Laser welding of thin metal sheets in lap joint geometry

Summary of the PhD thesis

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1. Introduction

In the assembly of battery packs for modern vehicles with hybrid or pure electric drive systems, permanent bonding technologies are gaining exceptional attention for various economic and practical reasons. Among these, the various welding processes, including laser welding, are also attracting particular attention. First of all, because of their wide range of customisation, automation and integration into production technologies [1-3].

However, laser welding technology is a relatively complex process with an exceptionally large number of degrees of freedom and parameters, and optimising and perfecting it for a given problem is a highly problematic and complex task. A properly optimised laser welding process can, however, achieve significant improvements at the lowest levels of battery cell assembly, which, due to the large cell number, can result in very significant overall improvements [18,26,27].

The optimisation of laser welding for battery technology applications is complicated by the fact that the concomitant electrical and mechanical behaviours of the welding processes is a rather new and rarely investigated field of research and development. Accordingly, there is currently no standardised measurement procedure or characterisation method for the simultaneous electrical and mechanical characterisation of laser welds [55,63,64].

Consequently, for most welding processes, the simultaneous optimisation of joints from both electrical and mechanical aspects is a problem, which is a critical aspect for battery technology applications.

As a result, the subject of my thesis is a comprehensive study of deep penetration laser welds produced on steel plates from an electrical and mechanical point of view.

The quality and properties of welds are influenced by a number of processes occurring simultaneously in the melt pool and in all the heat affected zones during their formation. In practice, almost all of these processes can be monitored individually and used to predict the quality of the weld after the laser welding process or, in some cases, during the laser welding process. The combined effect of these processes not only remains solidified inside the weld, but also on the surface of the weld, resulting in visually different weld morphology depending on the process parameters.

The realisation that this inherent property (bead morphology) of laser welds can be consciously applied to optimise welds from a mechanical as well as an electrical point of view is the result of my own research.

In addition, I have extensively investigated the possibilities of optimizing welds through geometric parameters such as weld contour, segment number, segment length, segment spacing and vertical extent.

2. Objectives

The first results of my experiments have shown that there are many possibilities to optimize laser deep penetration welding for battery technology applications. These opportunities arise mainly from the flexibility and versatility of the technique and the extreme complexity of the process in physical terms.

In designing my experiments, my primary objective was to jointly optimise the electrical and mechanical properties of welds created in a homogeneous manner (i.e. both strips of the same material) on metallic strips with overlapping joint geometry.

It is well known that there are basically two ways of optimising the properties of welds created by laser welding. The most commonly used and simpler method is optimisation by directly varying the laser and other additional parameters. The other method is to optimise the joint contour and configuration with fixed laser parameters, where the possibilities are limited in two dimensions only by the imagination.

Based on previous observations, different weld morphologies can be observed on the surface of laser welded samples after machining due to variations in laser parameters, mainly due to melt flow. One of the aims of my research was to investigate the relationship between laser parameters and the morphological classes that develop in plate materials and to investigate in detail the characteristic electrical and mechanical properties of each class.

Finally, the aim of my research was to optimize the electrical and mechanical properties of laser welds independently of the laser parameters. In other words, to observe regularity and tendency behaviour during the systematic variation of the contour of the welds.

3. Materials and methods

In my experiments, I used a self-built 400W maximum power fiber laser welding system (SPI SP-400C-0005: 1071 nm wavelength, 400 W maximum power, unpolarised, M2 = 1.08) and a professional 1000W maximum power welding station (Trumpf Trufiber 1000: 1075 nm wavelength, 1000 W maximum power, unpolarised beam M2 = 1.2). I have created seam laser welds on 0.5 mm thick cold-rolled DC01 steel strips and 0.25 mm thick nickel-coated stainless-steel strips in overlapped joint geometry.

For the electrical testing of the laser welded specimens, a four-point resistance method (Keithley 2401, with a measurement accuracy of 0.1% over the voltage range used for our experiments) with an external power supply (TTi CPX200, with an accuracy of 1.1% for the maximum current of 10 A used in the measurement process) was used. For the mechanical tests, I used a mechanical tensile tester (Tinius Olsen H5KT) and a digital 3D microscope (Olympus DSX510). The digital 2D and 3D images were evaluated manually in ImageJ software. I supplemented my investigations with Vickers microhardness measurements (Reichert microhardness microscope) and preparing grindings. I also created a physical model using Comsol software to gain a deeper understanding of the electrical flow processes.

4. New scientific results

1. As an approximation not previously used in the literature, the concomitant electrical and mechanical behaviour of the welds produced by autogenous welding of 0.5mm thick cold-rolled DC01 steel plates in a lap joint geometry was investigated by me. When investigating solely the electrical resistance, I found that the scanning speed ranges of 20-75, 50-150, 50-200, 50-220 and 50-240 mm/s are the most suitable parameter windows for producing samples with extremely low electrical resistance and excellent reproducibility (1.09±0.05 *k* factor) at incident laser powers of 300, 400, 600, 800 and 1000 W, respectively. Specimens prepared in the scanning speed ranges 50-75, 50-175, 50-200, 50-200 and 50-600 mm/s are considered to be intermediate and exhibit a nearly constant (255±6 MPa) tensile shear strength. When taking both properties into consideration, my results demonstrate that the scanning speed ranges of 50-75, 50-150, 50-200, 50-200 and 50-240 mm/s are optimal for the DC01 model system under investigation. [T1, T2]

2. I have shown that autogenous laser welding of 0.5 mm thick cold-rolled DC01 steel plates in a lap joint geometry in the 200-1000W power and 0.1-1100mm/s scanning speed window can result in five distinct seam morphology types (Rosenthal, single-wave, elongated keyhole, pre-humping and humping) that appear in the same scan speed sequence as previously described by Fabbro for laser processing of bulk materials only. I have specified where each morphology type appears in the power - scan speed plane, and have assigned a distinct electrical and mechanical behaviour to each of the five morphology types. [T2]

3. The results of my repeated experiments on 0.25 mm thick Hilumin® plates gave the same morphology map as measured on the DC01 model system, beyond the differences induced by the difference in material properties, demonstrating that my results are generalizable. [T2]

4. I have experimentally demonstrated that when autogenous laser welding of 0.5mm thick DC01 steel plates in lap geometry (400 W incident laser power, 50mm/s scanning speed 1075 nm wavelength, 0.35 mm spot diameter) is conducted, among the basic weld shapes I have investigated with a fixed joint cross-section (parallel line, perpendicular line, X, +, /, double perpendicular and double parallel lines), the ones with the lowest electrical resistivity (factor 1.031±0.010 k) and the highest tensile shear strength (540.3±19.1 MPa) are those consisting of at least two independent (non-overlapping) segments. [T3]

5. When producing laser welds consisting of multiple prallel segments in autogenous configuration (400 W incident laser power, 50 mm/s scan speed, 1075 nm wavelength, 0.35 mm spot diameter) on 0.5 mm thick DC01 steel plates, by systematically varying the segment length of each weld between 2.6-8 mm and their spacing between 1-8 mm, while keeping the total length constant at 16 mm, I determined the *k* factors and tensile shear strength of the patterns thus defined. I found that for shapes consisting of multiple parallel straight segments, the distance between the outermost segments (the vertical extent of the seam geometry) correlated with the electrical and mechanical behaviour of the welds. [T3]

6. When producing autogenous laser welds on 0.5mm thick DC01 steel plates in lap geometry (400 W incident laser power, 50mm/s scanning speed, 1075 nm wavelength, 0.35 mm spot diameter), I determined that the welds consisting of multiple, identical 8 mm long parallel segments can only achieve a significant improvement (more than 10%) in the *k* factor, indicating electrical conductivity, compared to the standard single weld, if the number of welds is increased from one to at least ten. However, increasing the number of segments does not yield a significant improvement in the tensile shear strength of the joint. [T3]

5. References

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