20.
THE ELECTRICAL BEHAVIOUR OF LASER SOLDERED STEEL SHEETS

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1. Introduction

In recent years, vehicle-related applications have become an increasingly prominent part of our ever-growing range of electronic devices. Today, the spectrum of fully electric and hybrid-powered vehicles spans from electric bicycles and scooters to drones, electric cars, and even aircrafts [1]. The reliable and safe operation of these vehicles' electric motors critically depends on the availability of high-capacity, efficient batteries [2].

To maximize the extractable energy from these battery cells and packs — within the limits of current battery chemistries — special attention must be given to minimizing energy losses within the system. A key contributor to such losses is the electrical resistance of the cell-to-cell interconnections [3]. Managing and minimizing the losses calls for robust, reproducible and well-controlled joining techniques, and reliable quality control. Among the many available joining technologies, laser-based approaches – such as welding, soldering, and brazing – have emerged as highly promising alternatives to conventional joining techniques. Notably, laser-assisted filler-based joining methods (e.g., soldering and brazing) have demonstrated superior electrical performance [4].

Electrical characterization of overlap joints – regardless of the joining method – remains a challenging task due to the lack of standardized measurement protocols. The four-point probe method is commonly used because it minimizes errors caused by contact and lead resistances, providing accurate and reproducible resistance values. However, it cannot isolate the resistance of the joint itself from that of the base materials, even when the probes are placed close to the joints. Previous studies have used varying probe distances (e.g., 21 mm, 16.5 mm, 11 mm) to compare samples, but the results always reflect the combined resistance of the joint and base sheets [4-6]. Our approach presented here focuses on evaluating the resistance of such joints by varying the spacing between voltage probes and deriving key characteristics from the resistance *vs.* spacing functions. This work presents both experimental measurements on laser-soldered DC01 sheets and numerical simulations using COMSOL Multiphysics® to gain deeper insight into their electrical performance [7].

2. Materials and methods

Joints were formed between two 0.5 mm thick and 30 mm long DC01 steel sheets. An overlap joint geometry was selected, as it as a common geometry of several battery pack connections, such as cap-to-cap, busbar-to-busbar, and cap-to-busbar joints. A detailed description of the optical setup and the sample holder can be found in [7].

To minimize parasitic effects, a four-point probe method was used: current was applied across the sheet ends (100 mm apart) using a TTi CPX200 power supply, and voltage drop was measured with a Keithley 2401 multimeter across probes centered on the joint (see Fig. 1). While this setup allows reliable comparison across samples, it still suffers from yielding cumulative resistance. In order to gain deeper insight into how the joint resistance can be approximated, the measurement distance, d was varied between 1 mm and 81 mm. To improve accuracy, the so-called *slope method* was employed [7]: voltage was recorded at multiple current levels, and resistance was extracted from the slope of the resulting $U(I)$ curve at every probe spacing applied. This approach is self-validating, as a linear $U(I)$ relationship confirms negligible heating and stable resistance. A maximum current of 10 A was used to ensure thermal stability during the short (1–2) s measurement interval.

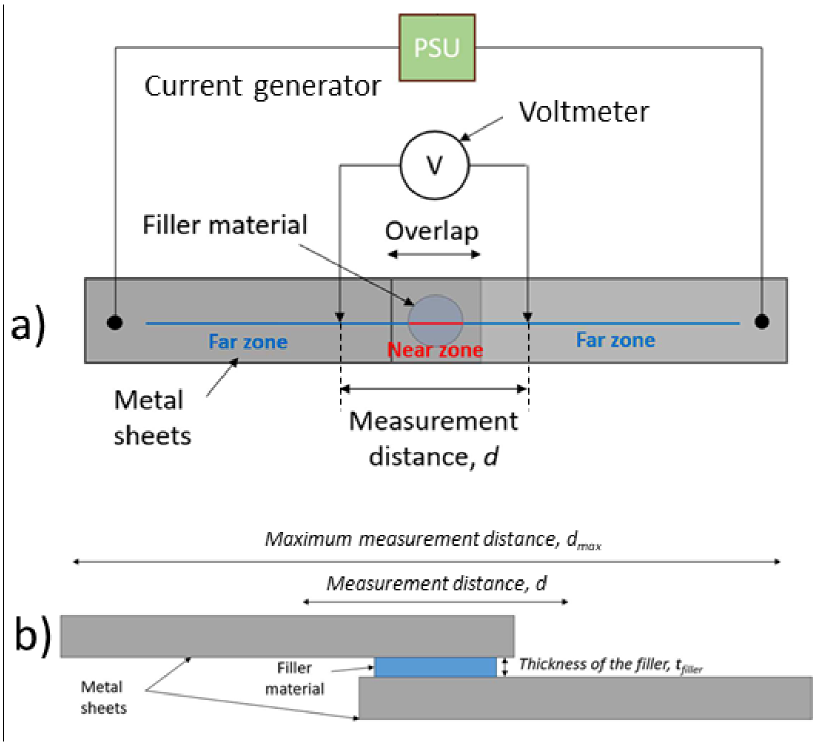

Figure 1. Top (a)) and side (b)) views of a schematic overlap joint.

Experimental work was supported by numerical simulations, performed in COMSOL Multiphysics® 5.5, aiming to investigate the current density and potential distributions near the joint. The model integrated an actual CAD geometry, AC/DC physics, and material data from COMSOL®'s library, complemented by experimentally determined values where applicable. Surface contact was modeled using the Cooper-Mikic-Yovanovich (CMY) correlation, which accounts for roughness, microhardness, and contact pressure [8]. The average surface roughness (ISO 4287:199 standard) was set to the measured value at $(2.20 \pm 0.13)\,\mu\text{m}$ while the Vickers microhardness was fixed to (244.16 ± 2.47) HV0.1. The finite element method was performed on an "extremely fine" mesh.

3. Results

By performing contact resistance measurements at multiple voltage probe spacings, we systematically investigated the dependence of the measured resistance on the geometric configuration of the four-point probe setup, on the specific resistivities of the sheet materials and solder, as well as on the geometrical characteristics of the re-solidified solder. All soldered samples in the series exhibited a consistent trend: the measured resistance was always lower than that of the base sheet material. Our results indicated that the *R(d)* function – expressing resistance as a function of the inner probe spacing – exhibits two distinct regimes: a *near zone*, when the volgate probes are located within the cross-section of the resolidified soldered, and a *far zone*, when the probes lie outside of it. Within each zone, the resistance varied linearly with distance. Notably, this linear behavior remained largely unaffected by the amount of filler material applied. The transition point between the two linear regions of the *R(d)* curve was found to correlate well with the outer perimeter of the effective soldered area. *Figure 2* also demonstrates that the accuracy of the numerical simulations improves significantly when increasing the geometric fidelity of the representation of the cross section of the re-solidified solder (as the blue arrows indicate in the figure).

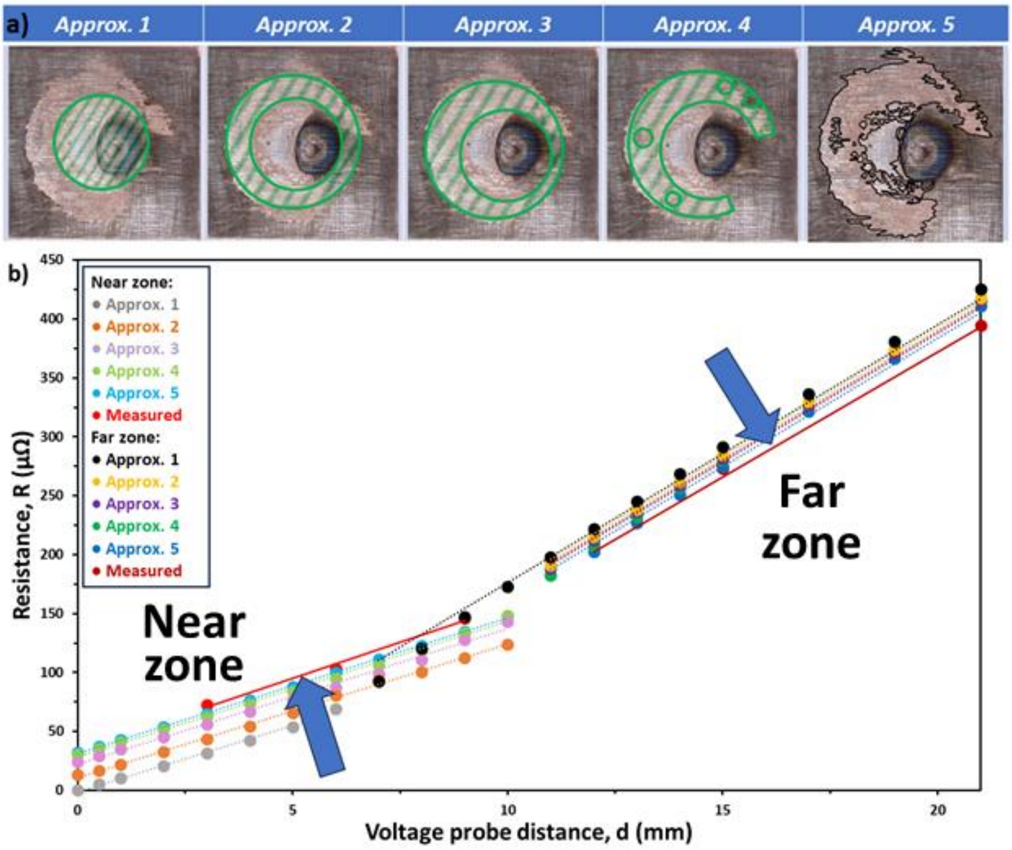

Figure 2. a) Five different approximations of the real geometry of the resolidified filler material, and b) result of these approximations compared to a measured dataset (solid lines)

The approach introduced by combining experimental measurements with finite element modeling in COMSOL® revealed how the morphology of the joint formed by the resolidified filler material influenced the electrical characteristics of the joint itself. The simulations confirmed the importance of five parameters in determining the electrical resistance of the joints, namely the effective- and the total area, the cross section and the position of the voids within the total joint area, and the thickness of the filler material. In order to deduce the effect of these parameters on the characteristics of the *R(d)* plots, these five relevant simulated parameters were changed from *-50%* relative to the measured value of each to find the effect on the electrical resistance of the joint.

The distance dependence of the resistance, *R(d)* is a linear function in both the near and far zones and it will be described in the form indicated in *Table 1*. Analytical relationships describing the slopes and intercepts of the *R(d)* lines in both regions were established, as functions of material properties of the base and filler metals along with the five geometric parameters. These findings are summarized in the *Table 1*. The slopes derived in the far zone were determined by the electrical properties and the geometry of the sheets to be joined. In the near zone, the slopes decreased with an increase in the volume of filler material. The equations, that describe the slopes in the far and near zones indicates that they are material specific, the former referring to the material to be joined, while the latter including quantities, referring to both the sheet and the filler material, while yielding no information about the electrical characteristics of the connection.

The intercepts of the straight lines in the far zone expressed in ohms indicate the difference in the resistance of the respective soldered joints as compared to that of the bare metal to be joined. The behaviour of the intercepts in the near zone also reflects the changes in the electrical characteristics of the joints due to the inhomogeneities in the number and distribution of the voids. Both intercepts are largely affected by the morphology of the joint: in the far zone, the effective soldered area has a greater impact, while in the near zone, the presence of voids plays a more significant role.

$R(d) = m_{n/f} \cdot d + t_{n/f}$	Slope (m)	Intercept (t)
Near zone	$m_n \approx \left(\frac{A_{sheet}}{c_1 \cdot \rho_{sheet}} + \frac{A_{eff}}{c_2 \cdot \rho_{filler}}\right)^{-1}$ $c_1 = d - t_{filler}$ $\quad c_2 = t_{filler}$	$t_n \approx A_{void}$
Far zone	$m_f = \rho_{sheet}/A_{sheet}$	$t_f \approx A_{eff}^{-0.65}$

ρ: the resistivity of the sheet or the filler

t_{filler}: the thickness of the resolidified filler

A_{void}: the total area of voids

A_{eff}: the effective soldered area

A_{sheet}: the cross-section of the sheets

d: the voltage probe distance

Table 1. Parameters of the R(d) linear relationships in the near and far zones

4. Conclusions

This study investigated the electrical resistance of laser-soldered joints, with a particular focus on the challenges of electrical characterization and the reduction of resistive losses within the joints. To evaluate the influence of the joint on the total sample resistance, measurements were performed by varying the distance between the two inner – voltage-sensing – probes. Based on probe placement, two distinct regimes were identified: a near and a far zone. In both regions, a linear relationship was observed between resistance and probe spacing.

Numerical simulations using COMSOL Multiphysics® complemented the experimental work and enhanced our understanding of how the electrical behavior of laser-soldered joints is influenced by the material properties of the components and the exact geometry of the re-solidified solder. Although the data were obtained from lap-jointed metal sheets, the extracted trends are more general in nature. Specifically, the slopes and intercepts of the linear *R(d)* curves in both the near and far zones were described using five geometric parameters of the solder. These findings hold particular relevance for electric vehicle (EV) applications, where minimizing resistive losses in battery interconnects is critical for improving overall system efficiency.

References

[1] Leijon, J. and Boström, C., World Electr. Veh. J. **13**, 139 (2022)
[2] Liu, W., *et al.*, Energy Reports **8**, 4058-4084 (2022)
[3] Zwicker, M. F. R., *et al.*, Journal of Advanced Joining Processes **1**, 100017. (2020)
[4] Brand, M. J., *et al.*, Journal of Energy Storage **12**, 45–54, (2017)
[5] Schmalen, P. and Plapper, P., Journal of Laser Micro/Nanoengineering **12**, 3 (2017)
[6] Hollatz, S., *et al.*, Batteries **6**, 24 (2020)
[7] Körmöczi, A., *et al.*, Materials **17**, 2736 (2024)
[8] Yovanovich, M.M. and Marotta, E.E., Heat Transfer Handbook, John Wiley & Sons Inc. (2003)

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