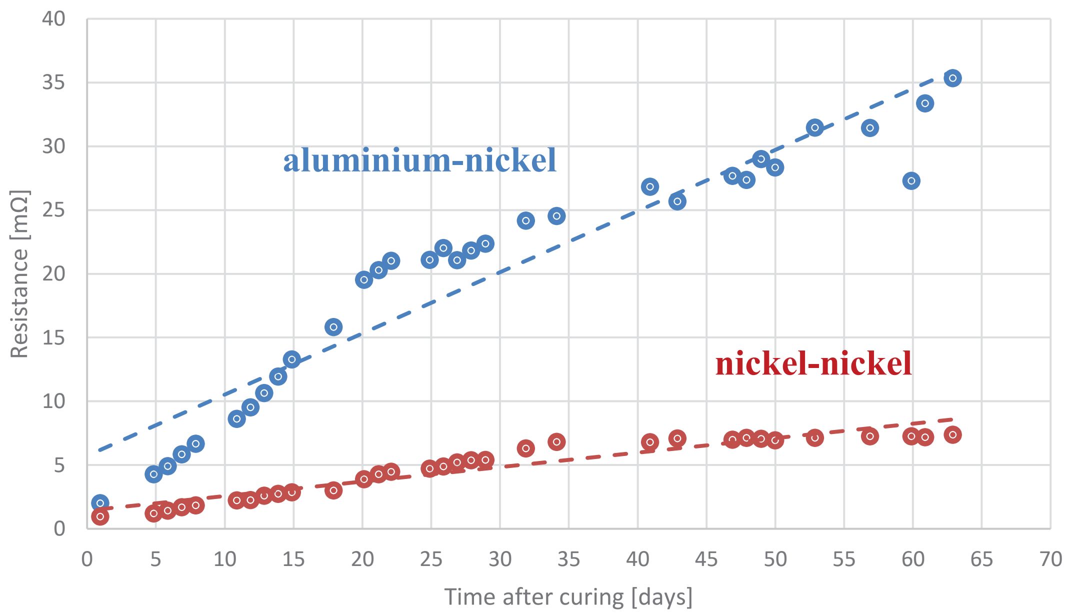
Conductive adhesive bonding for electrical connections in battery packs (CABEL)

Public report



Project within FFI Circularity
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Fordonsstrategisk Forskning och Innovation

Content

1 Summary

The need for a sustainable electric vehicle (EV) industry demands a transformative shift towards circularity, particularly concerning EV battery packs. This pre-study within the FFI Circularity program, titled Conductive Adhesive Bonding for Electrical Connections in Battery Packs (CABEL), addressed the limitations of conventional connection methods such as laser beam welding (LBW) or resistance welding. These traditional methods hinder circularity due to joint degradation, incompatibility with recycled materials, and profound difficulties in disassembly and end-of-life (EoL) repair. The project investigated electrically conductive adhesives (ECAs) as an alternative connection methodology.

Running from August 2025 to April 2026 with a budget of 900 kSEK, the consortium (RISE, Scania, Biesterfeld) executed experimental test regimes. Key findings indicate that while ECAs can provide exceptional mechanical strength (up to 624 N, significantly outperforming LBW at ~320 N), they present severe challenges regarding long-term electrical stability. Baseline LBW connections demonstrated a resistance of ~0.41 mΩ. The best-performing ECA joints initially achieved comparable resistance (~0.90 mΩ to 3.91 mΩ); however, long-term aging tests revealed a continuous and significant increase in electrical resistance over time, approaching 35 mΩ after 60 days. This degradation was particularly pronounced in dissimilar metal joints (aluminium-to-nickel), strongly suggesting the occurrence of galvanic corrosion facilitated by the silver filler particles in the ECA matrix. Furthermore, damp heat testing (70°C, ~100% RH) resulted in catastrophic joint failure, including complete debonding and erratic resistance spikes. However, preliminary development of a custom nickel-based adhesive at RISE demonstrated promising short-term electrical stability (4.39 mΩ after 14 days in aluminium-to-nickel joints), indicating a viable path to mitigate galvanic corrosion in future research.

The project concludes that while ECAs offer remarkable structural and manufacturing advantages - such as elimination of high-heat input and facilitation of dissimilar material joining - their electrical instability currently limits their direct application in high-voltage, high-current EV busbar-to-tab connections. Future research should focus on alternative filler materials (e.g., nickel-based flakes, carbon nanomaterials) to mitigate galvanic corrosion. Concurrently, the project identified single-sided spot welding as a highly promising, low-cost method for aftermarket battery repair.

2 Sammanfattning på svenska

Behovet av en hållbar fordonsindustri kräver en övergång till cirkularitet, med batteripaket för elfordon (EV) i spetsen. Denna förstudie inom FFI Cirkularitet, benämnd 'Ledande limning för elektriska kontakter i batteripack (CABEL)', har adresserat begränsningarna hos konventionella anslutningsmetoder såsom lasersvetsning (LBW) och

motståndssvetsning. Dessa traditionella metoder hindrar cirkularitet på grund av försämring över tid, inkompatibilitet med återvunna material och svårigheter vid demontering och reparation. Projektet har undersökt elektriskt ledande lim (ECA) som en alternativ metod.

Projektet, som pågick mellan augusti 2025 och april 2026 med en budget på 900 kSEK, genomfördes av RISE, Scania och Biesterfeld. Resultaten visar att även om ECA kan erbjuda exceptionell mekanisk styrka (upp till 624 N, vilket överträffar LBW på ~320 N), medför de allvarliga utmaningar när det gäller långsiktig elektrisk stabilitet. Lasersvetsade referensfogar uppvisade en resistans på ~0.41 mΩ. De bäst presterande limfogarna uppnådde initialt jämförbar resistans (~0.90 mΩ till 3.91 mΩ); dock visade åldringstester en kontinuerlig och betydande ökning av den elektriska resistansen över tid, vilken närmade sig 30 mΩ efter 6 veckor. Denna nedbrytning var särskilt uttalad i fogar med olika metaller (aluminium till nickel), vilket starkt tyder på galvanisk korrosion. Dessutom resulterade fuktvärmetester (damp heat, 70°C, ~100% RH) i fogbrott och oregelbundna resistans-spikar. Ett egenutvecklat nickelbaserat lim från RISE visade lovande initial elektrisk stabilitet (4.39 mΩ efter 14 dagar i fogar mellan aluminium och nickel), vilket indikerar potentialen för denna inriktning i framtida studier.

Projektet drar slutsatsen att även om ECA erbjuder anmärkningsvärda strukturella och tillverkningsmässiga fördelar, begränsar deras elektriska instabilitet för närvarande deras direkta tillämpning i EV-batterier. Framtida forskning bör fokusera på alternativa fyllnadsmaterial (t.ex. nickelbaserade lim) för att motverka galvanisk korrosion. Samtidigt identifierade projektet enkelsidig motståndspunktsvetsning som en mycket lovande och kostnadseffektiv metod för eftermarknadsreparationer.

3 Background

Driven by the rapid electrification of transportation, extensive research is currently focused on the development, design, manufacturing, and end-of-life management of electric vehicles (EVs). A critical bottleneck in achieving true circularity for EVs lies within the battery packs, specifically concerning the electrical connections between individual cells, tabs, and busbars.

Current industry practices rely heavily on laser beam welding (LBW), resistance welding and mechanical fastening. While LBW provides low-resistance, high-strength joints at high production speeds, it contradicts circular economy principles. Welded joints are permanent, making battery pack disassembly, material separation, and cellular-level repair highly complex and economically unviable. Furthermore, welding dissimilar metals (e.g., aluminium busbars to nickel tabs) can result in brittle intermetallic compounds that are prone to micro-cracking under thermal fatigue. The high heat input associated with welding also poses a significant risk of damaging sensitive internal battery cell components. Conversely, mechanical fasteners are bulky, add unnecessary weight, and are highly susceptible to loosening due to operational vibrations and thermal cycling, which inevitably increases electrical resistance and generates localized heating.

To overcome these fundamental limitations, adhesive bonding utilising Electrically Conductive Adhesives (ECAs) emerges as a highly promising alternative. ECAs typically consist of an insulating polymeric matrix (such as epoxy, polyurethane, or silicone) loaded with conductive filler particles (commonly silver, gold, or platinum). They offer numerous potential advantages over traditional methods: curing at low or ambient temperatures (eliminating thermal damage risks), the ability to join highly dissimilar and potentially recycled materials without forming intermetallics, uniform stress distribution across the joint, and crucially, the potential for easier disassembly and repair. Despite their extensive use in microelectronics, the application of ECAs in macro-scale, high-current EV battery pack connections remain largely unexplored, presenting a significant knowledge gap.

4 Purpose, research questions and method

The primary purpose of the CABEL project was to rigorously evaluate and demonstrate the feasibility of adhesive bonding as a novel, circularity-enabling solution for electrical connections in EV battery packs. To achieve this, the project focused on the following core research questions:

1. **Electromechanical Performance:** Can Electrically Conductive Adhesives (ECAs) match or exceed the electromechanical performance (electrical conductivity and mechanical strength) of traditional laser beam welded (LBW) joints?
2. **Environmental Durability:** How do ECA connections respond to long-term accelerated aging and harsh environmental conditions (such as high humidity and elevated temperatures)?
3. **Circularity and Repair:** Does the use of ECAs facilitate easier material separation, disassembly, and aftermarket repair compared to legacy joining methods?

4.1 Method

The project was executed through three Work Packages (WPs): WP1 (Experimental investigations and evaluations led by Scania), WP2 (Innovative adhesive materials led by RISE), and WP3 (Project management led by RISE). The experimental approach utilized standardised joint configurations simulating a battery module: joining an aluminium busbar to a nickel tab. The reference standard was established using Scania-provided laser beam welded (LBW) joints. The primary ECA tested was Hoenle ELECOLIT® 3648 (a silver-filled epoxy-based adhesive). Additionally, a custom nickel-based adhesive formulation (nickel mesh particles and Struers EpoFix resin) was developed and evaluated at RISE to investigate alternative filler materials.

4.1.1 Testing Procedures

1. Electrical Conductivity: Evaluated using highly precise 4-point resistance measurements (Megger Ohmmeter) to eliminate lead resistance. Current was applied through outer connections while voltage was measured across the inner joint, see Figure 1.
2. Temperature Dependence: Joints were subjected to elevated temperatures in a controlled oven environment, monitoring both surface temperature via thermocouples and real-time resistance to assess thermal stability and hysteresis, see Figure 2.
3. Accelerated Aging & Damp Heat: Samples were subjected to long-term room temperature aging (up to 42 days) and aggressive damp heat testing (70°C at ~100% Relative Humidity for 20 hours) to evaluate environmental degradation and moisture ingress, see Figure 3.
4. Mechanical Strength: Evaluated via destructive tensile shear testing at a stroke rate of 1 mm/min, comparing maximum force to failure against OEM requirements (200 N).
5. Microscopy & X-Ray Analysis: Employed to inspect the internal integrity of the adhesive layer, identifying porosity, voids, and interfacial degradation over time.
6. Repair Scenarios: Evaluated the performance of single-sided resistance spot welding as a potential low-cost aftermarket repair method.

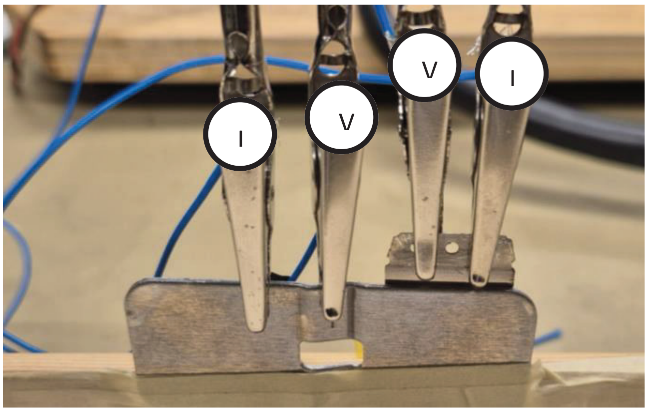


Figure 1 4-point resistance measurement set-up.

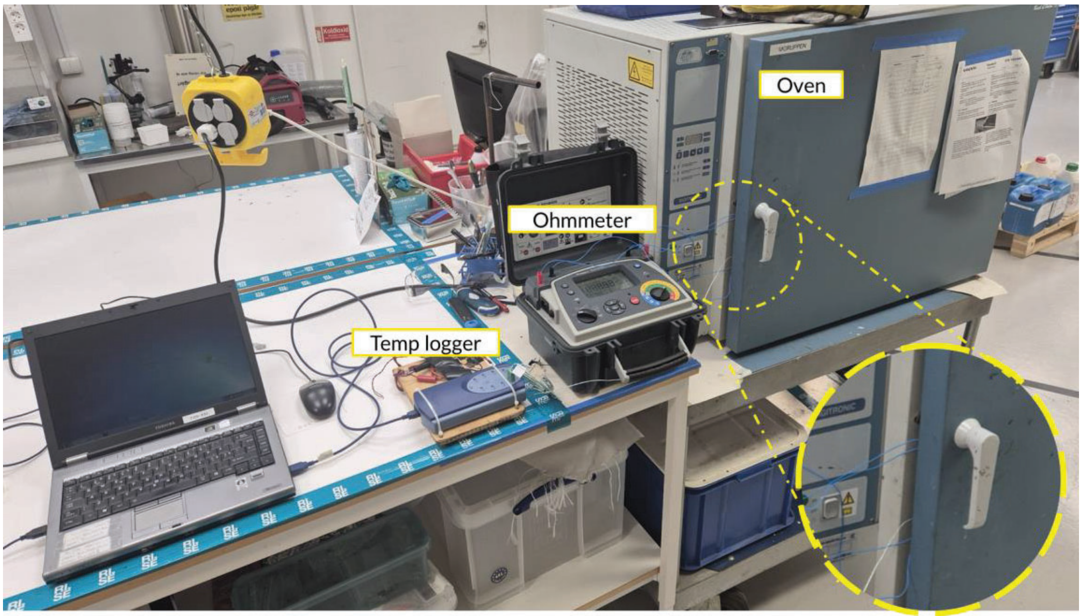


Figure 2 Resistance and temperature setup during elevated temperature measurements

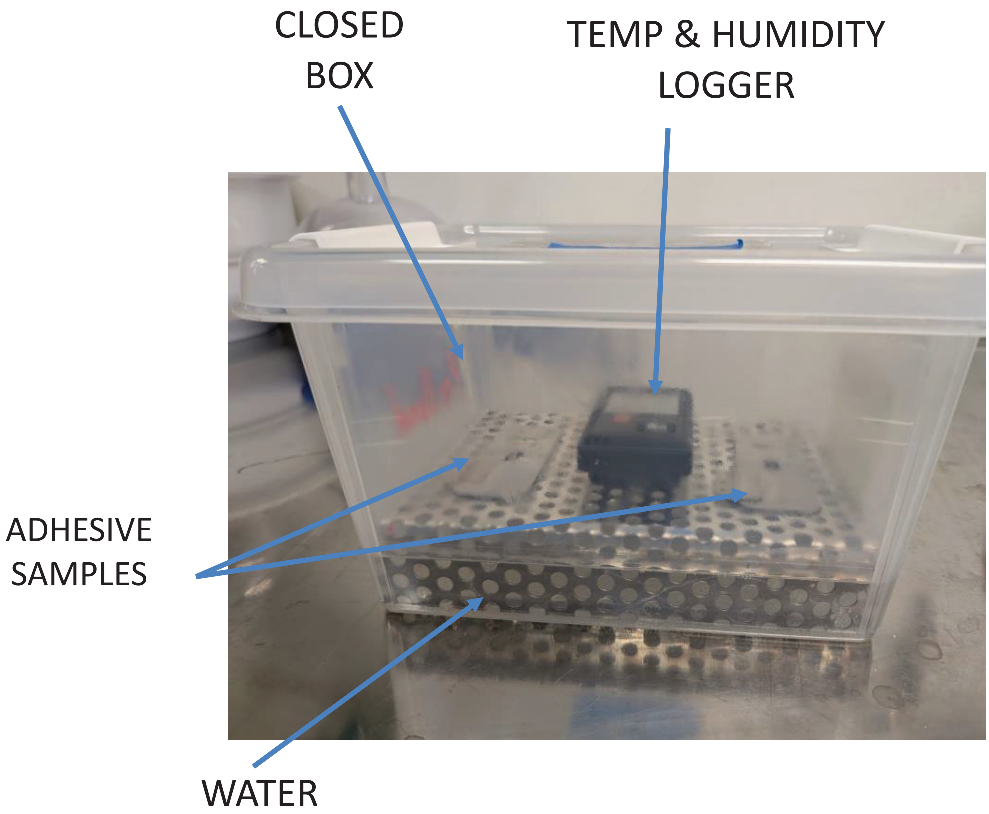


Figure 3 Damp heat experimental setup

5 Objective

As outlined in the original application, the overarching objective of this research was to determine and demonstrate the feasibility of adhesive bonding as a novel solution for electrical connections in EV battery packs. To achieve this, the project aimed to:

- Conduct an experimental investigation evaluating the performance of ECAs in simulated battery pack applications based on industrially relevant criteria (electrical conductivity and mechanical strength).
- Compare ECA performance directly to conventional methods (welded connections).
- Assess the ease of repair, disassembly, and material separation compared to legacy methods.
- Conduct a preliminary assessment of operator health and safety aspects regarding both serial production and EoL working conditions.

The objectives were largely met as described. However, due to unexpected electrical instabilities discovered during initial testing, the project expanded its scope to heavily investigate aging phenomena and damp heat performance to understand the root causes of failure. Consequently, slightly less emphasis was placed on full-scale battery module demonstration, prioritizing a fundamental understanding of the joint degradation mechanisms.

6 Results and deliverables

The experimental investigations yielded highly detailed data comparing laser beam welding (LBW) to electrically conductive adhesives (ECA). The findings are structured into electrical, environmental, and mechanical performance.

6.1 Electrical Conductivity and Temperature Dependence

6.1.1 Baseline Laser Weld (LBW) Performance

100 consecutive resistance measurements on a standard LBW busbar-tab connection at room temperature established a baseline. The measurements showed an average resistance of 0.41 mΩ (410 µΩ) with a standard deviation of 14.5 µΩ, see Figure 4. When subjected to elevated temperatures, the LBW joints exhibited a predictable, steady increase in resistance due to the positive temperature coefficient of the metals. At 80°C, the resistance increased by approximately 30% (approaching 605 µΩ), see Figure 5.

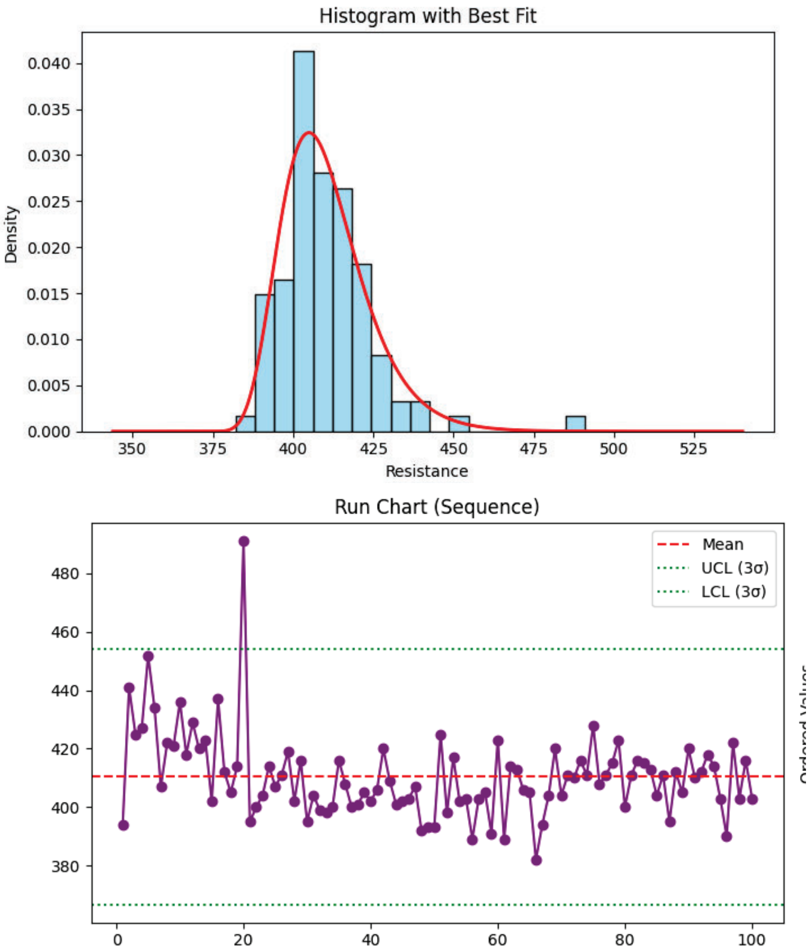


Figure 4 Repeatiblity measurements of resistance of LBW joints

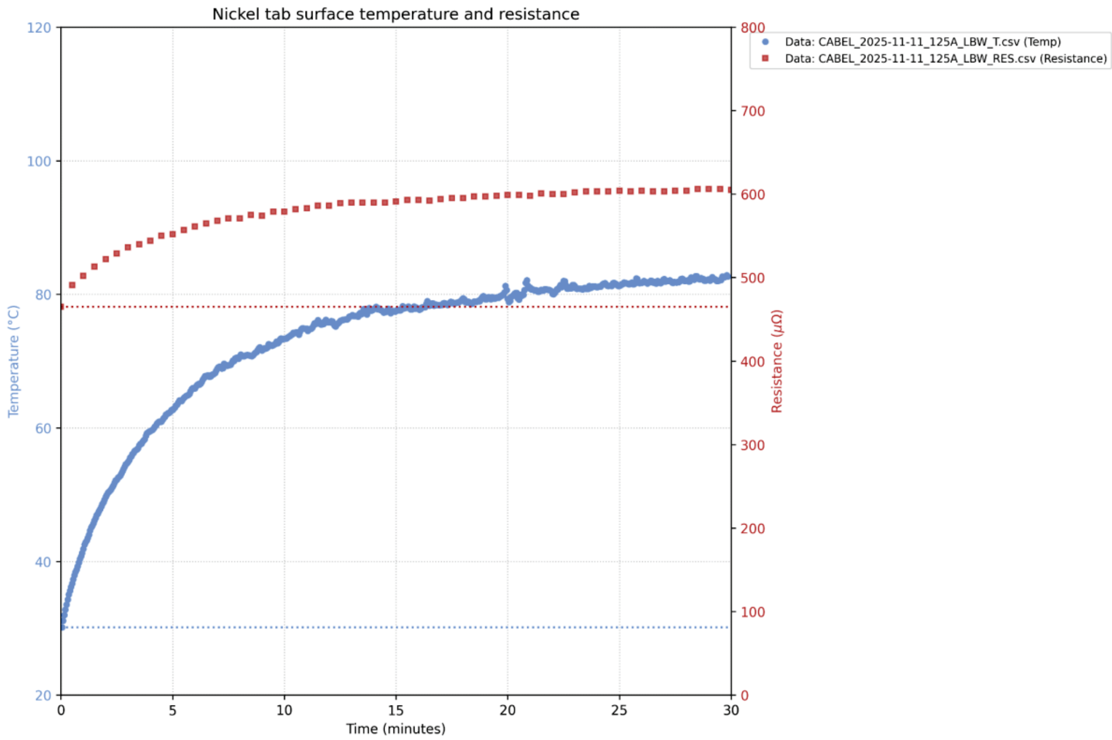


Figure 5 Resistance at elevated temperature of LBW joint.

6.1.2 Electrically Conductive Adhesive (ECA) Performance

Initial adhesive trials evaluated the impact of bond line thickness by utilizing 0.13 mm nylon lines to maintain a controlled gap. These gap-controlled samples exhibited unacceptably high and variable resistance, ranging from ~4 mΩ to over 31 mΩ. Subsequent trials removed the nylon spacers and utilized heavy clamping (foldback clips/weights) during the 150°C curing process to minimise the bond line. These 'no gap' samples performed significantly better, achieving average initial resistances between 0.90 mΩ and 3.91 mΩ. While this is higher than the LBW baseline, it demonstrates the fundamental capability of ECAs to create highly conductive pathways. However, significant sample-to-sample variation was noted, highlighting the high sensitivity of ECAs to assembly variables (dispensing volume, clamping force, alignment).

6.2 Aging, Damp Heat, and Degradation Mechanisms

The most critical finding of the CABEL project concerns the long-term electrical stability of the ECA joints.

6.2.1 Room Temperature Aging

Samples stored at standard room temperature without thermal cycling were monitored over an extended period of 63 days, see Figure 6. The results were highly concerning, as the electrical resistance increased continuously and non-linearly over the entire test duration.

The tab-busbars samples (nickel tab bonded to aluminium busbar using silver-filled epoxy) deteriorated rapidly. Climbing from an initial ~2.0 mΩ, the resistance reached ~26.8 mΩ at 41 days, and continued to rise, reaching up to 35 mΩ by day 63.

Interestingly, the tab-tab repair scenario joints (nickel bonded to nickel) showed better relative stability, but still exhibited a continuous degradation, increasing from ~1.0 mΩ initially to ~7.0 mΩ at 35 days and then remained relatively constant up to the 63-day mark.

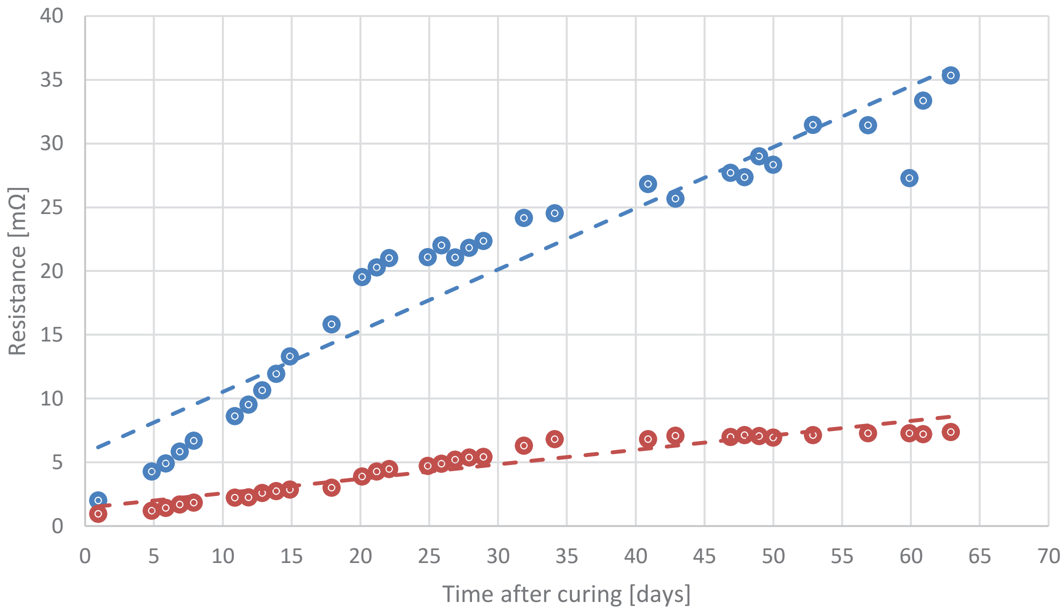


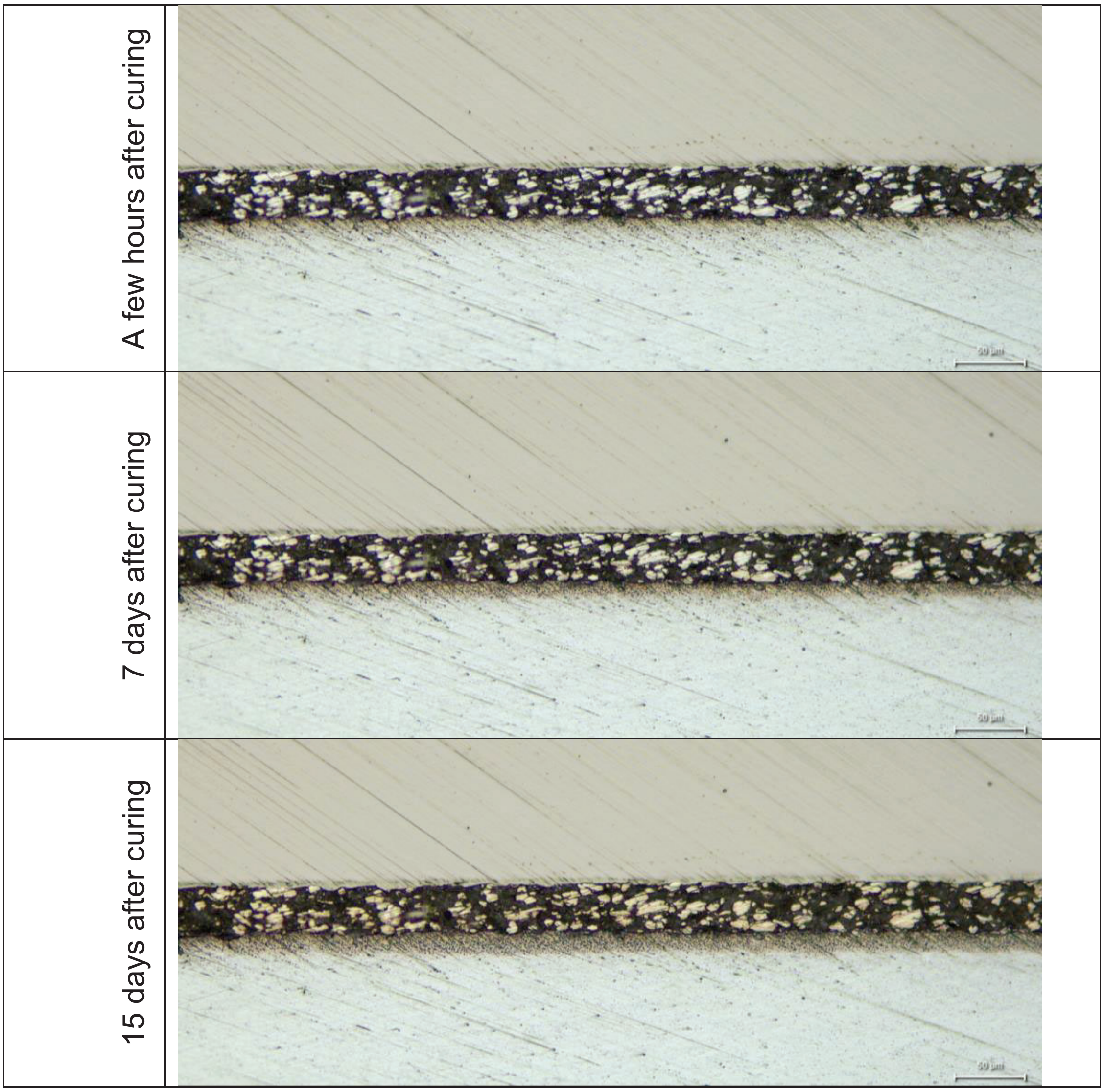
Figure 6 Resistance measurements over time.

This drastic difference strongly points to galvanic corrosion at the aluminium interface as the primary degradation mechanism. The electrochemical potential difference between the noble silver flakes in the ECA and the active aluminium busbar creates a micro-galvanic cell, rapidly oxidizing the aluminium surface and creating an expanding insulating barrier over time.

To physically investigate the mechanisms driving the electrical instability, optical microscopy was performed on cross-sections of the nickel-to-aluminium (tab-busbar) adhesive joints both immediately after curing and following a 29-day aging period.

The optical microscopy of the aged nickel-to-aluminium specimens provides subtle but critical visual evidence of the changes occurring at the bond line, see Figure 7. Over the

29-day period at room temperature, the cross-sections reveal a distinct, expanding region of discolouration (a slight change in colour which grows) directly at the boundary between the silver-filled adhesive and the aluminium busbar. This growing discoloured zone indicates the progressive formation of a new interfacial layer, suggesting the active development of the micro-galvanic cell and the oxidation of the aluminium surface.



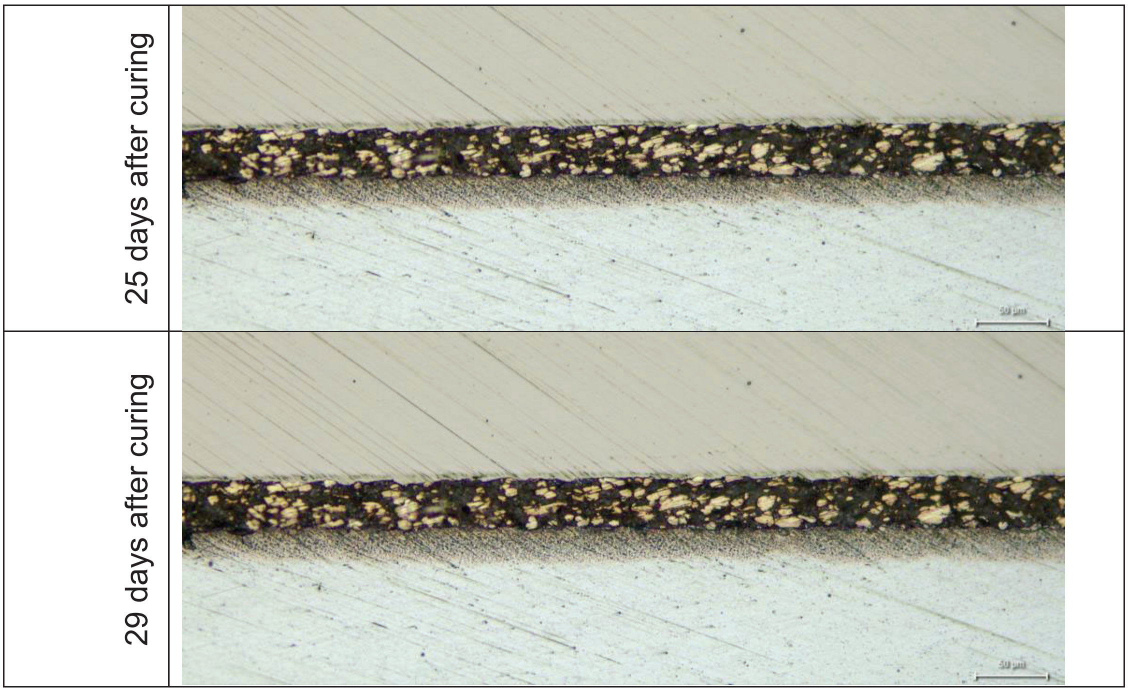


Figure 7 Light optical microscopy results of cross-sections at 200x magnification a few hours after curing, 7 days after curing, 15 days after curing, 25 days after curing and 29 days after curing.

While optical microscopy successfully visualises the mechanical separation and structural breakdown caused by the galvanic reaction, it is fundamentally limited to physical observation. It cannot chemically identify the composition of the insulating barrier forming at the interface. To definitively assess, map, and quantify the presence of non-conductive aluminium oxides (Al_2O_3) or aluminium hydroxides ($Al(OH)_3$) driving the resistance increase, future investigations should utilize Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-Ray Spectroscopy (EDX).

6.2.2 Temperature Hysteresis and Moisture

Oven testing of aged samples revealed complex hysteresis loops. Heating the samples initially caused resistance to rise rapidly, followed by a decrease and stabilization around 80°C. Cooling the samples caused sudden, sharp spikes in resistance, see Figure 8 and Figure 9. This behaviour could be attributed to the differing coefficients of thermal expansion (CTE) between the epoxy matrix, the silver filler, and the metal substrates, causing microscopic separation and reconnection of the composite network. The exact mechanisms and root causes of this behaviour needs to be further examined to be fully understood.

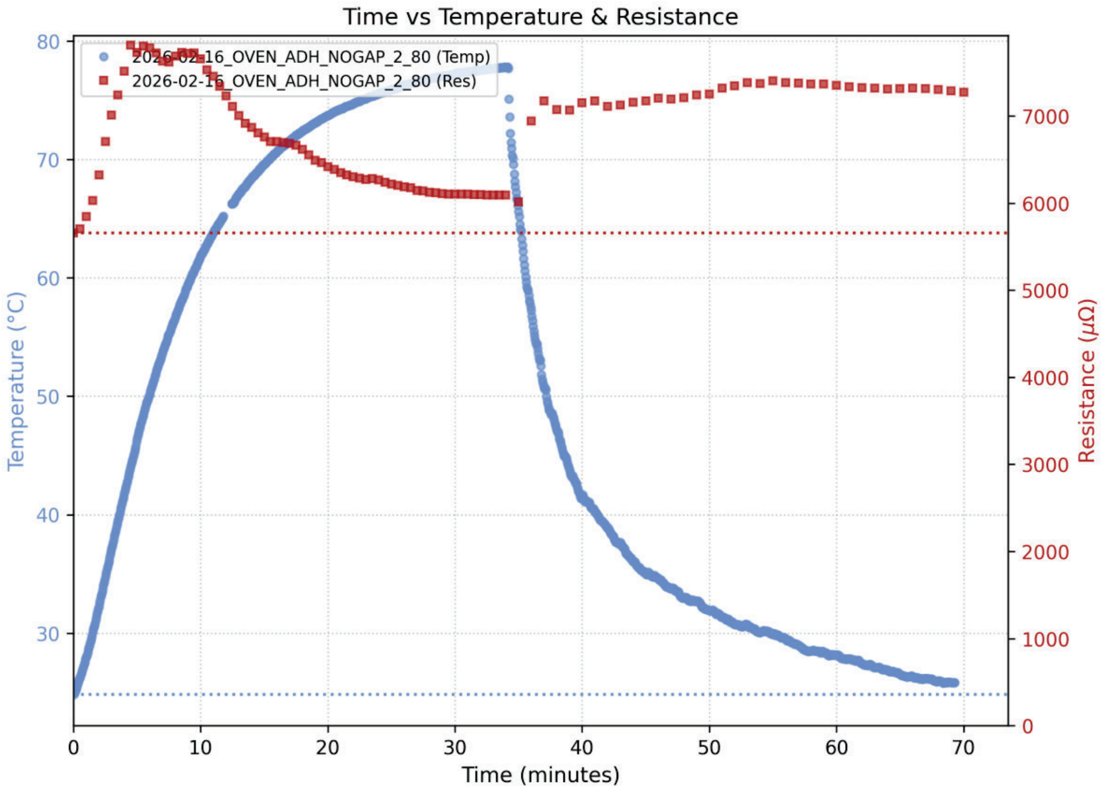


Figure 8 Resistance measurements at elevated temperatures and cooling of ECA samples

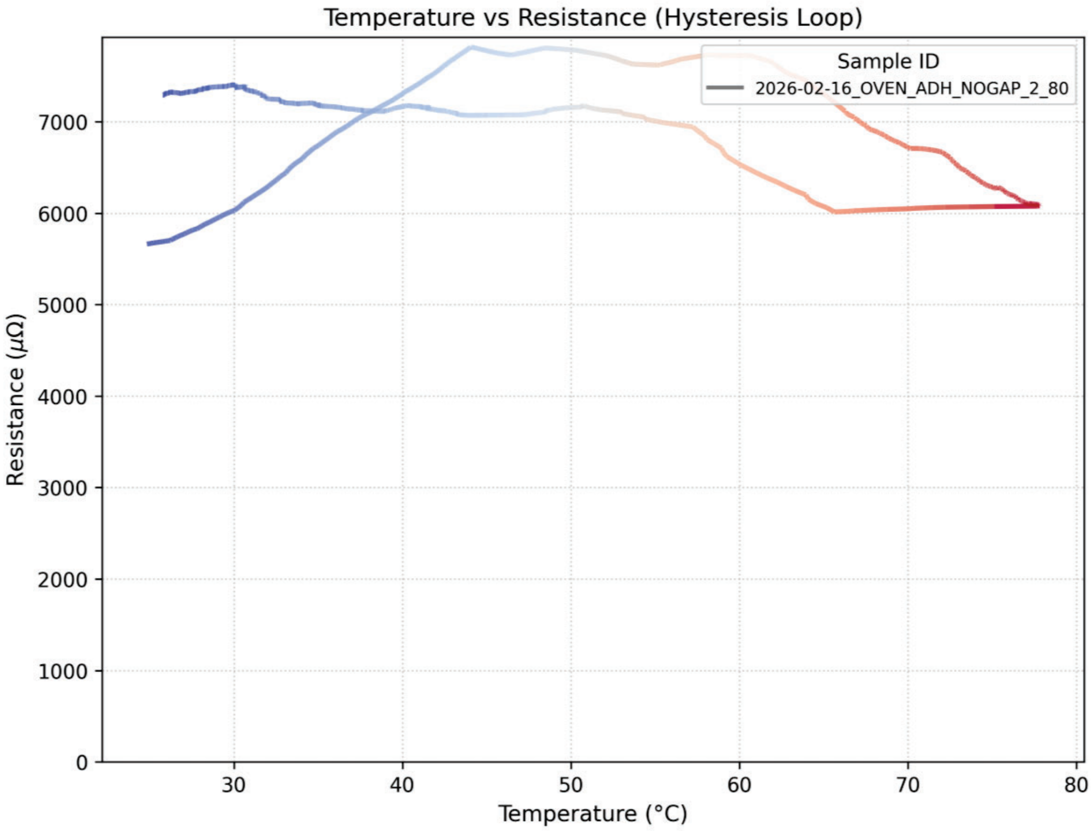


Figure 9 Hysteresis loop of resistance during heating and cooling of ECA samples

6.2.3 Damp Heat Testing (70°C, ~100% RH)

To accelerate environmental degradation, samples were exposed to severe damp heat for 20 hours. This had extreme effects on the results. The tab-tab-busbar samples suffered complete mechanical debonding. The remaining tab-busbar samples exhibited highly erratic resistance measurements that jumped drastically (from ~20 mΩ to over 480 mΩ) within seconds when measured. This indicates severe moisture ingress into the joint, swelling the polymer matrix, disrupting the composite network, and aggressively accelerating the galvanic corrosion process.

6.3 Mechanical Strength

While electrically unstable, the ECAs demonstrated superior mechanical performance. Destructive tensile shear testing (1 mm/min stroke) was conducted to benchmark against the OEM requirement of a 200 N pull force.

- Laser Weld (LBW): Failed at maximum forces ranging from 284 N to 320 N.
- ECA (No Gap): Failed at remarkably high maximum forces, ranging from 322 N to 624 N.

All 'no gap' adhesive samples comfortably exceeded both the OEM requirement and the baseline LBW strength. However, the failure modes varied. The strongest sample (624 N) exhibited a highly brittle, sudden fracture, whereas other samples showed more ductile yielding prior to failure. This variation in mechanical behaviour further underscores the process sensitivity of the adhesive application.

6.4 Alternative Repair and Diagnostics

Alternative Curing: Attempts to cure the ECA using a standard soldering iron were unsuccessful, as the heat transfer was insufficient to maintain the required 150°C at the bond line, peaking just below 80°C. Further experiments are required to fully understand this behavior and to determine if alternative soldering or localized heating methods have an industrial feasibility for ECA curing.

Non-Conductive Adhesive Control: Tests using a standard 2K cyanoacrylate/acrylic non-conductive adhesive (Loctite 3090) yielded resistances between 4.5 mΩ and 24.6 mΩ. This result indicates that clamping force alone creates significant metal-to-metal asperity contact through the adhesive layer, meaning the ECA's initial low resistance is partially mechanical rather than purely conductive-filler driven.

Single-Sided Spot Welding: As an alternative repair strategy, low-cost, battery-driven single-sided spot welding was evaluated. This method successfully welded nickel strips to nickel tabs, yielding a comparable resistance of ~2.0 mΩ (inclusive of the underlying laser weld). While this initially presents a highly viable solution for aftermarket repair, this method requires further research to be fully understood and qualified as a standardized repair procedure. Future qualification must include determining and validating the exact equipment and operational parameters, as well as investigating the long-term properties of the joints - particularly their performance and resistance stability in long-term and high-humidity environments.

6.5 Operator Health and Safety Assessment

A critical component of integrating Electrically Conductive Adhesives (ECAs) into standard battery pack assembly and aftermarket repair is evaluating operator health and safety, particularly in comparison to traditional Laser Beam Welding (LBW).

Hazard Profiles: LBW presents potential workplace hazards, including exposure to high-intensity laser radiation and hazardous welding fumes, which need to be addressed. Conversely, ECAs typically consist of epoxy or polyurethane-based matrices loaded with metallic filler materials. While these eliminate burn and radiation hazards by curing at low or ambient temperatures, they introduce chemical exposure risks. Prolonged skin contact or inhalation of unreacted epoxy resins, hardeners requires stringent chemical handling protocols, adequate ventilation, and appropriate personal protective equipment (PPE).

Production and Repair Environments: LBW relies on complex, energy-intensive equipment that requires heavily guarded, enclosed production cells, making it largely inaccessible for standard aftermarket repair workshops. Adhesive bonding is highly accessible and requires simpler dispensing equipment. However, to safely implement ECAs in both serial production and end-of-life (EoL) repair conditions, specific operator safety guidelines regarding chemical exposure and the handling of conductive particles must be established before full-scale implementation.

6.6 Mapping of Innovative Adhesives and Fillers

To address the performance limitations and galvanic corrosion issues observed with standard silver-filled ECAs, the project mapped innovative adhesive formulations and conductive fillers with potential for future EV battery applications. Achieving a robust conductive network (exceeding the percolation threshold) can be accomplished through various advanced filler categories:

- **Advanced Metal Fillers:** While silver (Ag) offers superior conductivity, its high cost and tendency for migration limit its use. Copper (Cu) offers excellent electro-migration characteristics and cost-effectiveness, though it requires surface modifications (such as silver coating) to prevent rapid oxidation. Nickel (Ni) presents high resistance to oxidation but generally possesses higher resistivity, often requiring electroless gold plating. These theoretical advantages were practically demonstrated in this project through the development of a custom nickel-based formulation, detailed in Chapter 6.7.

- **Carbon-Based Fillers:** Carbon nanotubes (CNTs), carbon nanofibres (CNFs), and graphene are emerging as highly promising candidates due to their exceptional thermal conductivity, high aspect ratios, and ability to form conductive networks at very low filler loadings. For instance, adding just 1 wt% of single-walled carbon nanotubes (SWCNTs) can significantly enhance electrical conductivity. Graphene, with its extreme specific surface area, can construct uninterrupted electrical networks with minimal filler volume, though achieving homogeneous dispersion in the epoxy matrix remains a manufacturing challenge.

- **Ceramic Fillers:** Ceramic materials such as Boron Nitride (BN), Titanium Carbide (TiC), and Titanium Boride (TiB) are being investigated for their thermal stability and chemical resistance. While traditionally insulating, specific conductive or semiconducting ceramics can serve as excellent secondary fillers to enhance overall thermal conductivity while maintaining the necessary electrical pathways.

- **Inherently Conductive Polymers (ICPs):** Polymers like polypyrrole (PPy), polyaniline (PANI), and polythiophene (PTh) conduct electricity through their conjugated molecular structures. Blending ICPs with an epoxy matrix provides a flexible, lightweight alternative to solid metal fillers. While their baseline conductivity is lower than metal networks, advanced doping techniques and hybridizing ICPs with carbon or metal fillers represent a highly promising frontier for creating flexible, corrosion-resistant, and chemically stable ECAs for automotive applications.

6.7 Nickel-Based Adhesive Development and Trials

To address the severe galvanic corrosion challenges observed with commercial silver-filled ECAs, a novel nickel-based adhesive was developed and evaluated at RISE. The customized formulation consisted of four parts nickel mesh particles (4/7 by weight) suspended in three parts epoxy-based resin (3/7 by weight, EpoFix Resin). The step-by-step procedure for preparing this adhesive is visually documented in Figure 10.

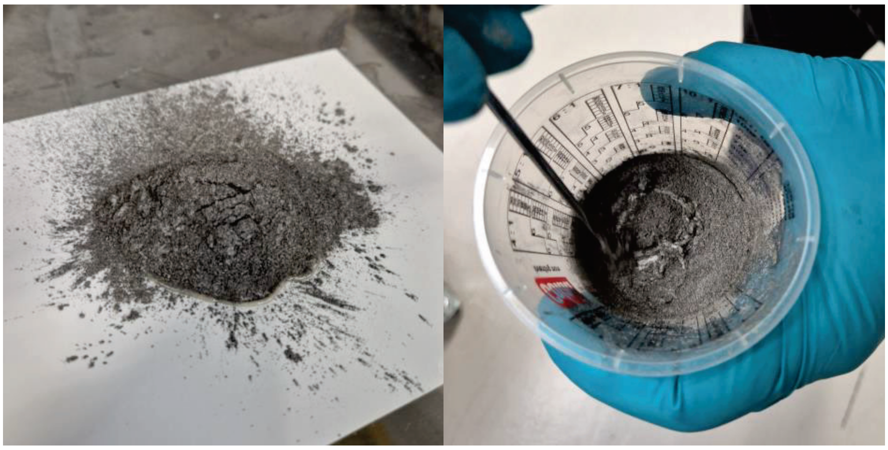


Figure 10 Formulation and manual mixing of the novel nickel-based adhesive at RISE.

Initial experimental trials were conducted using this custom formulation on both dissimilar metal joints (aluminium busbar to nickel tab) and similar metal joints (nickel tab to nickel tab). The early resistance measurements were highly promising. After a 5-day period, the nickel-to-nickel joints demonstrated a resistance of as low as 1.5 mΩ, while the aluminium-to-nickel joints recorded 4.39 mΩ. However, as noted with the previous trials, there were high variability between the samples.

Following a 14-day observation period, the resistance for the nickel-to-nickel samples increased to 5.71 mΩ. The aluminium-to-nickel joints exhibited stable behaviour, maintaining a resistance of 4.39 mΩ. Due to the limited overall duration of the project, comprehensive long-term aging and damp heat trials could not be completed for these specific samples. Nevertheless, the early electrical stability observed, particularly in the dissimilar joints, suggests that this nickel-based adhesive track is a highly viable approach to mitigate galvanic corrosion. This formulation warrants further exploration and rigorous long-term validation in future studies.

7 Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Results clarify limits of current Ag-filled ECAs for EV busbars.
Be passed on to other advanced technological development projects	X	Findings dictate the need for new filler materials (e.g. Nickel) in future studies.
Be passed on to product development projects	X	The single-sided spot welding method will be passed on for further qualification and implementation in aftermarket service and repair procedures.
Introduced on the market		ECA technology is not yet mature enough for this specific application.
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

Due to the nature of the findings highlighting specific material degradation mechanisms, a technical paper for submission to a materials engineering journal is currently under consideration. RISE proposes drafting a publication focusing on the accelerated aging and galvanic corrosion of silver-filled epoxies on aluminium substrates in EV applications; however, this proposal requires formal approval from the full consortium before proceeding. Public dissemination is also planned through a presentation at the Swedish Manufacturing R&D Clusters conference in 2026.

8 Conclusions and future research

The CABEL pre-study has successfully evaluated the feasibility of Electrically Conductive Adhesives (ECAs) for battery pack electrical connections, yielding critical insights for the automotive industry.

Key Conclusions:

1. **Mechanical Superiority:** ECAs are capable of forming joints that are significantly stronger than traditional laser beam welds, comfortably exceeding OEM requirements and offering excellent structural integrity.

2. **Initial Electrical Viability:** Under heavily optimized, controlled-gap conditions, ECAs can achieve initial electrical resistances approaching those of laser welds (sub 1.0 mΩ).
3. **Critical Electrical Instability:** Current commercial silver-filled ECAs are unsuitable for long-term use on aluminium busbars due to severe galvanic corrosion. Over an extended observation period of 63 days at room temperature, resistance increased exponentially, climbing from an initial ~2.0 mΩ to up to 35 mΩ. Exposure to moisture (damp heat) accelerates this degradation even further, leading to catastrophic failure.
4. **Process Sensitivity:** The electrical and mechanical performance of ECAs is highly sensitive to assembly parameters, making robust serial production highly challenging with current formulations.
5. **Repair Viability and Limitations:** While ECAs currently struggle as a primary joining method, single-sided resistance spot welding was identified as a highly promising, low-cost method for aftermarket repair. However, this method requires further research to be fully qualified, including the determination of exact equipment and parameters, as well as rigorous long-term testing under high humidity. Furthermore, standard soldering methods for curing ECAs proved insufficient and require further experiments to determine any true industrial feasibility.
6. **Operator Health and Safety:** Transitioning from Laser Beam Welding (LBW) to ECAs fundamentally shifts the workplace hazard profile. While adhesive bonding eliminates the risks of laser radiation, extreme heat, and hazardous welding fumes, it introduces chemical exposure risks. Safe implementation in both serial production and EoL repair environments mandates strict chemical handling protocols, adequate ventilation, and specialized PPE to mitigate exposure to unreacted resins and nano-scale conductive particles.

Future Research:
The findings demonstrate that while the structural and manufacturing benefits of ECAs are highly desirable for EV circularity, the materials science must evolve. Future research must urgently pivot to exploring innovative ECA formulations, specifically focusing on:

- **Advanced Conductive Fillers:** Drawing on the promising short-term trials of the custom nickel-mesh/epoxy formulation developed at RISE, future research should prioritize comprehensive long-term aging and damp heat validation of this specific track to definitively eliminate galvanic corrosion.
- **Inherently Conductive Polymers (ICPs):** Exploring the use of ICPs (like polypyrrole or polyaniline) that do not rely on a metallic percolation network, potentially offering a more flexible and corrosion-resistant matrix.
- **Secondary Ceramic Fillers:** Investigating the integration of specific ceramic fillers to boost thermal conductivity while preserving necessary electrical pathways.

- **Moisture-Resistant Matrices:** Developing robust, moisture-resistant matrix formulations designed specifically for the harsh environmental realities of automotive battery packs.
- **Validation of Alternative Repair:** Further validation and industrialization of single-sided spot welding for modular battery repair, prioritising long-term aging and performance stability testing in high-humidity conditions.

9 Participating parties and contact persons

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