Characterizing, optimising, and repairing electrically conductive joints in EV battery applications

Ethan Sullivan, Swerim AB

Oscar Andersson, RISE

EMPIRE, COMMIT, CODELAB and CABEL

- Improve joint properties, develop fatigue test method, standardise defect acceptance levels, and repair of busbar/tab joints
- Funding: Formas, Vinnova, Energimyndigheten
- Project duration
  - EMPIRE: 2021-2023
  - COMMIT: 2023-2025
  - CODELAB: 2025-2027
  - CABEL: 2025-2026

EMPIRE

HÖGSKOLAN VÄST, SWERIM, TRUMPF, MATERION, Polarium, SCANIA, GRÄNGES

COMMIT

EL SUPPLY, VOLVO, Volvo Cars Company, SCANIA, Hydro, LASERTECH, northvolt, SWERIM

CODELAB

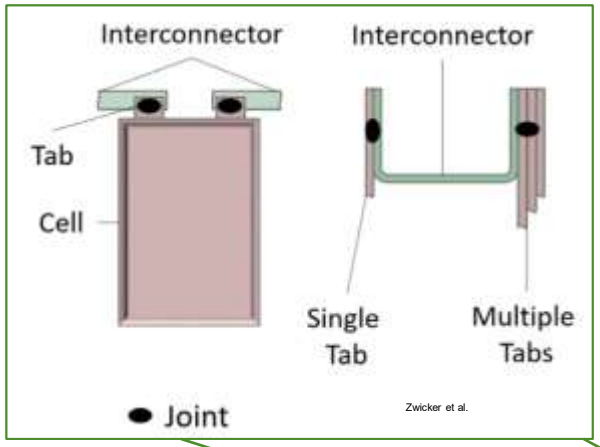
VOLVO, Volvo Technology AB, SVETS KOMMISSIONEN, TRATON, LASERTECH, SWERIM

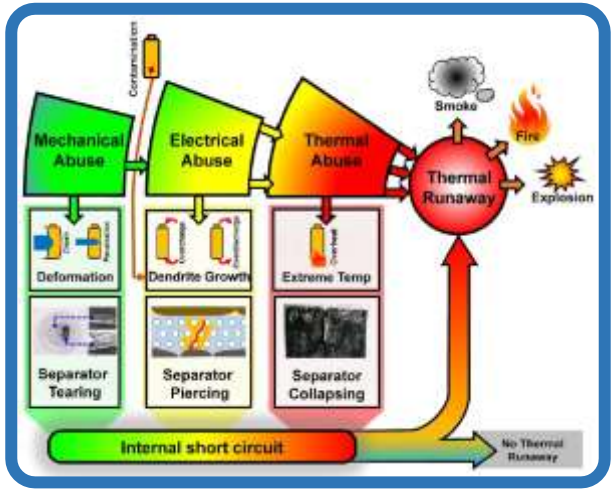
CABEL

SCANIA, TRATON, RI.SE, Biesterfeld

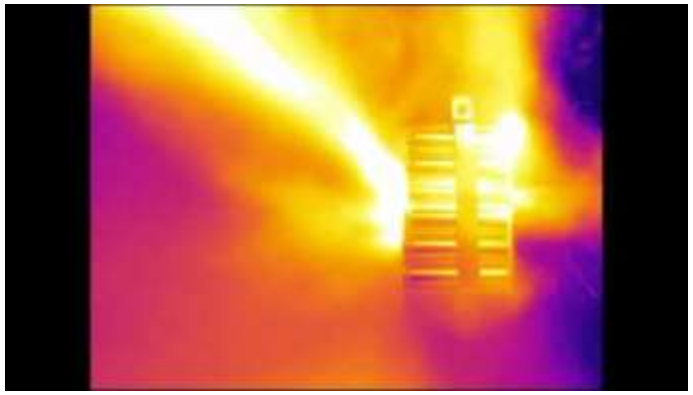
EMPIRE

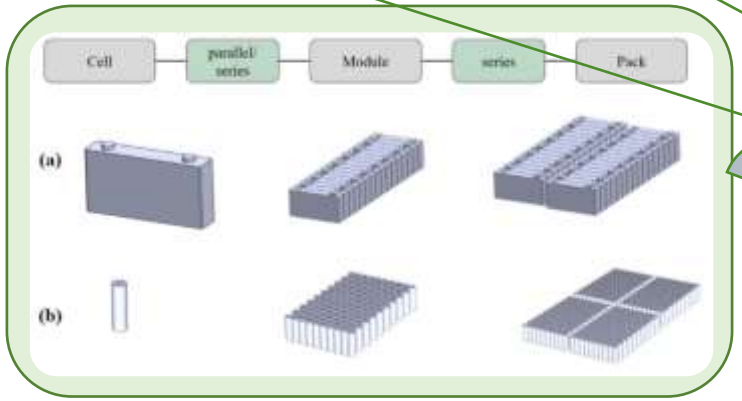
Poor joint quality can lead to mechanical failure, unplanned downtime, and *thermal runaway*

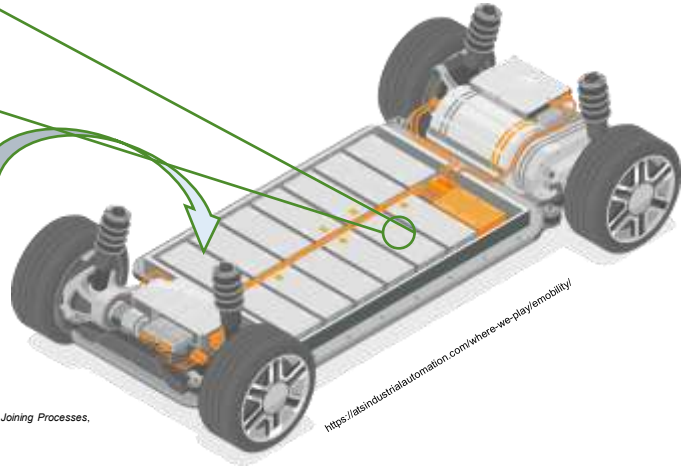




Forced thermal runaway of a 5-cell Li-ion battery





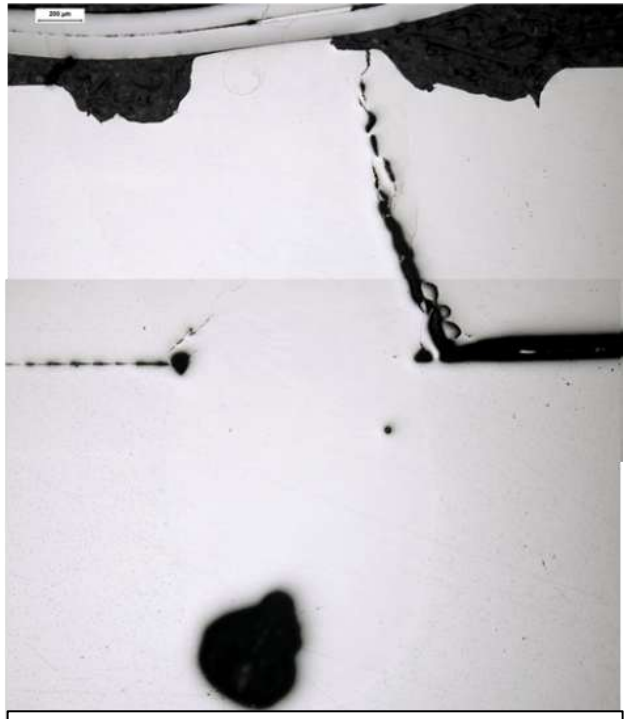


M. F. R. Zwicker, M. Moghadam, W. Zhang, and C. V. Nielsen, "Automotive battery pack manufacturing – a review of battery to tab joining," *Journal of Advanced Joining Processes*, vol. 1, p. 100017, Mar. 2020, doi: 10.1016/j.jajp.2020.100017.

Connected batteries = high reliability requirements (1 in 5 million NOK allowed!*)

*(based on 250 batteries per vehicle x 2 battery terminals per battery and an acceptable failure rate per vehicle of 1 in 10000)

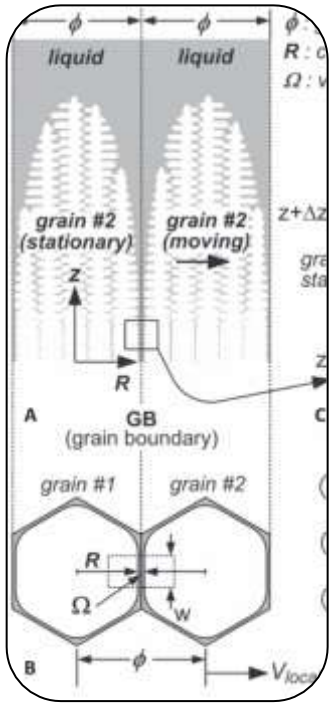
Laser welding of high-strength aluminium can lead to solidification cracking and reduced joint quality



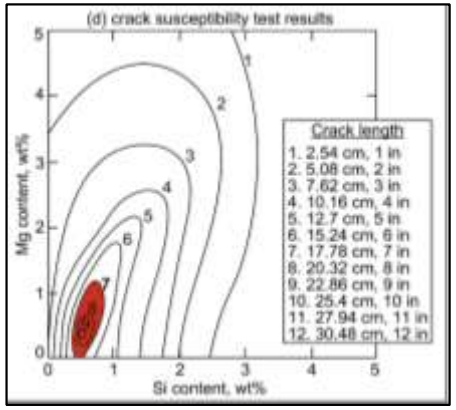
Laser-welded 6101/3003 (this work)

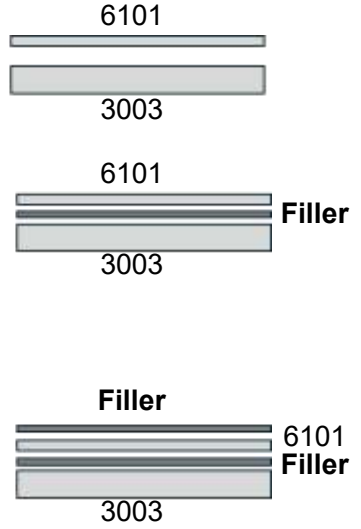
6xxx aluminium provides higher strength-to-conductivity for more demanding busbar designs, but suffers from solidification cracking

S. Kou, *Welding J.* 2015



J. Liu and S. Kou, "Susceptibility of ternary aluminum alloys to cracking during solidification," Acta Materialia, vol. 125, pp. 513–523, Feb. 2017, doi: 10.1016/j.actamat.2016.12.028.



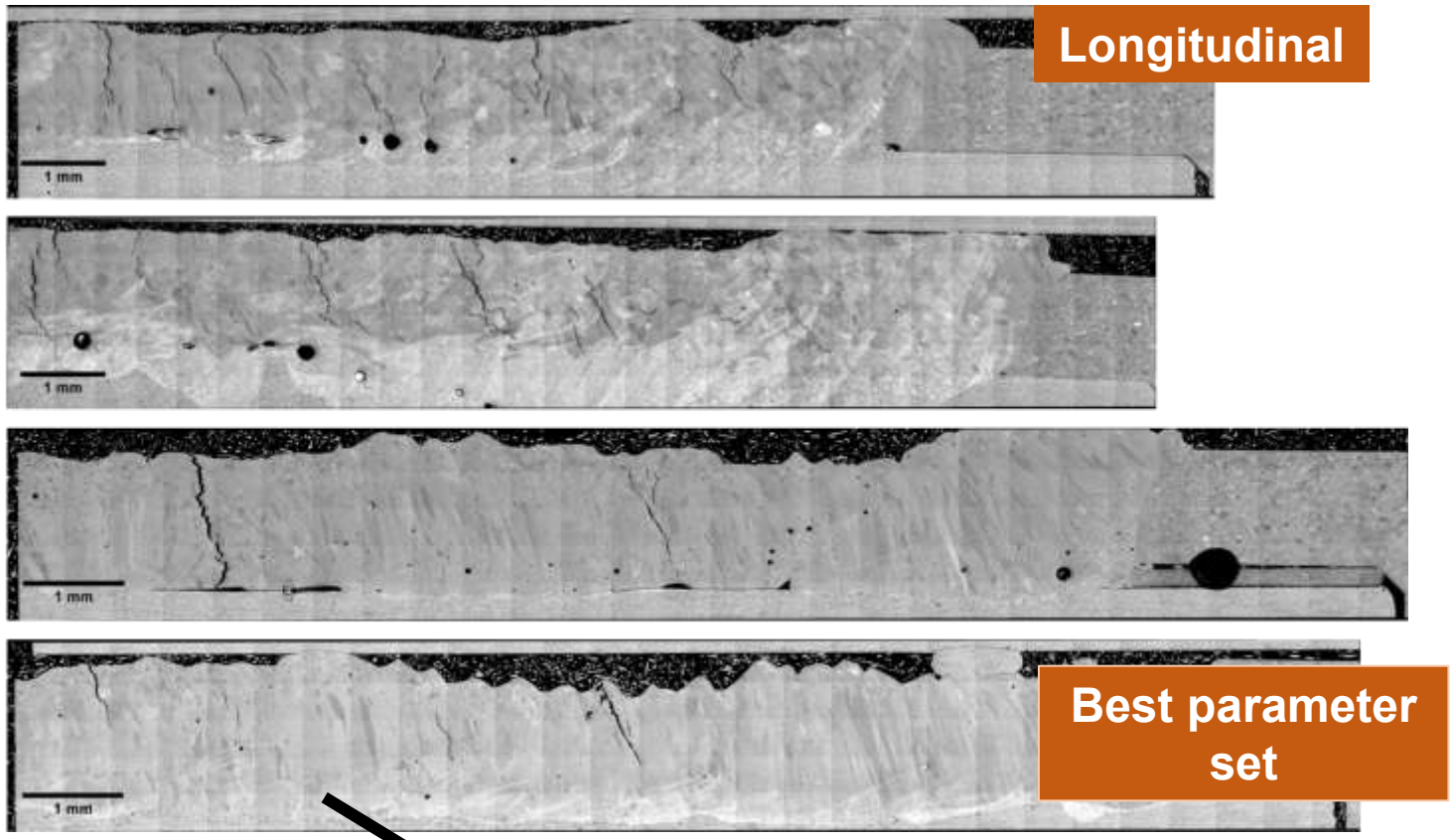


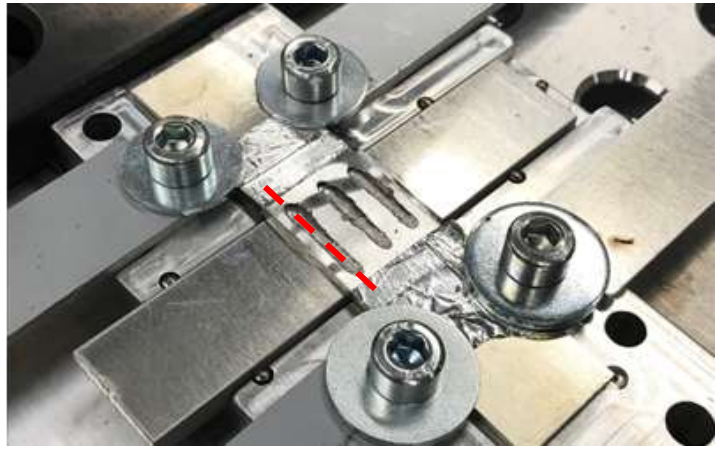
Sample	Aluminium alloy	Size
Lower strip	3003	114 x 24 x 3.2 mm
Upper strip	6101	114 x 24 x 1.2 mm
Filler foil	Al-Si alloy w/ built-in flux	160 micrometre thick foil

Laser-welded with three different laser powers

1) Adding a filler material will shift the composition away from the crack-susceptible regime
2) Built-in flux will clean the faying surface of oxides and reduce porosity

One foil with an intermediate laser power reduces the frequency of solidification cracks and reduced porosity





Laser oscillation could further improve Si-mixing and reduce occurrence of solidification cracks

The filler foil can be roll-bonded to the aluminium strip for scaling up production to industrial levels

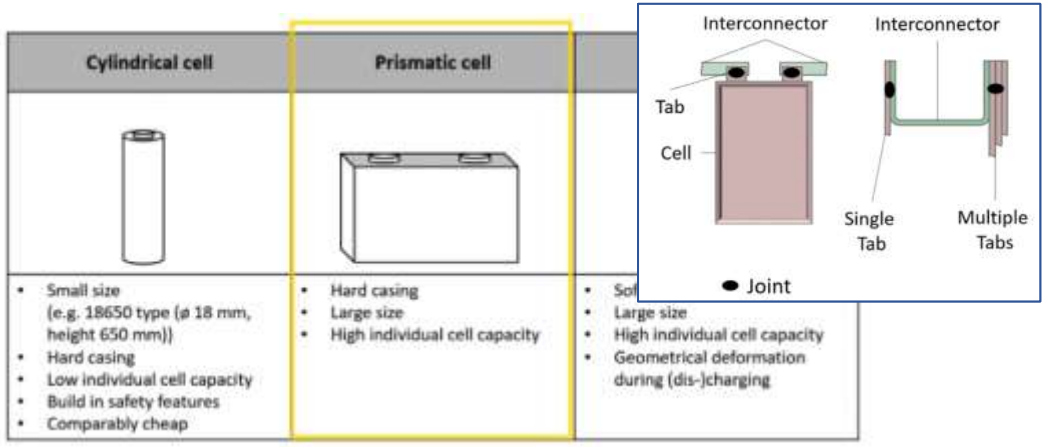
Conclusions – EMPIRE

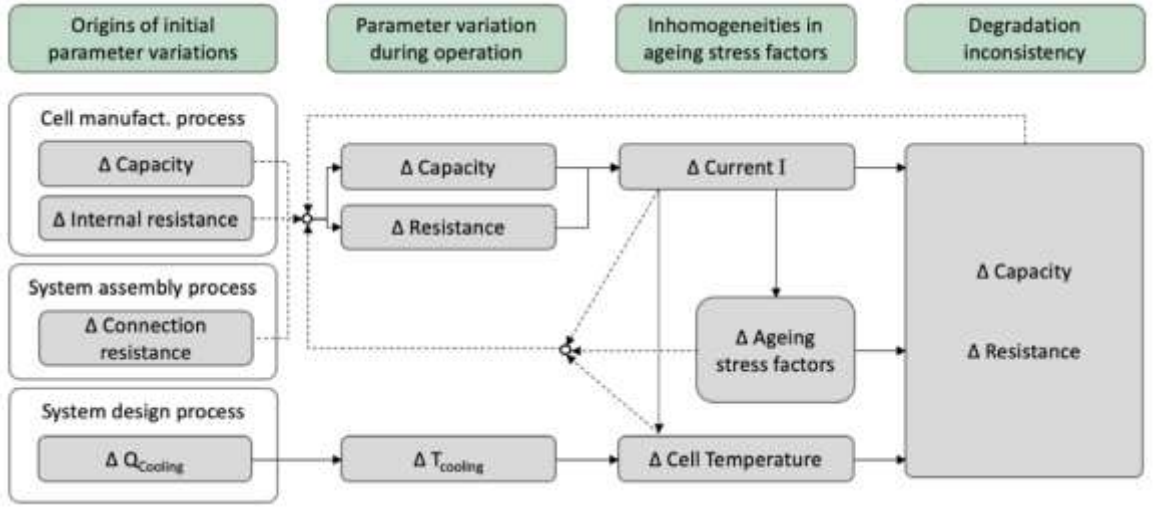
Aluminium-silicon filler foil with built-in flux	**Reduced solidification cracking and porosity in Al-Al joints**

COMMIT

Suitable test methods for evaluating the fatigue life of electrical joints and welds do not currently exist

[1]



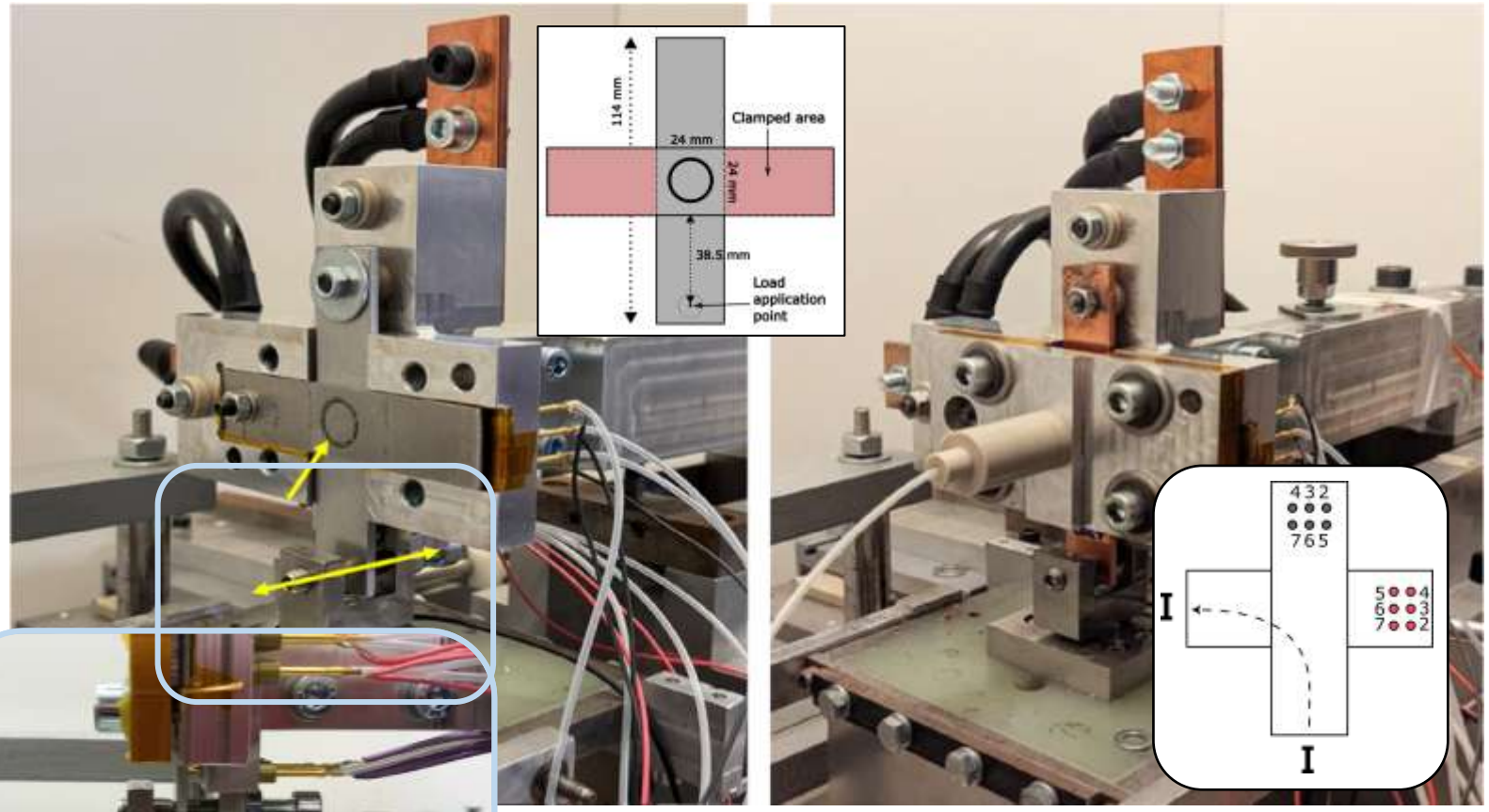


[2]

- **Thermal and mechanical fatigue measurement of welded busbar-tab electrical connections in prismatic battery cells**
- Battery modules are exposed to **dynamic loading + random vibrations**, **residual stress** imparted by the joining method, **elevated temperatures + temperature cycling** during normal operation and short-circuiting, which all affect the fatigue life of the welded connections

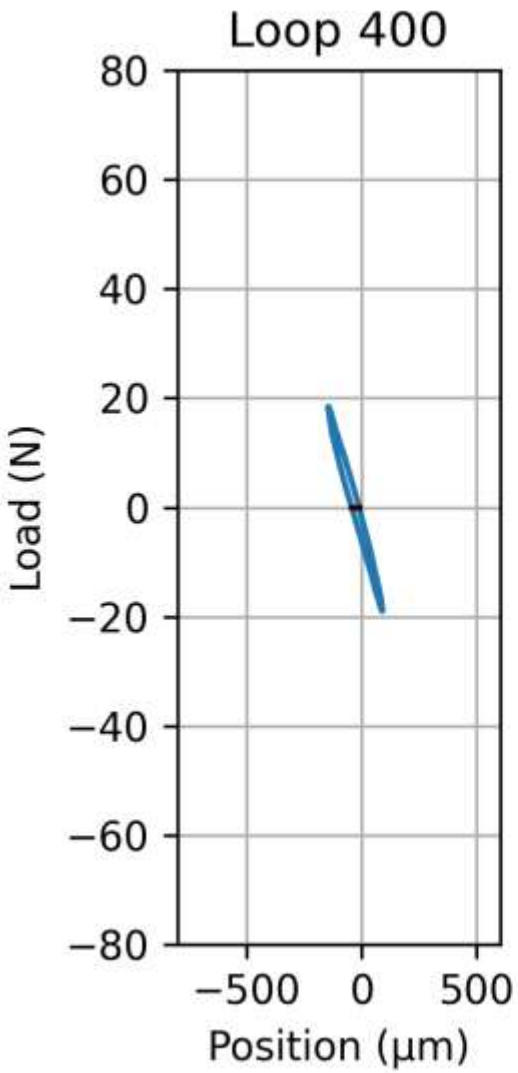
[1] M. F. R. Zwicker, M. Moghadam, W. Zhang, and C. V. Nielsen, "Automotive battery pack manufacturing – a review of battery to tab joining," *Journal of Advanced Joining Processes*, vol. 1, p. 100017, Mar. 2020, doi: 10.1016/j.jajp.2020.100017.
[2] M. Baumann, L. Wildfeuer, S. Rohr, and M. Lienkamp, "Parameter variations within Li-Ion battery packs – Theoretical investigations and experimental quantification," *Journal of Energy Storage*, vol. 18, pp. 295–307, Aug. 2018, doi: 10.1016/j.est.2018.04.031.

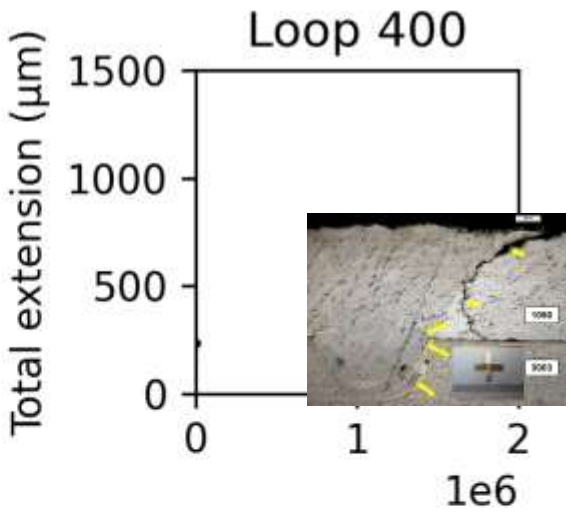
A new fatigue rig with capability for testing under high applied currents was developed

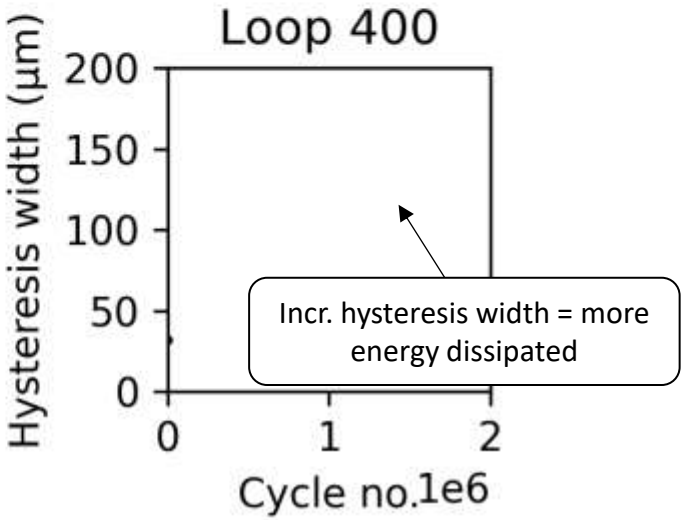


- Logging of force vs. displacement, voltage drop
- Displacement- and load-controlled operation
- Auto-stop in case of full fracture
- Load amplitudes up to 100 N
- Load frequencies up to 10 Hz have been tested
- Optional testing under higher current (300 A) to simulate fast charging

Fatigue damage was identified via force vs. displacement curves and voltage drop







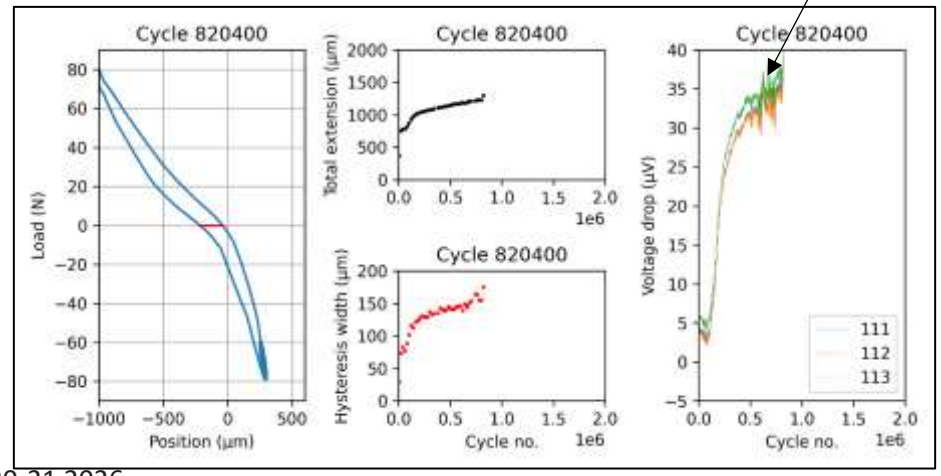
Incr. hysteresis width = more energy dissipated

What are signs of fatigue damage?

Force vs. displacement loop:
asymmetry, increasing total extension and hysteresis width

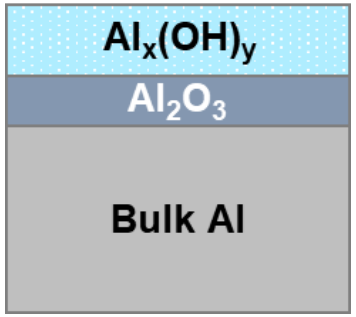
Voltage drop:
Increasing magnitude

Less current-bearing area from fatigue damage = incr. voltage drop

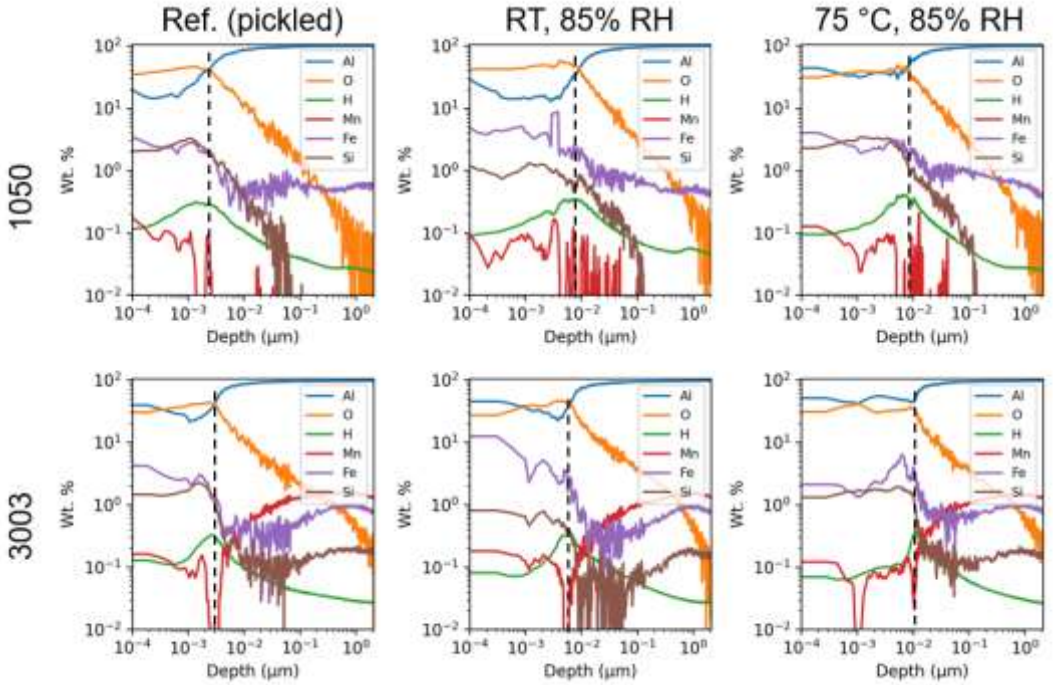


Case 1 – What effect does the passive oxide layer have on weld quality and fatigue properties?

Elevated temperatures and humidities were used to simulate 1 year of storage in 100% RH



All aluminum possesses a passive surface oxide layer that grows thicker in humid environments



RH (%)	Thickness (nm)
52	3
72	5
85	7
100	14

Oxide thickness on Al 3003 after 1 year of storage at room temperature

H. P. Godard, "Oxide Film Growth over Five Years on Some Aluminum Sheet Alloys in Air of Varying Humidity at Room Temperature," *J. Electrochem. Soc.*, vol. 114, no. 4, p. 354, 1967, doi: 10.1149/1.2426593.

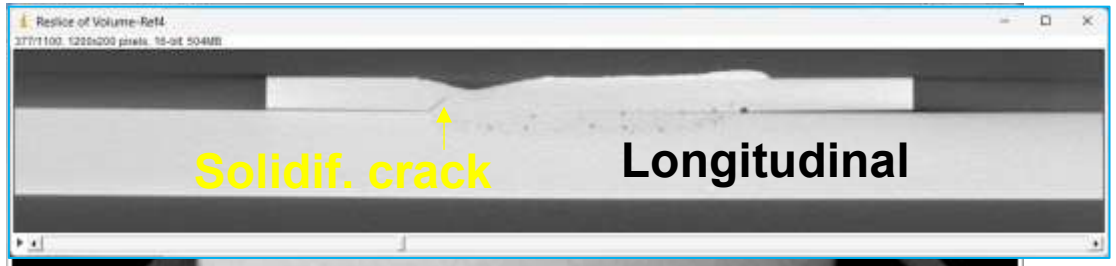
Higher temperatures and higher relative humidities (RH) can be used to accelerate the oxide growth and simulate long-term storage

Approximate oxide layer thickness (nm) as measured by GDOES. Based on the measurements in above figure.

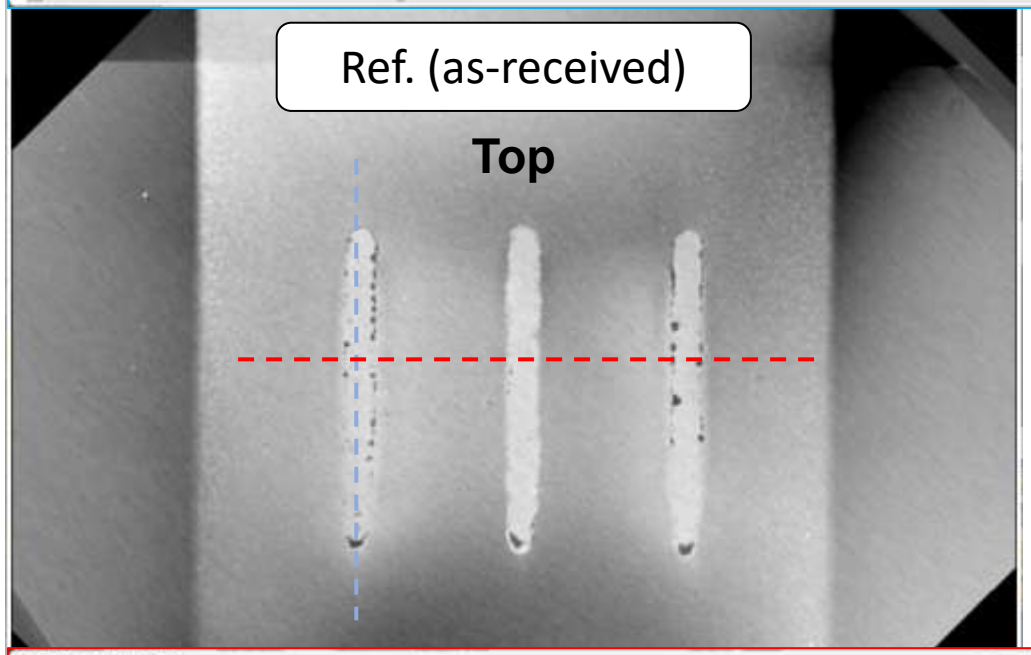
Aluminium alloy	Ref. (pickled) (nm)	RT, 85% RH 500 hours (nm)	75 °C, 85% RH 500 hours (nm)
1050	2	8	9
3003	3	6	10

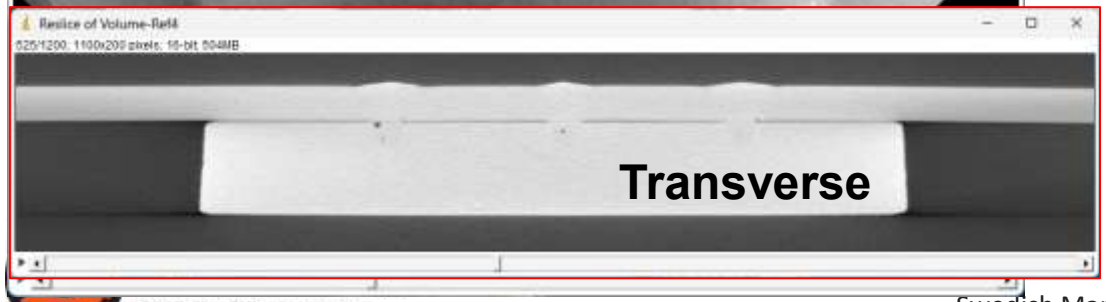
The heavily oxidized sample possessed more/larger pores in the weld toe

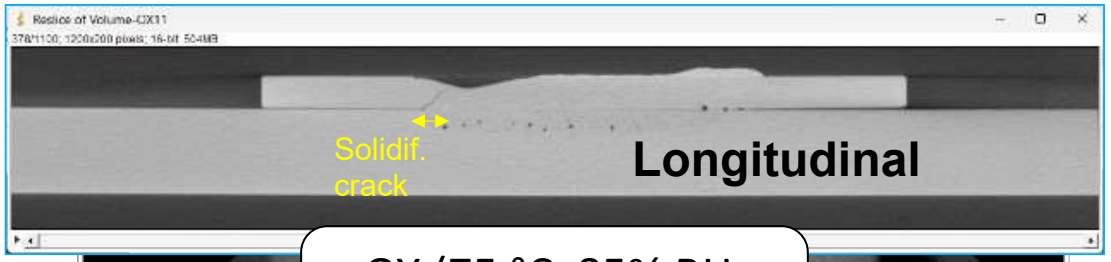
Case 1



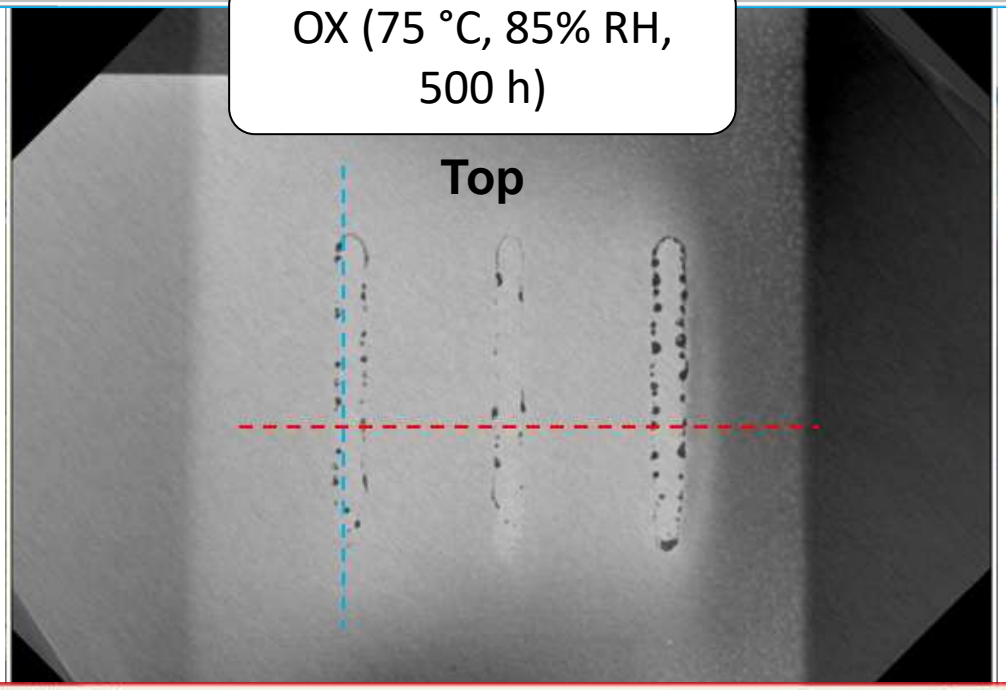
Ref. (as-received)

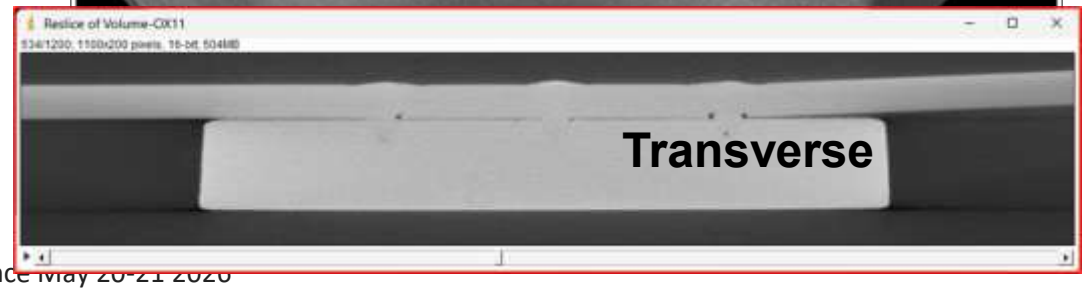






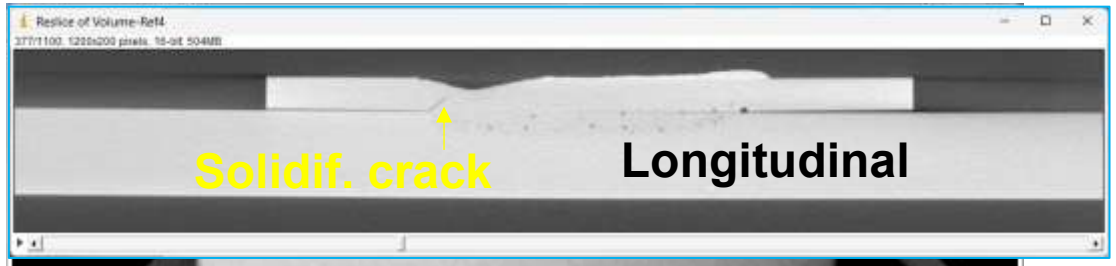
OX (75 °C, 85% RH, 500 h)





Fatigue cracks initiate at existing solidification cracks in the weld end crater

Case 1



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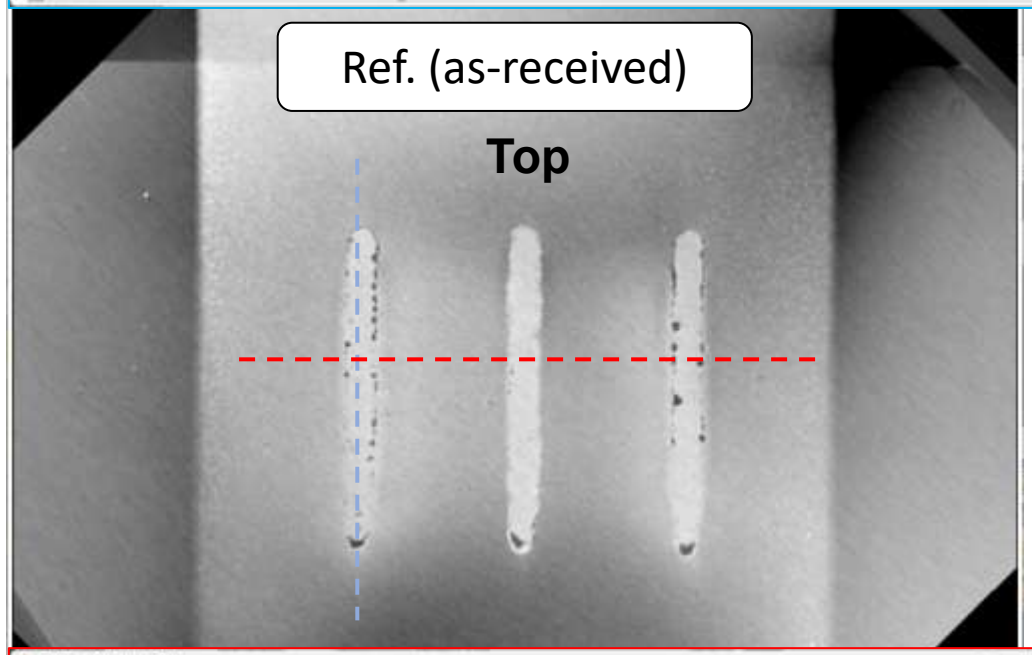
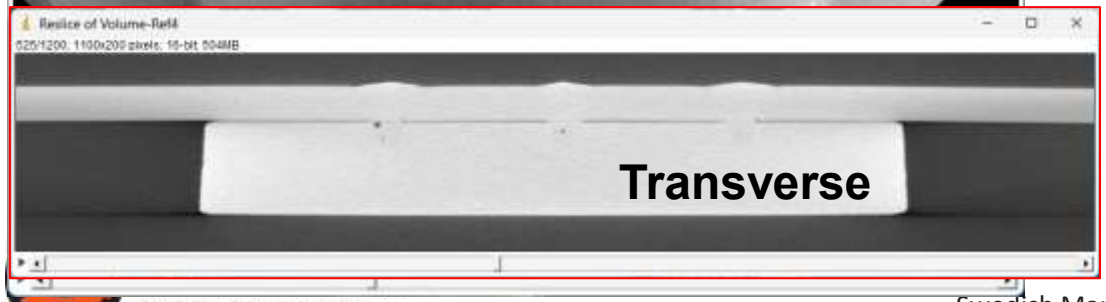
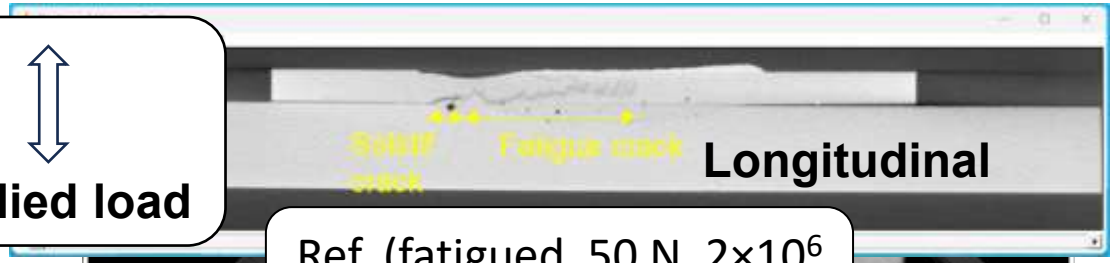
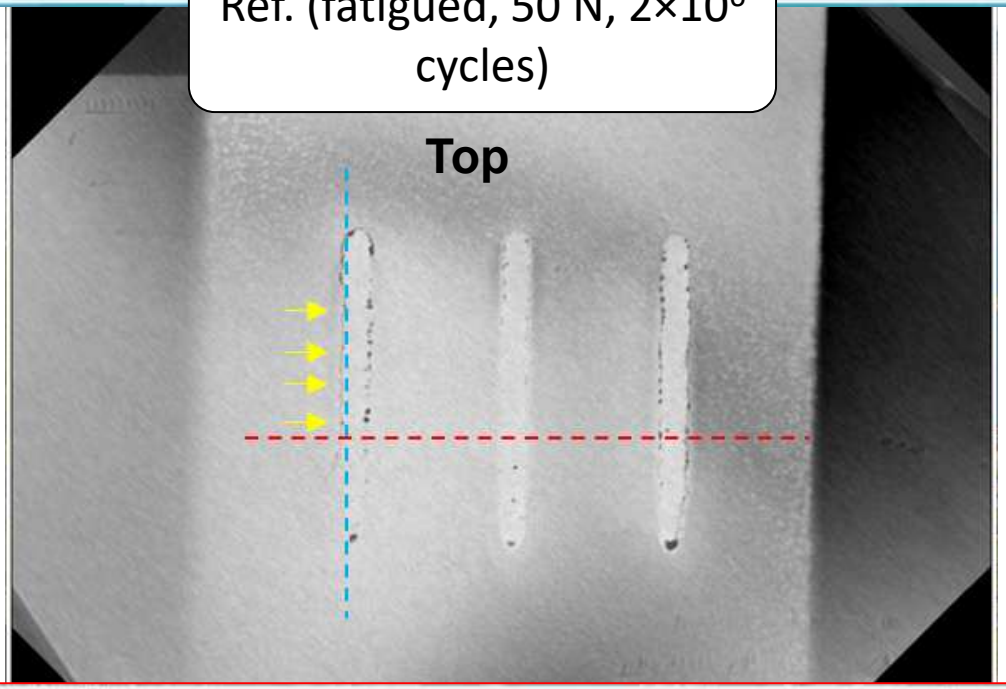


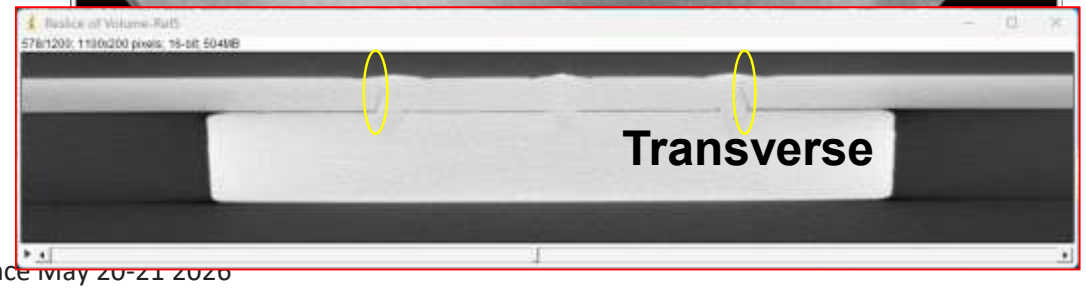


Applied load



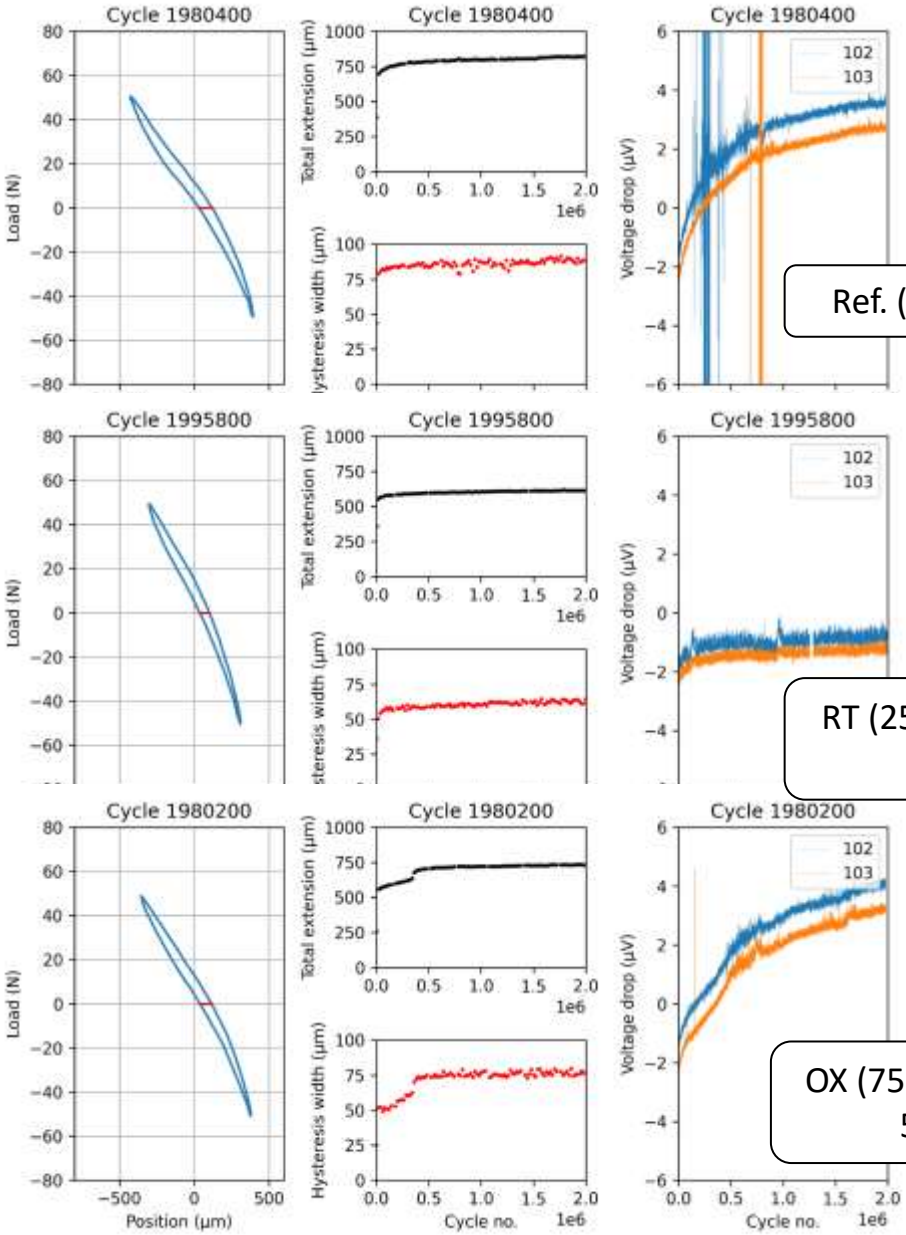
Ref. (fatigued, 50 N, 2×10^6 cycles)





Despite effect on size of pores, no trend of oxidation vs. fatigue performance could be determined

Case 1

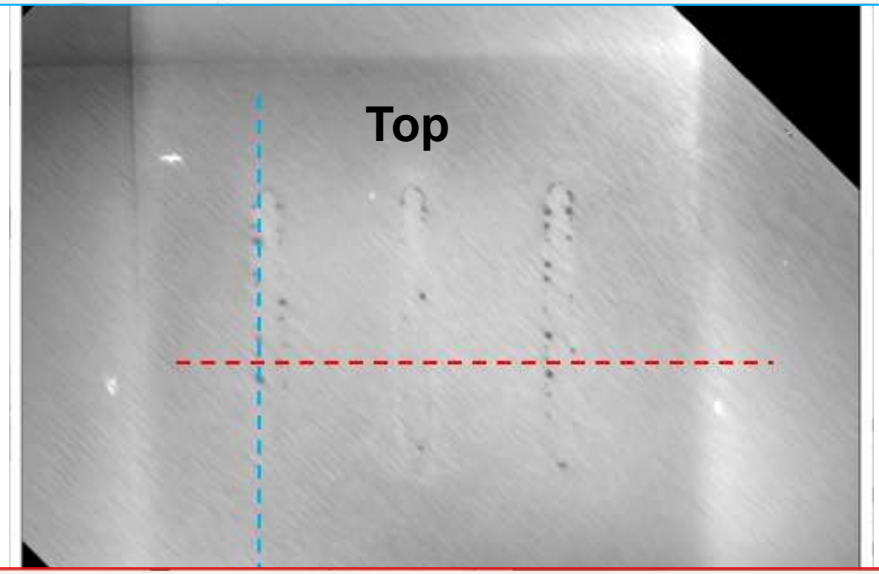


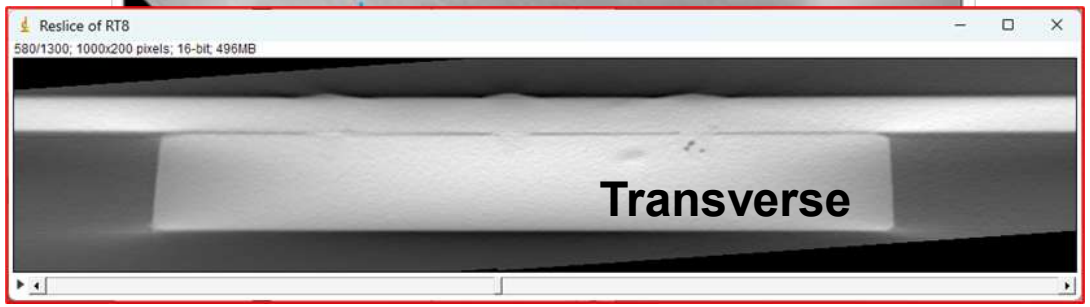
Ref. (as-received)

RT (25 °C, 85% RH, 500 h)

OX (75 °C, 85% RH, 500 h)

RT (fatigued, 50 N, 2×10^6 cycles)





CODELAB – Classification of defects in laser-welded aluminium busbars

Start: 2025-06-01 Time: 18 months Budget: 1,5 MSEK Funding: FFI Circularity

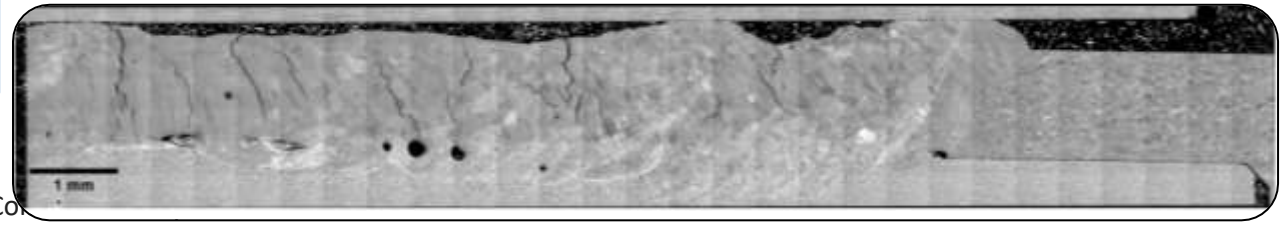
Current-carrying joints in EVs are subject to mechanical loads, vibration, elevated temperatures and temperature cycling

One weld failure can lead to catastrophic consequences. Ensuring a high joint quality is therefore critical

However, current laser welding standards do not account for the unique requirements of electrical joints

Societal and industrial needs

- Identification of gaps in current standards
- Harmonization of regulations and standards
- Cost-efficient QA
- Increased safety and reliability



CODELAB – Classification of defects in laser-welded aluminium busbars

Project scope

- Literature review: current state of the art (QA, defect types)
- Regulatory comparison across industries
- Industrial practice mapping with partners
- **Experimental verification and analysis**
- Framework draft for standardized quality control

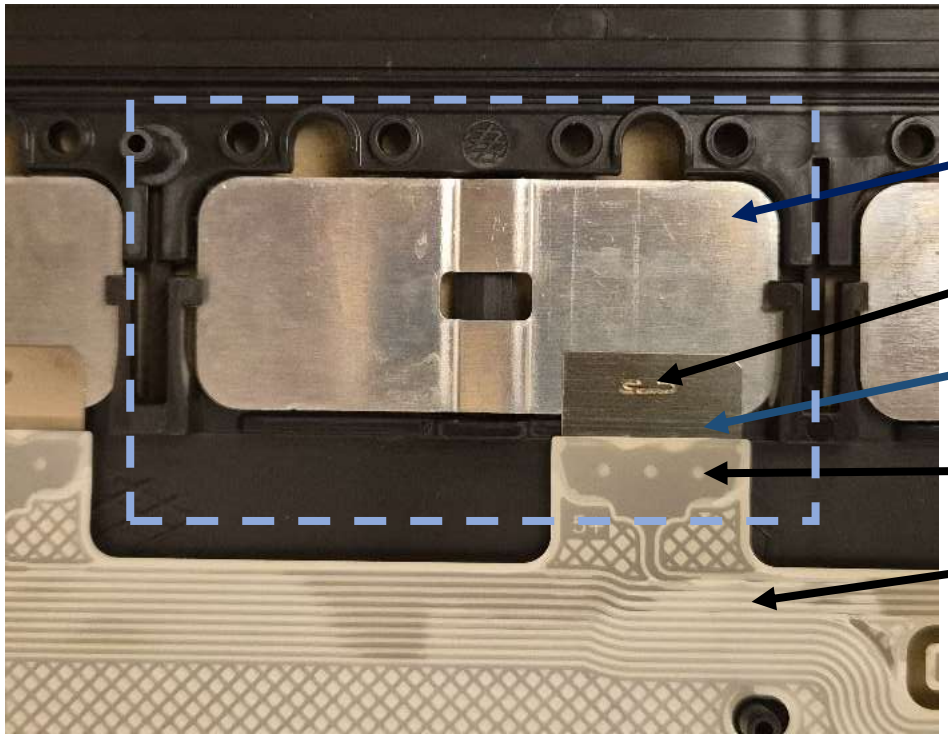
Project goals

- Identify key defects in laser-welded aluminum battery busbars
- Quantify mechanical + electrical/thermal impact of defects
- Propose preliminary acceptance criteria
- Contribute to a roadmap for future standards

CABEL

Conductive adhesive bonding for electrical connections in battery packs

Repair of busbar to tab joints

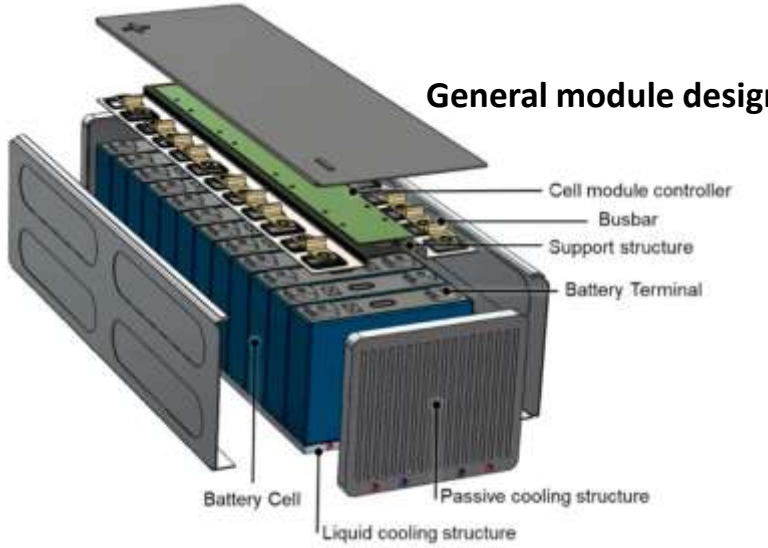


Circularity needs for repair solutions of joints in aftermarket.

Requirements on electrical resistance and mechanical strength.

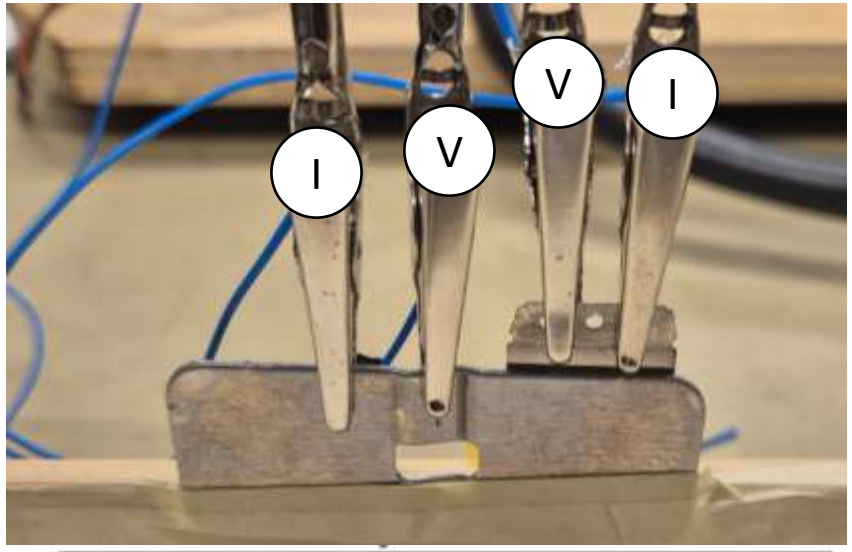
Repair solutions must be accessible and available at workshops.

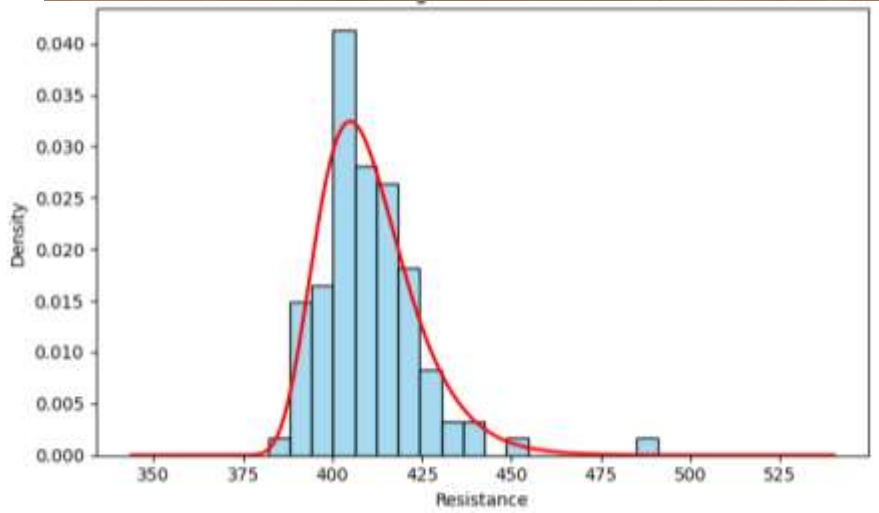
General module design



Benchmarking of electrical resistance of welds

- 4 point measurements of resistance
- 100 repeated measurements
- Variations in results
  - Min: 382 µΩ
  - Max: 491 µΩ
  - Average: 410 µΩ
  - Std. dev.: 14.5 µΩ
- Approximately log-normal distribution
- Resistance measurements should be repeated to get statistical significance.

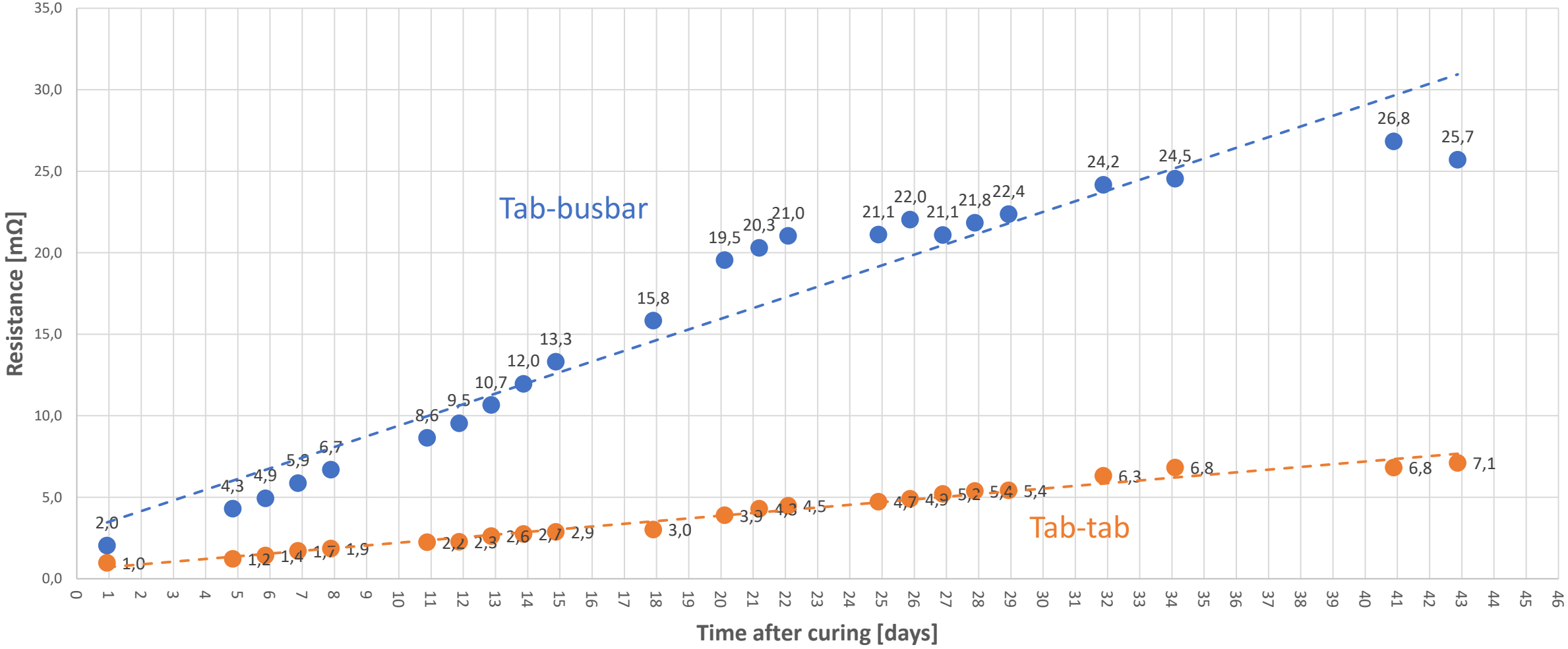




Adhesive bonding of tabs and busbars

- Silved filled (80 w% Ag) epoxy based adhesive.
- Nickel and aluminium surface pre-treatment.
- Curing at elevated temperature.
- High variations of resistance.
- Best samples comparable to resistance of welds shortly after curing (~0.9 mΩ)

Aging of adhesive specimens



Microscopy analysis

Microscopy of cross-sections done directly after curing, after 7 days and after 15 days.

Shows change at interface between adhesive and aluminium substrate.

Potential growth of oxides or hydroxides.

Silver (light)

Epoxy (dark)

Nickel based adhesive

Nickel flakes (~57 w%) and epoxy resin were mixed at RISE lab.

Initial result show promising resistance values of ~1.5 mΩ.

After 7 days the resistance was nearly unchanged.

Further analysis is needed to fully conclude the potential of nickel based adhesives.

Conclusions

- Electrically conductive adhesives (ECAs) are capable of forming joints that are significantly stronger than traditional laser beam welds, exceeding OEM requirements.
- Under optimized, controlled-gap conditions, ECAs can achieve initial electrical resistances approaching those of laser welds (<1.0 mΩ).
- Current commercial silver-filled ECAs are unsuitable for long-term use on aluminium busbars likely due to galvanic corrosion.
- The performance of ECAs is highly sensitive to assembly parameters, making robust serial production highly challenging with current formulations.
- Nickel based adhesives show promising initial results but need further investigation.

Thank you!

Questions?