STUDY ON MANUFACTURING CHALLENGES INVOLVED IN EV BATTERY WELDING

Tutkimus tuotantohaasteista sähköautojen akkujen hitsaamisessa

Lappeenranta–Lahti University of Technology LUT

Bachelor’s thesis in mechanical engineering

2023

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Examiner: Associate Professor Kush Mehta

ABSTRACT

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Study on manufacturing challenges involved in EV battery welding

Bachelor's thesis

2023

43 pages, 14 figures, 1 table and 1 appendix

Examiner(s): Associate professor Kush Mehta

Keywords: Battery, electric vehicle, EV, manufacturing, challenges, welding

A battery pack of an electric vehicle can consist of thousands of battery cells, which are also assemblies themselves. Ways to connect all of these highly varying components are required.

This bachelor's thesis aims to gather all the different challenges that complicate the welding processes during the manufacturing of the battery pack. With the challenges in consideration, suitable welding processes are be suggested for different components that are to be welded.

Many challenges are found, ranging from difficulty of reaching the location of the joint to microscopic damage done to the work material caused by the welding process. Some challenges are more specific to certain processes, like reflection in laser beam welding, heat input in fusion welding and joint type in friction stir welding.

Major challenges are worked around by simply not using the processes most influenced by them, but optimizing the weld to the greatest is still something that is researched, like welding dissimilar materials and minimizing changes done to the microstructure of the components. Research done in electric vehicle area and the rest of the battery technology support each other, as the basic principle between these energy storages is the same.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Konetekniikka

Riku Olkkonen

Tutkimus tuotantohaasteista sähköautojen akkujen hitsaamisessa

Konetekniikan kandidaatintyö

43 sivua, 14 kuvaa, 1 taulukkoa ja 1 liite

Tarkastaja: Apulaisprofessori Kush Mehta

Avainsanat: Akku, paristo, sähköauto, EV, tuotanto, haasteet, hitsaus

Sähköauton akkupaketti voi koostua tuhansista paristoista, joista jokainen on itsessään jo osakokonaisuus. Tapoja näiden kaikkien suuresti eroavien osien yhdistämiseksi tarvitaan.

Tämä kandidaatintyön tarkoituksena on koota eri haasteet, jotka monimutkaistavat hitsausprosesseja akkupakettien valmistamisessa. Nämä haasteet huomioiden, soveltuvia hitsausprosesseja ehdotetaan erilaisten kiinnitettävien komponenttien yhdistämiseksi.

Haasteita löytyy paljon, vaikeuksista kiinnityskohdan luokse päästävyydestä hitsauksesta johtuvaan mikroskooppiseen vahinkoon työstettävässä materiaalissa. Osa haasteista keskittyy enemmän tiettyihin prosesseihin, kuten heijastus laserhitsaukseen, lämmöntuonti fuusiohitsaukseen ja liitostyyppi FSW kitkahitsaukseen.

Suuremmat haasteet vältetään yksinkertaisesti käyttämättä prosesseja, joihin haasteet vaikuttavat eniten, mutta hienosäädön saavuttamiseksi tehdään tutkimusta, esimerkiksi eri ominaisuuksien omaavien materiaalien hitsaus ja osien mikrorakenteen muutosten minimointi. Tutkimus sähköautojen akkuihin ja muuhun akkuteknologiaan tukevat toisiaan, sillä perusperiaate näissä energiavarastoissa on sama.

SYMBOLS AND ABBREVIATIONS

Roman characters

q	electric charge	[C, mAh, As, Ah]
f	frequency	[Hz, 1/s]
T	temperature	[ºC, K]

Abbreviations

BMS	Battery management system
BEV	Battery electric vehicle
EV	Electric vehicle
FLW	Fiber laser welding
FSW	Friction stir welding
HAZ	Heat affected zone
IMC	Intermetallic compound
kWh	Kilowatt hour
LBW	Laser beam welding
LIB/Li-ion	Lithium-ion battery
MAG	Metal active gas
MIG	Metal inert gas
RSW	Resistance spot welding
TIG	Tungsten inert gas

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1 Introduction

In the introduction, the motivation to the topic is established by looking at the state of the current electric vehicle pricing. The scope of the thesis is explained, as well as the methods used to find the information and how the thesis is structured.

1.1 Importance of batteries in automotive use

To reduce emissions caused by transportation, the production of electric vehicles (EVs) and therefore high-capacity batteries has increased in significant numbers over the last decade. A study on global automotive consumers (Deloitte, 2022) found that more than 50% of US, Japanese and German customers are unwilling to pay more than about 500 euros worth only for an alternative powertrain. Currently, a battery electric vehicle (BEV) costs over 10 000 euros more than the equivalent internal combustion engine (ICE) powered car. As the cars are the same, bar the powertrain, the increase of cost naturally boils down to those. This often causes the BEV to compete with ICE cars in a higher segment, which makes it appear less appealing.

The battery pack is the most crucial part of a BEV, with multiple requirements it needs to fulfill. It has to have high capacity, but a large battery pack weighs more and intrudes into the cabin space. For minimal intrusion and optimal center of gravity, the pack is placed on the platform of the car, acting also as a structural element for body rigidity. This in turn makes replacing the battery more troublesome. Typically, structural elements of a car body are not designed to be removed. The battery must charge fast, maintain optimal temperatures for driving and charging, sustain varying weather conditions and vibrations, be safe to use and do maintenance on. Degradation, permanent loss of the maximum capacity must be kept to minimum. With all this in mind, it’s no wonder that the battery makes for the most expensive component of a BEV.

Battery cells have been used for a hundred years. BEVs use cells similar to some household electronics, just in higher quantities and capable of thousands of charging cycles. High-capacity battery production is still relatively new as a concept, so not everything is optimized to the maximum just yet. With the market in need for an inexpensive, below 25 000-euro electric car with an uncompromised range, manufacturers have great interest for decreasing production costs. Early adopters have great competitive advantage by occupying that market sector first.

Cost, automation, speed, mass producibility, accuracy, reliability, quality of the joint, quality control, reach to the joint location and accessibility to the technology. These are just some of the aspects that production designers will have to consider for each different joint when choosing from available and applicable joining methods. Before even getting to those finer details, it has to be settled that the process even produces a passable joint. Each joining process offers their own trade-offs, so it is up to manufacturers to decide on the characteristics they value the most.

1.2 Objective & methods to find the answers

We will find out what kind of challenges occur with the assembly of BEV battery components and modules, focusing specifically on connections done with welding. Welding remains a commonly used method for joining components permanently together, with no replacing procedure in sight. At the same time, batteries are highly sensitive electrical components, so great care must be taken. Solutions to the found challenges will be deducted in this paper, hopefully giving a push to the vehicular transition. We will look for answers regarding the following key questions:

- How difficult are batteries from the manufacturing perspective?
- What are the challenges in welding EV battery components?
- What welding processes should the joints be done with and why?

- Do the challenges cause active measures, or do they prevent the use of some otherwise preferred processes?
- Are there solutions to the challenges and what are they?

The thesis will start by finding out the battery components that need to be welded. Welding as a joining method and currently used processes are briefly explained. It will then go on to review challenges that emerge from the components to be welded and the processes available today and in the near future. Considering these, the optimal processes will be considered at the results part of the thesis. Finally, conclusions will summarize how well the desired goals were accomplished.

With many different welding processes, someone is claiming that they have managed to make it work, but to what degree? Usually, it is only the success that gets documented, so in order to find the challenges we will have to read between the lines to find what restrictions do different welding processes introduce and what are their relevancy with battery manufacturing?

Literature used will focus on the basics of lithium-ion battery cells, composition of modules and battery packs, methods of joining cells together, different welding processes and mass production of batteries. LUT Primo and Google Scholar are used as the databases for reputable references, and RefWorks is used to collect and organize them. For verification and additional information, the head of LUT Laser Laboratory will be interviewed. The questions are presented separately (Appendix 1).

2 Overview of the battery pack & welding processes in battery production

To provide the reader some information about the structures that are to be welded, the general construction of a BEV battery pack and its subcomponents are shown and explained. Additionally, important aspects of welding as a joining method for batteries are described. Figure 1 shows an exemplary battery pack with 17 modules.

Figure 2. High voltage battery system (© chesky / Adobe Stock)

Battery pack is an assembly consisting of thousands of components. Not all of them follow the same principles, but the use of common building blocks, the battery cells has ensured that they are not that far apart either. Orange cables in EV battery systems indicate that they carry high voltages (more than 1000 V). This is a required way to warn about the imminent danger.

2.1 Construction of a battery cell

A battery cell is an energy storage unit based on electrochemical reaction. It holds a potential difference between the positive and negative sides. When a circuit through the positive and negative sides is completed, electrons flow along it, powering the designated application until equilibrium inside the battery is reached, in other words, the battery is discharged. Today's EVs use LIBs, lithium-ion batteries due to their safety, energy density and high number of charge cycles. We have come to this, thanks to the heavy decline in price per kilowatt hour of LIBs, over 90 % since their first commercial use (Ziegler and Trancik, 2021)

Main components needed for a functional LIB cell are cathode, anode, electrolyte, separator and an enclosure. In addition to these, safety components and outer labelling are used.

Cathode is marked as the positive (+) terminal of a battery and anode is marked as the negative (-) terminal. Together they are considered electrodes. They are usually a thin sheet of a highly conductive metal, like copper or aluminium with coatings to improve their characteristics. The polarity difference between the electrodes attracts negatively charged electrons to flow towards the positive side.

Electrolyte is used to carry ions between the cathode and anode. It is often liquid or paste like substance, but solid-state electrolytes are expected to take over in near future. This would result in a solid-state battery, which is lighter, longer lasting, less prone to catch fire, and does not leak (Pistoia and Pistoia, 2014).

Separator is set in the electrolyte, between electrodes to prevent the electrons from using the shorter path and avoid short circuiting the electrodes. Lithium-ions can move freely through this plastic or ceramic sheet. (Warner, 2015)

Tabs are the passthrough to the otherwise sealed cell construction. They connect to the terminals, which are then connected to the rest of the circuit. The enclosure provides a housing to keep the components together, separating them from the outer world. Casings are made of plastic for its ability to withstand impacts and low weight. Other options are aluminium, or nickel coated steel, which have higher rigidity than plastic. Lids permanently close off the open ends, making the integrated terminals the only path in and out of the battery. If the casings are made by deep drawing, the bottom is already sealed.

There are different sized and shaped cells to fit the intended use. Cell types in vehicles demand safety, high capacity, long life and the ability to be recharged. Figure 2 shows battery cell types used with EVs and some of their stand-out features.

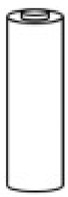
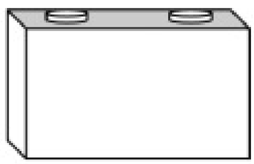
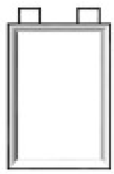
Cylindrical cell	**Prismatic cell**	**Pouch cell**
		
• Small size (e.g. 18650 type (ø 18 mm, height 650 mm)) • Hard casing • Low individual cell capacity • Build in safety features • Comparably cheap	• Hard casing • Large size • High individual cell capacity	• Soft casing • Large size • High individual cell capacity • Geometrical deformation during (dis-)charging

Figure 3. Different cell geometries used with EVs (Zwicker, Moghadam, Zhang and Nielsen, 2020)

The following three subsections go more in-depth into these cell types. As we will see, each of these carry their own advantages and limitations and have thus seen automotive use in recent market vehicles. No one geometry is dominating the BEV area, as of now.

2.1.1 Cylindrical cell

A cylindrical cell has its components enclosed in a cylinder-shaped metal can, made of steel or aluminium. This type of battery cell is similar in exterior shape to AA batteries used in household electronics. Inside, sheets of cathode, anode and separator materials are rolled together, with electrolyte in between. Visualisation of a cylindrical battery and its insides is presented in figure 3. A more detailed showcase of the positive terminal is shown in figure 4.

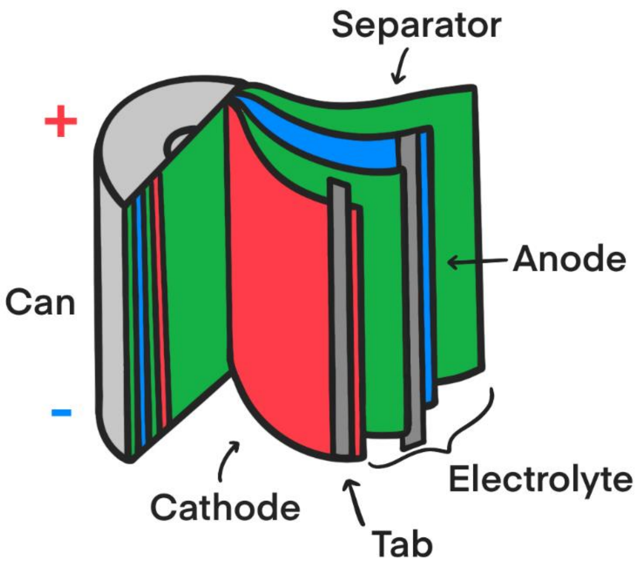


Figure 4. Open cylindrical cell

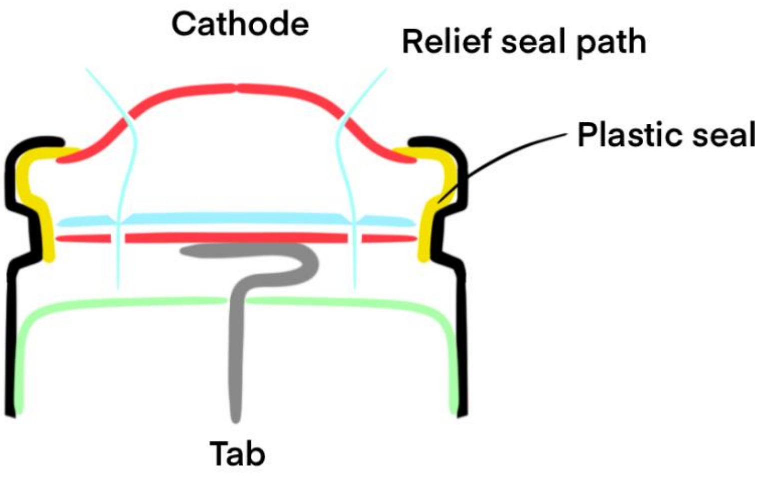


Figure 5. Lid in a cylindrical cell

Apparent welding connections in a cylindrical cell include tabs from cathode to positive and anode to negative terminal. These are the pathways away from the sheets into the terminals. The ends of the battery are closed off, to keep the components inside. The bottom is done during the manufacturing of the can, as it is deep drawn. The top is used as the access point to place the components and the electrolyte inside, permanently closed off once the cell is otherwise good to go. The positive side lid contains a safety vent, and material to conduct and seal. The full design may vary between manufacturers.

Stacking items with circular cross sections will result in unused space. As Joseph-Louis Lagrange proved in 1773, the maximum density of stacked circles is about 91 % (Hai-Chau and Lih-Chung Wang, 2010). With the contradicting desires for maximizing capacity and minimizing volume taken, any wasted space is a loss. That said, a cylinder's ability to maintain pressure from inside and out is stronger, when compared to enclosures with flat walls. The circular shape also prevents swelling and radiates heat well. Cylindrical cells are the most mass-produced cell type as of now and as a result, very cost effective to purchase.

Tesla's first mass market BEV, Model S (2012-) has a battery pack made of 18650-type battery cells. The first four digits represent the cell's exterior dimensions: 18 mm in diameter and 65 mm in height. The last digit signals that it is a cylindrical cell. The battery pack of the P85 model version has 7104 18650 cells split into 16 modules (Warner, 2015). The original model was rated with a range of 430 km on a charge.

2.1.2 Prismatic cell

Prismatic cells contain their components in a box shaped enclosure. The casing can be metallic or plastic, with terminal tabs located on the same side. Sheets of cathode, anode and separator are rolled into multiple layers with electrolyte in between. Resulting shape forms a structure named flat jelly roll. An open prismatic cell is shown in figure 5.

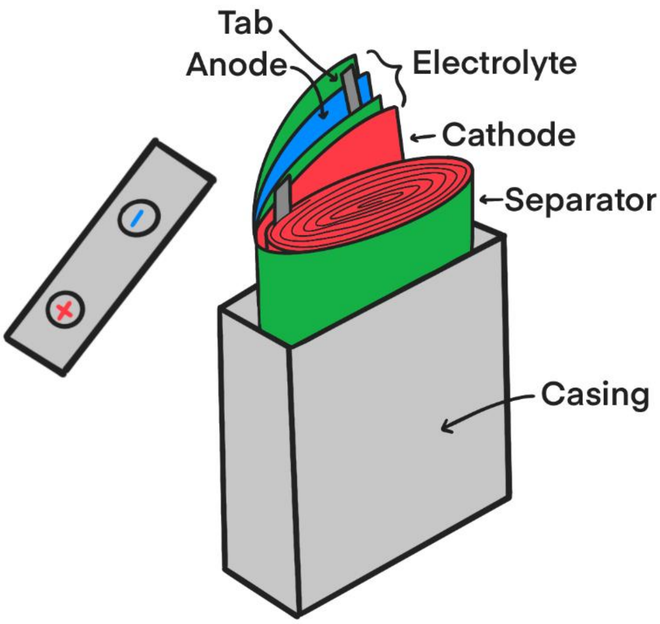


Figure 6. Open prismatic cell

Like with cylindrical cells, tabs are joined to the sheets of electrode, but this time both tabs point the same direction. The casing is either deep drawn or impact extruded, so visible seams are not apparent. Stacking prismatic cells is easy thanks to their flat sides, and wasted volume is minimal. Large flat sides are also good for radiating the thermal build-up away from the cell. Prismatic cells are larger than cylindrical and pouch cells and have a high cell capacity. This means less cells are needed to make a module or a pack, resulting in less connections, reduced assembly times and less likely defects.

On smaller electric vehicles, the size might prevent optimal utilization of the available space. Less cells in a pack means less redundancy. The death of a single cell might make the whole module unusable if the cells are connected in series. The boxy shape of prismatic cells is also susceptible to swelling from the accumulation of gases.

There is a concern of roll movement, which can result in internal short circuits. This is already known to potentially happen with 18650 cylindrical cells, and the jelly roll is less constrained in a prismatic enclosure. The movement in prismatic cells is not well enough researched aspect as of yet. (Berg, Soellner, Herrmann and Jossen, 2020)

As an example of automotive usage, the BMW i3 (2013-2022) electric cars use prismatic cells made by Samsung SDI. The battery pack has 8 modules and each module 12 cells in series configuration, so 96 cells in total. (SamsungSDI, 2020.) In its first model years the battery had a designation of 60Ah and about 120 km of range without the available range extender.

2.1.3 Pouch cell

In a pouch cell, the electrodes and separator are rolled into a thin package of multiple layers with electrolyte in between, like in a prismatic structure. Alternatively, only a single layer of each electrode can be used, with conductive current collectors beside them. The electrolyte in a pouch cell is a polymer layer, hence the alternative name “laminate cell” (Warner, 2015). Pouch cells do not have rigid casings. The components are sealed in foil instead. This makes them a lot more susceptible to damage, such as punctures. They can also bend from exterior forces or swell from built up gases. On the upside, pouch cells weigh less. The surrounding structure in the module is built to support the cells to ensure stress free operation. Example of a single layer pouch cell is shown in figure 6.

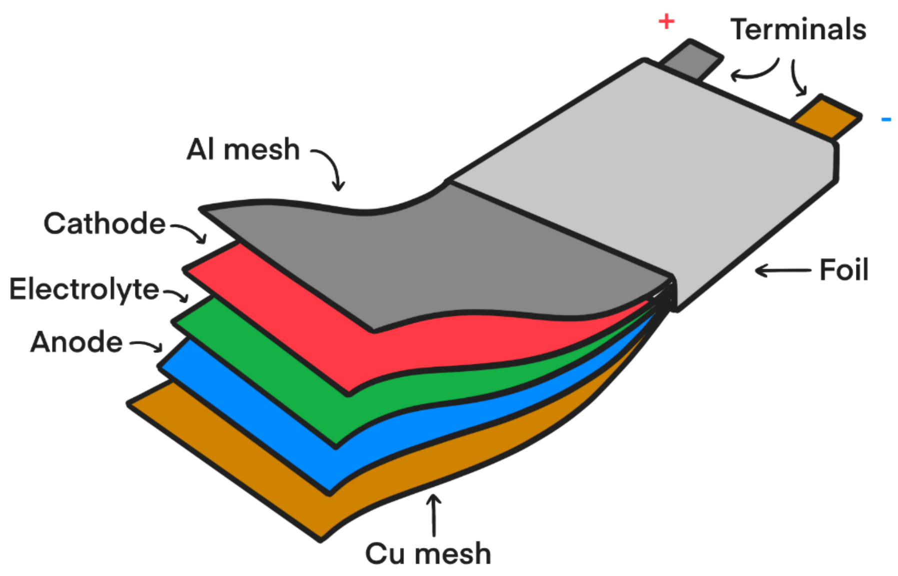


Figure 7. Open single stack pouch cell

Pouch cell has a highly cost-effective enclosure, which also takes up very little space, has excellent heat dissipation and stacks well. With no metallic can, the number of connections is minimized. In its simplest form, the tabs from current collectors can act directly as the terminals.

Pouch cells are appropriate when the battery is allowed to take up a large area, but the thickness is a concern. They can also be made in a large variety of sizes. These factors are why batteries used in smartphones are exclusively pouch-cells.

Pouch cells are also used in Volkswagen's ID3 (2019-) and other electric cars in Volkswagen AG that share the same platform, labelled "MEB". Each module contains 24 pouch cells. Number of modules varies between models, the 77-kWh pack includes 12 (total 288 cells), with a rated range of 550 km. (Volkswagen, 2019.)

2.2 Construction of a battery module

In BEVs, battery cells are grouped into framed modules. The module has to connect the cells both physically and electrically. A module is usually the smallest replaceable unit, because each mechanical connection between cells would have a chance to loosen under vibrations. Cell terminals are either welded to one another with tabs, or to a bus bar which collects the power from all the cells to a single highway. Depending on the desired application, the cells are connected in series, parallel or a mix of the two; a series connection increases voltage, parallel connection capacity. (Warner, 2015) A battery module is pictured in figure 7.

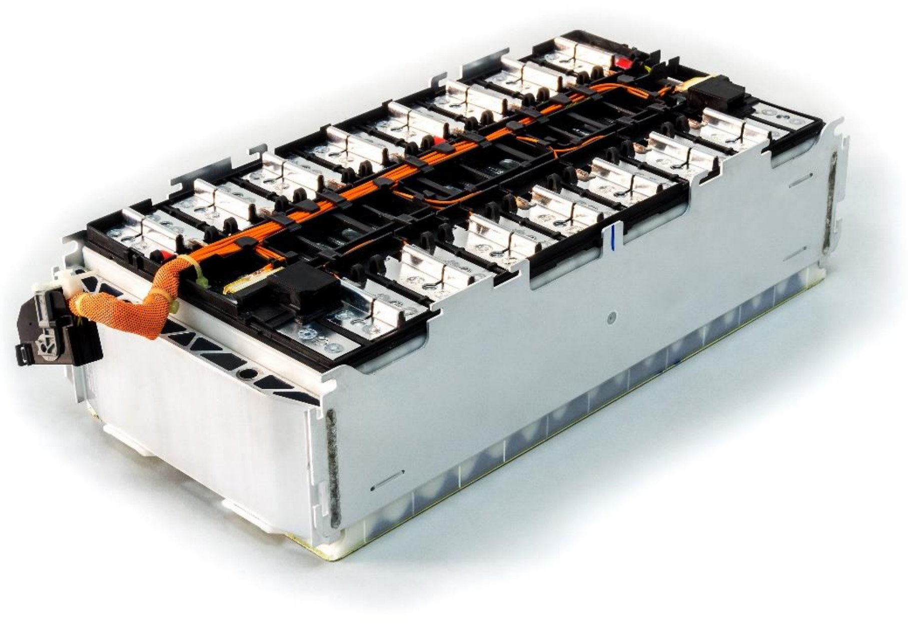


Figure 8. Battery module with top cover removed (© Nischaporn / Adobe Stock)

Car manufacturers can decrease design and production costs later down the road by designing a module that fits different segments of passenger cars. The number of modules is usually the main variable between different battery configurations. The packs can be highly similar in construction, higher capacity versions are just expanded to fit additional modules.

2.3 Construction of a battery pack

Battery modules and the support structure connecting them forms a battery pack. Support structure consists of the framing, bottom and top plates, and a bracket for modules (like seen in Figure 1). The battery management system, BMS is responsible for the control of charging, discharging, safety and thermal monitoring of the pack. Insulation, a cooling system and framing are also mandatory to compose a well-functioning battery pack. Connections at the pack level are mostly done by using mechanical means. They are able to withstand higher forces and can be disassembled for maintenance purposes. It is mainly the frame beams and reinforcement ribs that are welded in place.

Depending on the cell type, a battery pack consists of thousands (cylindrical), hundreds (pouch) or under a hundred (prismatic) cells. Like cells in modules, modules in the pack can be electrically connected in series or parallel to balance between power and capacity. The configuration is represented by using a designation, which tells the number of cells and modules used in series and parallel. For BMW i3 referred earlier, it is 12s8s; 12 prismatic cells in series and 8 modules in series (Warner, 2015). Because no parallel connections are used, each individual cell has a capacity of 60 Ah.

Aluminium is a great candidate for the frame material. For starters, it offers good weldability, corrosion resistance, tensile strength, lack of magnetism and low weight. It is also easy to manufacture, post-process and coat. There already exist some car frames, which are made of aluminium, such as the frame of Audi A8 D2 (1994-2002). (Lukkari, 2001)

When cars began getting electrical drives as part of their hybrid system, the additional batteries were placed anywhere that had available space. That’s because these vehicles were still designed with typical internal combustion engine architecture in mind. Added batteries were commonly placed below seats, or under the trunk floor. The battery pack of a fully electric vehicle is large, heavy and contains plenty of framing, thus it can be designed to act as a reinforcing element integrated in the bottom of the vehicle's chassis. Its purpose as rigid element is so important that mechanics are advised against entering the vehicle when the pack is removed, as to not stress the spaceframe. The battery position brings the centre of gravity low, which is already sought after in passenger cars to achieve better driving dynamics. Figure 8 shows the typical positioning of a battery pack and electric motors in a BEV.

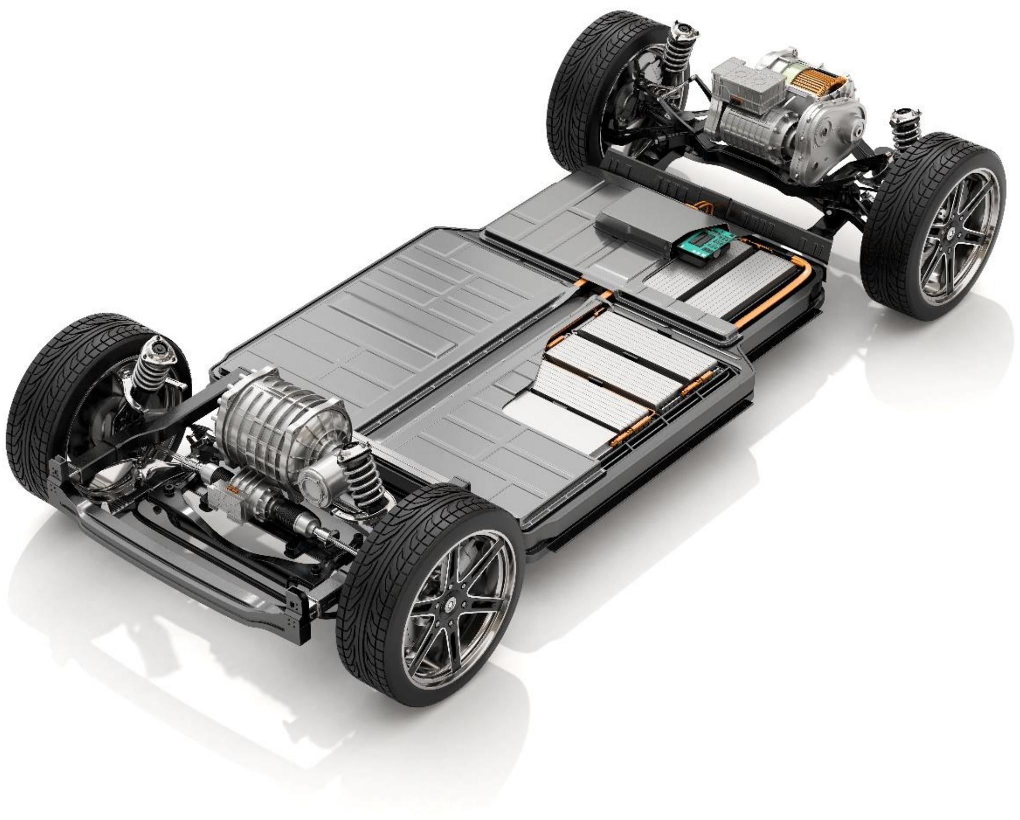


Figure 9. BEV platform with cutaways showing the LIB modules (© chesky / Adobe Stock)

Battery pack is made of many cells instead of one big cell to improve thermal management, reduce development costs, achieve higher voltages thanks to series connection and add redundancy; if one cell dies, BMS can cut it off from operation. With a large number of cells, the end user will not even notice the difference in the loss of capacity. There are lots of cell suppliers available and their ability to mass produce commonly sized cells is high.

2.4 Welding in battery production

There are options when it comes to joining components together. These are often categorized as thermal, chemical and mechanical connections. All of these are used to some extent with batteries. Welding, categorized as thermal, is a joining method that uses heat, pressure, or both to form a rigid and permanent connection between the joined parts. The union can be created by bonding the welded edges together or with an additional filler material. Welding processes can be categorized as fusion or solid-state methods. Welding is favoured in connections, where there is a worry of rigidity loss from vibrations and varying external forces. It takes less space than most mechanical connections, tends to be more cost-effective to put in place and is easier to automate.

Soldering is another way to connect electrical components. Difference to welding is that the joint is made by a filler material with a lower melting point compared to the main material. Heat input is kept low enough to only melt the solder. Soldering is mainly used to direct electricity from one component to another, in components where the current is low, such as microchips. It is not strong enough to form a load bearing connection and its ability to withstand vibrations is weak.

Battery component size varies from small metal plates in cells to beam support structures in the finished pack. There are also different materials and coatings used on them to achieve certain qualities. Care and preciseness must be taken when welding sensitive components, while other might have speed of the process or strength of the weld as the top priority. It should come as no surprise then that no one process is used across all the needed connections. Let’s consider the fundamentals of some currently used welding processes used with batteries.

In laser beam welding (LBW), a laser is focused on the intersection of the parts being joined, piercing and melting them. The process is precise, powerful, fast and highly used today. Lack of tool wear because of lack of contact with the work material, and the need for little post-processing or preparation (mainly fitting the components close enough to each other) makes the procedure ideal for automation. The process is highly variable too. For example, a way to limit the heat input on thin materials, is to beam the laser in pulses.

Fusion-arc processes, like metal inert gas (MIG), metal active gas (MAG) and tungsten inert gas (TIG) weld with heat created by an electric arc between the electrode of the weld gun and the work material. Sometimes, a filler material is used to create a larger volume of weld.

Ultrasonic welding (USW) has a sonotrode tip or disk, which causes linear oscillation between the materials at a frequency of 10 000 – 75 000 Hz (Kalpakjian and Schmid, 2014). The friction and movement between the materials causes them to join. The movement is done in a small area, so on larger surfaces the resulting weld nugget is comparable to a spot weld. Usually, the heat from friction does not get high enough to melt the materials, so the process occurs in a solid phase. USW is also suitable for welding a wire to a surface.

In resistance spot welding (RSW), two electrodes are pressed on the opposite sides of the work materials. A current between is created, forcing it to pass through. This produces a spot weld nugget up to 10 mm in diameter. RSW is used for lap-joining sheets, and it can be done on a fixed station or with a carriable tool. RSW is in high use in automotive industry, because the body of a car can easily have over 10 000 spot welds in it.

Friction stir welding (FSW) has a rotating tool, which traverses along the butt joint of the work materials pressed together. The tool softens the materials via friction and mixes them. This process, invented in 1991 shines with its environmental friendliness. It is energy efficient and doesn’t emit harmful emissions. (Mishra, De and Kumar, 2014)

An emerging solid-state method that has shown capability with dissimilar materials is magnetic pulse welding (MPW). It functions by accelerating and colliding the components using electromagnetic forces, causing the surfaces to adhere. Alternative joining methods with impact as the principle exist, but compared to something like explosion welding, MPW has a higher degree of control and safety. Using impact-based methods, the time to bond is short and heat input is low and localized to just the interface. (Khalil, Marya and Racineux, 2020) The welded area is all of the contact surface, which is more than what can be achieved with most other processes.

Hybrid welding combines laser welding and arc welding. The aim is to counteract the limitations of each. LBW alone can't close gaps because of the dense effect area but reaches high depths. Heat input of MIG is focused on a wider area, but the depth of heat transfer is limited. MIG filler material allows larger gaps to be closed. Hybrid welding is also reported to reduce porosity and cracking upon solidification. (Rao, Liao and Tsai, 2011) LBW alone is more prone to them, because of fast cooling.

There are other processes that have been used to limited success with battery components, but the mentioned processes seem the most promising. These welding processes are grouped and compared in Table 1. References used to form it are shown in the table.

Table 1. Common welding processes used with batteries compared in different areas

Process	Heat	Speed	Cost of machine/to run	Automation suitability	Weld result	Affected area	Joint type	References
FSW	Low	Med	High/Low	High	Continuous across joint line	Low	Butt, lap, spot	Kumar, Yuan and Mishra, 2015, Zwicker, et al., 2020
Arc welding	High	Med	Low-High/Low	High	Continuous across join line	High	All	Kalpakjian and Schmid, 2014
Laser-arc hybrid	High	High	High/High	High	Continuous across joint line	Med	All	Olsen, 2009

LBW	Low	Very High	High/Med	High	Continuous across joint line, spot	Low	All	Appendix 1, Zwicker, et al., 2020
MPW	Low	High	High/Med	High	Continuous over surfaces	Low	Lap	Khalil, Marya and Racineux, 2020
RSW	Low-Med	High	High/Low	High	Spot	Low	Lap	Kalpakjian and Schmid, 2014, Zwicker, et al., 2020
USW	Low	High	High/Low	High	Spot	Low	Lap	Zwicker, et al., 2020

As seen in the table, all processes gain strong remarks on the suitability for automation. They would have not reached their popularity in this area of manufacturing if that was not the case. Lot of the processes involve expensive machinery, but fusion welding ranks low to high, because man operated welding equipment is inexpensive by comparison. As you start to automate the process via servo controlled robotic arms with three-dimensional positioning of the welding head, costs begin to climb. Ranking speed is somewhat misleading, as the resulting weld profile is highly different between some of the processes.

3 Challenges in welding processes imposed by batteries

This section will review some of the topics that add to the difficulty of manufacturing when looking to achieve the wanted battery construction.

3.1 Dissimilar materials

With the importance of efficiency in contemporary products, there is a great interest in making components out of multiple materials to apply wanted properties in desired areas and use lighter materials in less critical areas. From industrial standpoint, this adds complexity in manufacturing. It is easier to weld components together when they are made of the same material. To combat these challenges, recent research has been focusing on this area to ensure safe and secure components made from more than one material.

Martinsen, Hu and Carlson explain well the concerns of joining materials with different properties: “The incompatibility on chemical, thermal and physical levels can create problems both for the joining process itself, but also for the structural integrity of the joints during the use phase of the product.” (Martinsen, Hu and Carlson, 2015) For example, differing thermal expansion characteristics result in shear stress upon solidification. (Braunovic and Slade, 1999) With this, the parts may end up under residual stresses.

In a battery, materials are chosen to best achieve the desired product, an electrochemical storage. As a result, different metals have to be chosen, but they still need to interact with each other. A common pair of materials in batteries is copper and aluminium, used in electrodes, tabs and terminals. Individually, both of these materials are considered weldable. The melting temperature of aluminium is 660 ºC and copper is 1085 ºC. The oxide layer of aluminium melts at 2000 ºC. This difference makes the use of traditional fusion based methods troublesome. High heat input can result in a weak joint, because of emerging intermetallic compounds (IMC) (Zhao et al., 2022). Areas involving IMC are hard but brittle.

They occur even if the melting point of the base materials wasn't reached. Figures 9 and 10 show the apparent IMCs that emerged from their respective welding processes during a heat treatment.

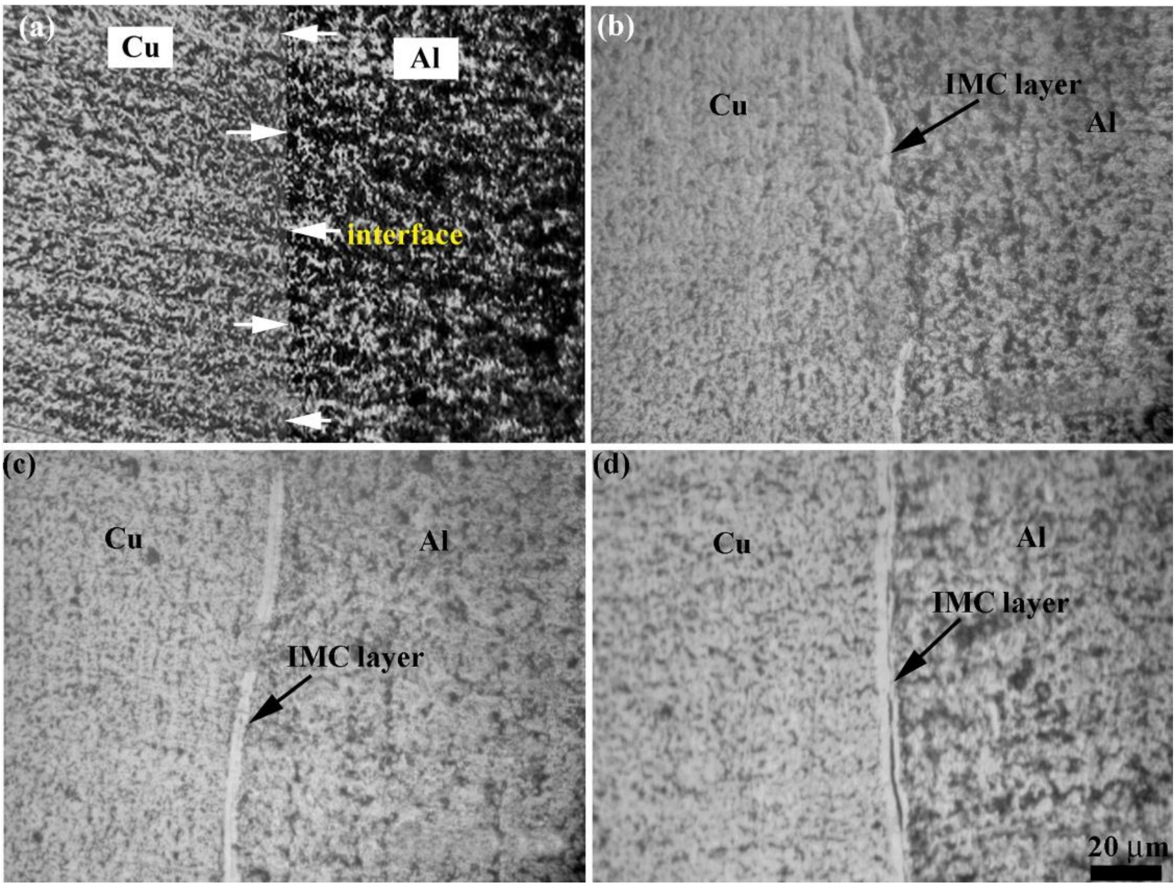


Figure 10. Friction welding and heat treatment at 300 ºC for 6 (b), 12 (c) and 24 (d) hours (Cheepu and Susila, 2020)

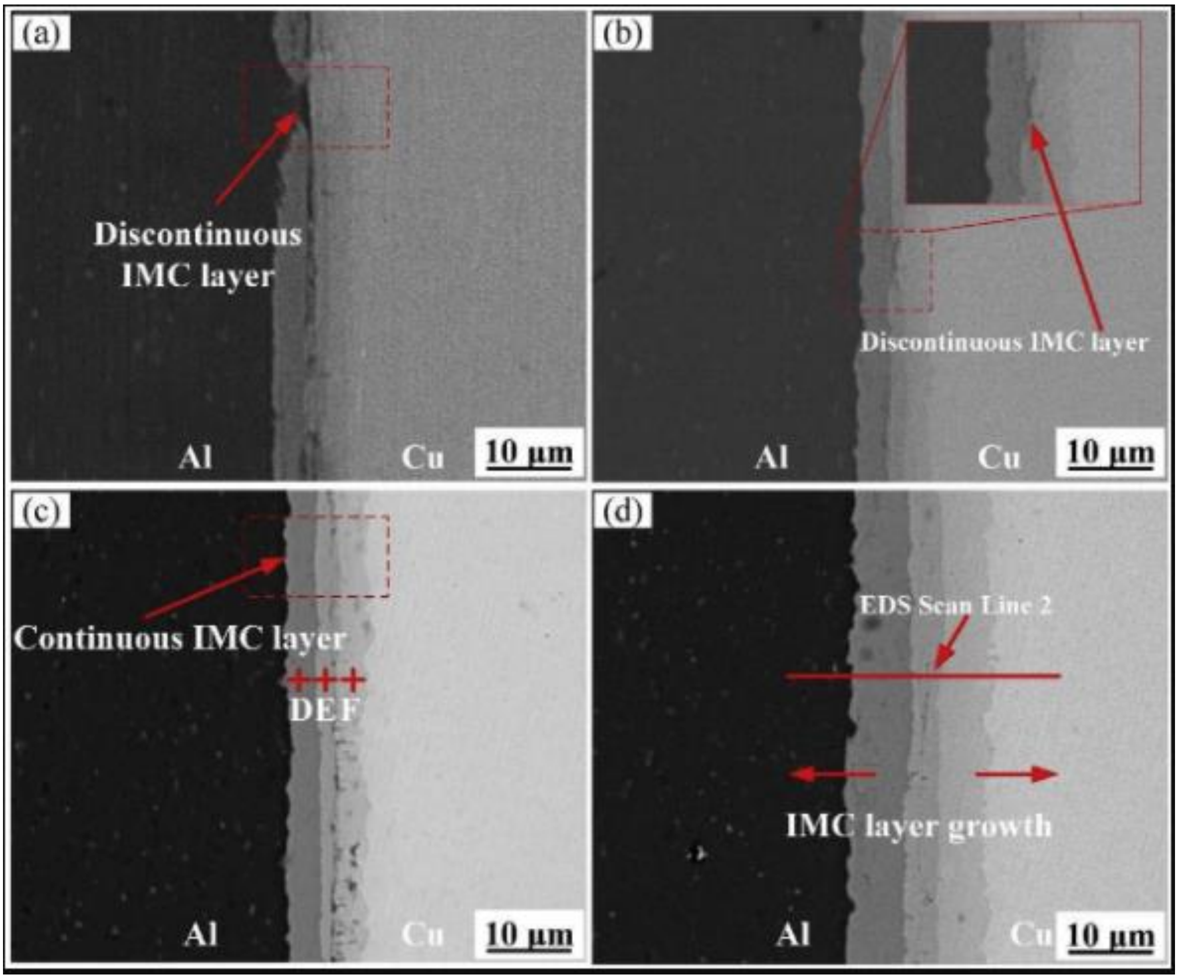


Figure 11. USW and heat treatment at 400 ºC for 6 (b), 12 (c) and 24 (d) hours (Ao et al., 2019)

Solid state methods are still favoured, as they don't require high operating temperatures to form a bond. Because of its high energy density, LBW can be an optimal choice too. Figure 11 shows a copper tab welded to an aluminium busbar using LBW, and the effects of increasing the power output.

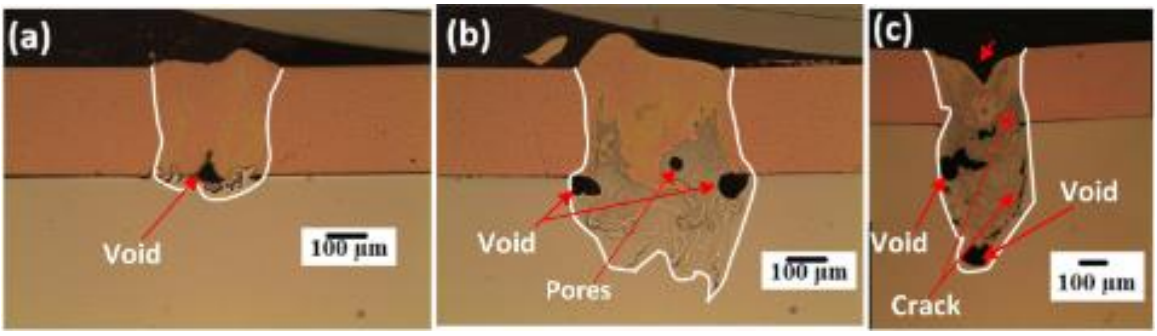


Figure 12. Macroscopic view of dissimilar material battery joint done with LBW (Kumar, Masters and Das, 2021)

Even when viewed at macroscopic scale, visible to the naked eye, it is seen that there is no straight interface between the materials. Instead, there is a mix of the materials around the interface. The amount of mix depends on the power used. Because of the mixing, material properties in the region around the interface cannot be those from copper or aluminium alone.

3.2 Changes in microstructure

Microstructure refers to the material viewed on a very small, microscopic scale. At this level, individual grains of the material can be viewed. Microstructure is highly important to consider on metals, as it has an effect on the resulting properties, like electrical conductivity and tensile strength.

Porosity means a void of space in an otherwise solid segment of the weld. The microstructures of different battery components face changes in their microstructures under typical cycles of charging and discharging. Yoon Koo Lee studied this and found that introduced porosity in the cathode is linked to degradation of the cell both in both electrical and mechanical properties (Lee, 2022). Fusion welding processes, especially LBW can introduce porous segments into the weld volume. Ways to reduce porosity do exist, like preheating the workpiece, or increasing current. The larger weld pool from hybrid welding allows the trapped nitrogen bubbles to escape the volume, leading to a significantly reduced porosity, at least in an aluminium alloy (Huang, Hua, Wu and Fang, 2019). Figure 12 displays porosities and a clear reduction in their appearance, upon increasing the used current (Yang et al., 2022).

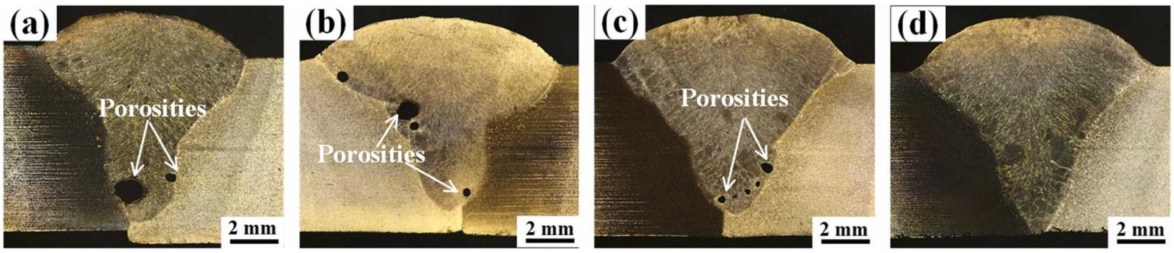


Figure 13. Porosity in laser arc hybrid welding (Yang et al., 2022)

With fusion welding, heat affected zone (HAZ) is the material volume around the weld location which didn’t melt, but still received a good amount of the introduced heat. These areas go under microstructural changes, as do the melted and solidified areas at the heart of the weld (Kalpakjian and Schmid, 2014). Amount of HAZ generated depends greatly on the used welding process. High energy density processes, like laser welding localizes it’s beam in a miniscule area, with very little heat conduction to surrounding volume, resulting in low HAZ. To ensure that manufacturing doesn’t result in faster aging batteries than the materials used would suggest, changes to the microstructures must be kept to a minimum.

3.3 Component size

In the worst-case scenario, joining components can destroy them. This results in wasted efforts and material used to manufacture that component. Electrode foils can be thinner than one tenth of a millimetre, so they cannot withstand excessive mechanical forces. Tabs connecting electrodes and terminals are under a millimetre thick. Their width depends on the cell type, but they generally aren’t wider than a centimetre. Such small components would deform entirely under large heat input welding processes, and as the second law of thermodynamics tells, they would not reform fully back to their original shape upon solidification. Not only wrong processes, but even accepted processes with incorrect parameters like current, pressure or heat can be detrimental to the components being worked on.

Small component size requires the need for precision. To achieve this, scanners are used in conjunction with the welding heads to inform the system of the positioning, and robotic joints with minute steps to meet it.

3.4 Sealing

Sealing the battery cell serves many functions. Electrolyte is a harmful liquid if digested, and the loss of it makes the battery a fire hazard. Therefore, the casing must be designed to keep the liquid substance inside. Weld alone is not enough, so a softer material like plastic is used to aid with sealing. Solid-state battery, where the electrolyte is solid instead of liquid or paste, is expected to take over in the future. This could add some leniency in sealing requirements.

When the lid is applied, the encasing will then on be permanently sealed. Therefore, no foreign substance like dust is able to enter or leave the cell. Small particles can cause short circuits inside the cell or abrasion on the separator layer. The closing procedure must be done in an environment designed to trap these particles elsewhere, and the procedure itself must not generate them. It also has to leave the plastic seal uncompromised. For best results, the weld has to be continuous along the seam.

Lids used to be applied by crimping, but after Sony had to recall hundreds of thousands of batteries due to risk of combustion in 2006, it was found that crimping caused small flakes of nickel plating to end up inside the battery, potentially short circuiting the cell. Cylindrical battery manufacturers then went on to use laser welding to close the lids. (Warner, 2015)

3.5 Electrical and thermal properties

Joints designed to be part of electrical circuits must be low in resistance. As mentioned in dissimilar materials, high heat input can result in IMCs. The IMC has 5-8 times the resistance of aluminium or copper (Kuryntsev, 2021). This means that the resulting joint increases the amount of energy wasted into heat in the electric circuit. Mechanical fatigue and stress from charge/discharge cycles will also play a role in wearing down the joint, increasing resistance. Ultimately this will decrease the range of what the BEV should have in theory. Heat generation in a battery pack is unavoidable, even with flawless joints. Still, excessive heating can degrade or damage the battery, even result in flames (Zwicker, Moghadam, Zhang and Nielsen, 2020). Many battery-powered items, even outside of automotive use are designed to stop operation if an overly high temperature is detected.

3.6 Component sensitivity

When welding partially or fully finished batteries, they should not be subject to additional stresses to ensure the operating life they are designed to have. Should residual stresses end up in the joint after the welding procedure is finished, they can result in a premature fracture of the bond. Some welding has to be done on top of already finished battery cells. The process must not pierce the lid of the joining procedure to maintain the sealing. This can be controlled on some methods by using the correct parameters, like shown in figure 13.

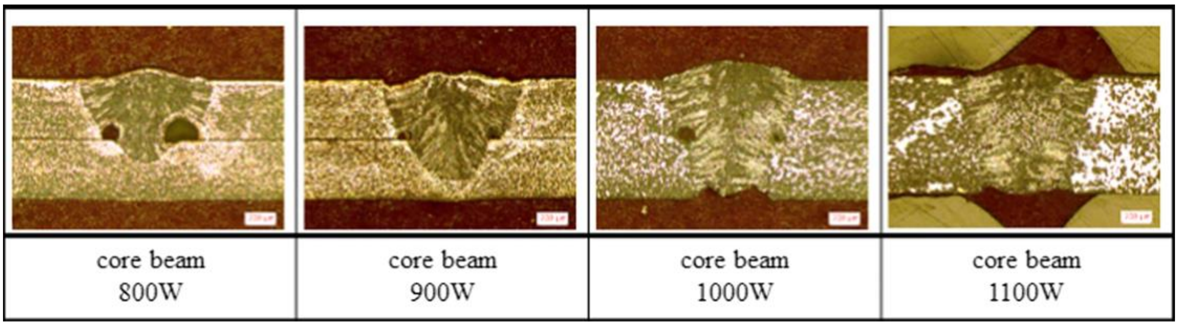


Figure 14. Al-Al joint with varying LBW power outputs (Cha and Choi, 2022)

As is seen from the figure, the lower sheet of aluminium is not pierced through if the power is kept low enough.

3.7 Accessibility

Access to the weld location isn’t always ideal. Welds in the battery tray can be in all directions, so locating them to the welding head requires either moving the assembly to a fitting orientation, or the use of a repositionable welding head. Should the joint be in a hole or a crevice, the welding has to be done from a remote location. Several processes require access to both sides of the work pieces. When welding in the lid for example, it simply isn’t possible.

Some processes require a set distance from the joint or enough clearance around the joint to operate properly. Fusion based methods involve a large welding head, especially if mounted on a robotic arm. LBW is dependent on the focal point of the mirrors to deliver the correct intensity, so the distance is adjusted accordingly. The inspection area of the on-board scanners is also reduced, should the welding head be placed right next to the joint.

3.8 Quantity

Depending on the cell geometry, a battery pack of a single battery electric vehicle can have thousands of cells. As a result, production rate for the cells, modules and packs is large. In 2019, Volkswagen claimed that they will produce 500 000 battery packs a year in one of their plants alone (Volkswagen Group News, 2019). To meet such claims with consistent quality, production capacity must be high, preferably automated.

The amount of work needed is partially dependent on the cells used. Figure 14 represents battery packs composed of cylindrical and prismatic cells.

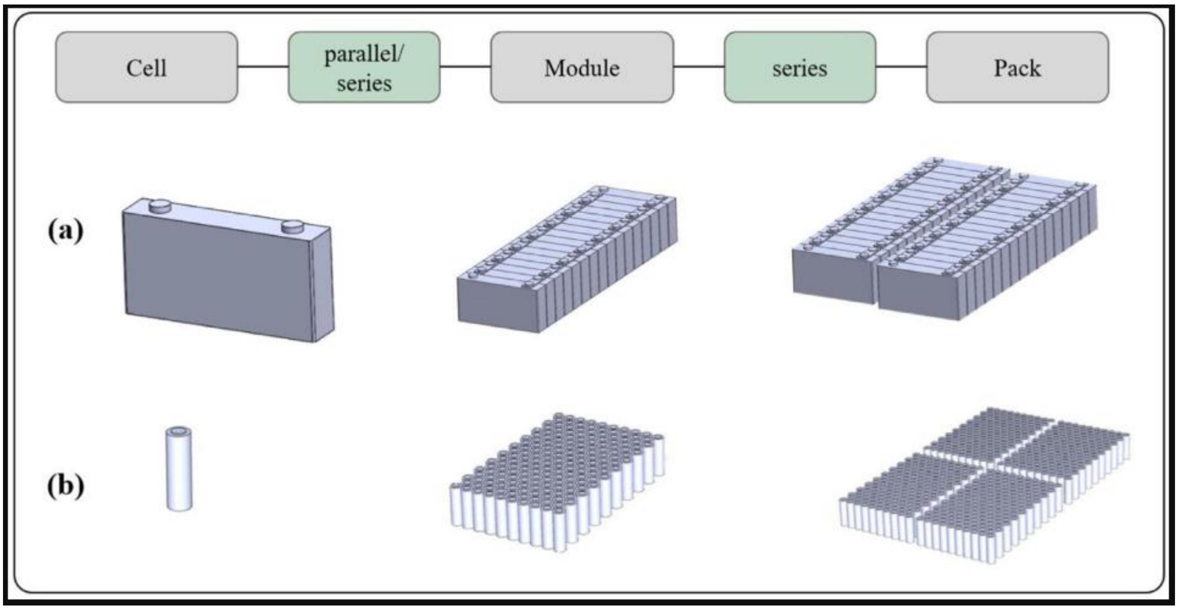


Figure 15. Battery packs composed of prismatic (a) and cylindrical (b) cells (Zwicker, Moghadam, Zhang and Nielsen, 2020)

Lot of cylindrical cells and therefore connections are needed to form a full battery pack. Complexity tends to creep up in such a case. In return, a smaller foundation allows for higher flexibility in design, whereas larger cells are something that more likely has to be built around on. Their stand-out feature is the low number of connections needed. (Zwicker, Moghadam, Zhang and Nielsen, 2020)

3.9 Coatings

Some battery components are introduced to coatings. For example, electrodes can be coated with carbon in an effort to increase performance and delay aging (DOBERDO et al., 2014). Coating materials complicate welding, so they should be applied after the joining, or the space saved for the joint of another component should be left clear.

3.10 Reflection

Reflective surfaces pose an issue to processes which involve lasers. Reflection lowers the energy absorbed to the work materials, decreasing efficiency. It can also cause a safety hazard to the surrounding area; the beam is not visible to the naked eye. Not only the surface, but also the molten pool of metal reflects some of the beam. According to the head of LUT laser laboratory, contemporary LBW machinery have the ability to recognize reflection coming back into it and shut down if a threshold is exceeded.

3.11 Joint type

Joint types used with batteries vary wildly; lap joints for tab-sheet, tee joints for reinforcement ribs and butt joints for lid-to-casing joints. Different welding processes fare better than others with certain joint types and some are simply incapable of producing a fitting result for the required connection.

4 Optimal welding processes

In this section, applicability of different welding processes is considered based on the challenges reviewed earlier. This allows us to estimate the severity of the challenges.

Summarizing from section 2, we know that weldable connections for a LIB cell are tabs to electrodes, terminals and lids to enclosures. In modules, cell terminals are connected with tabs or directly to busbars. Alternatively, they are connected to each other. Pack level connections involve structural strength bs to t improving support frames, ribs and panels.

The challenges listed in the previous section are some of the apparent ones. It seems that most welding done with battery cell components should be done using solid-state methods, with laser-beam welding being one of the few fusion processes that is precise enough.

4.1 Tab-to-sheet

Tab-to-sheet or tab-to-foil connections involve dissimilar materials, sensitive components and the requirement for minimal loss of conductivity. They are welded separately from the other components, so access to all sides is good. This lap joint like connection and its demands suit ultrasonic welding. The surface movement in USW breaks the problematic aluminium oxide layer yet the heat generated by friction generally doesn’t reach the melting temperature of copper or aluminium, so metallurgical changes are minor. No surprise then, USW is in extensive use regarding these components. The process can create the weld in under a second and modern machines can detect defects that occurred during the procedure.

Laser beam welding is also a good option for this connection. It is fast in operation, good with challenging geometries, suits automation, but is expensive and hindered by reduced absorption to the reflective materials, which copper and aluminium are. With correct wavelengths used, fiber laser welding can produce good results. Switching to a pulsed FLW reduces heat input, decreasing the amount of IMC created. Some other variations of LBW are still under research. For example, green laser welding has proven its feasibility for aluminium-copper joints, but still requires further investigation in long-term sustainability and IMC forming (Kaufmann et al., 2023).

Resistance spot welding also seems usable in this area, but some issues are apparent. RSW is suited for connecting thin sheets together and needs good access to both sides, which in this case it has. However, both copper and aluminium have good conductivity, so in other words, low resistance. As a result, high current is needed to pass through the materials in order to form the weld nugget between. Aluminium in RSW requires a high electrode force, resulting in inconsistencies and reduces the expected life of the RSW electrode (Chen, Liu and Ni, 2019). RSW produces a singular spot weld, so the sheet and tab can have some separation between each other around the nugget.

Magnetic pulse welding also has potential for tab-to-sheet connection, provided that the thin foils are not torn in the impact. The process has proven good results with copper-aluminium connections, (Psyk, Linnemann and Scheffler, 2019) but the usage has not taken off in production as of yet.

4.2 Tab-to-terminal

Tab-to-terminal connection is similar to tab-to-sheet. The cathode tab can be different from the one already connected to the sheet. It is easier to connect the terminal tab and the sheet tab later down the line, as they can be the same material. The total length of the tabs exceeds the length required to give more leeway in the lid application.

The anode side in a cylindrical cell introduces the difficulty of access. When the jelly roll is placed into the casing, the only access to the tab is through an opening in the middle of the roll. A pointy welding head, or remote welding is required, if welded from the side of the tab.

The tabs are bent, so that they are parallel with both the terminal surface and the electrode foils. (See figure 4.) Resulting contact area with the tab and the terminal is quite small, so precise processes are required. USW, LBW and RSW are able to form the weld with minimal changes to the surrounding area.

4.3 Lid-to-enclosure

Lids, or caps seal up the battery, as well as provide a safety vent that relieves built up pressure if needed. During the closing, air from the battery is removed to create a vacuum inside. It is important that the connection is free of gaps, to maintain the vacuum.

Most lid connections are done with welding. Formerly, a crimping process was used, but as explained earlier, a recall caused by this process shifted the production towards LBW. It offers high energy densities and precise positioning. The welding occurs from the top side, following the seam between the lid and the case. On cylindrical cells the seam is a circle, on prismatic cells, a rectangle. Penetration cannot be deep, as below the top part of the lid are insulation elements.

Complex geometry and sensitive area around the seam don't pose an issue for LBW, making it a good candidate for the connection.

4.4 Terminal-to-busbar & tab

When connecting terminals to components outside the battery cell, the cell itself is already finished. This complicates the joining procedure, as excessive pressure to the cells is to be avoided. With cylindrical and prismatic structures, the cell is underneath, so processes applying large pressure from above are not favourable. There is also no access to the bottom side of the weld location.

It seems logical to use processes like micro-TIG or LBW. They only need to access one side of the workpiece and with correct parameters, the depth of penetration can be limited to the interface of the parts.

A variation of LBW, laser wobble welding has shown its potency in a previous study when welding a thick aluminium busbar to thin steel tabs. The method created only a small volume of IMC. (Psyk, Linnemann and Scheffler, 2019)

While not the first process to come to mind, USW is not out of the question for this application. The battery cells of Nissan Leaf and Chevrolet Bolt EV 2nd Gen were joined this way (Zwicker, Moghadam, Zhang and Nielsen, 2020).

One alteration to using tabs to connect to busbars is doing it with wires instead. The wire is attached using ultrasonic means. Tesla used wire bonding in Model S P85 (Zwicker, Moghadam, Zhang and Nielsen, 2020). The wires act also as fuses thanks to their small diameter.

4.5 Battery pack framing

Battery pack itself, framing the modules is usually an all-aluminium construction, with large welds when compared to those featured in cells. With these joints, durability is the key. Constructions between packs may differ because the layout of the modules is open-ended. Some constraints come from the type of the cells used. Regardless, the pack is a large assembly with complex geometry, so manoeuvring the piece and getting the correct weld positions are a concern. Reinforcement ribs are fillet welded. Filler material is beneficial to increase strength of the joint. With these in mind, pack level connections have clearly very different requirements from cell welds.

The versatility of fusion based methods shines here. Fragile components are no longer a concern, the modules are slotted in after the frame is finished. Welding torches on robotic arms can access difficult locations and perform predetermined paths with consistent results. Laser-arc hybrid process combines the benefits of energy density and precision from laser welding and a higher gap tolerance and the use of filler material from MAG. Filler can also be introduced without the use of an arc-process.

Friction stir welding works well for applicable joints, so for example joining the bottom plate to the frame. The top plate is connected without welding, because access to the modules for maintenance is required.

5 Conclusions

This study proves that the field of battery welding is not simple and multiple complications come in the way of manufacturing a full battery pack. Thanks to the wide array of available processes, each connection can be made without the need to settle for a subpar weld. Even so, settling has not happened with the improvement of the processes, as the revolution to fossil fuel-free traffic is only beginning. Research is being made to optimize the safety, cost, durability and electrical stability of the joints. Some of it has to do with improving already used processes, but also bringing in processes not previously used in this field. The price to energy density in Li-ion batteries was rapidly lowering during the shift from 20th to 21st century, and now we have settled on a trend of slow and steady decline. As the slow disappearance of ICE cars is approaching, it is important that the general pricing can be matched or even undercut.

Batteries include worthy joining challenges, but fortunately many of them are not exclusive to battery production. Dissimilar material joining for example is also studied for weight reduction of ICE cars as a way to reduce fuel consumption, so research done in the area has a wider use range. What is certain however, is that welding will continue to see use as the main joining method. The alternatives just aren't able to offer the same space-efficiency, electrical passthrough and cost. Because batteries are not that different from each other, breakthroughs in automotive battery technology are also a win for large battery storages and mobile device batteries. Same also applies in vice versa.

It seems that laser beam welding has potentially the brightest future with battery components, because of its large degree of transformability for varying applications and high suitability for automation. What is still holding it back are the high investment costs, but the more it is adopted, the more affordable it becomes.

While doing research on the subject, it was easy to get side-tracked on the many variations that have been pulled off to join battery components together. The area is too large to go in-depth in, at least on a bachelor’s level. The research questions were answered, with explanation of the batteries and references to back up the claims. Not all the presented challenges were found from sources, but simply deducted by considering the manufacturing procedure. Challenges like accessibility to the joint or joint types might not be trivial enough to write research papers on, but they are factors to consider none the less. No doubt there are many more challenges to consider if the best possible battery module is to be produced. Still, this thesis should be able to provide the reader with a sufficient collection of information about batteries, their production from the point of view of welding and most importantly, what complicates it.

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Appendix 1. Interview questions

The following questions were asked from the head of LUT Laser Laboratory, D.Sc. Ilkka Poutiainen on April 18th, 2023.

Q1: LBW machinery is considered highly expensive, but so are other industrial class welding machinery. Is the pricing of LBW on a completely different level?

Q2: What are the running costs of LBW and does it pay itself back thanks to low preparation and post-processing demands?

Q2: What are the running costs of LBW and does it pay itself back thanks to low preparation and post-processing demands?

Q3: Laser is considered highly capable for welding dissimilar materials, like Al, Cu, Ni and stainless steel. Is this true? Are there any measures to keep in mind for best results, like the position of the materials?

Q4: What is the consistency of LBW? Are random flaws a result from the materials themselves?

Q5: Some surfaces are claimed to reflect the beam. Is this a realistic problem that has to be mitigated somehow? Is coating, wavelength alteration or pulsing used as a countermeasure? Are there concerns of safety hazards from reflections?

Q6: Is porosity and solidification cracking avoidable? Are the work components preheated to reduce this effect?

Q7: What is the applicability of LBW for tee-joints without the use of filler material? Is there a meaningful difference in strength compared to doing the fillet with hybrid welding?