlying pure aluminum is soft. In anodized aluminum alloys of the 2XXX series, the oxide film has a yellow tint and provides poor corrosion protection to the material, although the copper in these alloys improves mechanical properties. The anodized layer on the 3XXX aluminum alloy offers decent protection to the aluminum base, but the manganese alloy creates a brown color on the surface. A good protective layer of aluminum oxide has an aluminum alloy of the 4XXX series, and the resulting layer is dark gray. In anodized aluminum alloys of the 5XXX, 6XXX and 7XXX series, the oxide layer is transparent, clear and with excellent protection of the material from corrosion. If the percentage of zinc is more in some aluminum alloys of the 7XXX series, the oxide layer may turn brown (Fig.1) [10-11].

Fig.1 *Anodized details [12]*

However, sometimes anodizing is not enough, especially when the metal interacts with aggressive substances. For this reason, additional anti-corrosion protection is carried out - for example, application of powder paint or polymer coating.

• by painting or polymer coating

The use of paints and varnishes for coating is an easy, accessible, and relatively inexpensive technology to protect aluminum and its alloys from corrosion, providing a durable painted layer. The methods of applying the paint can vary: dry, wet, and powder. Depending on the environment the metal will come into contact with and the functional purpose of the aluminum products, the appropriate application method is chosen. In the first case (dry), the aluminum is first treated with a composition containing zinc and strontium. Then the paint itself is applied to the metal. Most often, aluminum is covered with powder paints. To ensure a high-quality powder coating on the aluminum part (product), the surface must be thoroughly cleaned of any dirt, oxides, grease, and dust. The aluminum product is degreased using special cleaning solutions and then rinsed thoroughly with water to remove any residual chemical particles on the surface. Subsequently, in special chambers, the products are dried, and paint is applied to the prepared surface using special electric or pneumatic guns, which allow uniform application of powder (paint) over the entire aluminum part. The uniform thickness of the coating better protects the part from external factors that provoke corrosion processes [13].

Fig.2 *Powder coating [14]*

The final stage of powder coating aluminum products involves polymerizing the powder so that it can adhere firmly to the metal surface. This operation can be carried out in several ways: by heating the metal, using gas burners, or through thermal polymerization. The painted aluminum product is placed in a chamber (furnace) preheated to 180-210°C. At this temperature, the polymer particles melt and merge, resulting in a uniform, durable layer of paint over the entire surface. This method is considered the most universal and can be used to coat any surface with medium-sized details.

Anodizing and powder coating are regarded as the best protection techniques for aluminum and its alloys.

Polymer painting of aluminum products involves applying a special polymer coating to the surface of the aluminum. This method not only changes the color and appearance of the profile but also improves its protective properties. Polymer coatings exhibit high resistance to external factors such as ultraviolet rays, moisture, and chemicals, thereby preventing corrosion and maintaining the quality of the products over an extended period. Polymer paints are available in various shades, allowing for the selection of the perfect color for any design and style. They are safe for human health and the environment, as they do not contain toxic substances (they are environmentally friendly). The coating is easy to maintain and ensures the preservation of the original appearance of the product over time, as it is completely recyclable and can be used an infinite number of times without losing its properties.

The most recent application is aluminum rolled products with a polymer coating [15]. The costs of pre-painted aluminum rolled products using liquid technology are lower than painting finished products. New types of coatings with increased service life for various applications are constantly being developed.

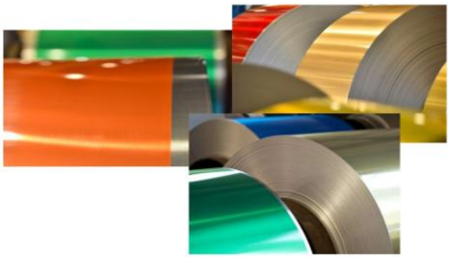

Fig.3 *Aluminum rolled products with polymer coating [16,17]*

• ***through insulators***

Very often, other metals act as catalysts for the initiation of corrosion processes in aluminum and its alloys. This typically occurs when the products or their components come into direct contact. To prevent the degradation of finished aluminum products, it is recommended to use special insulators. Insulators (seals) for aluminum clamps can include rubber, paronite, or bitumen (Fig. 4). Additionally, the brackets can be galvanized, primed, varnished, or painted. For aluminum constructions, to prevent galvanic corrosion, it is advisable to use fasteners made of stainless steel or galvanized steel. Another method to protect aluminum from corrosion when in contact with other materials is to coat its surface with cadmium.

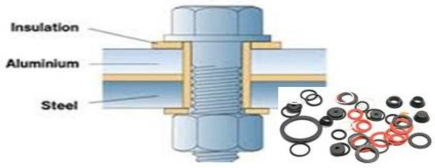

Fig.4 *Insulator between two metals*

• ***through other materials (metal coatings)***

Metallic coatings offer flexibility in both design and function due to the vast array of options available. The literature and industry provide substantial data on such coatings applied to aluminum alloys. Among these, electroless nickel coatings are particularly prevalent [18, 19]. The unique combination of properties offered by electroless nickel coatings and electroless composite nickel coatings—including thickness, hardness, wear resistance, corrosion resistance, lubricating capability, adhesion, and uniformity of the coating, as well as cost—makes them ideal for extensive use across various industries. Today, these coatings are firmly established as functional coatings in electronics, chemical processing, gas, petroleum, automotive, aerospace, and other industries.

The use of electroless nickel coatings with nanodiamonds (ND) [20, 21] on aluminum and aluminum alloys represents another promising method for protecting the material from corrosion.

Innovative technologies for corrosion protection

Advancements in surface treatment technologies have led to the development of enhanced and novel methods for corrosion protection. These new technologies aim to offer corrosion protection comparable to traditional techniques while also being environmentally friendly and having a reduced impact on human health.

One of the promising technologies for protection involves coatings based on rare earth elements such as cerium (Ce), lanthanum (La), neodymium (Nd) and praseodymium (Pr). These coatings function by depositing a protective film on the aluminum surface, which acts similarly to chromate coatings in preventing corrosion. The choice to use rare earth elements is driven by the need to replace chromate due to its carcinogenic nature. Harvey [22] reviewed cerium based conversion coatings for aluminum, highlighting their potential as an alternative to chromate coatings.

Brachetti-Sibaja et al. [23] provided a comparative study on the corrosion protection effectiveness of Ce and La films, as well as bilayer coatings of Ce/La and La/Ce oxides, deposited on aluminum alloy substrates using the radio frequency (RF) magnetron sputtering technique. They found that sputtered lanthanum (La) films with a thickness of approximately 390 nm and an average roughness of 66 nm exhibited the best corrosion protection properties in a chloride environment. The method of obtaining bilayer coatings, Ce/La and La/Ce, showed better barrier properties than the Ce films, which were inferior to those presented by the La films.

Another significant advancement is the development of organic-inorganic hybrid coatings. These coatings combine the durability and protective qualities of inorganic materials with the flexibility and environmental friendliness of organic compounds. Wang et al. [24] investigated the effectiveness of an enhanced organic-inorganic layer on the surface of aluminum alloy using a combination of hybrid inhibitors. It was found that the hybrid inhibitor system, consisting of cerium molybdate and 2-mercaptobenzothiazole, forms a protective layer on the aluminum alloy surface, enhancing its corrosion resistance while also exhibiting self-healing properties, contributing to long-lasting corrosion protection.

Another innovative method for enhancing the protective properties of aluminum alloys involves polymer coatings with embedded corrosion inhibitors in the polymer matrix. Xavier and Vinodhini [25] developed an innovative epoxy coating. The inorganic nanofiller hafnium carbide (HfC) was modified with 4-amino-5-pyridin-3-yl-3H-1,2,4-triazole (APTT). The resulting

APTT/HfC was encapsulated with graphene oxide (GO) in the epoxy matrix. The new coating was compared with other coatings and found that the EP-GO/APTT-HfC coating exhibited excellent barrier properties, hydrophobicity, and mechanical properties in seawater under long-term exposure.

3. Conclusion

The corrosion protection of aluminum alloys focuses on both traditional and innovative surface treatment techniques. Traditional methods, such as coatings, provide effective and reliable protection for aluminum and its alloys against corrosion, ensuring safe and long-term performance of components in aggressive environments. The advancement of surface treatments, evolving from traditional coating methods, is necessary for corrosion resistance, reducing maintenance costs, and enhancing the environmental friendliness of coatings.

The future of corrosion protection for aluminum and its alloys lies in the integration of environmentally sustainable materials as coatings, the advancement of polymer coatings, and the implementation of nanotechnology. All new technologies must ensure the safety, effectiveness and durability of the component in the long term.

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