Comparative Electrochemical Evaluation of Surface Treatments for Corrosion Protection of Marine Aluminum

Kaavya Koteshwar

[1]*Student, IB Diploma Programme, Heritage International Xperiential School, Gurugram, Haryana, India*

***Abstract** - This study comprehensively investigated the electrochemical corrosion protection performance of different surface treatments applied to marine-grade aluminum under simulated marine conditions. Four surface conditions were evaluated: untreated control, anodized only, painted only, and anodized followed by painting. The specimens, cut to 5 × 5 cm with a thickness of 3 mm, were exposed to half-immersion in a 3.5% NaCl solution for 21 days. Corrosion behavior was characterized using potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). The combined anodizing and painting treatment demonstrated the highest corrosion resistance, with an 85% reduction in corrosion current density compared to untreated aluminum. It also exhibited the lowest corrosion rate (0.012 mm/year) and the highest polarization resistance (12,450 Ω·cm²). Anodizing alone provided better protection than painting alone, but both were significantly less effective than the combined treatment. The results highlighted the synergistic interaction between anodizing and painting, where the anodized layer improved paint adhesion and offered baseline electrochemical protection, while the paint provided an effective barrier against chloride penetration. This combination offered substantial durability benefits for marine applications*

Keywords: electrochemical corrosion, marine conditions, anodization, anticorrosion paint

1.INTRODUCTION

Marine aluminium alloys have been widely adopted in shipbuilding, offshore platforms, and marine equipment due to their high strength-to-weight ratio, good machinability, and relatively low cost (Davis, 1999). Despite the presence of a natural oxide layer that provides some degree of corrosion protection, these alloys are vulnerable to the aggressive chloride ions present in seawater. In marine environments, chloride-induced breakdown of the passive film leads to localized forms of corrosion such as pitting, crevice, and galvanic corrosion (Davis, 1999; Fan et al., 2023). These processes are accelerated by fluctuating temperature, oxygen gradients, and variable pH conditions. The combined effect of these factors reduces the structural integrity and service life of aluminium components (Davis, 1999).

To mitigate corrosion, various surface treatments have been developed. Anodizing produces a thicker, denser oxide film through electrochemical oxidation, which can be further enhanced through sealing treatments (Davis, 1999; ISO, 2018b). Painting systems, particularly those using marine-grade epoxy primers and polyurethane topcoats, provide a physical barrier to corrosive agents and improve aesthetics (ISO, 2018a; Standard Norge, 2022). While these treatments are effective individually, the synergistic effects of combining anodizing and painting have not been extensively studied in marine-specific conditions using standardized electrochemical testing methods (ASTM International, 2023b; ISO, 2016).

The aim of this work was to quantitatively compare the corrosion performance of untreated, anodized, painted, and anodized-then-painted aluminium specimens in a controlled saline environment, to understand the potential synergy between anodizing and painting, and to provide guidance on the most effective surface treatment strategies for marine applications (ASTM International, 2021; ISO, 2018a; ISO, 2018b)

2. MATERIALS AND METHODS

Marine-grade aluminium sheets were sectioned into 5 × 5 cm specimens of 3 mm thickness. Four surface treatment categories were prepared: untreated control (mechanically polished to 1200 grit), anodized only, painted only, and anodized followed by painting. The anodizing process used 15% sulfuric acid at 20°C with a current density of 150 A/m² and voltage of 15–18 V for 45 minutes, followed by hot water sealing at 96°C for 30 minutes (ISO, 2018b). The painting process consisted of a zinc-rich epoxy primer layer with a dry film thickness of 75 µm and a polyurethane topcoat with a thickness of 50 µm (ISO, 2018a; Standard Norge, 2022). The coated specimens were cured for seven days at room temperature before testing.

The specimens were half-immersed in 3.5% NaCl solution prepared with distilled water, maintained at 25°C and pH 7.0, for a duration of 21 days (ASTM International, 2021). Electrochemical testing was conducted using a three-electrode cell, with the specimen as the working electrode, a saturated calomel electrode (SCE) as the reference, and a platinum mesh as the counter electrode. Potentiodynamic polarization scans were performed from −250 to +250 mV vs. OCP at a scan rate of 0.125 mV/s (ASTM International, 2023b; Stern & Geary, 1957). Electrochemical impedance spectroscopy measurements covered frequencies from 100 kHz to 10 mHz with a 10 mV RMS amplitude (ISO, 2016).

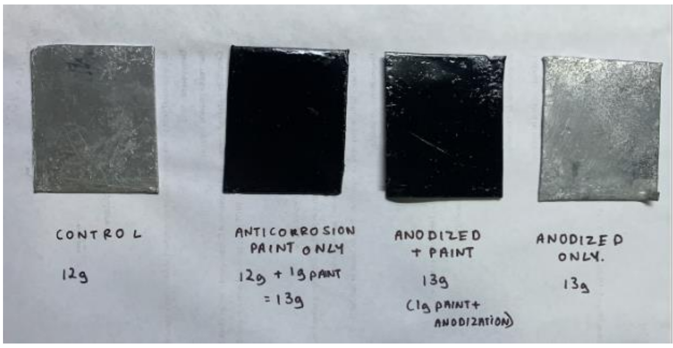

Fig -1: Photographs of test specimens before immersion testing: (a) untreated control (b) anodized only (c) painted only and (d) anodized then painted specimens.

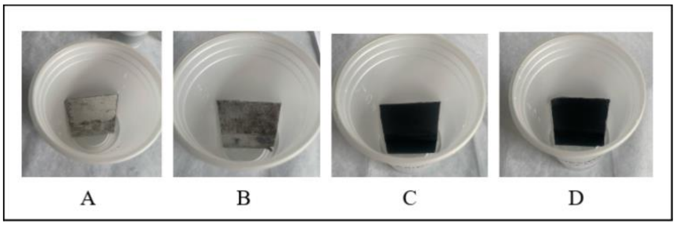

Fig -2: Experimental setup showing half-immersed test specimens in saline:(a) untreated control (b) anodized only (c) painted only and (d) anodized then painted specimens.

3. RESULTS AND DISCUSSION

Treatment	OCP (mV vs. SCE)	i_corr (μA/cm^2)	Corrosion Rate (mm/year)	Polarization Resistance (Ω·cm^2)
Control (C)	-820 to -780	8.2	0.095	1,850
Anodized (A)	-750	2.1	0.024	8,750
Painted (P)	-680	3.8	0.044	4,200
Anodized + Painted (AP)	-650	1.2	0.012	12,450

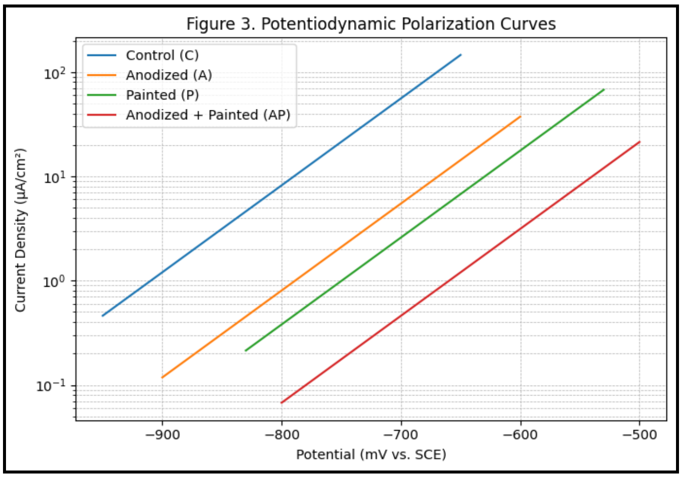

Fig -3: Potentiodynamic polarization lines

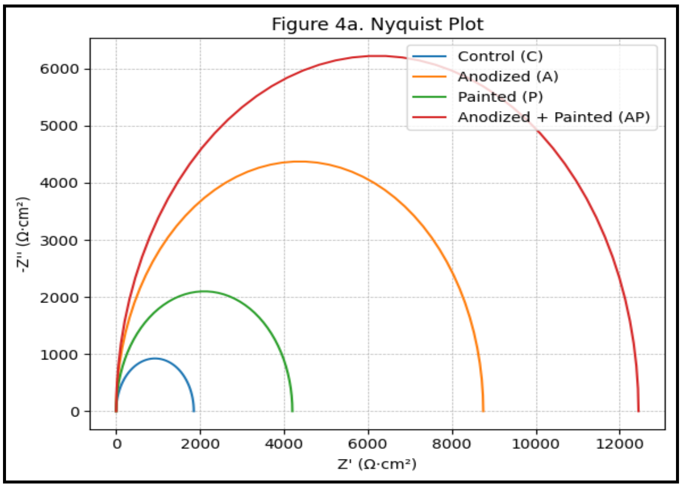

Fig -4: Nyquist Plots

The open circuit potential (OCP) measurements revealed that the control specimens shifted from −820 mV to −780 mV over the immersion period, indicating active corrosion (Davis, 1999). Anodized specimens maintained a stable potential of approximately −750 mV, while painted specimens exhibited moderate stability at −680 mV. The anodized-then-painted specimens displayed the most stable performance, maintaining an OCP of −650 mV with minimal fluctuations (Davis, 1999). (Note: OCP indicates interfacial condition but is not a direct measure of corrosion rate; rate metrics are derived from i_corr and/or R_p per standard practice.) (ASTM International, 2023a; Stern & Geary, 1957).

Potentiodynamic polarization results indicated that the untreated control specimens had a corrosion current density of 8.2 μA/cm^2, corresponding to a corrosion rate of 0.095 mm/year. Anodized specimens showed significant improvement with an i_corr of 2.1 μA/cm^2 (0.024 mm/year), while painted specimens exhibited 3.8 μA/cm^2 (0.044 mm/year). The anodized-then-painted treatment demonstrated the best performance with an i_corr of 1.2

μA/cm² (0.012 mm/year), reflecting an 85% reduction in corrosion current compared to the control. These interpretations follow standard Tafel/Stern–Geary analysis and the accepted conversion of i_corr to corrosion rate (ASTM International, 2023a; Stern & Geary, 1957).

Electrochemical impedance spectroscopy results supported the polarization findings. The polarization resistance values were 1,850 Ω·cm² for the control, 8,750 Ω·cm² for anodized, 4,200 Ω·cm² for painted, and 12,450 Ω·cm² for anodized-then-painted specimens. The coating resistance of the combined treatment was approximately 3 times higher than that of painted-only specimens, highlighting the effectiveness of the anodized underlayer in preventing chloride ingress (ISO, 2016; Gamry Instruments, n.d.). The Nyquist/Bode behavior expected for high-barrier organic coatings—larger semicircle diameter and higher low-frequency |Z| is consistent with these R_p trends (ISO, 2016; Gamry Instruments, n.d.).

The calculated synergistic parameter (S = 1.34) confirmed a positive interaction between anodizing and painting. This was attributed to the anodized layer providing enhanced surface roughness and chemical bonding sites for improved paint adhesion, combined with the barrier properties of the paint layer (Davis, 1999; ISO, 2018b; Standard Norge, 2022).

3. CONCLUSIONS

The combined anodizing and painting treatment offered the most effective corrosion protection for marine-grade aluminum in saline environments. It achieved the lowest corrosion rate, the highest polarization resistance, and demonstrated clear synergistic benefits compared to either treatment alone (ASTM International, 2023a; ISO, 2016). Anodizing alone provided superior performance over painting alone, indicating the importance of electrochemical protection in addition to physical barriers (Davis, 1999). These findings suggested that for applications where aluminum components are exposed to aggressive marine environments, a sequential treatment of anodizing followed by the application of marine-grade paint provided the most durable and cost-effective solution (ISO, 2018a; Standard Norge, 2022).

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