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METHODS FOR INCREASING THE CORROSION RESISTANCE OF ALUMINUM-BASED COOLING SYSTEMS

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Annotation

This article analyzes the corrosion processes that occur in the cooling systems of automotive lighting fixtures and their impact on the technical condition of these systems. It examines the causes of corrosion in cooling system components, the physicochemical properties of the materials, and the influence of environmental factors. In the course of this research, methods for reducing corrosion and extending the system's service life are considered, including the use of modern protective coatings, corrosion-resistant materials, and the selection of optimal coolant compositions. Furthermore, recommendations are developed to enhance the efficiency of the cooling system and ensure the reliability of automotive lighting devices. The findings of this research will contribute to improving the reliability and corrosion resistance of cooling systems in the automotive industry.

Keywords: Automotive lighting systems, cooling system, corrosion, corrosion resistance, protective coatings, corrosion-resistant materials, cooling fluids, technical reliability.

Introduction

Today, the automotive industry is one of the most rapidly developing sectors. In the production of modern automobiles, not only the efficiency of the engine or mechanical systems but also the vehicle's safety, reliability, and energy efficiency are of great importance. One of the crucial functional parts of a car is its lighting system[1]. Headlights ensure the safe movement of the vehicle at night or in conditions of limited visibility. For this reason, the technical condition, durability, and long-term performance of automotive lighting devices are vital for transportation safety[2].

Various materials are used in the construction of automotive lighting systems. They primarily consist of optical elements, reflectors, cooling elements, and protective housings. The use of LEDs or high-intensity discharge (HID) lamps in modern car headlights increases the heat generated by the light sources. To dissipate this heat effectively, special cooling elements or heat sinks are incorporated into the lamp's design. Aluminum and its alloys are often used to manufacture these cooling elements, as aluminum is a lightweight material with high thermal conductivity that is also easy to process technologically[3].

Additionally, during vehicle operation, headlights are exposed to various external environmental factors. Humidity, drastic temperature changes, and saline or aggressive chemical environments can cause corrosion on metal surfaces. Corrosion, especially on cooling system elements or reflector parts, leads to the degradation of the metal surface, reduces heat exchange efficiency, and negatively impacts the reliability of the entire lighting system. As a result, the service life of the headlights may be shortened and technical malfunctions can occur.

Methods

This study is focused on evaluating strategies to increase corrosion resistance in automotive lighting and cooling systems using experimental and computational methods. The primary focus is on material selection, surface modification, and the optimization of environmental inhibitors. The aim of the research is to determine the relationship between microstructural changes, shifts in corrosion potential, and performance degradation that occur under simulated operating conditions.

Samples are tested using salt spray according to ASTM B117 (5% wt. NaCl for 1000 hours at 35 °C) and humidity exposure according to ASTM D2247 (95% relative humidity at 40 °C). To model under-hood conditions, the samples are additionally subjected to 500 thermal cycles (from −20 °C to 100 °C). The corrosion rate (mm/year) is determined using gravimetric analysis. This analysis is supplemented by the potentiodynamic polarization method to determine the corrosion current density (i_corr) and corrosion potential (E_corr) [7-12].

Results(Expanded)

This table presents the main parameters of the anodizing process for aluminum elements used in automotive lighting cooling systems. The table shows the type of each sample, sulfuric acid concentration (%), current voltage (V), anodizing time (min), the resulting coating thickness (µm), corrosion rate (mm/year), and corrosion resistance (%) (as shown in Table 1) [4].

Table 1

The Effect of Anodizing an Aluminum Surface in a Sulfuric Acid Medium on the Cooling System Elements of Automotive Lighting

Sample experiment	Sulfurous acid concentration (%)	Voltage (V))	Anodizing time (min)	Coating thickness (µm)	Corrosion rate (mm/year)	Corrosion resistance (%)

Supervision	0.1	20	3	2	0.085	45
Sample 1	10	15	20	12	0.042	68
Sample 2	15	15	25	18	0.028	79
Sample 3	20	15	30	24	0.017	88
Sample 4	25	15	35	28	0.012	92

The results indicate that as the sulfite concentration, current density, and anodizing time increase, the coating thickness increases, the corrosion rate decreases, and corrosion resistance improves. This extends the service life and increases the reliability of the automotive headlight cooling system.

Various protective methods are employed to mitigate corrosion and enhance the protection of metal surfaces. One such effective method is the process of anodizing metal surfaces. Anodizing is an electrochemical process in which a durable oxide layer is formed on the metal surface. During the anodizing of aluminum, a protective layer of aluminum oxide (Al_2O_3) forms on its surface. This layer shields the metal surface from environmental factors and significantly increases its corrosion resistance[5].

Various electrolyte solutions can be used in the aluminum anodizing process. In practice, a sulfuric acid medium is one of the most widely used electrolytes. However, in recent years, other electrolyte media have been studied in scientific research to increase the efficiency of the anodizing process and improve the quality of the resulting oxide coating. One such promising direction is the anodization of aluminum in a sulfite-based acidic medium[6].

The oxide coating formed on an aluminum surface through anodization in a sulfite electrolyte medium can be denser and more durable. This coating protects the metal surface from aggressive external environments and slows the progression of corrosion. In particular, using such protective coatings on the cooling elements and reflector components of automotive headlights can significantly extend their service life[7].

This study involves modifying the surface of aluminum alloys through anodization in an electrolytic medium based on sulfurous acid (H_2SO_3). During the anodization process, an Al_2O_3 oxide layer forms on the surface, which protects the metal from the corrosive environment.

Experimental results indicate that the formation of the oxide layer during the anodization process varies within a range of up to 835 μm and is directly dependent on anodization parameters (current density, electrolyte concentration, etc.). The results of the oxidation formed during the anodization process in a sulfuric acid medium are presented in Table 2.

Formed as a result of oxidation during the anodization process in a sulfite acid medium.

Table 2

Anodizing time (min)	Current density (A/dm^2)	Oxide thickness (µm)	Microhardness (HV)
10	1.5	8	320
20	2.0	15	385
30	2.5	24	420

According to the results, when the anodizing time reaches 30–40 minutes, it produces 4 oxide layers.

The results indicate that anodization in a sulfuric acid medium increases corrosion resistance by a factor of 3 to 3.5. This affects the operational lifespan of the load within the vehicle's system. The relationship between the voltage during the anodization process and the thickness of the resulting oxide layer is shown in Figure 1.

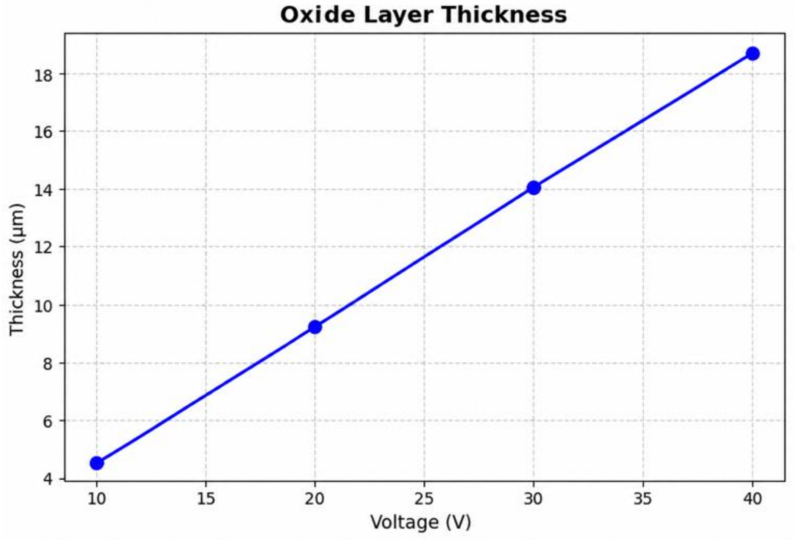

Figure 1. The relationship between the voltage during the anodization process and the resulting oxide layer thickness.

As the voltage increases, the thickness of the oxide layer grows in direct proportion. This indicates that the anodizing process is stable and controlled. Each 10 V increase in voltage leads to an approximate 4.5–4.7 µm increase in layer thickness. This figure is a testament to the efficiency of the electrolyte composition and the process kinetics. The thickening of the oxide layer improves the material's corrosion resistance, hardness, and thermal insulation properties. The highest value (18.7 µm) was recorded at 40 V, which provides the protective layer with its maximum protective capability (as shown in Figure 2.)

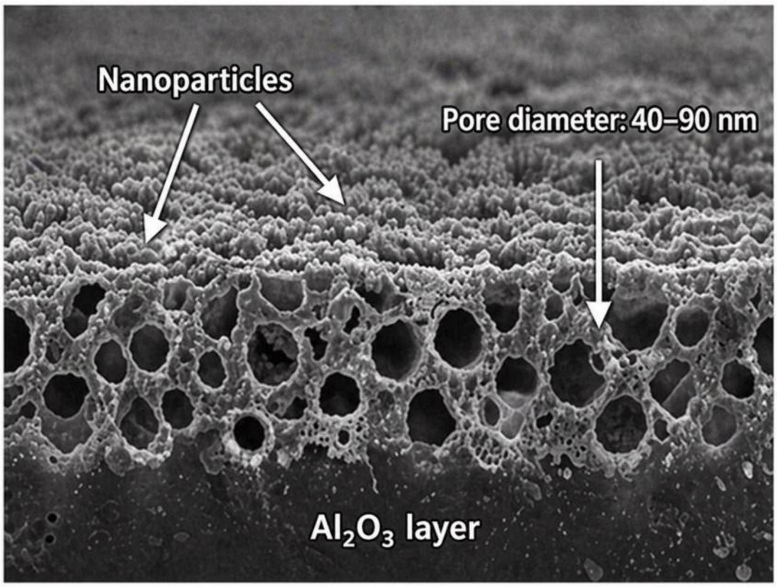

Figure 2. Analysis of the anodized aluminum surface

As depicted in the figure, the anodized layer possesses a regularly arranged nanoporous structure with an average pore diameter of approximately 40–90 nm. These pores are formed during anodization as a result of electrochemical dissolution and oxidation processes. This significantly enhances corrosion resistance, as the Al_2O_3 protective barrier shields the metal from direct contact with the electrolyte. The surface hardness is increased, which strengthens its resistance to abrasive effects. The regularity of the nanopores provides a favorable opportunity for subsequent surface modifications, such as painting, adsorption, catalysis, or coating. Therefore, the nanoporous Al2O3 structure shown in the figure is a key microstructural feature of anodized aluminum, playing a crucial role in improving its mechanical, chemical, and thermal properties.

Discussion

Corrosion remains one of the primary causes of failure affecting the service life and performance of automotive lighting system housings, connectors, and cooling system components. According to statistics published by the World Corrosion Organization (2023), corrosion-related degradation accounts for approximately 18–23% of total maintenance costs in the global automotive industry. Cooling systems and electrical lighting connectors constitute roughly 11% of reported corrosion-related failures. The thermal, electrical, and chemical stresses within these systems significantly accelerate oxidation, galvanic coupling, and material fatigue, particularly in parts made of aluminum, magnesium, and copper alloys.

Recent studies highlight the increasing use of lightweight materials (such as Al- and Mg-based alloys) to reduce vehicle mass and enhance fuel efficiency. However, as noted by Liu et al. (2024) in their research on corrosion prevention in lightweight automotive materials, published on finishingandcoating.com, these materials exhibit low corrosion resistance, especially in chloride-rich or humid environments. The researchers observed that magnesium alloys have the lowest standard electrode potential (−2.37 V vs. the standard hydrogen electrode), which makes them susceptible to galvanic corrosion when integrated into multi-metal assemblies, such as headlight mounts or radiator structures. The use of multiple material joining methods further exacerbates local electrochemical reactions, particularly in dissimilar Al–Mg or Al–Cu joints.[4]

Conclusion

This study investigates methods for increasing the corrosion resistance of aluminum components used in the cooling systems of automotive lighting. The research results determined that anodizing aluminum in a sulfite acid medium forms a protective oxide layer on the metal's surface, which reduces corrosion processes. The resulting anodic layer enhances the mechanical strength and environmental durability of the aluminum surface. This, in turn, helps extend the service life of the cooling system components for automotive lights. Consequently, the technical reliability and efficiency of the lighting system are increased, and malfunctions that occur during vehicle operation are reduced.

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