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Welding methods for electrical connections in battery systems

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Abstract

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The demand for high energy battery assemblies is growing in sectors such as transportation. Along with it is the need for reliable, efficient and cost-effective ways to electrically connect the batteries to ensure their performance. Battery cells are most often put into modules or packs when produced for electrically driven vehicles. The variable of greatest influence when welding battery packs is the contact resistance between the cell and the connection tab. It is crucial to minimize this variable as much as possible to prevent energy loss in the form of heat generation.

The purpose of this project is to conduct a comparative literature study of different welding techniques for welding batteries. The compared techniques are resistance spot welding, laser beam welding and ultrasonic welding. The performance was evaluated in terms of numerous factors such as production cost, degree of automation and weld quality.

All three methods are tried and proven to function in the production of battery applications. Each method has separate strengths and limitations which makes them complement each other. Thus, it is important to look at several factors when deciding which welding technique is the most suitable for the desired application. The scale of production, economical aspects as well as battery cell geometry were concluded to be the most important in making this decision.

Keywords: Resistance spot welding, laser beam welding, ultrasonic welding, battery cell, electrical performance, weld quality, cost analysis, automation degree, production yield

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Welding methods for electrical connections in battery systems

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Abstract

The demand for high energy battery assemblies is growing in sectors such as transportation. Along with it is the need for reliable, efficient and cost-effective ways to electrically connect the batteries to ensure their performance. Battery cells are most often put into modules or packs when produced for electrically driven vehicles. The variable of greatest influence when welding battery packs is the contact resistance between the cell and the connection tab. It is crucial to minimize this variable as much as possible to prevent energy loss in the form of heat generation.

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1. Introduction

The market for all batteries continues to grow as the global demand for wireless and environmentally safe electronics increases. This includes electronic devices such as mobile phones, tablets, and electric cars. Market growth encourages suppliers and manufacturers to research and develop their methods, materials and products in order to meet demand. This demand for battery powered products has resulted in the development of better battery performance during the last 20 years. [1, 2]

Batteries are often separated into two categories, primary batteries and secondary or storage batteries. Primary batteries are designed to only be used once, by drawing a current until the voltage becomes too low and then discarding the cell. Secondary batteries are constructed in a way to allow the cell to be recharged after partial or complete discharge. However, the cell can normally not be completely restored to its original state upon recharge. [1]

The world demand for both primary and secondary batteries is predicted to grow 7.7 % annually, furthermore the market is anticipated to reach a value of US$120 billion in the year 2019 according to the industry research firm The Freedonia group. The largest contributor to this growth is secondary, or rechargeable batteries, which according to Frost & Sullivan was projected to account for 82.6 % of the market globally in 2015. This demand is primarily due to mobile phones and tablets as well as electric vehicles. Although the figures for the latter product have turned out to be overestimated and have since been adjusted accordingly. Batteries can, besides being divided into primary and secondary cells, be classified by their chemistry. The most common types are based on either lithium-, lead- or nickel systems where lithium is by far the most used as seen in Figure 1 below. No other chemical system comes close to surpassing it. Nevertheless, lead-acid batteries still account for a large portion of the market and are experiencing a continuously growing demand as they serve as an economically viable option for bulk use. [2]

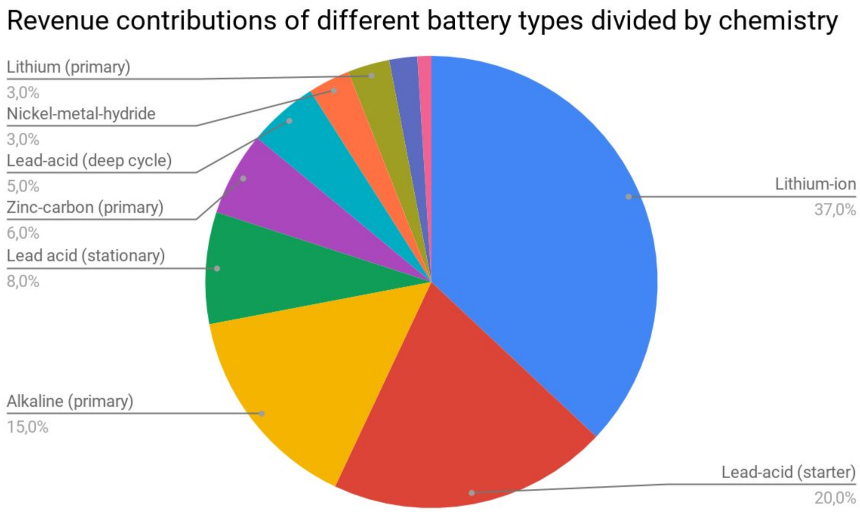

Figure 1: Revenue contributions for the global battery market by each type of battery categorized according to chemistry. [2]

An electric battery is generally defined as some sort of device that converts chemically stored energy into electricity. Every battery cell has two electrodes, the cathode and the anode, separated by an electrolyte that can either be in liquid or solid form which allows ions to migrate between the electrodes. The choice and quality of materials, as well as the complex relations of electrode and container design all affect the performance of the cell. This will influence the amount of energy that can be drawn from it as well as the price of the product. The major difference between primary and secondary cells however, lies in the electrical properties. A battery's electrical properties encompass the capacity as well as the magnitude of the current that can be drawn from it. A secondary cell needs to be constructed in a way where the total electrochemical reaction must be reversible upon recharging at the same, or at least a similar, rate as the discharge rate. A primary cell only needs to drive the electrochemical reaction forwards. Primary cells are therefore generally easier and cheaper to construct than secondary cells. [1]

In recent years, two main battery aspects have developed. One being the increased specific energy which enables longer runtimes. The other an improved specific power for high-current load applications. [2] For electrically driven vehicles, a standard battery pack usually consists of hundreds or even thousands of individual battery cells, commonly lithium-ion batteries. With the ongoing market growth, battery pack manufacturing has also to meet the demand for an increased stored energy capacity. [3] However, advances in the field of batteries also presents new challenges. One significant challenge faced by the company who outsourced this project, APR Technologies AB henceforth referred to as APR, is the amount of energy converted into thermal energy.

A greater battery capacity increases the heat generated from electrical resistance during the discharging and recharging of the battery. One method of redirecting the heat and minimizing any damage caused to the cell is through different cooling systems. This is essential since a battery's capacity and performance is greatly affected by the operating temperature. [4] APR works on supplying cooling systems for space applications, in the context of this project they are interested to look into the possibility of implementing their technology for battery modules consisting of, on average, 48 lithium-ion batteries.

The cells in the module are connected in series, and are intended to be a secondary, or rechargeable battery source for electric cars and other energy demanding devices. The modules are required to carry a specific operational current which is limited by, amongst other factors, how the cells are connected and conduct a current. Typically, and in the case of this project, a conducting metal connects the cells. This connection determines the conductive abilities of the module and therefore also the required cooling system. [5]

1.1 Project Purpose

The purpose of this project is to perform a literature study comparing different welding techniques, specifically in relation to welding batteries to give insight into techniques used in small scale as well as in mass production.

1.2 Limitations

The techniques investigated in this project are resistance-, laser and ultrasonic metal welding. APR provided a template containing research topics that were of greater interest for investigating industrial level applications of the methods. The template can be found in section 3.1 Limitations.

1.3 Project structure

The project will consist of a comparative literature study researching the welding techniques mentioned above. A minor laboratory study will also be performed. In this, key parameters for welding together nickel strips using resistance spot welding will be determined through the measurement of the electrical resistance. The use of resistance spot welding as the investigated method was chosen by APR due to their access to equipment and knowledge of this particular method. This is a small part of the project and this report, and only to be seen as a subsidiary project. The method, result, and discussion of this laboratory study will all be found in Appendix 1. A list of possible equipment distributors for the different welding techniques investigated will also be attached in Appendix 2. The references ranked according to their relevance will be attached in Appendix 3.

2. Theory and background

This section comprises background theory that acts as a further introduction to the welding techniques investigated in this report. It includes theory on the principle of resistance, application challenges faced by the welding techniques, and fundamental information on the operating principles of each technique.

2.1 Resistance

The physical phenomenon exploited in resistance spot welding to achieve adhesion between materials is called electrical resistance. Resistance is defined as the ratio between applied voltage to the current through a substance or material. This follows equation 1 stated below. Where U is voltage, I is current and R is resistance. [6]

$$U \propto I \Rightarrow U = R \, x \, I \Rightarrow R = \frac{U}{I}$$

When electrons are deflected in a material they can be deflected either coherently or incoherently. Coherent deflection implies the electron scattered against a rigid atomic lattice defect and did not transfer any of its energy to the defect. Incoherent deflection implies the electron transferred some of its energy to the defect. Solely coherent deflectors may result in a measureable resistance R, but only incoherent defects give rise to energy dissipation and heat generation. Heat generation is related to equation 2 below. [7]

$$P = R \times I^2$$

Contact resistance, which is the form of resistance applicable to all three welding techniques, is similar to this model. The local heat generation at the surface interface is typically relatively higher because there are more incoherent defects there. Thus resulting in a greater heat generation between the surfaces, which is ideal for welding. [7]

2.2 Challenges faced by the welding joints

There are various challenges when choosing a welding method for a specific application such as battery welding. Table 1 summarizes the categories encompassed, the challenges and their respective explanations. [3]

Table 1: Challenges faced by the welding methods. [3]

Category	Challenge	Explanation
Electrical and Thermal	Generate joints with low electrical resistance	Reduces energy loss, heat generation and reduces the temperature increase during the charging and discharging of the cell.
	Generate joints using a low thermal input	Reduces the risk of melting, disturbing or compromising the cell.
	High thermal fatigue resistance	Increases the durability and reliability of the cell performance.
Material and Metallurgical	Compatibility with joining dissimilar materials	Reduces the risk of/avoids creating intermetallic layers, which have high electrical resistance and a brittle nature.
	Variability of materials and surfaces	The methods must overcome joint properties such as highly conductive and reflective materials, surface coatings, oxide layers, and joint stack-ups.
Mechanical	Joint strength	The generated joints must have satisfactory strength for their purpose.
	Avoid mechanical and vibrational damage while joining	Reduce the formation of residual stress and vibrational energy in the event of this causing cell damage or joint failure.

2.3 Resistance Spot Welding

One of the oldest welding methods is resistance spot welding (RSW) which was invented by Elihu Thomson in 1877. It is one of the most widely used manufacturing processes for joining sheet metals. [8] RSW is a technique where two or more metal sheets are welded together through the application of an electrical current and pressure between two electrodes. The electrical resistance of the material at the interface results in the generation of heat and melts the materials together without the use of filler material or gases. When welding with batteries, stray currents may arise from the battery. This current counteracts the applied current and must therefore be accounted for with a higher applied initial current. Too high of an applied current may however lead to electrode sticking. [9]

The method typically uses a dual pulse. The first pulse eliminates contaminations and oxides, and the second pulse welds the work pieces together. The temperature increases in the affected area, the interface, and eventually reaches the material's melting point. A weld nugget forms in the affected area after cooling. This is a small volume of the material which has melted and then fused together. Figure 2 is a visual representation of RSW. [10]

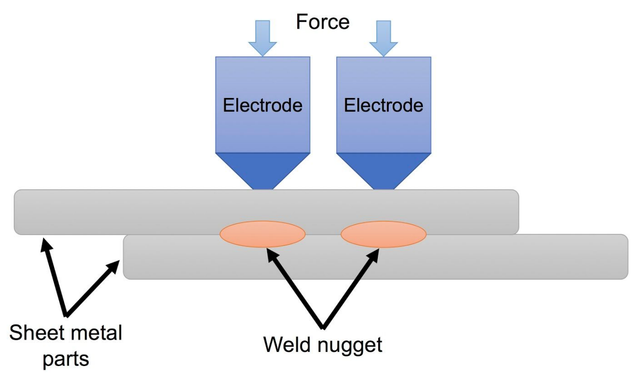

Figure 2: Representation of resistance spot welding used on multiple layers of metal.

An AC is most commonly used as a source in RSW which, through the use of an inverter, is converted into and utilized as DC. This is true both in large scale and micro RSW. The inverter functions by rectifying the three phase current into a single phase, filtering it, converting it into a square wave current, amplifying it, and inverting the negative pulses. Thus, resulting in only positive DC power. [11]

Another type of "spot welding" is Micro-TIG, where TIG stands for "Tungsten inert gas", or pulsed arc welding uses a pulsed TIG arc to join thin materials by fusion. The heat input is much lower than in conventional TIG welding due to the short duration of the arc pulses. Micro-TIG is especially suitable for applications using nickel, copper and steel and can generate welds between dissimilar materials. Micro-TIG typically uses DC but an AC can also be used. AC is often used for aluminium applications due to the functional mechanism of first removing oxide layers. Currently, there are no reports of electric vehicles or hybrid electric vehicles using this technique for the welding of battery packs. [3]

2.4 Laser Beam Welding

Laser beam welding or LBW is a welding technique in which a laser beam provides a concentrated heat source that fuses the materials together. A lasing medium, a lasing cavity, and a pumping source are all primary components in a laser welding machine as shown in Figure 3. The design of the cavity determines the form of the outgoing beam and reflective lenses are used to focus the laser. The quality of the beam that is produced can vary and when welding, a beam with little diffraction is desired to create a concentrated heat source with a small spot size. [12]

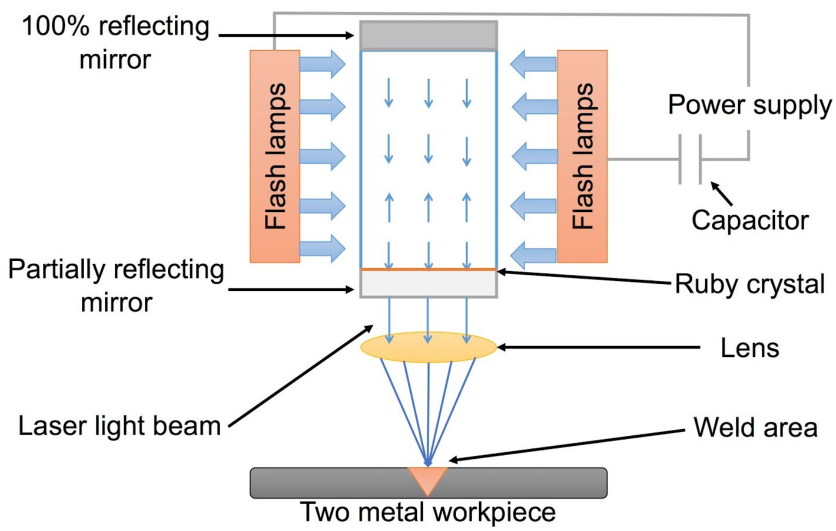

Figure 3: Schematic of laser beam welding on multiple layers of metal.

LBW is commonly performed using keyhole mode welding in which the extreme power density of the laser beam causes the metal to melt and evaporate [12]. As the metal atoms evaporate from the surface, forces in the opposite direction of the evaporation causes a local vapor pressure. The vapor pressure creates a hole which is known as the keyhole by depressing the molten metal. Due to the formation of the keyhole, and the laser beam reflecting inside the cavity, the energy efficiency of the welding process improves significantly. Some of the evaporated atoms ionized by the intense beam create a plasma over the weld area. The plasma can in some cases interfere with the beam. A shielding gas can be used to prevent this. Keyhole mode produces a weld with a high depth to width ratio as compared to other welding techniques. [9, 12]

2.5 Ultrasonic Welding

Ultrasonic metal welding or UMW, is a solid-state welding technique which forms a bond by applying moderate static pressure and an ultrasonic oscillation of about 20 kHz between two parts of metal, as seen in Figure 4. The solid-state weld is formed through the high frequency motion between the parts causing continuous shearing and plastic deformation, while also removing any oxide layers or contaminants. The complete bonding mechanism is not fully understood, but some combination of metal interlocking, micro melting as well as metallic and chemical bonding is believed to aid in the creation of the bond. Most metals can be ultrasonically welded and the method is excellent for welding together thin foils, as well as thicker sheets with spot or seam welds and also wires. [14, 15].

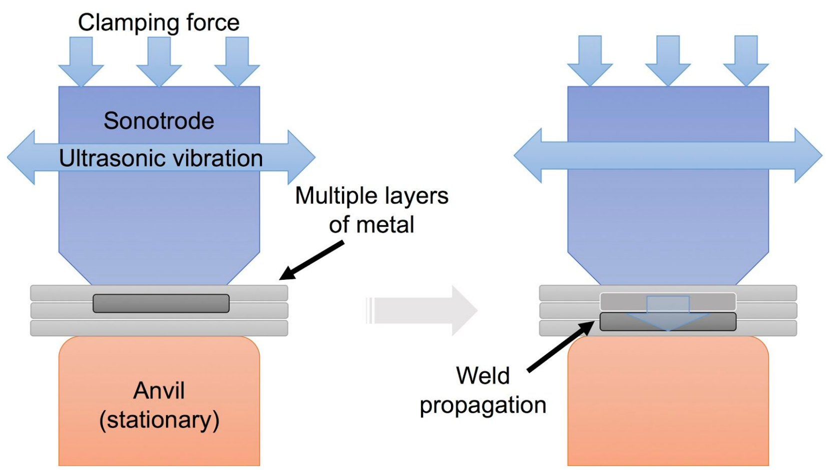

Figure 4: Schematic of ultrasonic metal welding on multiple layers of metal.

Another type of ultrasonic welding is ultrasonic wire bonding, or UWB. It is a one-sided access ultrasonic method where a metal wire, typically between 0.01 mm to 0.5 mm, is auto-fed onto the substrate, as seen below in Figure 5. The weld itself is created just as in conventional ultrasonic welding. The sonotrode applies static pressure and an ultrasonic oscillation, creating a so called first bond, which then travels through to the following substrates to be connected. This technique is frequently used in the microelectronics industry and is considered to be the most cost-effective and flexible for electrical connections. It is also used for connections in high power applications, such as battery packs in electrically driven vehicles. However, heavy gauges of feed wires, often of aluminum or copper, are required for these types of connections. [15]

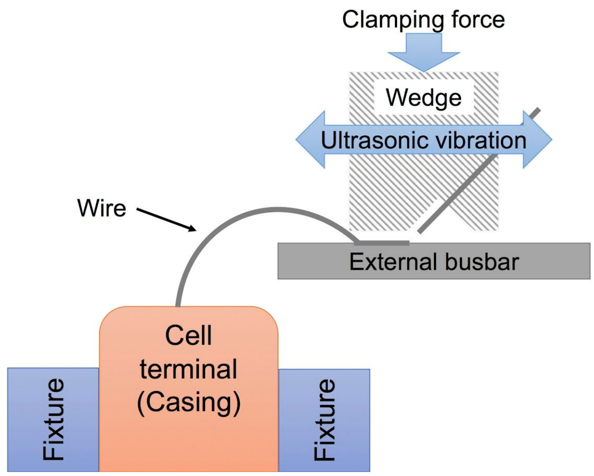

Figure 5: Schematic of ultrasonic wire bonding setup on a battery cell terminal.

3. Method

This project is a literature review outsourced by APR. The research provided on the different welding techniques is intended to support a potential new branch of the company. A template containing the topic of the project was given at the start of the project, it included relevant factors and necessary information to continue the research. The search was then performed using Uppsala University's Library database and Google scholar which cover a wide range of articles and sources. Three methods for welding batteries were given in the template, being laser beam-, ultrasonic-, and resistance spot welding. These different welding methods were used as keywords for finding new litterature. The keywords used were:

- ❏ Battery welding
- ❏ Heat battery welding
- ❏ Laser welding
- ❏ Micro-TIG welding
- ❏ Battery packs
- ❏ Ultrasonic welding
- ❏ Ultrasonic wire bonding
- ❏ Li-ion batteries
- ❏ Spot welding
- ❏ Welding cost
- ❏ Weld quality
- ❏ Welding methods
- ❏ Resistance spot welding
- ❏ Laser welding battery
- ❏ Connection resistance
- ❏ Battery management
- ❏ Automation degree welding
- ❏ Market analysis Batteries
- ❏ Pouch cells
- ❏ Electrical Resistance
- ❏ Production yield welding
- ❏ Cost analysis

Article headlines did not accurately reflect the relevance of the content. Because of this an article's relevance was determined by reading the abstract and conclusion. Relevance was determined by how much the content of the article coincided with the topics of the template. The reliability of the method in an article was determined by comparing it to methods in other articles. If a method was used in several articles then it was deemed reliable. When finding an article that met the relevance requirements, other parts of the article were then also read. Articles using the different welding techniques did not necessarily include the method's effect on batteries. Data collection therefore also included contacting companies and individuals educated and experienced in the field.

3.1 Limitations

The scope of the research and data collection of the report were adapted to APR's requests. Therefore the keywords and articles used are more adapted towards a company looking into a field that requires welding. For this reason certain topics of academic interest may be overlooked.

The template mentioned above included the following points:

- ❏ Electrical performance
- ❏ Effect on battery cell
- ❏ Cost analysis
- ❏ Automation Degree and Production Yield

4. Results

The results of the literature study of each welding method below follow the same disposition for easier comparison later in the discussion. The disposition of each set of results includes the main advantages and disadvantages, as well as the performance related to the topics of the template mentioned above.

4.1 Resistance spot welding

RSW is the oldest and a widely used welding method in the automotive industry. One of the advantages with RSW is that it does not require filler materials or gases and is easily automated for industrial production applications. It is a relatively cheap and fast joining process, at the same time a good level of quality control can be achieved. Thin sheets can be perfectly joined but however, RSW has difficulties producing large nuggets. [10]

A disadvantages with the method is that it is not as useful for highly conductive materials and has difficult to join more than two layers. The quality of the welds are as well often hard to investigate due to the weld's location being between the welded material and the weld quality may vary from weld to weld due to noise, variability and errors that arise. Electrode sticking is also a common problem for RSW where the material may stick to the electrode tip while welding. [10]

4.1.1 Electrical performance of resistance spot welding

Choice of electrode alloy is determined by the material being welded and the desired weld effect. The electrodes used must have an electrical and thermal conductivity higher than that of the welded material to keep the electrode from getting too hot. Therefore, RSW is not suitable for welding highly conductive materials. Based on the Resistance Welding Manufacturers Association material types definitions, there are three main groups. The first A, being mostly copper based alloys, B is refractory metals and refractory metal composites and C specialty materials such as dispersion-strengthened copper. [16, 17]

The most commonly used electrode material are copper based alloys. The metallic strips used for battery connections with the help of RSW are made of a variety of materials. These include the following and are listed in no particular order; steel, nickel, copper and aluminium. However aluminium and copper can prove to be difficult to weld using RSW due to their excellent thermal and electrical conductivity. In addition, because the temperature control is restricted to one temperature, dissimilar melting temperatures of welded materials is also a limitation. [3]

Two conductive materials often used in connecting batteries are nickel and steel based alloys. The thickness of the bands used when welding should be less than 0,4 mm for nickel and less than 0,3 mm for bands made of steel based alloys. This is due to the material's conductance becoming too large if these thicknesses are exceeded. Bands thicker than this has too great of conductance which will restrict current from reaching the substrate and result in a poor weld. Qualities of a poor weld include a weak adhesion, and poor conductance which are often the result of too small of a weld nugget. [18] The solution should then be to increase the weld size, however, RSW has difficulties producing relatively large nuggets and the typical nugget size varies between 0,9 to 2,0 mm [10].

The size of the weld nugget depends on the diameter of the electrode, the peak time and peak current. If the conducted current is too low or conducted for too short of a time the generated heat will not suffice to melt the materials and fuse together. Conversely, overheating of the materials may occur if too high of a current is applied during a long peak time. Adequate joints can be achieved by balancing the peak time and peak current, but the joint will still be relatively weak. [10]

The three primary spot-welding process parameters that are changed are welding time, welding current and electrode force. The welding time during RSW is very short, it varies between micro- and milliseconds. Too short of a welding time or a low applied electrode pressure may provide insufficient surface contact and lead to a poor weld. On the other hand, too long of a welding time or excessive applied electrode pressure may generate too much heat and deform the sample.

This could result in a metal flame which damages the electrode tips and leaves a burn mark between the spots. In order to achieve the best weld results it is good practice to start by using the shortest weld time, and then increase in increments. [17, 19]

The applied current needed for welding depends on the resistance. Decreasing resistance requires an increased current, and vice versa. Too high of a welding current may also cause crack formation and weld voids which can decrease the tensile strength. [17, 20] A welding force is also applied by the tip of the electrode. This force ensures a more stable connection between electrode and working metal throughout the welding process. Too much force may cause deformation both giving a greater surface area of connection but also warping the material. Insufficient welding force may cause metal sparking. [19]

The quality of the welds generated with RSW can achieve high reliability through robot automatization. RSW has already been used as a joining technology in the battery industry and automotive production for a long time [21]. Meanwhile the quality of the welds using RSW are often hard to investigate due to the weld's location being between the welded material. Meaning weld quality may vary from weld to weld due to noise, variability and errors that arise. [22] However, process parameters can be monitored such as voltage, current, dynamic resistance and sheet temperature. Monitoring these parameters grant insight into the weld quality through comparison to known welds. Which has been found to be easier to do in laboratory environments in comparison to industrial scale production. Though recent advancements in sensor technology used in industry have led to better monitoring and consistent weld quality, with trends pointing towards further development. [17]

4.1.2 Effect on the battery cell

Small-scale resistance welding is often the preferred method for joining Li–ion batteries into battery packs. This process ensures strong joints with an almost complete elimination of the heat impact on the joined workpieces during a short time. An additional advantage is the possibility of joining different parts that often significantly differ from each other regarding their geometry. [23]

Since the heat exposure to the battery cell is short, the amount of heat transferred into the cell is small. Meaning the heat remains close to, and on the surface where it is quickly absorbed by the surrounding atmosphere. Thus the welding method has a minimal impact on the battery as there are no catalyzing reactions in the battery caused by the heat. On the other hand deformation may occur if too great of a welding force is applied by the electrodes. This deformation may alter the temperature distribution and hinder the current from flowing the shortest path. Possibly causing the current to flow more into the battery, thus causing a heat transfer to the core of the battery. Resulting in a worse weld due to an insufficient temperature at the contact points. However the welding force may not be too low either. A weak applied force, and thus connection, may produce a light arc which causes metal sparking, and results in a poor weld. Though it would not pose any danger to the battery. [19]

4.1.3 Cost analysis

The most basic expenses for RSW are the cost for the power source and the welding gun. This is where RSW are superior to other alternative methods for welding due to its low price. The main economic effects, applicable to both mass production and small scale production, include; cost of electricity, cost of an inert environment in the form of gas, the material costs of connection bands and lastly labor costs. Automation and semi-automation are shown to provide several cost benefits. Studies indicate a reduction of overall energy consumption, labour costs, and material costs due to less waste with a higher degree of automation. The potential savings of electrode materials due to wear or degeneration is limited, but is still a factor to be considered. An automated process results in less wear on the electrode and in turn lower material costs. Regarding labor costs, including educating personnel and wages, they are reduced with automation also ensuring weld quality and minimizing stops in production. In the event of equipment failure then maintenance and initial costs are the only affected costs in a fully automated process, with no concern placed in non-productive employee costs. [24]

Another factor that has influenced spot welding is the application of inverters as converters to the equipment's power source. An inverter increases the machine's efficiency and output power. [25] Machine downtime is found to be one of the greater disadvantages of RSW. Through increasing the power output by a significant amount downtime is decreased. Production is proven to increase by a factor of seven for a specific application using an inverter when compared to the same application with a typical power supply. It also has the added benefit of producing better quality welds due to a more consistent output of DC instead of AC. In total, by using an inverter the power output, the quality of the weld and the weld yield all increase which correlates to lower costs. The ability to generate DC using an inverter has resulted in nearly all producers and distributors of RSW equipment to include them in their products. [26]

4.1.4 Automation degree and production yield

RSW is the method most frequently used in the automotive, and various other transportation industries. The method has also been applied to certain electronic and medical industries. Its popularity is due to the quick, and simple welds that can be created while still maintaining a high quality at a low cost. In addition to these factors it is a method that is adaptable to scalable automation. Automated RSW allows for high volume product flow which is advantageous in most industries. However, the weld quality as mentioned earlier, which influences product properties such as crashworthiness, fuel efficiency and vehicle safety, is of utmost importance.

The result of automation, while primarily positive for product quality, may also result in weld quality variation and effectively harming production profits. [21, 22, 27] Automation does however provide control over the welds by controlling parameters such as the welding current, electrode tip diameter and electrode force [28].

Small scale RSW has a very short welding time and high current intensity. The well controlled process parameters localize the affected heat area. The majority of the heat is near the electrode tips and influenced by their pressure. Only a small amount of energy is required during the process and dissipates quickly. Small scale welding creates quality welds suitable for joining small workpieces, including cases where the materials have different thicknesses. [23]

Modern development of RSW has culminated in integrating artificial intelligence (AI) and observing its effect on the weld quality. The aim is to compensate for limitations of the method in an automated process through selection of the correct welding parameters. This is done using pattern recognition and a hopfield neural network to predict the weld strength and weld nugget diameter. [29, 30] Further development within automation of RSW involves researchers trying to find a mathematical relationship between different welding parameters and programming it into AI software [31].

RSW has a weld frequency of up to one weld per second depending on the material and the material thickness. This is determined by how the cell module or weld heads move which is in turn affected by the length of the weld cables. Due to material resistance increasing linearly with the length, and that a large enough voltage must be conducted, the voltage limits the length of the weld cables. [32]

4.2 Laser beam welding

One of the greatest advantages of LBW is the precise and non-contact welding which can be adapted to fit small areas with low accessibility using a concentrated heat source. LBW can also create larger welds, and does not require filler material. A disadvantage of the method is that it is rather complex and therefore requires special training and experience for proper operation. Another disadvantage is that metals with an be difficult to weld [9]. The incoming laser beam may be reflected by the metal and the absorbed effect reduces significantly. high reflectivity c[12]

LBW applied to battery cells uses one of two main types of lasers, either fiber laser or pulsed Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) laser [33]. Storing the laser energy in capacitors and then releasing in pulses means there is an initial peak force greater than the average force of the pulse. The high energy delivered instantaneously in a pulse is better adapted to reflective metals than lasers emitting continuous waves. Continuous waves are constant, uninterrupted laser beams. Pulsed lasers result in a lower total heat input than continuous wave lasers due to the short duration of the pulse. Pulsed laser is therefore more advantageous than continuous wave laser for heat sensitive components such as battery cells. Both fiber lasers and Nd:YAG lasers are available with both continuous- and pulsed energy delivery. [34, 35]

4.2.1 Electrical performance of laser beam welding

LBW requires work pieces to be properly aligned for improved welds and often faces difficulties welding materials with poor metallurgical affinity. The supposed random diffusion of materials in a melt leads to the formation of brittle intermetallic compounds when dissimilar materials are brought together in a fusion. Two materials that often display poor metallurgical affinity are for example copper and aluminum. The formation of brittle intermetallic compounds reduce both of the material's mechanical resistance as well as thermal shock resistance. [36] A negative correlation is found between the solubility of a material and the material's risk of forming intermetallic phases. Thus meaning that a lower solubility increases the risk of forming intermetallic phases. A similar, but positive, correlation is found between cooling rates and brittle microstructures when welding certain steels. Higher cooling rates result in a greater number of brittle microstructures. [9, 12] LBW is therefore most suitable for materials with similar or identical compositions such as aluminum and aluminum or copper and copper [37]. Materials, especially metals, with dissimilar compositions tend towards poor welds when using LBW because of their difference in elemental composition and thermo-physical properties [38].

Important parameters in LBW include laser power, welding speed and pulse rate due to their influence on the weld quality, weld bead geometry, and dimensions of the weld. Both laser power and welding speed influence the weld zone dimensions. The difference is that laser power has a direct correlation and welding speed has an inverse correlation. Improving the weld quality is achieved by carefully optimizing the initial laser welding parameters. [39]

Parameter control also allows LBW to adapt to the thickness of the material tabs and can create thin or thick weld nuggets. In battery cell welding it is important to create thin welds due to the relatively thin battery cases and the risk of the weld penetrating the case and thus damaging the core. If a thicker weld is desired LBW can succeed in welding tabs several millimeters thick using keyhole mode welding. [9, 33, 40] Lastly, laser beam welds, when compared to ultrasonic and resistance welds, have higher shear and peel strengths when welding materials such as aluminum, copper and nickel to identical materials [37].

4.2.2 Effect on the battery cell

LBW results in a higher initial heat, because of it being a high power fusion process, compared to RSW and UMW. However, the rapid pulses used by the laser generates a relatively low heat to the battery cell as a whole, which dissipates quickly and primarily only heats up the cell terminal. Higher heat yields may potentially damage the cell core, but are typically not an issue when handling the method properly. Combining the high power density with the control over the beam or pulse length allows the user to limit the generated heat. The high initial energy in the laser pulse increases the temperature of the terminal to a maximum. Studies show that this temperature typically decreases below 70℃ after three seconds and therefore does no harm to the lithium-ion cell. [9]

LBW is the method best adapted to creating small weld nuggets. When the size of the weld nugget is smaller than the current, the current is restricted. Restricting the current increases the resistance and the generated heat during charging and discharging. This decreases the function of the battery cell in the long term. [9]

4.2.3 Cost analysis

LBW is an expensive method to implement due to the high investment costs needed for automation. The costs consists of the equipment generating the laser beam, and the robotics operating the laser for welding. The high expenses make the method more profitable for large scale production and for products with a high degree of repetition. This is true even if it is a wide mixture of types of welds with relatively low amounts of each type, as long as the total amount is large. [41, 42]

In a study comparing assembly costs of LBW and RSW it was concluded that even though the number of robots needed for operation of the laser has decreased, LBW is still very expensive. The sensitivity of LBW equipment makes transporting it, prior to installation, more complicated than for RSW. This contributes to greater costs needed for safe transportation. Although, one laser source is enough for four welding guns, the expenses tied to the technology overshadow this advantage meaning that a large number of spot welding machines are still cheaper. [43] On the other hand, research also supports that the efficiency, and the current price of lasers make it possible for laser processes to compete economically in various industrial areas [44].

4.2.4 Automation degree and production yield

As mentioned before LBW is a non-contact process which, compared to methods that require contact, increases efficiency in mass production. The welding method of LBW can be repeated efficiently, thus simplifying automation. It is possible to achieve a welding process that is three to four times faster than RSW using keyhole mode laser welding without reducing the weld quality [41, 42]. As an example, LBW can generally create up to 20 welds per second depending on the material and thickness [32]. Automated LBW is frequently used in high volume applications in industries such as the automotive, medical equipment and electronics industry [45]. Thus, the high investment costs associated with LBW indicate that both a high production rate and products with repetitive welds are necessary for profitable production. [41, 42]

4.3 Ultrasonic welding

As mentioned in section 2.4, UMW is a solid-state welding method with many advantages in comparison to fusion welding processes. One advantage is the excellent welding quality achieved when using thin, dissimilar, and multiple layers of highly conductive metals such as Cu and Al. This is crucial in battery cell joining and for battery tab joining. Another advantage is the fact that no filler material or gases are needed, which make it more environmentally friendly compared to conventional welding. [40] UMW also creates a very thin, typically a few microns, layer of bonding interfaces. The bonding interface eliminates metallurgical defects that commonly exist in most fusion welds such as porosity, hot-cracking, and bulk inter-metallic compounds. Therefore, it is often considered the best welding process for li-ion battery applications. Furthermore, the required energy input is lower compared to the other methods covered in the report and the weld time is short, meaning the weld zone only experiences a low temperature increase. [13]

A challenge in using UMW is that it requires two-sided access to the object. The anvil is on one side for support, and the sonotrode on the other for passing the ultrasonic vibrations into the material. Therefore, UMW is especially used on pouch cells and may not be suitable for prismatic and cylindrical battery cells as the ultrasonic vibrations may cause damage to the battery cells structural integrity. Other disadvantages include that the method is restricted to lap joints, prone to sonotrode sticking if the process parameters or product varies too much, and that creating a satisfactory weld is challenging with high strength materials, therefore the method is primarily suitable for soft materials [13, 40]. There is also a restriction to joint thickness which lies around 3 mm. [40]

UWB is similar to UMW in that it can be applied to dissimilar metals and shares the same advantages. For example, being able to weld highly conductive materials, leaves miniscule to no metallurgical defects, is a solid state welding technique, and results in a low temperature increase in the weld zone. For battery packs, the bonded wire at the battery terminal can be used to protect the pack against thermal and mechanical impacts, as well as internal defects. UWB is also suitable for creating electrical connections between cylindrical battery cells. Although proper fixation of the cell is paramount for the welding, as any significant lateral movement will reduce the vibration amplitude and consequently diminish the power of the welding process. Therefore, the cells and busbars in the module need to be fully fixated to successfully use this welding technique. [40] A disadvantage of UWB is the restriction it puts on the current carrying capacity. UWB can only properly weld light gauge wires which physically limits the size of the drawn current from the battery cells. [13]

4.3.1 Electrical performance of ultrasonic welding

UMW and UWB are both capable of welding materials that have high electrical and thermal conductivity as well as high reflectivity. These properties are highly desirable in battery welding and battery usage because they are linked to improved electrical performance of the battery. However, a limiting factor of the electrical performance is a result of the weld quality. The weld is the smallest area the current passes which is perpendicular to the current. It is therefore the section of the path of the current which generates the most electrical resistance and heat. This applies both to the welds in UMW and the wires in UWB. The heat generated due to resistance may in turn causes long term battery damage. [46]

The weld quality using UMW and UWB depend on both the machine-, and the material parameters. The most important machine parameters are oscillation amplitude, welding force and transferred welding energy. As for material parameters, in UMW, besides the materials chemical-, mechanical- and physical properties, the geometry of the upper welding part bears great significance. The geometry of the upper part affects the energy absorption in the material, the geometry of the lower welding part is not as significant for the energy adsorption. However, the topography is rather important as the roughness of the lower surface strongly impacts the amount of friction generated in the weld zone. If the surface roughness is too high, hot spots can arise and cause large temperature gradients which ultimately can lead to fracture for more brittle materials. On the contrary, too low of a surface roughness will cause the welding parts to slip and a weld will not be formed. [47]

As an example of the electrical performance of UMW, the relationship between the electrical resistance and weld quality was studied. Brass with a thickness of 2 mm was welded to the negative terminal of a cylindrical lithium-ion cell made of nickel-plated steel. The weld with the smallest measured electrical resistance was 0.169 mΩ when using an oscillation frequency of 20 kHz. [9] This value is smaller than the internal resistance of conventional lithium-ion batteries. Hence, the weld would not cause any significant resistance heating of the battery during charge or discharge [48].

4.3.2 Effect on the battery cell

High currents must flow through the welds between battery cells in order to deliver the electricity needed to power a battery electric vehicle. These welds are the bottleneck of the electric circuit. Electrical resistance causes the temperature in the welds to raise when a current is conducted. This temperature increase may be harmful to lithium-ion battery cells. Therefore, large weld areas, and thus lower resistance, give a net positive effect. They both increase the mechanical strength of the welds, and reduce the temperature and thermal stress at the joints. Considering this, UMW is more suitable for battery tab joining than other types of welding as mentioned earlier, for example RSW. [40]

Hence, it is crucial to understand how much heat is generated in the weld and whether the heat can damage the battery. Lithium-ion batteries must operate within a safe and reliable operating area, which is restricted by temperature and voltage windows. Exceeding the restrictions of these windows will lead to rapid attenuation of battery performance and even result in safety problems. [49] The constant current through the welds gradually heats up the circuit. Currently a solution to this is the incorporation of thermal management systems that aim to decrease the operating temperature of the batteries, as this decrease in temperature slows down the capacity deterioration of the batteries. [46, 50]

4.3.3 Cost analysis

The use of ultrasonic vibrations in material processing has two main economical advantages. One being a lower energy consumption and the other lowering the production cost of the process. Furthermore, when employing ultrasonic vibrations for welding processes immense benefits are gained in mechanical properties, surface quality and reduced tool wear to name a few. [51]

The horn and anvil are reported to be a major production cost in automotive lithium-ion battery manufacturing. As a result, monitoring the wear of the horn and anvil is critically needed to ensure battery weld quality and reduce production costs. Therefore, a tool condition monitoring (TCM) system is highly desirable for UMW. If a TCM system is not available, a conservative tool replacement strategy is generally utilized to ensure satisfactory quality. Although this empirical strategy is straightforward to implement, it may sacrifice useful tool lives and increases production costs. [40]

4.3.4 Automation degree and production yield

Regarding automation capabilities, UMW is an attractive alternative to other welding methods for welding multiple layers. It is for instance used in several applications within the electrical industry and aircraft sector, to name a few. [13] Both UMW and UWB are frequently used in battery pack manufacturing by manufacturers, original equipment manufacturers and tier 1 suppliers, i.e. the module- or system supplier to a original equipment manufacturer [40, 52].

A study compared several welding techniques, including RSW, LBW, UMW and UWB. Ultrasonic welding techniques performed at the highest level of production when looking at manufacturing readiness levels, which "...indicate options and development status of battery joining from a manufacturing perspective. Manufacturing readiness levels (MRLs) are used to provide a relative measure of technology maturity, risk level, and extent of application." [40]. The automation capacity is, as mentioned, one of the several advantages with ultrasonic welding. As well as its ability to be integrated into existing production lines. It is possible to monitor welding parameters through software with data storage and statistical evaluation. Furthermore, UMW is characterized by short welding times, less than one second for metal welding, which also contributes to the low-energy input of the technique. [47]

4.4 Comparison of the welding techniques

To conduct a comparison of the welding techniques in the above sections, MRL indices can be used. As mentioned in section 4.3.4, MRLs are used to assess a technology based on certain criteria such as maturity and extent of application, to name a few. In Table 2 below, selected criteria from this assessment are shown for welding methods used for joining of cylindrical battery cells on a module level as cylindrical cells. The criteria were chosen to match the investigated factors in the literature study. The summarization of the MRL assessment for the joining of pouch- and prismatic cells is also included as they are also used in battery packs for various applications. The main focus lying on cylindrical cells is due to its geometry being the most efficient in relation to thermal management. Each factor is rated between 1-5, where 1 is the lowest and 5 is the highest. The joining technology with the highest total score is deemed the most suitable for the corresponding cell geometry, and the lowest total score is deemed the least suitable respectively. Micro-TIG is also included in this assessment as it on many accounts performs better than conventional RSW, and could be useful in a comparison when deciding on the optimal welding technique for a chosen application. [40]

Table 2: MRL indices for assessing maturity of current joining technologies for module level joining. [3]

Factor	Weight	Joining technologies- Cylindrical cell			
		RSW	Micro-TIG	UWB	LBW
Total		**3.71**	**3.93**	**3.86**	**4.07**
Joint resistance (similar materials)	5	4	4	4	5
Joint resistance (dissimilar materials)	5	2	4	5	3
Heat transfer from process	5	3	3	5	4
Potential mechanical damage	5	4	4	4	5
Joint current capacity	5	3	3	2	5
Joint durability	5	4	4	3	4
Potential vibration damage	5	5	5	4	5
Cycle time	4	4	4	4	5
Repeatability	4	3	4	4	4
Cost per battery connection	4	5	5	4	4
Investment	3	4	4	4	2
Easy automation	5	4	4	5	5
Flexibility i.e. easy to adapt	3	3	3	2	3
Safety	5	4	4	4	3
		Joining Technologies- Pouch cell			
		RSW	Micro-TIG	UMW	LBW
Total		**3.71**	**3.93**	**4.07**	**4.07**
		Joining technologies- Prismatic cell			
		RSW	Micro-TIG	UWB	LBW
Total		**3.71**	**3.86**	**3.79**	**4.07**

5. Discussion

In this section the investigated welding techniques are compared, with the main advantages and disadvantages of each technique shown in Table 3 below.

Table 3: The main advantages and disadvantages of resistance-, laser- and ultrasonic welding.

Welding techniques	**Advantages**	**Disadvantages**
Resistance spot welding	❏ Low initial cost ❏ Can weld thin sheets ❏ Easy to automate and good for production ❏ Good quality control	❏ Difficult welding highly conductive material ❏ Difficult to produce large nuggets ❏ Difficult welding multiple layers ❏ Electrode sticking
Laser beam welding	❏ Non-contact process ❏ High precision of welding ❏ Good for mass production ❏ Relatively small heat-affected zone	❏ High initial cost ❏ Material reflectivity ❏ Needs good joint fit-up ❏ Harder to weld dissimilar materials together
Ultrasonic welding	❏ No or minimal metallurgical defects ❏ Excellent for joining of dissimilar metals ❏ Most metals, even highly conductive can be welded ❏ Low temperature increase and low energy input	❏ For UMW two sided access is needed ❏ UMW is primarily suitable for pouch- and prismatic cells ❏ May cause structural damages to battery cell if fixated improperly ❏ Sensitive to high surface roughness

From the results it is evident that all methods mentioned in this report can be and are used in some sort of battery welding application. As seen from Table 3, the most suitable joining method largely depends on the battery cell geometry. There are, however, many different aspects other than geometry that need to be considered when deciding the most suitable welding technology for electrical connections. The choice of welding technique also depends on the scale of the intended production. For example, LBW has the highest initial investment costs, but may have a greater production yield compared to RSW, UMW and UWB as the welding is time efficient.

Furthermore, the requirements put on the electrical connections between battery cells is also important to consider, such as how large of a current will be drawn from the cells. If hundreds or thousands of cells, divided into battery packs, are connected, small increases in electrical resistance could lead to great energy losses. Therefore, in these instances, the weld quality that can be achieved depending on the technology is of great importance.

All of the methods have proven to have satisfactory weld quality, however when regarding weld strength Laser Beam Welding (LBW) excels. In the case of welding dissimilar materials, Ultrasonic Metal Welding (UMW) and Ultrasonic Wire Bonding (UWB) create the best welds out of the investigated methods. However, due to the limitations of UMW regarding cell geometry, UWB is applicable in more instances. Resistance Spot Welding (RSW) or UMW should be applied to materials with high surface reflectivity, and LBW should be avoided. Although, when welding materials with high conductivity then LBW and UMW should be applied while RSW is not suitable.

As previously mentioned, UMW is not suitable for cylindrical cells since the ultrasonic vibrations cause structural damage to the battery cell. However, it is suitable and preferred when regarding other cell geometries since the heat transfer from the process is low to moderate. RSW, Micro-Tungsten Inert Gas (TIG) welding and LBW on the other hand are applicable to most battery types and not limited to a specific cell geometry. RSW and Micro-TIG exhibit the largest heat transfer, apart from UMW applied to cylindrical cells, out of the methods which needs to be considered in high energy applications. LBW applies a large amount of energy to the substrate to melt the metal and create the weld. The short weld time limits the heat diffusion and minimizes the heat affected zone.

Most of the techniques do not require filler materials or gases to create the electrical connections, with the exception of certain LBW applications. Therefore increasing or decreasing the production scale of the methods is limited to investing in the raw materials and machinery. The criteria ‘cost per battery connection’ and ‘investment costs’ for the methods applied to cylindrical batteries of the MRL assessments are found in Table 2. The first criterion shows that Micro-TIG and RSW have the lowest cost per battery connection. However, LBW and UWB also received a high score and therefore also have a relatively cheap cost per battery connection. The second criterion of investment cost is significantly higher for LBW than for the other welding techniques, i.e. RSW, Micro-TIG and UWB. Despite this, LBW receives the same score as UWB when it comes to cost per battery connection and also has a shorter weld time than any of the other methods meaning a higher production rate. Regarding automation capabilities, UWB and LBW received the highest MRL score of five while RSW and Micro-TIG received a four. This is supported by other articles in the literature study. They state that all techniques are easily automated and are used in automated production lines for various applications.

6. Conclusion

To conclude, all three methods are tried and proven to function in the production of battery applications. Each method has separate strengths and limitations which makes them complement each other. Thus, it is important to look at several factors when deciding which welding technique is the most suitable for the desired application. The method of choice therefore depends on the product's material properties, geometry and cost.

The MRL assessment comparing RSW, Micro-TIG, UMW/UWB and LBW, in the context of connecting batteries, concluded that the best method for all cell geometries was LBW. The method that obtained the lowest score was RSW.

RSW is the most suitable method for small scale and limited production due its low initial costs and low maintenance costs. It is easy to use and produces good weld quality. RSW has a simple setup and is easily semi-automated or fully automated. The most suitable method for mass production is, however, UMW/UWB or LBW. Determining which of the two is best depends on the requirements set by the product. LBW has the highest initial cost out of the methods, but considering its application to mass production the initial cost would be able to be disregarded to a certain extent. However, UMW has the advantage of being capable of welding a wider range of materials, and is therefore more suitable when welding dissimilar materials.

7. References

Below are the references found in order of their appearance in this study.

[1] Encyclopædia Britannica. Britannica Academic; 2016. Battery. [Cited date 2019-04-12]
Available from: https://www.britannica.com/technology/battery-electronics

[2] Battery University. Global Battery Market. 2016. [Last updated 2016-04-11; Cited date 2019-05-08].
Available from: https://batteryuniversity.com/learn/article/global_battery_markets

[3] Abhishek D, Dezhi L, Williams D, Greenwood D. Joining Technologies for Automotive Battery Systems Manufacturing. World Electric Vehicle Journal. 2018; vol. 9.

[4] AVID Technology Group Ltd, Maughan R. What is the Best Electric Vehicle Battery Cooling System. 2019. [Cited date 2019-05-08]. Available from:
https://avidtp.com/what-is-the-best-cooling-system-for-electric-vehicle-battery-packs/

[5] Davide A. Battery management systems for large Lithium-ion battery packs 2010 Artech house. Li-ion BMS 1.3 p. 15-16.

[6] Electrical4U. What is Electrical Resistance? Definition and Unit of Resistance.
[Updated date 2018-10-31; Cited date 2019-04-12]
Available from: https://www.electrical4u.com/what-is-electrical-resistance/

[7] Datta, S. Electrical Resistance: An Atomistic View. Institute of Physics Publishing: Nanotechnology. 2004; vol. 15: p. 433-451.

[8] Neid H.A. The Finite Element Modeling of the Resistance Spot Welding Process. Welding Research Supplement. 1984: p. 123-32.

[9] Brand M.J, Schmidt P.A, Zaeh M.F, Jossen A. Welding techniques for battery cells and resulting electrical contact resistances. Journal of Energy Storage. 2015; vol. 1: p. 7-14.

[10] Abhishek D, Dezhi L, Williams D, Greenwood D. Weldability and shear strength feasibility study for automotive electric vehicle battery tab interconnects. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2019.

[11] Amada Miyachi. The Benefits of Inverter Technology. vol. 1 , 2015. [Cited date 2019-05-14]

[12] Philips D.H. Welding Engineering: An Introduction. New York: John Wiley & Sons; 2015.
5, High Energy Density Welding Processes; p. 114-22.

[13] Balle F, Ultrasonic Welding. JOM. 2012; vol. 64

[14] Cai W, Kang B, Hu J.S, Ultrasonic Welding of Lithium-Ion Batteries. New York: The American Society of Mechanical Engineers; 2017. 1.4.1, Ultrasonic Metal Welding, p. 6-7.

[15] Cai W, Kang B, Hu J.S, Ultrasonic Welding of Lithium-Ion Batteries. New York: The American Society of Mechanical Engineers; 2017. 1.4.1, Ultrasonic Metal Welding, p. 10.

[16] Philips D.H. Welding Engineering: An Introduction. New York: John Wiley & Sons; 2015. 3, Resistance Welding Processes; p. 74-94.

[17] Kimchi M, Phillips D.H, Resistance Spot Welding Fundamentals and Applications for the Automotive Industry. Morgan & Claypool publishers; 2017.

[18] Amada Miyachi. Some thoughts on choosing the best battery welding technology. 2015 [Updated date: 2015-05-05; Cited date 2019-05-15]. Available from: info.amadamiyachi.com/blog/some-thoughts-on-choosing-the-best-battery-welding-technology

[19] Masomtob M, Sukondhasingha R, Becker J, Sauer D.U, Parametric Study of Spot Welding between Li-ion Battery Cells and Sheet Metal Connectors. Engineering Journal. 2017; vol. 21.

[20] Aslanlar S, Ogur A, Ozsarac U, Ilhan E, Demir Z, Effect of welding current on mechanical properties of galvanized chromided steel sheets in electrical resistance spot welding. Materials & Design. 2005; vol. 28; p. 2-7.

[21] Andersson O. Process planning of resistance spot welding. KTH Industrial Engineering and Management. 2013.

[22] Jou M. Real time monitoring weld quality of resistance spot welding for the fabrication of sheet metal assemblies. Journal of Materials Processing Technology. 2003; p.102–113.

[23] Godek J. Joining lithium–ion batteries into packs using small-scale resistance spot welding. Welding International. 2013; vol. 27(8): p. 616-22.

[24] P.Y Petrov, I.V Alekseev, E.A Kolesnik. 2017. IOP Conf. Ser.: Earth Environ. Economic evaluation for use of advanced welding equipment.

[25] Saleem J. Power electronics for resistance spot welding equipment. 2012 [Cited date 2019-05-14] Available from: http://www.diva-portal.org/smash/get/diva2:543835/fulltext01.pdf

[26] Amada Miyachi. Spot welding: improve quality and reduce cost with inverters. 2017 [Cited date 2019-05-14]
Available from: http://info.amadamiyachi.com/blog/improve-quality-reduce-cost-with-inverters

[27] Ambroziak A, Korzeniowski M. Using resistance spot welding for joining aluminium elements in automotive industry. 2010. Wrocław University of Technology, Łukasiewicza 5, p. 50-371 Wrocław, Poland.

[28] K. Vignesh, A. Elaya Perumal, P. Velmurugan. Optimization of resistance spot welding process parameters and microstructural examination for dissimilar welding of AISI 316L austenitic stainless steel and 2205 duplex stainless steel. 2017. Springer-Verlag London 2017.

[29] P. Podrzˇaj*, I. Polajnar, J. Diaci and Z. Karizˇ. Overview of resistance spot welding control. 2008 Science and Technology of Welding & Joining.

[30] Cho Y, Rhee S. New technology for measuring dynamic resistance and estimating strength in resistance? spot welding. 2000 Meas. Sci. Technol.

[31] Faridh Ahmad Zaharuddin M, Donghyun K, Rhee S. An ANFIS based approach for predicting the weld? strength of resistance spot welding in artificial intelligence development. 2017. Department of Mechanical Engineering, Hanyang University.

[32] Shannon G. Improve Tab to Terminal Connections in Battery Pack Manufacturing. Amada Miyachi America.

[33] Shannon G. Battery Welding Solutions Using Laser and Resistance Technologies. 2009; vol. 13. Miyachi Unitek Corporation.

[34] Amada Miyachi. Fiber Laser Welding. [Cited date 2019-05-15]
Available from: https://www.amadamiyachi.eu/knowlegde-base/fiber-laser-welding

[35] EBindustries. CW and Pulsed Laser Welding. [Cited date 2019-05-15]
Available from: https://www.ebindustries.com/cw-and-pulsed-laser-welding/

[36] Walter D, Schmieder B, Moldovan V. Nothing Less Than More Affordable Lithium-Ion batteries. Laser technik journal. 2014: p. 44-47.

[37] Speth D, Eastman J, Laser welding batteries for electric vehicles. Industrial laser solutions. 2012.

[38] Esfahani M.R.N, Coupland J, Marimuthu S. Numerical simulation of alloy composition in dissimilar laser welding. Journal of Materials Processing Technology. 2015; vol. 224: p. 135-142.

[39] Auwal S.T, Ramesh S, Yusof F, Manladan S.M. A review on laser beam welding of copper alloys. The international Journal of Advanced Manufacturing Technology. 2018; vol. 96 p. 475-490.

[40] Lee S, H. Kim, Tae & Jack Hu, S & Cai, Wayne, et al. (2010). Joining Technologies for Automotive Lithium-Ion Battery Manufacturing: A Review. ASME 2010 International Manufacturing Science and Engineering Conference, MSEC 2010.

[41] Miller E, Shuang L. Should your operation convert from spot welding to laser keyhole welding? The fabricator; 2018 [updated date 2018-02-21 ; cited date 2019- 05-14]
Available from:
https://www.thefabricator.com/article/laserwelding/should-your-operation-convert-from-spot-welding-to-laser-keyhole-welding-

[42] Hgtech. High degree of automation of the laser welding machine. [Updated date 2018-07-30; Cited date 2019-05-14] Available from:
https://www.hgtech-laser.com/info/high-degree-of-automation-of-the-laser-welding-27812013.html

[43] Klinger J.F. Mass & Cost Saving Potential of Laser Welding Compared to Spot Welding. Stockholm; KTH. TRITA-AVE 2012:04; ISSN 1651-7660

[44] Mueller R. Choosing the Low Cost Method for Manufacturing. NuTech Engineering Inc; 2011

[45] Rofin. Laser Welding.[Cited date 2019-05-14].
Available from: https://www.rofin.com/en/applications/laser-welding/

[46] Leng F, Tan C.M, Pecht M. Effect of Temperature on the Aging rate of Li Ion Battery Operating Above Room Temperature. 2015.

[47] Wagner G, Balle F, Eifler D. Ultrasonic Welding of Hybrid Joint. JOM. 2012; vol. 64: p. 401-6.

[48] Product Specification Lithium-ion Battery LFP-26650-3200HT. Cited date 2019-05-15.
Available from: http://www.batteryspace.com/prod-specs/2812.pdf

[49] Languang L, Xuebing H, Jianfeng H, Jianqiu L, Minggao O. Journal of Power Sources.
A review on the key issues for lithium-ion battery management in electric vehicles. 2013. 226: p. 272-288

[50] Selman J.R, Hallaj S.A, Uchida I, Hirano J. Journal of Power Sources.
Cooperative research on safety fundamentals of lithium batteries. 2001; 97-98: p. 726-732

[51] Kumar S, Wu C.S, Padhy G.K, Ding W. Application of ultrasonic vibrations in welding and metal processing: A status review. Journal of Manufacturing Processes. 2017; 26: p. 295-322.

[52] Black J, Hashimzade N and Myles G. A Dictionary of Economics. 5 ed. Oxford University Press. 2017.

Appendix

Appendix 1- *Resistance Spot Welding Experiment : Welding methods for electrical connections in battery systems*

Appendix 2- *List of possible equipment suppliers for different welding techniques*

Appendix 3- *Relevance Ranking of Sources*