Economic analysis and environmental impact of anti-corrosive protection systems in a full-scale aeronautical fuselage part from aluminium – copper – lithium alloy

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Abstract The present work conducts an economic comparison between the traditional chromium-based corrosion protection system and a chromium-free alternative, employing sulphuric acid for anodization. Past studies have proven that the sulfuric acid protection system is more effective on the modern AA2198 lithium enriched aluminium alloy compared to the industry standard AA2024 aluminium copper alloy. Industries have long been searching for an effective substitute to chromium because of its toxicity but there has been less research done on the economic aspect of its replacement. This investigation utilizes the activity-based costing method to compare the chromic acid protection system on an AA2024 alloy with the sulphuric acid protection system on an AA2198 alloy. Visits were conducted to the Hellenic Aerospace Industry in order to document the work process of the protection systems and form an activity model to study. For the cost calculations, a 3.85 m2 workpiece was used as a baseline to derive the cost figures and acquire comparative results.
The findings indicate that the sulphuric acid protection system, applied to the AA2198 alloy, is not only 13.7% more cost-effective but also more environmentally friendly with 82.3% less carbon emissions, presenting a compelling case for its adoption as a replacement to the use of chromium.
Keywords: Anodization, aluminium alloy, sustainable materials, LCA, circular economy.

1. Introduction

Aluminium and its alloys are extensively employed in the aerospace sector due to their advantageous combination of high mechanical strength and low density. Aluminium Alloy (AA) 2024 exemplifies these qualities, offering excellent tensile strength, formability, and fatigue resistance, primarily due to its significant copper content [1]. However, the presence of copper also contributes to increased susceptibility to corrosion, particularly in humid environments, necessitating the implementation of protective systems. In response, AA2198 has been developed as a modern alternative to traditional alloys like AA2024. The incorporation of lithium (Li) improves both mechanical performance and corrosion resistance. Nevertheless, the use of anti-corrosion treatments remains essential [2].

A standard corrosion protection system for these aluminium alloys typically involves anodization—forming a protective oxide layer on the alloy surface—followed by the application of a coating through spray painting [3]. Hexavalent chromium has traditionally been employed in both processes due to its proven effectiveness and reliability. However, this compound is a recognized carcinogen with severe environmental and health impacts [4]. As a result, the European REACH regulation seeks to limit its usage and promote the development of chromium-free alternatives. While various substitute methods are still under investigation, sulfuric acid anodizing has emerged as a promising option. Although its application on AA2024 presents challenges and does not fully replicate the protective performance of chromic anodization, it has demonstrated significantly better compatibility with AA2198 [5].

2. Case study

The sulfuric acid-based corrosion protection process was applied to an aircraft demonstrator constructed from AA2198 at the Hellenic Aerospace Industry (HAI). This demonstrator served as the reference model for the calculations presented in this study. It comprised an AA2198-T8 metallic fuselage panel with dimensions of 1.6 m in length, 1.2 m in width, and 2.3 mm in thickness (hereafter referred to as the demonstrator). The central structural frame was produced using additive manufacturing (3D printing) and included six (6) laser beam welded stringers (1.2 mm thick), two (2) hydroformed frames, and mechanically milled pockets ranging from 1.6 mm to 1.9 mm in thickness. The total surface area of the demonstrator was 3.85 m².

3. Methodology

To facilitate a cost comparison between the sulfuric acid and chromic acid protection systems, the overall process was divided into three main sub-processes, each further broken down into specific activities. Additionally, a "door-to-door" approach was employed to evaluate the carbon footprint of both systems, focusing on their respective energy consumption. This assessment aimed to determine the relative environmental sustainability of the two protection methods.

The processes for the sulfuric acid and chromic acid protection systems are largely similar, with only minor differences, primarily in the anodization stage. The procedure is divided into three sub-processes. The first sub-process involves preparing the demonstrator for treatment by removing surface contaminants. This begins with manual degreasing using a cloth, followed by a more thorough cleaning in an alkaline bath. The demonstrator is then rinsed with tap water at room temperature and immersed in a deoxidizing bath to eliminate the oxide layer formed during alkaline treatment. After a second rinse, the demonstrator proceeds to the second sub-process, which starts with anodization—either using chromic or sulfuric acid. The primary distinction between the two anodization methods lies in the chemical composition and the specific manufacturing parameters, both of which affect overall processing time and energy consumption.

Following anodization, the component is rinsed with cold, deionized water and dried using compressed air. It is then manually degreased once more before spray painting is applied, starting with a primer layer and followed by the protective topcoat. The third and final sub-process is quality control, which includes visual inspection and performance validation through salt spray and adhesion tests (conducted over 30 days on sub-scale samples) to confirm the effectiveness of the anodization and coating systems.

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4. Results

Owing to the longer processing time and higher voltage requirements of the anodization stage, the chromium-based protection system results in a 75.6% increase in carbon emissions compared to its sulfuric acid counterpart. Furthermore, chromium trioxide is highly toxic and poses significant environmental and biological hazards upon exposure. The disposal of chromium-containing waste necessitates transportation to specialized treatment facilities, whereas sulfuric acid waste is considerably easier to manage and can typically be processed on site.

5. Conclusions

This investigation compares the costs of the conventional, yet hazardous, chromic protection system applied to the AA2024 alloy with the modern, chromium-free sulfuric acid protection system used on the AA2198 aircraft demonstrator. The findings of the investigation indicate that the sulfuric acid protection system offers both greater economic benefits and improved environmental sustainability, while also eliminating the need for hexavalent chromium in aluminium alloy protection systems.

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