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Laser beam welding of copper foil stacks using a green high power disk laser

Sophie Grabmann[a,*], Lazar Tomcic[a], Michael F. Zaeh[a]

[a] *Institute for Machine Tools and Industrial Management (iwb), Boltzmannstraße 15, 85748 Garching, Germany*

* Corresponding author. Tel.: +49 (0) 89 289 15493; fax: +49 (0) 89 289 15555. *E-mail address:* sophie.grabmann@iwb.tum.de

Abstract

A major challenge in the manufacturing of lithium-ion batteries is the qualification of a production system that is able to provide the high quality requirements of the cells. For internal contacting, the demands on the joining process are very high due to the low foil thicknesses and the temperature sensitivity of the battery components. Currently used joining methods, like ultrasonic welding, have limitations, such as the risk of mechanical damages. Laser beam welding is a promising approach based on the contactless process principle.

In this paper, process experiments on the laser beam welding of copper foils using a beam source emitting at a green wavelength are described. Stacks of 30 copper foils with a thickness of 10 µm each were welded. Different process strategies were applied and compared. The weld seams were evaluated by means of cross sections and topographic analyses. The investigations showed promising results using a beam source emitting at a green wavelength for the joining of foil stacks.

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Keywords: Laser Beam Welding, Green Wavelength, Copper Foil Stacks, Lithium-Ion Battery, E-Mobility

1. Introduction

Within the context of the current energy and climate policy, the importance of sustainable drive concepts is increasing [1]. In particular, a transformation from vehicles with conventional combustion engines to electric drive vehicles has taken place in the recent years. Energy storage systems are a key factor in this development. Due to their high energy density, lithium-ion batteries (LIBs) are currently the main power source in electric vehicles (EVs), hybrid electrical vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs) [2]. A major challenge in the manufacturing of LIBs is the qualification of production systems and processes that allows for the product to meet the high quality requirements. During the cell assembly, the metal carrier foils of the stacked electrodes need to be welded and connected to the tabs [3]. Aluminum (cathode) and copper (anode) foils are used as current collectors [4].

2. State of the Art

Currently, ultrasonic welding is the preferred method for cell-internal contacting [5]. However, there are some process limitations, such as the risk of a mechanical damage of the foils [6]. SCHEDEWY *et al.* [7] showed that laser beam welding as a contactless process can be an alternative joining method for cell-internal contacting. Along the weld seams in overlap configuration welding defects, like pores and lack of fusion, were found. Compared to the ultrasonic welding process, laser beam welding causes less mechanical stress on the foils, as shown by ENGELHARDT *et al.* [8]. The authors investigated continuous wave (CW) laser beam welding of 30 aluminum foils (EN AW 1050, 15 µm). Here, weld defects, such as high porosity, were found within the weld seams. The welding of the

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thin foils is very challenging due to the multiple interfaces and the entrapped air between the single layers.

Different experiments have been carried out to investigate the suitability of laser beam welding for electrical contacting of foil stacks. DE BONO *et al.* [9] examined different stacking configurations. The number of foils in the stack as well as the foil thickness were varied. Using a circular oscillation strategy, 30 overlapping copper (CW004A) foils with a thickness of 17 µm could be joined reproducibly. In these investigations, the occurrence of spatters was not addressed. For welding of stacks with 100 µm thick copper foils, a surface roughening was necessary to improve absorption of the near infrared radiation.

In order to minimize the heat input, MOHSENI *et al.* [10] used intensity modulated millisecond pulses for welding a copper foil stack with 15 foils (CW008A, 15 µm). By means of cross sections it was proven that the spike pulse process allows for fully contacted stacks.

From the presented studies, the challenges of defect-free foil welding become clear. The described investigations used a beam source emitting at a infrared wavelength. To meet the demands of a stable and spatter-free welding process, the use of green laser radiation can be advantageous for the contacting of copper foils. The absorption coefficient of green radiation (λ = 515 nm) for copper at room temperature is about 7 times higher than for infrared radiation (λ = 1030 nm). PRICKING *et al.* [11] showed that the dependence on the surface condition of copper decreased using the green laser which can positively influence the welding of battery carrier foils.

HAUBOLD *et al.* [12] investigated the different process regimes for the laser beam welding with green radiation on copper samples of 1 mm thickness (CW004A). A stable heat conduction welding process was realized. This could be advantageous for the welding of foils, as no material is vaporized.

ALTER *et al.* [13] demonstrated in their experiments on 2 mm thick copper sheets (CW004A) that spatter-free heat conduction welds can be achieved even at high welding speeds.

The described investigations used single cooper sheets with thicknesses above 1 mm. The results prove that the reliable welding of copper is possible using a high power disk laser emitting at 515 nm. The application of green laser radiation has not yet been investigated in detail for the cell-internal contacting.

3. Objectives

The joining processes as well as the weld seams for cell-internal contacting need to meet many different quality requirements. Based on the state of the art a list of requirements was elaborated, which provides a framework for evaluating different joining processes.

Preliminary work has shown that laser beam sources emitting at a green wavelength enable new perspectives for joining processes in the battery production. The objective of this paper was to apply green laser radiation to overlapping copper foils. A special clamping device was designed. Within this paper, three welding strategies were assessed, whereby a complete connection of all foils was the main focus.

4. Requirements Analysis

Based on a specification of the critical factors regarding the battery components, quality requirements on the joining process and the weld seam were identified. They are summerized in Figure 1.

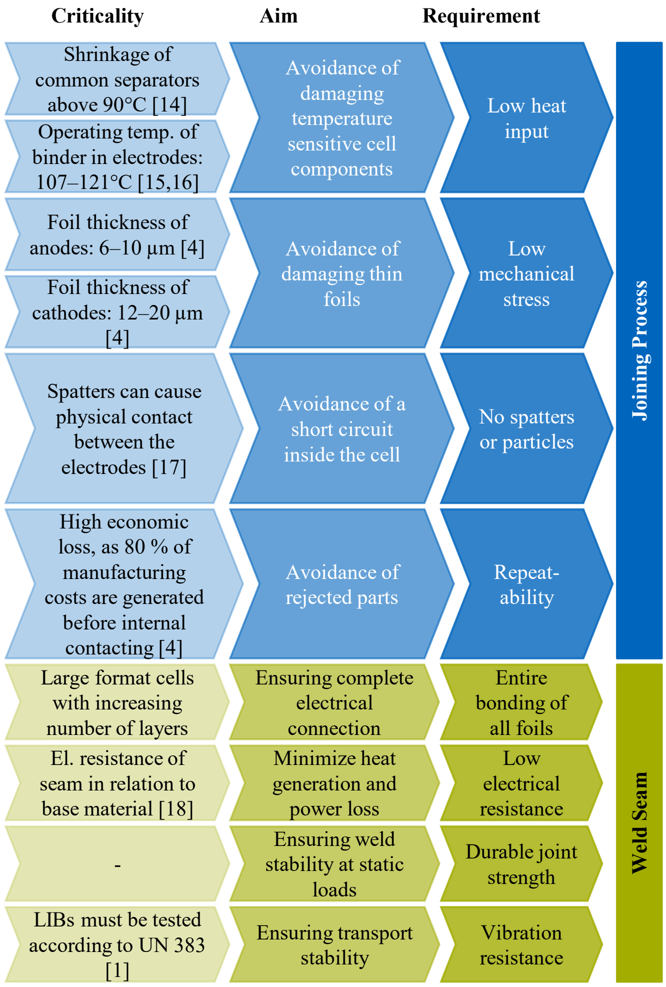

Fig. 1. Quality requirements for the joining process as well as the weld seam for cell-internal contacting

5. Experimental setup and method

5.1. Laser system and welding strategy

The experiments were carried out using the beam source TruDisk 1020 of TRUMPF Laser GmbH with an emission at λ = 515 nm. The characteristics of this laser system are listed in Table 1. A programmable focusing optical (PFO) scan system from TRUMPF Laser GmbH was used. The aspect ratio of 1:2.93 resulted in a processing field size of 138 mm x 134 mm. Three different welding strategies were examined: A continuous wave (CW) process, a sine oscillation of spot position and power, and a square pulse were applied. For the CW and the square pulse strategy a linear welding trajectory along the y-axis was chosen. A linear beam movement in y-direction with the welding speed v_w was superimposed with a sinusoidal beam oscillation in x-direction for the sine oscillation strategy. The schematic profiles are depicted in Figure 2. The presented results are discussed based on an exemplary parameter set (see Table 2), which was repeated twice.

Table 1. Properties of the laser system Trumpf TruDisk 1020

Parameter	Value
Max. laser power $P_{L,max}$	1 kW
Wavelength λ	515 nm
Fiber core diameter d_f	50 µm

Table 2. Parameters of the used welding strategies

CW Strategy		Oscillation Strategy		Pulse Strategy	
Laser Power P_L	400 W	Max. Laser Power $P_{L,max}$	440 W	Max. Laser Power $P_{L,max}$	800 W
Welding Speed v_w	12.5 mm/s	Min. Laser Power $P_{L,min}$	220 W	Pulse Time t_p	1 ms
		Amplitude x	0.2 mm	Frequency f	150 Hz
		Frequency f	20 Hz	Welding Speed v_w	5 mm/s
		Welding Speed v_w	10 mm/s		

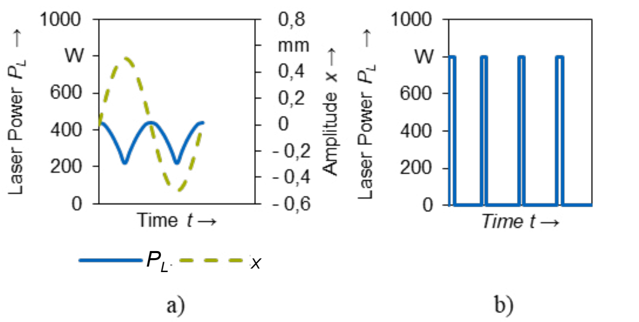

Fig. 2. a) Schematic temporal profile of the laser power and the x-position over the time for the oscillation strategy (power reduce at turning points to avoid overheating) b) Schematic temporal profile of the laser power over the time for the pulse strategy

5.2. Clamping device and materials

The clamping conditions are fundamental for successfully welding the foils. For this purpose, a clamping element (see Figure 3) was designed that applied a punctual force at three points. Thus, a bending of the clamping bridge was avoided and an appropriate compression of the foils was realized.

All experiments were carried out on stacks of 30 copper (CW020A) foils. The thickness of a single foil was 10 µm.

All stacks were welded with a weld seam length of 20 mm. The selected focal distance resulted in a minimum focal diameter on the top foil.

5.3. Experimental and analytical approach

For this paper, the weld seam results were analyzed by means of cross sections and surface images. A cross section was taken from each weld seam in the middle of the weld. The main focus of the investigation was whether all foils could be entirely bonded together. This criterion is classified as the minimum requirement for a functional joint, as it influences all other weld seam criteria, shown in Figure 1. Therefore, the layer-to-layer-fusion was examined. A complete connection was essential to optimize the process with regard to the further requirements.

In addition, the weld seams were evaluated regarding the resulting weld seam geometry and the seam collapse. These parameters affect the mechanical and the electrical properties of the seam as the electrical resistance of a conductor depends on its charge-carrying cross-sectional area.

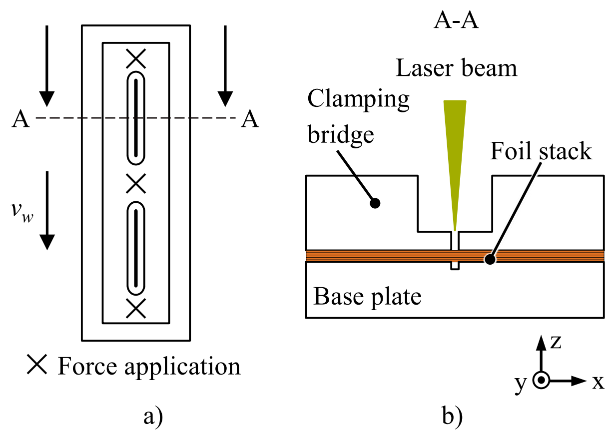

Fig. 3. Schematic drawing of the clamping device: a) top view, b) sectional view

6. Results and discussion

6.1. Layer-to-layer-fusion

One challenge for welding the foil stacks was to regulate the energy input. On the one hand, a connection of the lower foils is required, while on the other hand the upper joining partners must remain undamaged. For each process strategy, parameters could be found which allow a complete bonding of all foils. In Figure 4 cross sections for those parameters are shown.

6.2. Weld seam geometry

The cross-sectional areas of the weld seams (see Figure 4) differed distinctly in their size and their shape. The biggest area was measured for the oscillation strategy and the smallest for the pulse process. A quasi-rectangular weld seam cross-section was found for the CW strategy, in which the width of the weld pool was similar at the top and bottom foil. After using the oscillation strategy an almost semi-circular weld seam cross section was found. Overall, the seam was wider at the top than in the CW process. However, the width of the seam decreased from the top to the bottom foils. In both strategies, no collapse of the seam on the top side was observed.

The squared pulse strategy showed the smallest weld seam on the upper side. Despite the overall lowest energy input (E_L = 480 J), a collapse of the seam on the weld seam surface was observed. It is assumed that this was due to the high peak power. The seam width declined conically from top to bottom.

	CW Strategy	Oszillation Strategy	Pulse Strategy
Energy input E_L	640 J	871 J	480 J
Weld seam area A_{WS}	$2.86 \cdot 10^{-2}$ mm²	$3.65 \cdot 10^{-2}$ mm²	$0.76 \cdot 10^{-2}$ mm²

Fig. 4. Metallographic cross sections of the different welding strategies

Randomly distributed pores appeared in the weld seams using the CW and the sine oscillation strategy. The application of the sine oscillation strategy lead to smaller pores in the weld seam. A typical reason for the pores are instabilities in the melt pool. It is presumed that they result from the increased energy input in the CW and the oscillation strategy compared to the pulse strategy. In further investigations, the melt pool characteristics should be examined in detail.

6.3. Surface inspection

A major requirement regarding the welding process is a low heat input. In all three welding processes a heat-affected zone (HAZ) was observed on the seam surface, characterized by the temper colors in the seam adjacent zone (see Figure 5). The width of the weld seam w_s and the width of the heat-affected zone w_{HAZ} were measured at the surface. The measurement of the widths was taken at 10 random points across the weld seam. Table 3 lists the determined mean values as well as the minimum and the maximum values. The smallest HAZ was found for the pulse process, while the HAZ of the CW and the oscillation process were similar. This observation corresponds to the total energy E_L applied. In the pulse process the least energy was used.

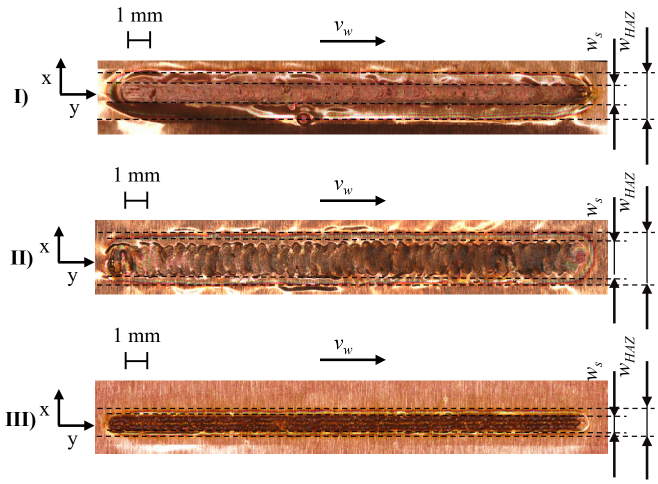

Fig. 5. Top view of the welded foil stacks from: I) CW strategy, II) oscillation strategy, and III) pulse strategy

Table 3. The mean, the minimum, and the maximum values of the measured seam width w_s, width of the heat affected zone w_{HAZ}, from: I) CW strategy, II) oscillation strategy, and III) pulse strategy

STRATEGY	$w_{S,MEAN}$ IN MM	$w_{S,MIN}$ IN MM	$w_{S,MAX}$ IN MM	$w_{HAZ,MEAN}$ IN MM	$w_{HAZ,MIN}$ IN MM	$w_{HAZ,MAX}$ IN MM
I)	0.83	0.75	0.93	2.06	1.80	2.23
II)	1.44	1.37	1.56	2.07	1.90	2.20
III)	0.55	0.48	0.58	1.01	0.88	1.08

7. Summary and outlook

For this paper, the laser beam welding of copper foil stacks with green laser radiation was investigated. The following conclusions could be drawn:

- All examined welding strategies allowed a complete connection of stacks consisting of 30 copper foils.
- Differences were mainly found in the resulting weld seam shape.
- The thermal load in the adjacent seam area was analyzed by the width of the HAZ $w_{HAZ,mean}$. The heat-affected zone was reduced by 50% in the pulse process compared to the other two process strategies. In subsequent investigations, it will be clarified if the thermal load leads to critical temperature values for the battery components.

It was shown that the green laser is suitable for the joining of copper foils. Further investigations to analyze the dependence between the process strategies and the electrical and the mechanical properties have to be conducted. In addition, the requirements of the welding process have to be analyzed in greater detail with temperature measurements, electric resistance tests, or an analysis of the spatter. The formation of pores during the welding process needs to be examined in detail.

With regard to an industrial application, an increase of the number of weldable foils has to be investigated. Furthermore, tests regarding the contacting of the foil stacks to a tab should be conducted.

Acknowledgements

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