Influence of Protective Surface Coating on Heat Transfer with Aluminium Enclosers

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Abstract. Aluminium casings are widely adopted in electric vehicles due to their lightweight and structural efficiency. However, their thermal behaviour under protective coatings is a critical factor for battery thermal management. This study investigates the impact of three commonly used coating techniques—anodizing, cathodic electrodeposition (CED) with topcoat, and powder coating—on the effective thermal conductivity of aluminium enclosures. A controlled heating experiment was performed using a hot air source applied to a defined surface area, while temperature gradients between the inner and outer surfaces were monitored using thermocouples and thermal imaging. The analysis focuses on how coating influence heat transfer, which is essential for maintaining optimal battery operating temperatures. Experimental results demonstrate that coatings introduce thermal resistance, and the extent of this effect varies significantly with coating type. These findings provide practical insights for selecting surface treatments that balance thermal performance and durability in electric vehicle battery systems.

Keywords: Aluminium battery casing, thermal conductivity, anodizing, cathodic electrodeposition, powder coating, electric vehicle thermal management.

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1 Introduction

The rapid adoption of electric vehicles (EVs) has intensified the need for efficient battery thermal management systems to ensure safety, performance, and longevity. Aluminum is widely used for battery casings due to its favorable properties such as low density, high strength-to-weight ratio, eco-friendly recyclability, and excellent thermal conductivity [1].

Despite these advantages, aluminum is highly vulnerable to corrosion when exposed to moisture and environmental contaminants, which can compromise the reliability and safety of battery systems. To overcome this limitation, applying protective coatings is essential. In addition to corrosion resistance, thermal behaviour of these coatings is also a critical design factor for battery enclosures. In practical applications, aluminum surfaces are often coated to enhance durability and corrosion resistance, which can significantly influence heat transfer characteristics [2]. Efficient heat dissipation prevents thermal runaway, enhances performance, and prolongs battery life [3].

Hence, understanding this trade-off between protective coatings and thermal performance is essential for optimizing battery enclosure design.

When applied to aluminum battery enclosures, coating evaluation must encompass below criteria's

- Corrosion protection: Preventing environmental degradation using barrier function and environmental endurance.
- Weather resistance: Protecting enclosures from UV exposure and cyclic temperature stress.
- Thermal management: Ensuring heat generated during operation is efficiently dissipated to avoid hotspots or thermal runaway.
- Mechanical integrity: Maintaining adhesion and resistance to wear over the lifecycle.
- Regulatory compliance: Meeting EV standards such as AIS-156, AIS-038, and AIS-048.

Fig. 1. White rust observed in aluminum casing

This research focuses on three coating technologies commonly adopted in automotive applications to extend
the lifespan, performance and reliability of aluminum housings, each delivering different benefits. These are
anodizing, cathodic electrodeposition (CED) with a topcoat, and powder coating.

1.1 Anodizing

Anodizing generates a porous aluminium oxide layer that enhances corrosion resistance and surface hardness. It can significantly increase surface emissivity, improving thermal radiation; for example, emissivity can rise from ~0.14 to ~0.9, reducing thermal resistance in heatsinks [4].

1.2 Cathodic Electrodeposition (CED)

Cathodic electrodeposition (CED) followed by a topcoat is widely used in automotive industries to ensure uniform coating thickness, strong adhesion, and superior corrosion protection.

1.3 Powder Coating

Powder coating is valued for chemical resistance, dielectric performance, and weather durability. EV-focused powder systems can provide thermal conductivities on the order of 0.2–1.0 W/(m·K) with robust environmental stability [5].

While anodizing excels in boosting surface emissivity and powder coating provides practical dielectric and corrosion protection, limited comparative data exists on their combined thermal performance in real-world battery applications. Notably, the integration of thermal metrics into standard corrosion-evaluation protocols (e.g., salt spray or weather resistance) remains under-explored This study aims to experimentally evaluate the thermal conductivity of aluminum battery casings with different coating systems using a simple test. The findings aim to assist engineers and designers in selecting coatings that optimize functional performance for next-generation electric mobility systems.

Anodizing Powder coating CED
CED+Topcoat

Fig.2 Different Types of Industry Coatings

2 Methodological Exploration

To investigate the thermal behavior of coated aluminum battery enclosures, a systematic experimental procedure was developed. Aluminum samples with dimensions 100 mm × 100 mm and a thickness of 3 mm were selected to represent typical battery casing sections used in electric vehicles. For each test case, one surface of the sample was coated using one of the selected technologies—anodizing, cathodic electrodeposition (CED) with topcoat, or powder coating—while the opposite surface remained uncoated for comparison. This configuration allowed for the evaluation of heat transfer across the coated surface when subjected to controlled heating on the uncoated side.

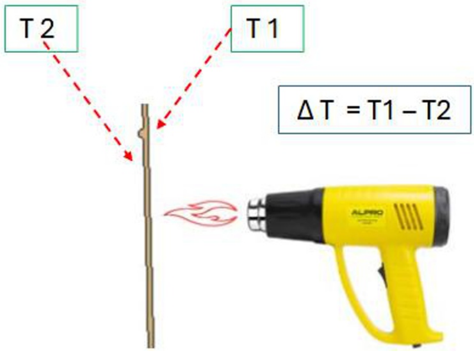


Fig.3 Experimental Concept - Heat Dissipation Case Study

Temperature measurements were performed using calibrated K-type thermocouples, which were positioned at two distinct points on the coated surface to capture the thermal gradient. These sensors were interfaced with Keysight data acquisition software, enabling real-time monitoring and accurate logging of temperature variations throughout the test. Prior to experimentation, all sensors were calibrated to ensure measurement precision [7].

In this study, two specific regions of the cross section were instrumented to capture representative thermal behavior, as the objective was to evaluate the effect of the coating on heat transfer. Four thermocouples were used in total: two mounted on the inner surface and two on the outer surface. These measurement points were selected to provide comparative temperature data across the coated cross-sections.

The samples were placed in a controlled environment to minimize external thermal influences. Heat was applied to the uncoated surface using a hot air gun, ensuring uniform heating across the designated area. The heating process was conducted in incremental steps at target temperature levels of 35°C, 40°C, 55°C, 60°C, and 70°C. At each step, the temperature was maintained for a stabilization period of 5–10 minutes to achieve thermal equilibrium before recording measurements. This approach allowed for consistent data collection under steady-state conditions, which is essential for accurate thermal analysis [7].

The experiment was repeated for all coating cases, including bare aluminum (reference), anodized coating, CED coating, CED coating with topcoat and powder coating. Data collected during the tests were stored in the Keysight system for postprocessing. The recorded temperature values were analyzed to determine heat transfer characteristics for each coating type. Graphs were plotted to illustrate the relationship between applied temperature on the uncoated side and measured temperature on the coated side, enabling a comparative assessment of thermal conductivity across different coatings. This methodology aligns with established practices for evaluating thermal performance in coated aluminum systems and provides insights into the influence of coating on heat dissipation [5][6].

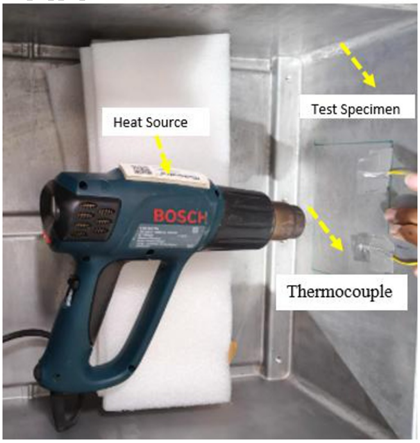


Fig.4 Actual Experimental Setup for heat dissipation Study

Sample Details and Coating Variations Experimental setup: The experiment was performed on aluminum battery box samples with different surface finishes to understand the influence of coating thickness on thermal behavior. The tested conditions included:

- Bare Aluminum (reference baseline)
- Anodized Sample with a dry film thickness (DFT) of 45–48 µm
- CED + Topcoat Sample with a total DFT of 55–60 µm, including approximately 10 µm topcoat
- Powder-Coated Sample with a DFT of 140–150 µm

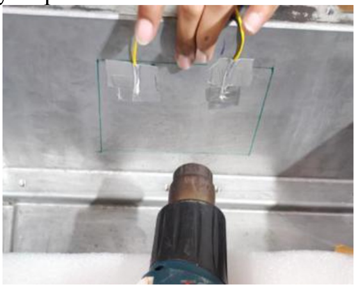
POWERCRON 6000CX (CR 691B / CP 524) e-coat material is used in the project as the primary corrosion-resistant underlayer. It is a lead-free black cationic epoxy electrocoat offering high throwing power and uniform coverage on steel and aluminum. Key properties include strong adhesion, high hardness, and resistance to impact, humidity, water soak, and over 500 hours of salt-spray exposure. With low VOC and no heavy metals, it ensures durable, environmentally compliant protection for automotive components

Topcoat – 04060H40320-62 (Stoven Semi-Gloss Black) is top-coat material is used in the project as the final protective finishing layer. It provides a semi-gloss black appearance with uniform film build, stable viscosity, and consistent non-volatile content. Major properties include excellent adhesion (100/100), good gloss levels, and strong hardness without surface scratching. When stoved at 130–135 °C, it cures into a smooth, defect-free, recoat-friendly finish suitable for durable automotive exterior applications

Powder Coating – Interpon 600 SG Engine Black is the powder-coating material is used in the project as a weather-resistant exterior protective layer. It is a polyester-based smooth-finish coating offering excellent UV stability, flow, and aesthetic coverage. Major properties include strong adhesion (5B), scratch hardness of 2 kg, good flexibility, and resistance to impact, salt-spray corrosion, humidity, and xenon-arc weathering with ≥80% gloss retention. With 60–80 μm film build and ROHS compliance, it ensures durable exterior performance

Previous studies have shown that anodized and painted coatings significantly reduce thermal contact conductance, with thicker layers acting as thermal insulators [4][6]. This experiment aimed to quantify these effects under controlled heating conditions.

The coating quality was verified through standard automotive validation methods, including Dry Film Thickness (DFT) measurement using a calibrated DFT meter to ensure uniform deposition. Additional quality checks involved cross-hatch adhesion testing and salt-spray testing to evaluate long-term protective performance. Weathering stability was confirmed through UV–humidity exposure, and mechanical robustness was validated via pencil hardness tests, ensuring compliance with functional and durability requirements.



Uncoated Side Coated Side

Fig. 5. The image shows thermocouple positioning in the experiment inside(uncoated) and outside(coated) respectively

In real battery systems, heat is generated internally by the cells during charge–discharge cycles, and this heat subsequently dissipates through the enclosure. Although the present experiment does not reproduce electrochemical heat generation, the objective was to replicate the directional heat flow from the cell side toward the enclosure. Therefore, a controlled forced convection heat gun was used as a surrogate heat source. This approach ensured uniform heating, repeatability across coating conditions, and the ability to reach the target temperature levels in a stable and measurable manner. While not identical to cell-generated heat in an operating battery pack, the imposed heating profile effectively represents the thermal load transferred to the enclosure during real world cell operation and enables a meaningful comparison of how different coatings influence heat dissipation.

Fig 6. Thermal image sensor shows the temperature at different locations of casing

As shown in the above images the thermal imaging sensor was also used to verify the temperatures at different locations anyhow thermocouple was considered main temperature measuring device.

3 Results and Analysis

Measured response in terms of temperature difference, ΔT and time difference Δt was recorded for five applied temperature set points on the uncoated face (T1): 35°C, 40°C, 55°C, 60°C, 70°C. The five surface conditions tested were:

1. Bare Al enclosure
2. Powder coating
3. Anodizing
4. CED
5. CED + Topcoat

Temp°C	Temperature difference, ▲T (°C)				
	Bare aluminum	Powder coating	Anodizing	CED & Topcoat	CED
35°	0.57	0.8	1.45	1.48	1.80
40°	0.82	0.88	2.00	1.80	2.30
55°	1.68	1.68	2.99	3.97	4.30
60°	2.05	2.18	3.95	4.67	4.60
70°	3.95	3.95	4.85	5.8	5.10

Table 1 shows temperature difference (ΔT, °C) between uncoated to coated surface

The coated surface temperature rise (ΔT2) increases steadily with applied temperature across all processes. Bare Aluminum shows the smallest rise at every set-point—from 0.57 °C at 35 °C to 3.95 °C at 70 °C—reflecting its strong heat transfer capability. Powder coating tracks very close to Bare Al: it is slightly higher at low temperatures (0.80 °C at 35 °C; 0.88 °C at 40 °C) but matches Bare Al at 55 °C (1.68 °C) and 70 °C (3.95 °C) and is only marginally lower at 60 °C (2.05 °C vs 2.18 °C). In contrast, Anodizing, CED, and CED + Topcoat exhibit larger ΔT_2 values throughout the range; for example, at 70 °C, Anodizing reaches 4.85 °C, CED 4.32 °C, and CED + Topcoat 5.80 °C.

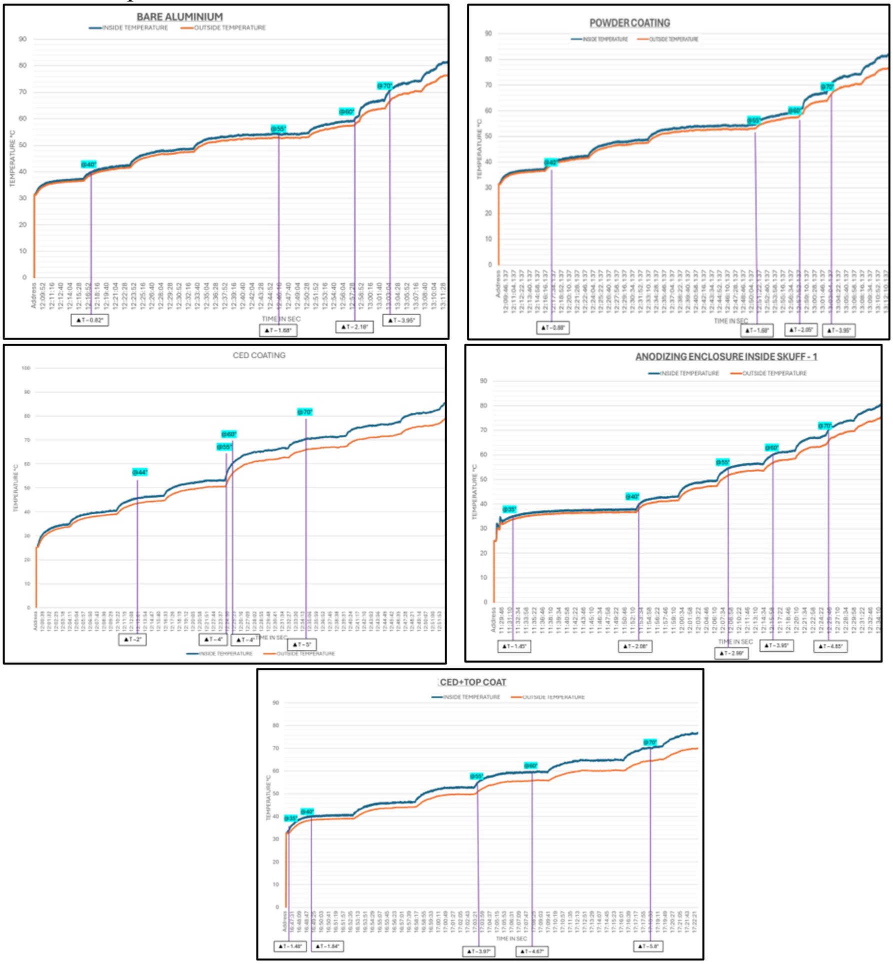


Fig 7 : Graphs showing summary of temperature differences (°C) vs time (s) for Bare aluminum, Powder coating and CED coating

Relative thermal resistance at the mid-point (55 °C). To isolate coating effects, we normalize each process to Bare Aluminum at 55 °C $R(rel)(55∘C) = \Delta T2$ process / $\Delta T2$ Bare Al, {Powder coating =1.00, Anodizing=1.78, CED+ Top =2.36, CED=2.41} Powder coating ≈ Bare Aluminum

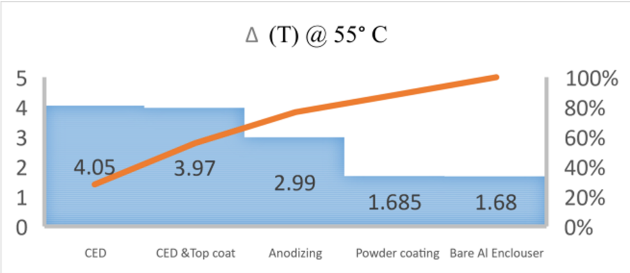


Fig. 8. - Heat dissipation characteristics at 55, °C

Expressed as a relative ratio (ΔT2_process / ΔT2_Bare), the midrange setpoint (55 °C) provides a concise comparison: Powder coating = 1.00 (i.e., indistinguishable from Bare), Anodizing ≈ 1.78, CED + Topcoat ≈ 2.36, and CED ≈ 2.41. At 35 °C, these ratios are larger—Powder 1.40, Anodizing 2.54, CED + Topcoat 2.60, CED 2.04—illustrating the stronger low temperature difference. At 70 °C, the ratios drop to Powder 1.00, Anodizing 1.23, CED + Topcoat 1.47, and CED 1.09, highlighting the convergence at the upper end. Over the full range, the mean ΔT_2 values are ~1.84 °C (Bare), ~1.87 °C (Powder), ~3.05 °C (Anodizing), ~3.54 °C (CED + Topcoat), and ~3.08 °C (CED), which succinctly captures the overall additional rise each process introduces relative to Bare.

Temp °C	Time difference, ▲t (sec)				
	Bare aluminum	Powder coating	Anodizing	CED & Topcoat	CED
40°	62	62	203	295	127
55°	67	67	75	298	135
60°	49	49	50	372	114
70°	208	310	118	512	424

Table. 2. shows time difference (Δt, sec) between uncoated to coated surface

The time-delay trend shows that coating systems significantly influence heat-transfer response. Bare aluminum consistently exhibits the shortest delay, confirming fast conduction, while powder coating remains close, indicating minimal thermal resistance. Anodizing introduces moderate delay due to its oxide layer acting as a partial insulator. CED and CED + Topcoat demonstrate the longest delays, showing strong heat-blocking capability, especially at elevated temperatures. As temperature increases, the time gaps between coatings widen, reinforcing those multi-layer organic coatings slow heat penetration more effectively than inorganic or thin-film coatings. This aligns with the temperature-difference results, where coatings with higher time delay also show greater thermal insulation performance.

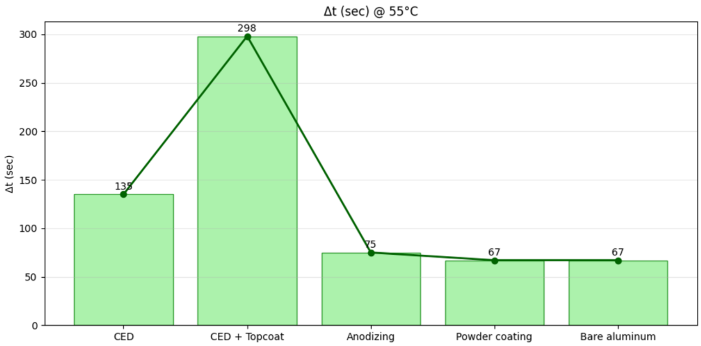


Fig. 9. – Time take for heat dissipation 55, °C

4 Conclusion

The experimental results confirm that protective coatings have a significant impact on the thermal performance of aluminum substrates. Among the tested systems, powder coating demonstrated thermal behavior almost identical to uncoated aluminum, showing negligible temperature rise and a 0% increase in heat-transfer time at lower temperatures. This indicates that powder coating provides corrosion protection without compromising heat-dissipation efficiency and remains the most cost-effective option compared to anodizing and CED-based coatings.

In contrast, anodizing and CED-based coatings exhibited substantially higher thermal resistance, as reflected by increased temperature gradients and longer time delays. Anodizing resulted in approximately 78% higher thermal resistance and produced over 200% higher time delay at lower temperatures (e.g., 62 s for bare aluminum vs. 203 s for anodized at 40 °C). CED coatings showed even stronger effects: CED alone increased time delay by ~105%, while CED + Topcoat increased it by more than 370% at the same temperature. These combined temperature and time-based findings clearly establish that coating type, thickness, and organic loading significantly influence heat-transfer behavior.

Overall, while all coatings fulfil their protective role, their thermal impact varies considerably. When both cost and thermal performance are considered, powder coating emerges as the most advantageous and thermally efficient solution.

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