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A Novel Approach for Welding Metallic Foils Using Pulsed Laser Radiation in the Field of Battery Production

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Abstract

In the production of battery cells for electromobility, many cell internal and external joining operations are required. These connections must have both high mechanical strength and excellent electrical properties. In particular, the cell-internal contacting poses a great challenge, as multi-layered stacks of highly conductive metallic foils have to be joined while the bonding areas are in immediate proximity to temperature-sensitive materials. Conventionally, these bonds are produced by ultrasonic welding due to the reduced occurrence of intermetallic phases and the low heat generation. This process is limited in terms of the strength and thickness of the welds. Within this work, experiments were conducted on contacting metallic foils by pulsed laser beam welding. The aim was to join stacks of 15 oxygen-free copper foils with a layer thickness of 15 µm at a high weld seam quality and with good process stability. Suitable parameters for welding with temporally power modulated pulses (spike pulses) were determined. The results were compared to continuously welded (cw) samples. In comparison, pulsed welding showed a great potential for producing high quality welds over the entire thickness of the foil stack and was characterized by low susceptibility to mechanical weld defects.

Keywords: Li-ion Battery, Metallic Foils, Welding, Pulsed-Laser Welding

1. Introduction

The increased demand for battery-powered electric vehicles (BEVs) because of environmental and economic requirements has led to a major revolution in the automotive industry. A current trend focuses on the development of Li-Ion batteries as energy supply for BEVs. Within a high-voltage energy storage system for applications in electromobility, up to several thousand individual Li-ion cells have to be connected at different junctions. Due to the increasing demand for this type of energy storage, many research projects have focused on the development and improvement of a suitable welding technology for internal and external cell contacting. The corresponding welding technology must, however, fulfill the entire functionality such as electrical conductivity and mechanical stability without damaging the cell material during the joining

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process. Recently, laser beam welding (LBW) has gained in relevance due to high process speeds and high weld quality. Currently, laser processes are mainly used for external contacting. Internal contacting by means of LBW is a challenging process, above all because of the large number of interfaces between the metal foils to be joined and the sensitivity of the cell materials to high temperatures generated by the laser beam.

2. State of the Art

Battery cells, as the basic components of energy supply systems in BEVs, are mostly available in three formats: cylindrical cells, prismatic cells and pouch cells. A number of BEV manufacturers are currently adapting the design of their energy storage systems to the use of pouch cells. This is due to their comparatively higher energy density and simpler manufacturing processes. Pouch cells consist of a stack of electrodes, alternating cathodes and anodes. Between the individual electrodes there is a porous separator layer made of a polymer. Aluminium and copper foils are used as the substrate for the active material of the electrodes. Conventionally, these foils are welded with metallic ultrasonic welding (USMW) to ensure mechanical stability of the electrode stack and good electrical conductivity. However, ultrasonic welding processes can lead to a number of connection defects within the weld seam and in the electrode stack, such as structural deformation due to vibration or the formation of cracks due to a direct mechanical contact between the joining tool and the workpiece. In addition, the difficulty in designing the USMW process increases with the number and volume of welding components. (Engelhardt et al. 2015, Xi et al. 2017)

LBW is an alternative process for joining foil stacks. Within the process category, two different welding modes can be distinguished: continuous and pulsed LBW. Engelhardt et al. 2015 investigated the process of continuous laser welding of aluminium foils. They showed that LBW can reduce mechanical risks to the foil stack and at the same time increase the process speed for mass production. Especially for cell designs with more than 30 foils, LBW offers great potential, as the attainable limit of the USMW process lies here. In addition, it could be shown that the pore formation in the foil stack is mainly due to the instability of the capillary bottom during LBW.

Since the performance of a Li-ion battery is extremely sensitive to the temperature stress of the cell components during the manufacturing process, the input of heat into the cell elements, for example through joining processes, must be minimized. (Santhanagopalan et al. 2015)

With regard to the heating process of the cell components during joining, pulsed laser welding can be advantageous over continuous processes because the melting zones solidify faster. The quality of the joints depends not only on the material properties, but also on the welding source and its parameters. Schmitz et al. 2018 used the pulsed laser welding process to connect thin copper sheets and Hilumin battery cells. Ventrella et al. 2010 also investigated the pulsed laser welding process, with the focus on the welding of heterogeneous material connections.

For welded connections between round cell housings and bus bars, Schmidt et al. 2016 showed that discrete step welds meet the requirements for mechanical and electrical properties and also lead to a greatly reduced use of energy. Schmitz & Zaeh 2016 compared these results with various pulsed laser welding strategies. The obtained findings showed that the spike-pulse welding strategy provided results for the contacting of round cells to other strategies at lowest energy input due to the high peak intensity. The investigations showed that the spike-pulse welding strategy developed by Dijken et al. 2003 is well suited for welding components with high gap tolerances in overlap joints.

Based on the existing knowledge, a new approach for the pulsed laser welding of copper foil stacks is presented in the following. The aim is to enable a complete weld-through of foil stacks without additional aids and with contactless processing from one side. In addition, the heat input into the battery components should be kept at a minimum and a high weld seam quality should be achieved.

3. Objectives and Approach

For high mechanical strength and electrical conductivity between battery films, a large welded contact area across the entire height of the foil stack is required. However, a large joining area is generally associated with a large heat input. Based on the stated advantages of the spike-pulse welding strategy, the process appears to be suitable for contacting of copper foils for cell-internal applications. The shape of a spike-pulse is shown schematically in Figure 1. Three power levels can be distinguished if the laser power is depicted over time. The preheating process is used to melt the upper layers of the film stack before applying a high power pulse. This presses the melt into the lower layers. The reheating power is used for homogenizing the weld seam. During the spike-pulse welding process, the spot is not moved relative to the sample surface. Using the spike-pulse method, a weld seam is created by lining up a series of stationary welding spots at a defined distance. The overlap length between two points is determined by the focal diameter and the displacement of the single spots. Compared to continuous welding, this type of process allows for a greater number of degrees of freedom for the application of the process. In order to demonstrate the potential of improvement through the spike-pulse process, reference investigations were carried out using a cw process.

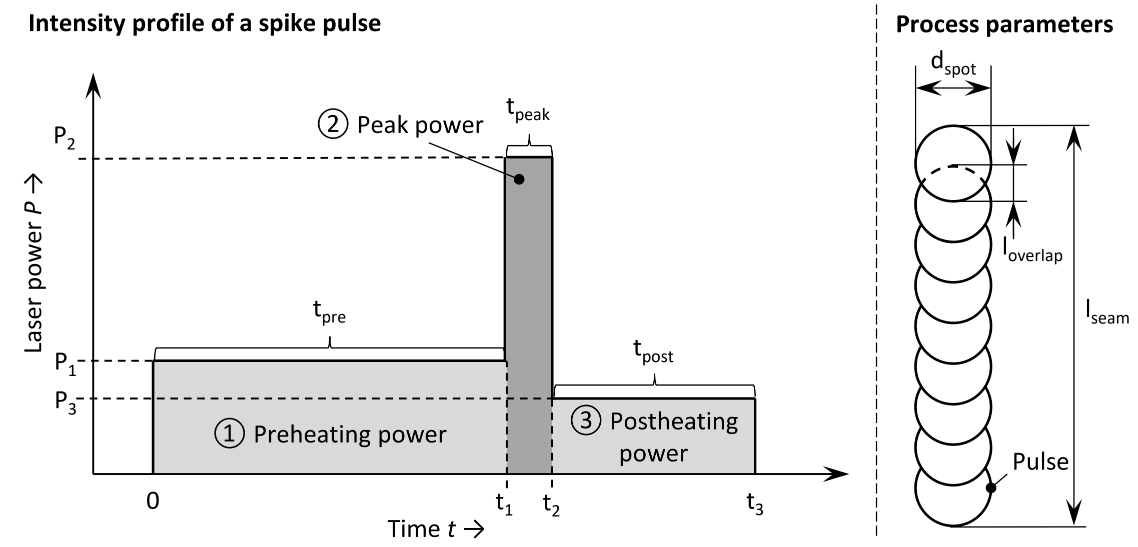

Fig. 1. Schematic temporal profile of the laser power over the duration of a spike-pulse (left, according to SCHMITZ ET AL. 2018) and specific process parameters for pulsed welding (right)

4. Experimental Setup

For the experiments, an Ytterbium-doped YAG (Yttrium-Aluminium-Garnet) multimode disk laser from TRUMPF Laser GmbH was used. The laser beam source can be operated in continuous (cw) or in the micro-second pulsed mode. With the aid of an optical fiber, the radiation was directed to the welding optics. A PFO 33 scan system from TRUMPF Laser GmbH was used. The characteristics of the devices are listed in Table 1. All welding tests were carried out on stacks of 15 Cu-OF foils with a layer thickness of 15 µm each. The foils were pressed together with the clamping device made of aluminium (see Figure 2). Overlap welding was carried out in a gap in the clamping mask. The clamping device ensured an unsupported weld.

Table 1. Properties of the laser beam source (left) and the scanning optics (right)

Laser beam source		**Scanning optics**	
Model	Trumpf TruDisk 4001	Model	Trumpf PFO 33
Max. laser power P_L	4 kW	Focal length f	255 mm
Wavelength λ	1030 nm	Focus diameter d_f	170 µm
Beam parameter product BPP	4 mm·mrad		
Fiber core diameter d_c	100 µm		

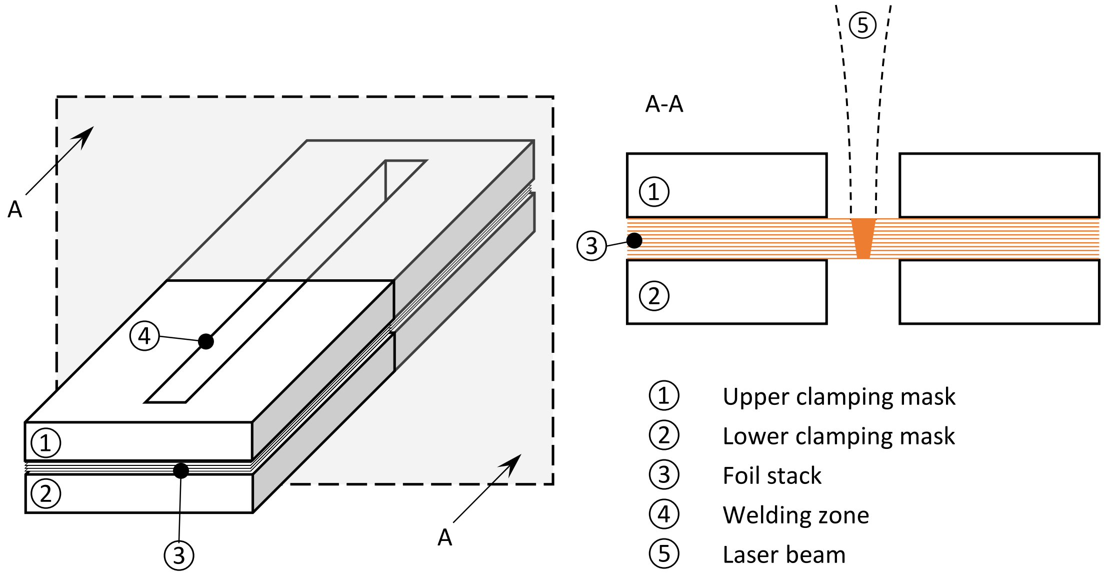

Fig. 2. Clamping device for the experimental studies

5. Results and Discussion

In the following, the results of experimental investigations for the comparison of a conventional continuous welding strategy with the spike-pulse strategy are presented exemplarily. For the design of the welding process, comprehensive parameter studies were carried out with both welding methods. The differences in the process results are presented and discussed on the basis of the best parameter sets (see Table 2) achieved. These parameter sets were selected on the basis of the maximum number of foils bonded and under the condition that the stack of foils did not burn through during the welding process. Within the scope of this work, only metallographic and microscopic methods were used to evaluate the weld seams. The analysis of mechanical strength and electrical conductivity will be considered in future investigations. First, the welding process was designed in a way so that a visually high quality seam was produced with a reproducible welding depth and a high degree of bonding between all foils. It was assumed that these are the basic requirements for good mechanical and electrical properties.

Table 2. Process parameters of the exemplary weld seams for a continuous welding process (left) and a spike-pulse process (right)

Process parameters			
Continuous welding strategy		Spike-pulse welding strategy	
Laser power P_L	600 W	Preheating power P_{pre}	450 W
Welding speed v_W	12 mm/s	Peak power P_{peak}	1300 W
		Postheating power P_{post}	300 W
		Preheating time t_{pre}	6 ms
		Peak time t_{peak}	1.4 ms
		Postheating time t_{post}	2.6 ms
		Overlap	40 %

In Figure 3, the continuous and pulsed weld seams are compared using metallographic cross sections and surface images. The cross-sections of both seams clearly show that the critical areas for complete bonding are located in the bottom and top foils, while the layers in the middle of the stack are less critical. With the continuous welding strategy, it was not possible to achieve complete bonding across all films in the stack. With a further increase of the line energy, originating from the parameter set shown, significant ejections and burn-through occurred along the weld seam. Most of them were located at the end of the seam. These defect types were also evident in the cw weld shown as an example (see Figure 4).

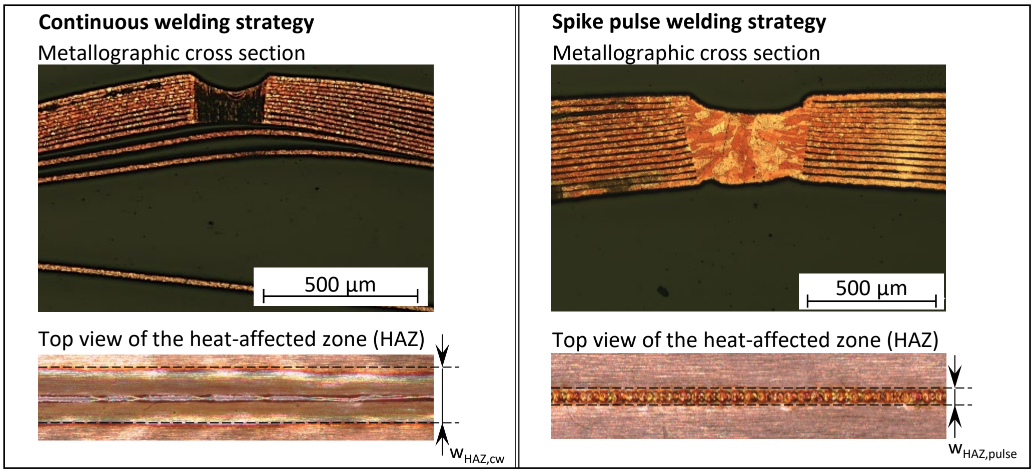

Fig. 3. Metallographic cross sections of the weld seams (top) and top view of the weld seams with highlighted heat-affected zone (HAZ) (bottom)

In addition, a clearly distinguishable heat-affected zone with a width of $w_{HAZ} \approx 1.5$ mm could be detected for the continuous welding process. This indicates that there is a strong thermal impact on the temperature-sensitive materials within the cell, e.g. the polymer separator. By using the spike-pulse strategy all foils could be welded together. In particular, the lower layers were bonded without significant indentations. Nevertheless, a reduced joint cross section was observed in the area of the upper film. Looking at the connection over the entire weld seam length, it can be seen that the connection of all foils is maintained and that there is no change in the welding result along the seam. In addition, the pulsed welded seam has a significantly smaller heat-affected zone with dimensions in the order of magnitude of the actual weld seam ($w_{HAZ} \approx 0.25$ mm).

In addition to the joining cross-section of a weld seam, the stability of the welding process should also be considered. In particular, thermally induced defect patterns generally make the reliable joining of copper difficult. The surface roughness is a measure for the evaluation of the welding process stability and the weld seam quality. In Figure 4, the depth deviation relative to the foil surface next to the joining zone over the length of the seam is plotted for the two comparative weld seams. The surface profile of the weld samples was measured using a 3D macroscope VR-3100 from Keyence. Compared to the spike-pulse weld seam, the continuously welded sample has a significantly higher surface roughness. Furthermore, in the area of the weld seam end, a significant burn-through of the weld seam occured in combination with strong melt ejections. The pulsed welded seam, on the other hand, has significantly lower roughness deviations. A considerably more stable welding process can therefore be observed here.

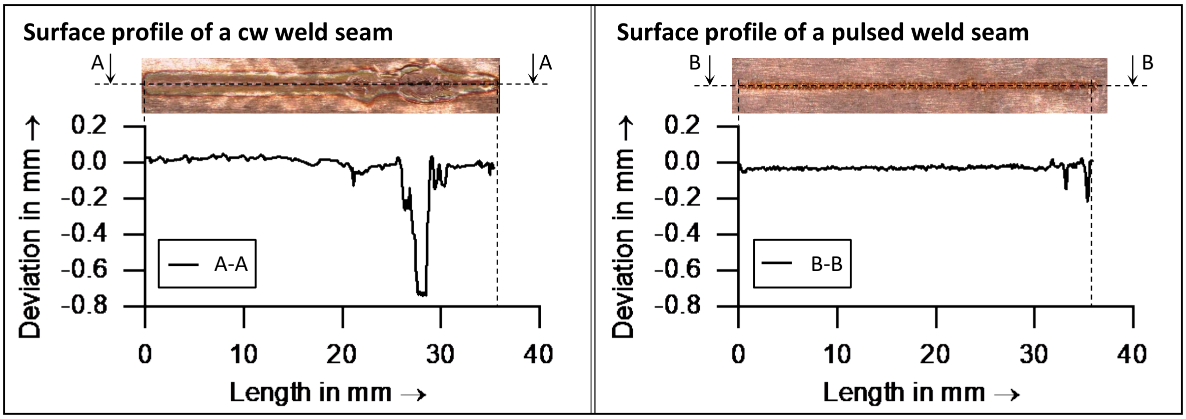

Fig. 4. Deviation of the centrally measured weld seam height from the sample surface along the weld seam for the comparative weld seams

6. Conclusion

Within this work, a comparison between continuous and pulsed welding of film stacks for the internal contacting of pouch battery cells was conducted. The potential of the spike-pulse welding strategy, in which the laser power is modulated along the duration of one pulse, was demonstrated by means of fundamental experimental investigations. In contrast to a conventional continuous welding process, the pulsed welding process was capable to achieve a complete connection of 15 stacked copper foils and to significantly reduce the heat-affected zone adjacent to the weld seam. In order to fully qualify the process for the connection of battery foils, further investigations regarding the mechanical and electrical properties of the joint will be carried out.

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