Laser soldering of thin metal sheets in overlap joint geometry

Summary of the PhD thesis

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1. Introduction

Due to the growing environmental awareness, environmentally friendly solutions are receiving increasing attention across various fields of science, including electric vehicle development [1]. The rise of electromobility is critical in the future of transportation as a tool in the fight against climate change. Consequently, new hybrid and fully electric propulsion systems emerge as alternatives to traditional internal combustion engines [2]. The energy source of these vehicles is the battery pack, in the modules of which multiple cells are assembled together using preferentially permanent bonding. In pursuit of enhancing the electrical performance of battery packs, soldering, particularly laser soldering, emerges as an attractive option due to its ability to produce electrical connections superior to those obtained using concurrent technologies [3]. Additionally, easy automation, customization and integration into workflows make laser soldering a manufacturing technology worth of consideration [4].

Laser soldering is a process with numerous degrees of freedom and parameters. Accordingly, its optimization is a complex task. However, when properly optimized, laser soldering can boost the electrical performance of the modules, leading to significant improvement in the overall characteristics of the battery pack [5].

While posing significant challenges, optimization of laser soldering offers an appreciable potential in battery technology applications. Since critical electrical and mechanical aspects of the soldering process are relatively unexplored, including lack of standardized measurement methods of the electrical characteristics of the laser soldered couples, comprehensive evaluation of the possibilities and limits of laser soldering in production of bonds with electrical characteristics superior to those produced using concurrent technologies together with proper mechanical properties offers an inspiring research field. The results may lead to the simultaneous optimization of the bonds in terms of both electrical and mechanical performance, which is particularly important in battery technology [6, 7, 8].

2. Objectives

In light of the aforementioned demand and motivation, the main objective of my work was to simultaneously optimize the electrical and mechanical properties of the laser soldered joints created in overlapped bonding geometry, using autogenous laser welding (where both strip materials were identical). To achieve this goal, I had to elucidate the effects of the pre-treatment of the metal sheets to be joined and the amount and the position relative to the laser beam of the solder material on the properties of the joints, as well as how the resistance and the tensile-shear strength of the laser soldered sheet pairs depended on the process parameters, namely laser power and irradiation time. Visualization and description of the morphologies of the molten solder material as appearing on the surface of the torn metal sheets after processing formed another task. Finally, the analysis of the results should lead to the identification of the relationship between the electrical and mechanical characteristics of the joints formed and the observed morphological classes in the solder material, and the process parameters used.

Since the electrical resistance of the joints is of paramount importance in the battery technology, the measurement of the electrical properties of the joints produced by laser soldering needed special attention. The lack of accepted standards posed an extra motivation. The effect of the geometric characteristics of the formed joints on the resistance of the soldered sandwich was revealed through modelling. For this purpose, it was necessary to construct a realistic model that, after selecting the appropriate boundary conditions, helped in unravelling the underlying physics.

3. Materials and methods

The laser soldering experiments were performed using a self-built laser welding system with a SPI SP-400C-0005 fiber laser, delivering 400 W maximum power at 1071 nm wavelength, with an unpolarized beam of M2=1.08 quality, as the energy source. The measurements were conducted on nickel-coated stainless steel stripes, Hilumin®, the material of the casing and tabs of battery cells. To generalize the results, all experiments were repeated using DC01 steel stripes. Laser soldering was performed in autogenous mode, i.e., the sheet materials to be soldered were identical, in overlapped bonding geometry. A standard tin-based solder (Sn99.3Cu0.7) was used as the solder material, placed in form of thin sheets between the two metal sheets to be bonded. The sandwiches were fixed in a specially designed sample holder during processing.

The focus of my research work was on the measurement of the electrical and mechanical characteristics of the laser soldered sandwiches. The electrical resistance of the joints was determined using a four-point probe, powered by a TTiCPX200 power supply and a Keithley 2401 voltage meter. Mechanical testing was conducted using a Tinius Olsen H5KT tensile testing machine. The morphology of the resolidified solder remained on the surfaces of the torn metal sheets was mapped using an Olympus DSX510 digital 3D microscope. The 2D and 3D images recorded were manually analysed using ImageJ software. Vickers microhardness measurements were performed using a Reichert microhardness tester. To simulate the effects of different solder geometries on the electrical properties of the joints and understand thereby the results of the electrical resistance measurements better, a physical model was created using Comsol software.

4. New scientific results

Modelling the joining process of Li-ion cells that make up the battery pack, laser soldering experiments were performed on Hilumin®, a commonly used material for producing the tabs and casing for most cells, and DC01sheet pairs in a lap joint geometry. By systematically mapping the effect of pre-treatment (sheet cleaning method, surface roughness, amount of solder) and the laser power and irradiation time, the dependence of the electrical resistance, tensile shear strength and morphology of the soldered sandwiches on the process parameters was elucidated.

T1.1 Following the fracture of laser soldered sheet pairs, through optical microscopy of the torn surfaces I showed that 1) the fracture occurred in the solder layer in all cases, and 2) based on the appearance of the fractured surfaces I identified three morphological types of joints.

I realized that the most homogeneous morphology, that concomitantly exhibited the least number of gas bubbles trapped in the resolidified solder material, could be achieved by perfect melting of the entire volume of the solder. Bonds characterized by this morphology – coined as type II – were produced by irradiating 1.6 mm3 of solder at 80 W for 5 s for Hilumin® sheet pairs, and 4.8 mm3 of solder with 120 W laser power for 5 s for DC01 sheet pairs [A1, A2].

<u>T1.2</u>. Regarding the effects of varying experimental conditions on the electrical and mechanical properties of the joints formed by laser soldering in lap joined geometry:

- I have shown that with appropriate pre-cleaning of the metal sheets to be soldered, an improvement of up to 5% can be achieved in both the electrical and mechanical properties, for both the Hilumin® and DC01 sheet pairs, with no significant difference between the acetone, ethanol or propanol cleaning investigated.

- I have demonstrated that the surface roughness had a significant effect on the electrical and mechanical properties of the laser soldered sheet pairs. A reduction in the average surface roughness, Ra, from 2.63 to 2.04 micrometers resulted in 11.9 and 14.4 % decrease in the resistivity, and 1.7 and 2.5-fold increase in the tensile shear strength of the laser soldered Hilumin® and DC01 sheet pairs, respectively.

- By varying the volume of solder from 0.40 mm3 to 3.20 mm3 at a constant laser power of 80 W and irradiation time of 5 s I have demonstrated that there is an optimal solder volume. For the tested power-time pair, the solder volume of 1.6 mm3 yielded the best joints both in terms of electrical and mechanical performance.

Based on these results, I used acetone cleaning in all my experiments. Since I have shown that below an average surface roughness of Ra=2.15 µm, achieved by using p1200 polishing paper, further decrease in roughness no longer yields significant improvements, I used p1200 polishing paper during the pretreatment procedure for all experiments [A1, A2].

T1.3. In the laser power – irradiation time process parameter window mapped, I distinguished 6 zones: in which as a result of soldering with the particular laser power – irradiation time pair 1) no joint is formed between the pair of sheets, 2) a joint is formed, 3) the joint has optimal properties, 4) the upper surface of the upper plate melts while a good joint is still formed, 5) the laser beam melts the upper plate and drills a hole in it, while 6) in the middle zone of the joint, the hole formation reaches the lower plate. I have verified that these six zones appear in the same power sequence for all irradiation times.

I have shown that among the three morphological types identified by the appearance of the fractured joint surfaces, the one with the most homogeneous molten material, containing the fewest trapped gas bubbles, due to perfect melting of the solder, shows the best electrical and mechanical characteristics [A1, A2].

T1.4. By varying the laser power at fixed irradiation times and the irradiation time at constant laser powers, I have measured the dependence of the electrical resistance and tensile shear strength of the laser soldered Hilumin® and DC01 sheet pairs on these two process parameters. I have experimentally demonstrated that an increase in both the laser power and irradiation time improves the electrical and mechanical properties of the joints and reduces the scatter in the data, as long as the given power–irradiation time pair does not result in melting of the top sheet. I have found that for laser soldering at energies higher than this melting threshold, both investigated properties of the joint deteriorate abruptly with an increase in the scatter in both the electrical resistance and the tensile-shear strength values [A1, A2].

Since due to geometric constraints the electrical resistance of a joint cannot be measured by itself, the electrical characterization of the laser soldered sheet pairs is a complex task. There is no accepted standard for the measurement method. My results, along with the introduction of an improved electrical resistance measurement method that eliminates the problems caused by the application of high currents, provided correlations between the electrical resistance of the sandwich and the volume, geometry and morphology of the solder that forms the joint, contributing to a better understanding of the complex processes involved.

T2.1. I have made the four-point resistance measurement method used for the characterization of the soldered sheet pairs self-controlled. Instead of calculating the electrical resistance from the single voltage drop at a constant, and necessarily high current value, a technique used exclusively up to now, I measured the voltage drop at several current values and derived the resistance value as the slope of the straight line that resulted from plotting the voltage drop as a function of current. By increasing the current during the measurement up to a value when the measured points still fitted the straight line perfectly, I managed to eliminate the error caused by the heating effect of high currents [A3].

T2.2. Based on the behaviour of the measured resistance – measurement distance functions, I distinguished between near and far zones. I have shown that the boundary of these is marked by the edge of the soldered area. The resistance – distance functions in both zones are described by straight lines. The slopes of the straight lines in the near zone and the intercepts in both zones vary sensitively with the amount of solder, however this has no effect on the slopes in the far zone for either the Hilumin® or DC01 sheet pairs. This indicates that, while the first three quantities are related to the joint, the slope in the far zone is a measure of the material quality of the sheets to be soldered. The variation of the three quantities related to the joint as a function of the volume of solder is fully consistent with the morphological picture described in thesis statement T1.1. [A3].

T2.3. Numerical modelling in COMSOL Multiphysics environment proved to be useful for exploring the effects of experimental parameters that are difficult or impossible to change experimentally. Numerical simulations with approximate models have shown that the following five geometrical properties of the solder material influence its electrical behaviour: the thickness of the resolidified solder material between the two sheets, the effective joint area, the total area of the holes, the total joint area, actually the sum of the effective joint area and the total area of the holes, and finally the distribution of the holes within the entire soldered area.

In order to gain insight on how the geometry of the resolidified solder material affects the electrical behaviour, it was fundamental to realize that in the continuous joint areas about 97% of the current flows through the outer 10% rim, while each hole acts as a source of "return currents".

Based on my simulation results for the near and far zone slopes and intercepts, I have found that the slope of the function R(d) in the far zone is material specific indeed (cf. 2.2), being defined by the ratio of the electrical conductivity of the sheet material to the cross section of the sheet perpendicularly to the direction of current flow. In the near zone, the slopes correlate with the amount of solder material, decreasing with increasing solder volume. I have formulated the correlation between the slope and the specific resistance and cross section of the sheets and the solder material which remains valid in both the near and far zones.

My calculations revealed that the intercepts in the far zone showed a reciprocal dependence on the effective joint area with an exponent of 0.65. Their variation indicates how the contribution of the resistance of the solder material to the resistance of the soldered sheet pair varies. On the other hand, the behaviour of the intercepts in the near zone is dominated by the holes remaining in the solder: the intercepts vary in proportion to the total area of the holes. In In short, the intercepts in both zones carry information about how and to what extent the geometry of the solder joint affects its resistance. [A3]

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6. Publications

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[A2] **Andor Körmöczi**, Gábor Horváth, Tamás Szörényi, Zsolt Geretovszky, „Laser soldering of nickel plated steel sheets”, Journal of Laser Applications, 36 (1), 012030 (2024), IF(2022): 2,1

[A3] **Andor Körmöczi**, Gábor Horváth, Tamás Szörényi, Zsolt Geretovszky, „Combined experimental and numerical modelling of the electrical behaviour of laser soldered steel sheets”, [under review],