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Laser micro welding – a flexible and automatable joining technology for the challenge of electromobility

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Abstract

In our everyday life, electrified objects such as mobile phones, bicycles and automobiles are indispensable. The constant trend towards the electrification of everyday objects reveals a variety of possible designs of single battery cells or battery cells connected to a module, which have to be produced automatically in large quantities depending on the application.
Laser micro welding offers decisive advantages compared to conventional joining methods such as ultrasonic or resistance welding. In addition to a high degree of automation, a laser-based joining process is contactless, highly flexible and requires no additional materials which increase the transition resistance. The key technology here are highly brilliant fiber laser sources which, due to their good focusability and the resulting small spot sizes, can provide high intensities with a simultaneously low total energy input. The presented work contains the results of the contacting of different types of battery cells by laser beam micro welding.

Keywords: Laser Micro Welding; Copper; Battery Cells

1. Introduction

Over the past decades, global emissions of greenhouse gases have increased continuously. According to statistics, transportation is responsible for about a quarter of global carbon dioxide emissions. [1,2] Nevertheless, greenhouse gas emissions in Germany have already fallen from 1.248 million tons of CO_2 equivalent in 1990 to 905 million tons of CO_2 equivalent in 2017. [3] The rising number of electric vehicles in Germany is contributing to a continuation of this trend. The heart of this vehicle is the electric motor, which

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is powered by an energy storage system – usually a battery. The energy storage system is characterized above all by a high energy density and a high energy content. However, the power density is low in order to enable the longest possible range. [4]

Besides the very important field of electrified transportation, lithium-ion batteries are also used in various other applications: In battery-powered tools, in consumer electronics such as mobile phones, laptops or digital and video cameras as well as in e-bikes or forklift trucks. There is also a large market for stationary energy storage devices such as private home storage systems. For all those applications lithium-ion batteries are the preferably used technology. The main advantages compared to other battery technologies are their high specific energy content and the ability to deliver higher battery power, making lighter and more compact battery systems possible. [5,6]

2. Design of traction batteries

A traction battery is a battery system used in electric and hybrid vehicles consisting of a variety of rechargeable lithium ion cells [7]. The key factors in developing a traction battery are electrical performance requirements, safety aspects, weight, pack design, cost and thermal management [8]. In general, a battery pack can be divided hierarchically into three levels (Figure 1):

- Cell level: A single battery cell consists of a positive and a negative electrode, a separator, the electrolyte and a housing [6,7].
- Module level: In a module several cells are connected serial or parallel and assembled mechanically with the aim of achieving sufficient energy, power, voltage and capacity parameters [9].
- Pack level: A battery pack consists of modules that are connected serial or parallel. The traction battery is completed by connecting this battery pack to sensors and a battery management system and placing it in a mechanically safe housing.

Various joining methods are possible to use to contact lithium-ion battery cells to battery systems. Within this work possible joining methods are listed and evaluated with regard to the suitability for contacting the respective cell type.

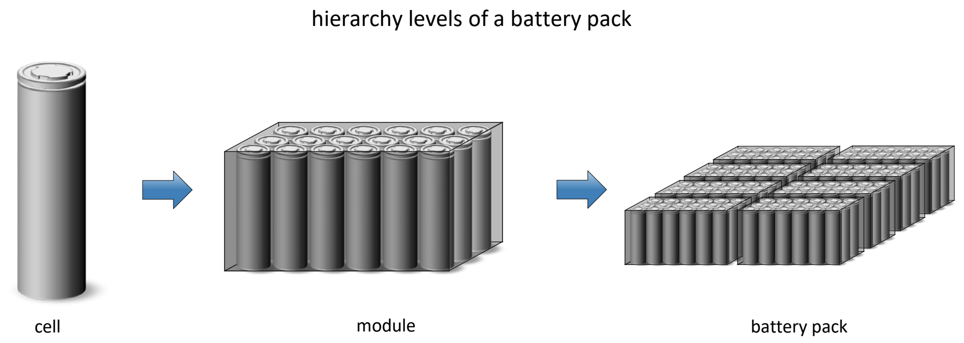

Fig. 1. Schematic representation of the different hierarchy levels of a battery pack

Three different cell formats are used in electric and hybrid vehicles: the cylindrical cell, the prismatic cell and the pouch cell (Fig. 2). Depending on the cell chemistry, cell geometry and shape factor, the cell has a different energy density, lifetime and safety behavior. [6,10]

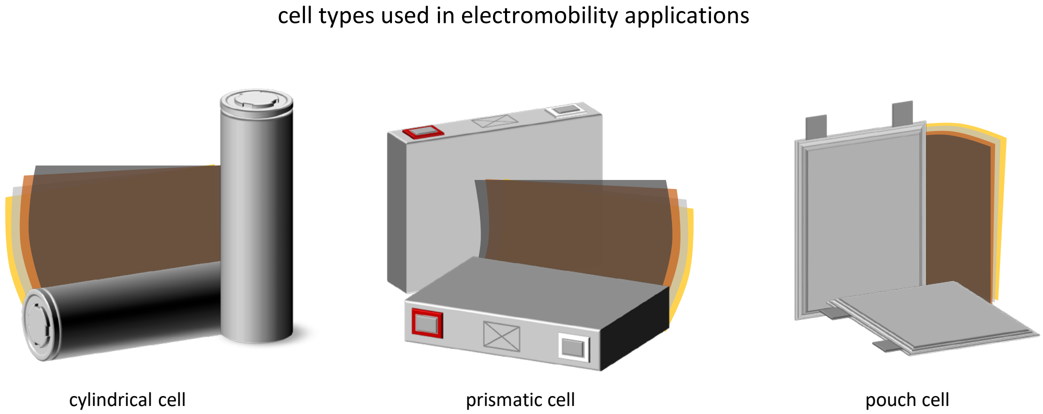

Fig. 2. Schematic representation of the different cell types used in electric transport applications

Cylindrical cells are produced in different dimensions. In the automotive industry, but also in e-bikes, laptops and battery-powered tools, the 18650 form factor is currently used. But the trend goes towards larger cell formats like the form factor 21700 will probably be increasingly used in electric vehicles. The first two digits of the designation denote the diameter of the cell, whereas the next two denote the height in millimeters. According to a study on the development of lithium batteries in the automotive industry, the current cell capacity of the 18650 form factor is 3.3 Ah and of the 21700 form factor 4.8 Ah. No increase is predicted for the 18650 cell in 2020, but an increase to 5.2 Ah is expected for the 21700 cell. [2,10,11,12]

Prismatic cells are enclosed by an aluminum or steel container which ensures mechanical robustness, structural stability and moisture protection. The shape allows high heat dissipation and efficient packaging, allowing prismatic cells to achieve greater energy density at module level than cylindrical cells. In comparison, however, production costs are higher and mechanical strength and energy density are lower. Despite different approaches to standardize the dimensions of the prismatic cell type, there are a large number of different form factors. [2,6,9]

The pouch cell is a prismatic cell with a flexible housing, which usually consists of plastic-coated aluminum foil on both sides. Further designations for this cell format are "coffee bag cell" or Lithium-Polymer cell, since a polymer-based electrolyte is used. The decisive advantages of this cell format are very efficient cooling properties, scalability, high energy densities, relatively low production costs and a very efficient packaging alongsidde low weight. The disadvantages are the low mechanical stability, tightness and inflation of the cell in the event of uncontrolled gas development. Due to the flexibility of the cells, holding devices are required when using the modular construction method to prevent the cells from coming loose or slipping. [12,13]

The three different types of battery cells can be contacted using different joining methods. These include ultrasonic welding, soldering, resistance welding, screwing or bracing and laser beam welding. Due to the non-contact joining process, the flexible application possibilities with regard to material options and the resulting low contact resistance, laser beam welding is one of the most important methods for contacting battery cells. [6,14]

3. Laser micro welding for contacting battery cells

3.1. General requirements for the welding process

A successful and stable joining process between battery cells depends on one basic criterion: The heat energy input. By reaching the necessary melting temperature for welding, the cells, the battery cells are exposed to thermal stress, which must be minimized in the joining process.

The alloys of the frequently used connector materials copper and aluminum have a low absorption rate (< 10 %) with simple interaction between light and material - so called heat conduction welding - when conventional laser beam sources in the wavelength range around 1 µm are used. The formation of a vapor capillary – so called deep penetration welding - leads to a sudden increase in absorption and thus in the efficiency of the joining process. To generate this vapor capillary, it is necessary to exceed the intensity threshold for deep penetration laser beam welding. The intensity is defined as the quotient of laser power and focal diameter.

This allows the intensity to be influenced in two ways. Firstly, by increasing the laser power even with larger focus diameters (> 100 µm), the intensity threshold for deep penetration welding can be exceeded.

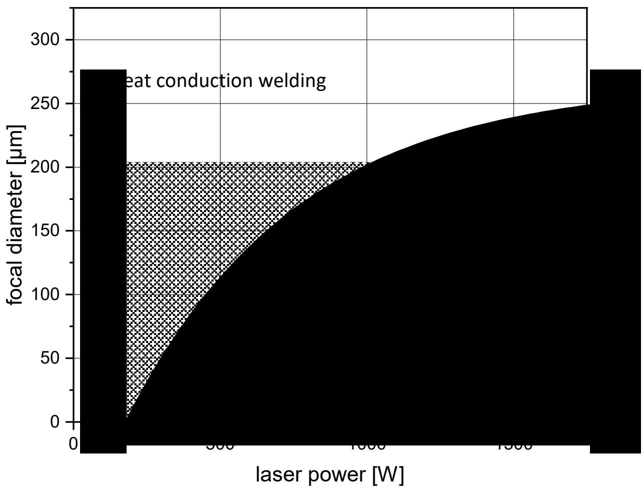

Fig. 3. Threshold between deep penetration and heat conduction welding of Cu-ETP by using a Gaussian intensity distribution. The measurement has been conducted using a fiber laser with a wavelength of 1070 nm.

This also results in an increase in the energy input and thermal load of the batteries to be joined, which can lead to permanent damage to the cells (figure 3). Due to the larger focus diameter, however, the resulting weld seam has a larger connection area. On the other hand, when using moderate laser power (< 500 W), the focus diameter can be reduced (< 40 µm) so that a deep penetration welding process can be realized, while keeping the energy input to a minimum level. This results in narrow and slender weld seams, which are characterized by smaller connection areas but reduced thermal load. By using a spatial power modulation – a linear feed with superposed circular motion – or increasing the number of weld seams, possibly with cooling breaks in between for a thermal stress relief, however, the joint cross-sections can be increased.

3.2. Cylindrical Cells

Contacting cylindrical cells by using laser radiation results in two different welding tasks due to the mechanical design of the cell type. On the one hand, the positive pole on the upper side and on the other hand the negative pole consisting of the jacket housing must be contacted (figure 4).

The contacting of the positive pole is not critical when cylindrical cells are used, as there is a cavity underneath the formed pole. For example, the welding process does not require exact control of the welding depth, as a slight through-welding through the positive pole usually does not damage the cell. Nevertheless, care must be taken to reduce the heat input in order not to damage the seal on the positive pole. Furthermore, excessive mechanical stress leads to deformation of the positive pole.

Contacting the negative pole on the contrary is more challenging in terms of avoiding cell damage. Possible strategies of contacting can be using the outer surface, the underside or the beaded edge on the upper side of the cell. For all three contacting surfaces, a precise control of the welding depth is necessary. If the welding depth is too low, the current carrying cross-section will be reduced and the electrical resistance

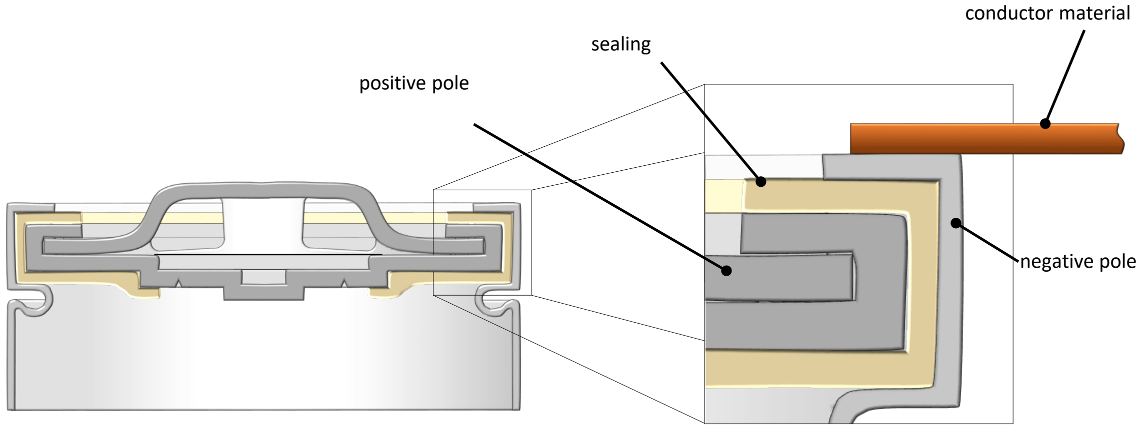

Fig. 4. schematic view of the inner structure of a cylindrical battery cell

in the battery module will be increased, which leads to a high contact resistance and thus to a rising temperature at the joint in use. A weld seam which penetrates the housing of the cell, leads to irreparable damage to the battery cell, which is manifested by electrolyte leakage.

When contacting the beaded edge of the battery cell, there is no electrolyte directly below the joining zone, but a polymer sealing ring which seals the cell on the one hand and serves as an insulator between the negative and positive pole on the other (figure 4). If the thermal stress caused by the joining process at the beaded edge is too high, the sealing ring will be damaged by heat conduction within the cell, which causes a leakage at the top of the cell even though the sealing ring was not directly hit by the laser beam. Furthermore, depending on the manufacturer of the cylindrical cell, the beaded edge on the upper side of the battery cell is shaped differently. Due to the forming process, the joining zone can therefore has the shape of a line contact between the battery and the actual conductor material. The resulting gap leads to a reduction in process capability and thus to a fluctuation in the welding depth.

The contacting of the cell on the side wall at the cylindrical housing leads to a linear contact by using a flat conductor, similar to the curved beaded edge on the upper side. The contact on the bottom side of the battery cell is often geometrically restricted by the manufacturer, as in most cases the contact of the negative electrode on the cell housing is realized on the inside of the cell.

In summary, the contacting of conductor materials to a cylindrical battery cell requires on the one hand a low heat input and on the other hand a precise control of the welding depth in order to guarantee a stable and reproducible joining process.

3.3. Pouch-Cells

The contacting of pouch cells is mainly dominated by the characteristic properties of the cell connectors. Conventional pouch cells have two connection electrodes, which are led out of the outer foil and consist of two different materials. At the positive pole, the electrode is made of copper, usually coated with nickel, whereas the negative pole is made of aluminum.

If copper or aluminum connectors are used and the individual pouch cells are connected in parallel or in serial, this can result in a similar (copper-copper or aluminum-aluminum) and a joint with dissimilar materials (copper-aluminum or aluminum-copper).

Due to the exposed electrodes, the joints of the same material are not critical for laser beam welding with regard to the danger of cell damage due to through-welding. Similar to cylindrical cells, however, minimized thermal energy input into the electrodes must also be taken into account during contacting, so that on the one hand the inner cell chemistry and on the other hand the sealing through the outer foil at the feedthroughs is not damaged.

The material combination of copper and aluminum plays a decisive role in the contacting of electrodes that are not identical in material. Due to the intermetallic phases that occur during a melt-based joining process, both the durability and the electrical conductivity of the joint are negatively affected. In order to reduce these intermetallic phases, special attention must be set on the one hand the different melting points of the two materials (Table 1) and the way in which they influence the intermixing process and on the other hand to the energy which is required to heat and melt copper and aluminum.

Table 1. Physical properties of aluminum and copper [15,16,17,18,19,20]

	Copper (CW004A)	Aluminum AW-1050A
thermal conductivity [W/m·K] (T = 20°C)	349	229
electrical resistant [Ω·mm²/m]	0,023	0,028
melting temperature [°C]	103	660
specific heat capacity [J/Kg•K] (T = 20°C)	0,386	0,901
specific heat capacity [J/Kg·K] (T = 1.100°C)	0,629	1,025
specific melting enthalpy [KJ/kg]	203,5	398
density [g/cm³]	8,93	2,7

The energy E, which must be used to heat a volume of a material above the melting point, is defined by

$$E = \rho \cdot V \cdot c \cdot \left((T - T_U) + h_{fus}\right) \quad (1)$$

in which ρ is the density, V the volume, c the specific heat capacity, T the temperature and h_{fus} the specific melting enthalpy. [21]

Due to the higher melting temperature and the higher energy deposited per cubic centimeter of copper (figure 5), the overlapping welding of the two materials results in different characteristics of the melting zone.

For example, a welding process in overlap with copper as the upper joining partner leads to a considerable shaping of the weld seam in the aluminum (figure 6 left). This results in a particularly large proportion of intermetallic phases, since the large molten volumes result in a homogeneous mixing of the two metals.

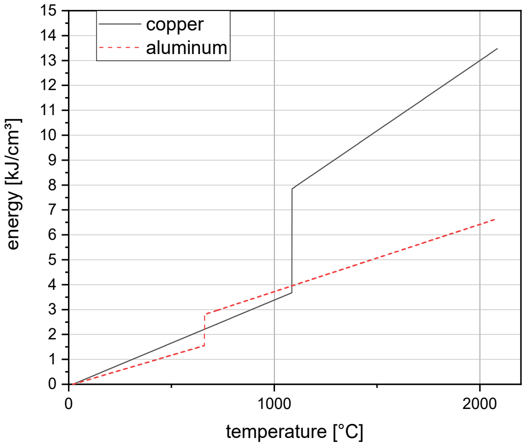

Fig. 5. Energy required to heat one cm³ of copper or aluminum at 20°C

A different picture emerges when the joint is designed with aluminum as the upper and copper as the lower joining partner. Due to the lower amount of energy and melting temperature, the molten aluminum does not succeed in heating and melting the copper in a large volume. As a result, weld seams are created which allow a very specific control of the welding depth into the lower joining partner and thus reduce the

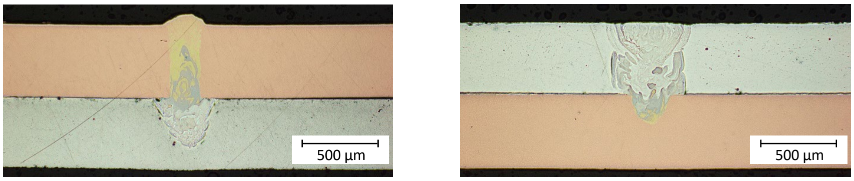

Fig. 6. cross section of a welded joint with different materials: (left) Cu-ETP upper joining partner and Al99.5 lower joining partner; (right) Al99.5 upper joining partner and Cu-ETP lower joining partner

mixing of copper and aluminum (figure 6 right).

The resulting reduction in intermetallic phases leads to an increase in the mechanical strength and electrical conductivity of the resulting joint.

3.4. Prismatic battery cells

Due to the higher power density, the housing and terminals of prismatic battery cells are often made of aluminum alloys. The desire to contact this type of battery cell with highly conductive connectors made of copper-based alloys contradicts the preferred joining arrangement in terms of avoiding intermetallic phases (figure 6). Analogous to the contacting of the other two cell formats, the energy input for this welding task must also be minimized.

In order to reduce the contact resistance of the joint, it is necessary to contact the terminals with multiple weld seams. However, this leads to an increased thermal load on the battery. This can be remedied by sequential processing of the individual terminals of a battery pack to enable them to dissipate the heat and thus prevent damage to the cell.

4. Conclusion

In order to face the global challenge of climate-friendly private transportation, automobiles that allow emission-free transportation are needed. Electric mobility has shown the greatest growth potential in recent years. The three different battery cell types used to store the energy must be connected to form a battery pack in order to fulfil the electrical requirements.

Laser microwelding using beam sources with good focusability allow reducing the thermal load and at the same time generate a high connection area. All three types of battery cells exhibit specific characteristics which must be taken into account when joining battery cells together and which have a corresponding influence on the welding process.

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