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Published in:
Journal of Advanced Joining Processes

Link to article, DOI:
[10.1016/j.jajp.2020.100017](https://doi.org/10.1016/j.jajp.2020.100017)

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

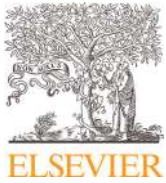
Citation (APA):
Zwicker, M. F. R., Moghadam, M., Zhang, W., & Nielsen, C. V. (2020). Automotive battery pack manufacturing – a review of battery to tab joining. *Journal of Advanced Joining Processes*, 1, [100017].
<https://doi.org/10.1016/j.jajp.2020.100017>

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Automotive battery pack manufacturing – a review of battery to tab joining[☆]

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ARTICLE INFO

Keywords:

Battery pack
Battery joining
Welding
Connection resistance
Interdisciplinary requirements
Electromobility

ABSTRACT

Automotive battery packs used for electromobility applications consist of a large number of individual battery cells that are interconnected. Interconnection of the battery cells creates an electrical and mechanical connection, which can be realised by means of different joining technologies. The adaption of different joining technologies greatly influences the central characteristics of the battery pack in terms of battery performance, capacity and lifetime. Selection of a suitable joining technology, therefore, involves several considerations regarding electrical and mechanical properties and an assessment of production and operational conditions. Particularly, during the operation of an electric vehicle, challenges and mutual dependencies of the electrical and mechanical system emerge. The present work provides an overview of interdisciplinary challenges occurring at joints which are exposed to electrical current with a strong focus on interconnecting batteries for electric cars. It summarizes common quality criteria for the joining technologies and recombines those with criteria deduced from an electrical engineering point of view. Scientific literature concerning different joining technologies in the field of battery manufacturing is discussed based on those criteria. The most common joining techniques are ultrasonic welding, wire bonding, force fitting, soldering, laser beam welding, and resistance welding. Besides those, friction stir welding, tungsten inert gas welding, joining by forming and adhesive bonding are presented.

Introduction

Electromobility becomes increasingly important as the world's largest automotive market, China, started to ban combustion engines. As of March 1, 2019, the Chinese Hainan province banned sales of fossil fuel cars and aims to entirely shift to alternative propulsion technologies before 2030 ([Hainan province to ban sales of diesel, petrol cars from Mar 1 2019](#)). This general trend of shifting away from fossil fuel cars ([Pham, 2017](#), [Economist, 2017](#)) will result in high demand for electric vehicles as electromobility is the most mature alternative propulsion technology ([Chu, 2017](#)). Electric cars store energy in battery packs consisting of interconnected individual battery cells ([Perner and Vetter, 2015](#)). The most commonly employed batteries are Lithium-ion rechargeable batteries ([Warner, 2015](#), [Rahn and Wang, 2013](#)). Three different battery cell types are employed in the automotive field which are small solid cylindrical cells, larger solid prismatic cells, and larger soft pouch or polymer cells ([Warner, 2014](#)). The three types, presented in [Fig. 1](#), mainly differ in size, geometry, and individual cell parameters as capacity and supplied power. The dimensions of the three cell types, particularly for the prismatic and pouch cells, vary between cell man-

ufacturers and car manufacturers. There are, however, the standards ISO/PAS 16,898:2012 and DIN 91,252:2016–11, which define the dimensions of the three types.

Automotive battery packs are commonly designed and manufactured in a pack–module–cell structure as schematically depicted in [Fig. 2](#). The actual designs differ mainly in how the desired pack capacity and power is achieved. One may connect fewer large battery cells with a high individual cell capacity in series. They can be clustered in modules as shown in [Fig. 2\(a\)](#). Alternatively, multiple small battery cells with low individual cell capacity can be connected in parallel and subsequently connected to modules with high capacity as shown in [Fig. 2\(b\)](#). Mixed types where series and parallel connections are combined also exist. Parallel connections ensure the highest capacity and amperage requirements, whereas series connections are used to enhance the supplied power ([Brand et al., 2016](#), [Gallagher and Nelson, 2014](#)). The two approaches can be comprehended when considering the batteries in BMW's i3 and in Tesla's Roadster. In the latter case, the pack consists of 11 modules connected in series. Each module is built of 9 sheets, connected in series. Each sheet consists of 69 individual cylindrical cells connected in parallel with an individual cell capacity of 2.16 Ah ([Warner, 2015](#), [Rothgang](#)

[☆] This paper belongs to the AJP2019 special issue. The waiver code is JAJPGI8XQHkvOA.

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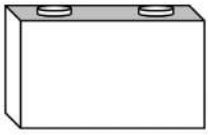

Cylindrical cell	Prismatic cell	Pouch cell
		
<ul style="list-style-type: none"> • Small size (e.g. 18650 type (ø 18 mm, height 650 mm)) • Hard casing • Low individual cell capacity • Build in safety features • Comparably cheap 	<ul style="list-style-type: none"> • Hard casing • Large size • High individual cell capacity 	<ul style="list-style-type: none"> • Soft casing • Large size • High individual cell capacity • Geometrical deformation during (dis-)charging

Fig. 1. Overview of different cell types used in automotive battery applications: (left) cylindrical cell, (middle) prismatic cell, (right) pouch cell.

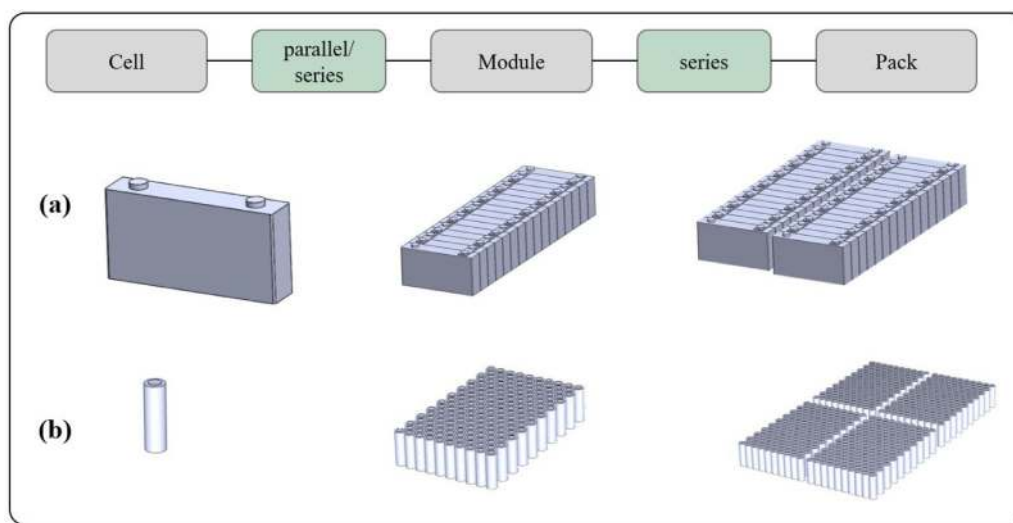


Fig. 2. Overview of battery packs indicating two constructions with (a) cylindrical and (b) prismatic cells.

Table 1

Examples of electric vehicle batteries (cell configuration: s – series-, p-parallel connection).

Vehicle	Tesla Model S 85 kW	Tesla Roadster	BMW i3	Nissan Leaf	Chevrolet Bolt EV - Second generation	Volkswagen MEB – modular electric vehicle drive matrix (I.D. family models)
Reference	(Warner, 2015, Narayanaswamy, 2018)	(Warner, 2015, Rothgang et al., 2015)	(Rothgang et al., 2015, Narayanaswamy, 2018, The Composition of EV Batteries: Cells? Modules? Packs? Let's Understand Properly!, 2020)	(Warner, 2015, Cai, 2016)	(Cobb, 2015)	(In brief: Key components for a new era – the battery system 2019, Modular electric drive matrix (MEB) 2020)
Modules	16	11	8	58	7	Up to 12
Cells per module	404	621	12	4	24 & 32	24
Cell configuration	74P6S16S	69p9s11s	1p12s8s	2p2s48s	96s2p	–
Total no. of cells	7104	6831	96	192	192	Up to 288
Cell Type	Cylindrical 18,650	Cylindrical 18,650	Prismatic	Pouch	Pouch (12.7 by 17.7-cm)	Prismatic or Pouch
Cell manufacturer	Panasonic	–	Samsung SDI	AESC	LG Chem	–
Joining technology	Wire bonding	–	Laser welding	Ultrasonic welding	Ultrasonic welding	–

et al., 2015). This cell configuration is designated 69p9s11s, where p and s refer to parallel and series connections, respectively. On the contrary, BMW's i3 connects 96 prismatic cells with an individual cell capacity of 60 Ah in series, whereas they are physically built into 8 modules of 12 batteries each and thus designated as 12s8s (Warner, 2015, Rothgang et al., 2015). Table 1 provides an overview of batteries, pack configuration and applied joining technology for some common electric vehicles

The way a car battery is designed depends on the manufacturing company and its preferences. Building a system with fewer large cells, as in the BMW i3, decreases the overall system complexity. At the same time, large cells limit the design flexibility of the pack. However, large and more complex battery systems as applied by Tesla, for instance, enhance the system's reliability in case of an open wire failure (Rothgang et al., 2015).

This paper aims to provide an overview of interconnecting battery cells when manufacturing battery modules and packs. In the following sections, typical challenges will be summarised, requirements for joining technologies stated, and scientific literature concerning battery interconnection joining will be analysed. The work at hand is meant to supplement earlier reviews on the same topic published by Lee et al. (Lee et al., 2010), Cai (Cai, 2016) and Das et al. (Das et al., 2018).

Interdisciplinarity of battery pack design

Mechanical challenges

Mechanical phenomena play an important role when it comes to battery module operation and safety requirements. During operation battery modules are exposed to dynamic loading and random vibrations, which may cause short circuits and fire (Shui et al., 2018). Random vibrations have a particularly high influence on modules with a large number of single cells due to their periodic structure. The module's structural dynamics can be impaired as a high modal density in many frequency ranges is promoted. Moreover, the battery interconnection joints will to some extent be pre-stressed due to the interconnecting by joining which may, in turn, affect the dynamic response of the entire battery back noticeably (Hong et al., 2013). In the case of employing thin prismatic or soft polymer cells, the above-introduced effects may be enhanced due to dimensional changes of the cells during operation (Lee et al., 2003). Lithium-ion and polymer batteries generally behave dynamically in terms of structure and dimension during charging and discharging (Lee et al., 2003), which has a recognisable impact if the casing is soft. The reason for expanding during charging and contracting during discharging is a lattice expansion or contraction of the host material. This effect can remain permanently due to an irreversible expansion of the electrode, and dead material and pressure changes in the cell (Lee et al., 2003).

Thermo – mechanical challenges

If materials with different thermal expansion are joined and heat is generated at the contact interface, inhomogeneous thermal expansion might introduce shear loading and in severe cases even plastic deformation or fracture in the contact region, which in turn may negatively influence contact behaviour and thus the connection resistance (Braunovic, 2017).

Electro – thermal challenges

When interconnecting batteries regardless of the joining technology and the electric circuit type, i.e. parallel or series connection, one will unavoidably obtain a joint with an inherent electrical resistance. This resistance will occur at the connection point between battery and interconnector. This resistance is here designated as connection resistance. During charging and discharging of a cell, module, or pack the existence of a connection resistance has two direct effects, namely loss of electrical energy across the interface and heat generation in the contact region, where both depend on the resistance.

The loss of energy will directly influence the battery performance, as during charging and discharging introduced energy will be partially dissipated, which in turn reduces the available battery module capacity. In other words, the larger the resistance, the more energy will be dissipated, and thus less energy can be used to propel a car, i.e. the possible range is shortened (Taheri et al., 2011).

The dissipated energy will be transformed into heat at the contact region of the battery cell. Heating of the battery can cause faster cell degradation or ageing (Fleckenstein et al., 2011) or thermal runaway, which consequently results in battery damage (Yang et al., 2016). In extreme cases of heating, even safety issues as fire or explosions are possible (Wang et al., 2012). Chemical transformations and increased

ageing rates within Lithium-ion cells have been reported to occur in a temperature range of about 55 to 65 °C (Araki and Sato, 2003, Leng et al., 2015). Temperatures around 80 °C have also been found in literature (Brand et al., 2013). Cell manufacturers recommend operating cells below 60 °C (Datasheet: Panasonic NCR18650B 2020, Lithium Ion Rechargeable Battery Technical Information: US18650VTC5 2013) to 75 °C (Specification of product: Samsung INR18650-25R 2014) depending on the manufacturer. The aforementioned effects can get intensified if corrosion appears at the connection (Campestrini et al., 2016). Saw et al. (Saw et al., 2013) found for lithium iron phosphate cells that the presence of a connection resistance of 10 mΩ caused recognisable temperature gradients of up to 10 °C across cylindrical 18,650 cells which was just within the allowable temperature range and may impair the cell capacity.

Electro – mechanical challenges

As the mechanical joints between batteries and conductors are not only having a structural purpose but also conduct current from or to the cells it is crucial to consider electromechanical effects, too. Fatigue is a known phenomenon and of concern in structural applications but also promotes an increase in electrical resistance. The electrical resistance of specimens during fatigue tests is used to predict fatigue life, where the interplay of fatigue damage and electrical resistance is isolated from other factors as specimen length change for instance (Sun and Guo, 2004, Starke et al., 2006). Constable and Sahay (Constable and Sahay, 1992) investigated the interplay of fatigue and electrical connection resistance of lead and solder joints in electric-circuits. Zhao et al. (Zhao et al., 2014) investigated the same for ultrasonically welded aluminium copper samples. In both studies, an increase in connection resistance with progressing fatigue damage was found, whereas no absolute numbers were stated as the focus lay on the investigation of fatigue rather than the connection resistance.

Metallurgical challenges

Corrosion, the deterioration of material properties and function, is known to appear at joints in the field of integrated circuits (Qiu, 2006) and electric contacts. Here, the most known and apparent types, are atmospheric, localised, crevice, pitting, and galvanic corrosion (Braunovic, 2017).

Fretting or fretting corrosion is defined as surface degradation at a metal to metal contact interface caused by oscillatory movements of the two surfaces with slip amplitudes of less than 125 µm (Qiu, 2006). Fretting was thoroughly investigated in the field of microelectronics and electronic connections and found to be apparent in almost all commonly applied conductor materials as for instance copper, aluminium, or nickel, and was reported to have a noticeable influence on the connection resistance (Antler, 1985). For more information on fretting in relation to connection resistance, see Timsit and Antler (Timsit and Antler, 2017) or Antler (Antler, 1985).

Oxidation of metal to metal contacts is considered to be the most serious mechanism of degradation in mechanically joined electrical connections (Mechanical connectors for aluminium cables in investigation of degradation mechanisms in connector clamps and bolted terminations 1972). The oxidation layer of aluminium grows immediately and is rather thin compared to the size of conducting asperities (α -spots), making it a less severe degradation mechanism when aluminium is a joining partner (Braunovic, 2017). Copper oxidation, however, is more complex, the oxidation layer grows at a slower rate and was reported to exhibit insulating and conducting properties (Braunovic, 2017).

Intermetallic compounds, e.g. between copper and aluminium give direct implications; namely loss of mechanical strength and increase of electric connection resistance (Timsit, 2017). The formation is possible during joining and often controllable. Additionally, the presence of temperature and current during operation may promote diffusion and

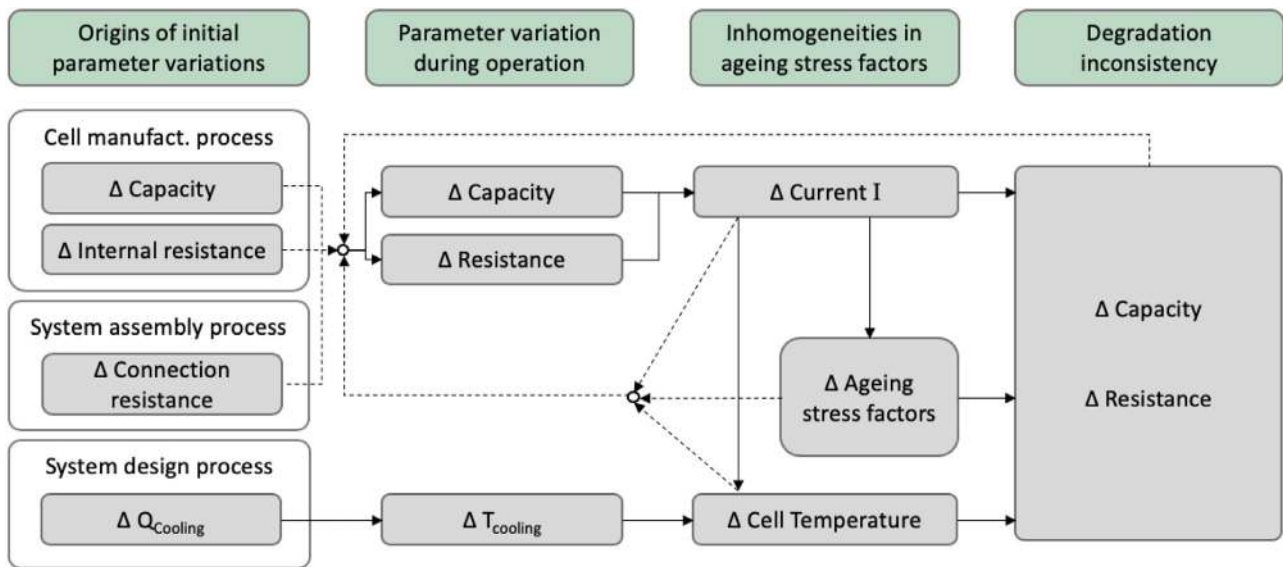


Fig. 3. Overview (adapted from Baumann et al. (Baumann et al., 2018)) of variations in battery module parameters and their consequences; particularly origins of initial parameters in battery modules, further alteration during operation, yielding inhomogeneities in ageing stress factors and eventually an inconsistency in ageing.

thus the uncontrolled formation of intermetallic compounds (Braunovic, 2017). For a thorough review of the formation of intermetallic compounds in electric connections, see (Braunovic, 2017, Timsit, 2017).

The above metallurgical challenges are some of which the authors think are most important. Further influences from surface films, surface contamination and coatings may be found elsewhere, e.g. in (Slade, 2017).

Electrical challenges of parallel connections in battery modules

A major phenomenon when considering battery modules with parallel connections is that individual cells in battery modules degrade (or age) at different rates (Campestrini et al., 2016) which leads eventually to a shortened battery module lifetime. Battery ageing or degradation can be described as an increase in internal cell resistance and loss of cell capacity (Paul et al., 2013). More information can be found elsewhere (Barré et al., 2013, Baumann et al., 2018, Vetter et al., 2005).

Battery modules have inherent initial parameter variations, which consequently lead to parameter variations during operation. As an immediate result, differences in further battery parameters are caused, which are ageing stress factors at the same time. As a consequence, not only ageing occurs but also it happens at different rates for different cells. Furthermore, ageing contributes in turn to an increase in parameter variation, and thus a complex circle of mutual parameter interaction emerges in battery modules. Fig. 3 summarises those mutual interactions as earlier identified by Baumann et al. (Baumann et al., 2018). The explanation of Fig. 3 is made in accordance with Baumann et al. (Baumann et al., 2018).

Initial parameter variation

Baumann et al. (Baumann et al., 2018) identified battery cell capacity, internal resistance, connection resistance, and the cooling system as determining initial parameters. Capacity and internal resistance differ due to cell manufacturing as well as chemical and material differences as impurities for instance (Baumhöfer et al., 2014, Santhanagopalan and White, 2012). The connection resistance between individual cells and cell inter-connectors may be different due to the applied joining process (Brand et al., 2015). Lastly, the cooling system was identified as a cause for parameter variation (Yang et al., 2016), if the cooling capacity is unevenly applied to cells across the battery module, different

operation temperatures appear. The latter cause for parameter variation is excluded from explanations in this work.

Immediate effect of parameter variation

Differences in cell capacity, internal resistance and connection resistance cause different current rates within the module's cells. Before considering the effects, the reasons for different current rates are explained.

The presence and difference of a connection resistance in combination with the differing internal cell resistance becomes more crucial when considering cells connected in parallel. Here, the circuit will act as a current divider according to Kirchhoff's current law, where the current is distributed inversely to the resistance. One may consider a two resistor circuit where $R_1 > R_2$ which leads to a difference in current rates following $I_1 = (R_2/R_1) I_2$ (Bernstein and Böge, 2014). While the connection resistance is an ohmic resistance, the internal resistance is a combination of ohmic resistance and individual cell impedance, which makes the latter more complex and dynamically depending on other parameters (Brand et al., 2016, Baumann et al., 2018).

It cannot be ultimately stated which resistance has more influence. However, Offer et al. (Offer et al., 2012) concluded that even differences in internal cell impedance of 10–20% are having a much lower influence than comparably high connection resistances with a large scattering range. Baumann et al. (Baumann et al., 2018) state that the relative inhomogeneity of the connection resistance and the internal resistance is to be considered when evaluating the former type. Wu et al. (Wu et al., 2013) also confirm the notable influence of the connection resistance.

Differences in current rates can also be caused by uneven individual cell capacities (Kenney et al., 2012). However, in this case, it is not related to the current divider phenomenon, but currents will divide proportionally to the cell capacities (Brand et al., 2016). Also at this point, the reader is referred elsewhere for more details (Brand et al., 2016, Baumann et al., 2018).

Differences in ageing stress factors and inconsistent ageing

The current is an important ageing stress factor. It is shown in the third column of Fig. 3, whereas factors that are not discussed here are indicated by " Δ Ageing stress factors". Differences within those factors may amplify each other and cause inconsistent degradation across the module, which leads to further parameter variations. From here on,

Table 2
Overview of materials in lithium-ion battery interconnections.

	Cylindrical cell	Pouch cell	Prismatic cell
Housing	Nickel-plated steel, steel, aluminium	–	Steel, aluminium
Negative tap/ terminal	Nickel-plated steel, steel, aluminium, nickel, copper	Copper, nickel plated copper	Copper, aluminium, nickel
Positive tap/ terminal	Nickel-plated steel, steel, aluminium	Aluminium	Aluminium, nickel
Collector-, bus-bar, interconnector	Copper, nickel, nickel-plated steel, nickel-plated copper, aluminium		

complex and dynamic mutual interactions between all involved parameters emerge. Moreover, the differences in ageing which are caused by initial parameter variation and by stress factors do add up (Paul et al., 2013, Baumhöfer et al., 2014). It is, however, not clear whether or not initial cell parameter variation is getting worse when ageing proceeds. Some researchers found that current split is getting impaired as ageing proceeds (Gong et al., 2015, Huynh, 2016), whereas others state the opposite effect (Brand et al., 2012, Pastor-Fernandez et al., 2016). Campestrini et al. (Campestrini et al., 2016) report in their study that the connection resistance and not the cell internal resistance, increased substantially with ageing.

To summarise, inconsistencies in connection resistance within battery modules contributes noticeably to an overall parameter variation and eventually to inhomogeneous ageing of individual cells. Therefore, from a manufacturing point of view, a requirement to a joining technique is that a narrow scattering range of resulting connection resistance is achievable.

Quality criteria

In order to assess the suitability of a joining technology for battery interconnections appropriately, it is necessary to deduce interdisciplinary requirements. Here, four categories can be defined in accordance with Das et al. (Das et al., 2018):

- **Electrical and thermal requirements**
 - Resulting joints should have low electrical resistance with a narrow scattering range
 - Thermal input during manufacturing should be as small as possible
 - High thermal fatigue resistance of created joints
- **Material and metallurgical requirements**
 - Low corrosion risk
 - Joining of dissimilar materials
 - Adaptability to a variety of surface conditions and materials
- **Mechanical requirements**
 - Strong interconnections
 - Good fatigue and creep resistance
 - Low pre-stress level
 - Avoid mechanical or vibrational damage during joining
- **Economic requirements**
 - Suitability for mass production
 - Low acquisition costs
 - Good possibility to be stabilised and standardised

Joining technologies for automotive batteries

As mentioned before, there exist different battery types and thus different joining tasks can be defined. Generally, batteries being connected in parallel or in series are interconnected by means of joining them to an interconnector, i.e. an electric conductor. The latter may also be found designated as collector bar or busbar. Fig. 4(a) and Fig. 4(c) show schematically and by an application, respectively, how cylindrical cells are interconnected. Pouch and also prismatic cells may be connected as presented in Fig. 4(b) and Fig. 4(d). The major difference is that in the case of cylindrical cells the interconnector will be directly joined onto the cell housing whereas pouch and prismatic cells have externally located connector tabs which are joined to the interconnector.

The most frequently observed materials in battery interconnecting are summarised in Table 2.

The most commonly deployed joining technologies are ultrasonic welding, wire bonding, force fitting/mechanical assembly, soldering and brazing, laser and resistance spot welding. Besides those, the work at hand also considers friction stir welding, tungsten inert gas welding, joining by forming and adhesive bonding. Those technologies will be presented in the following with focus on scientific literature assessing the suitability for battery joining tasks. The process technologies ultrasonic welding, wire bonding, force fitting/ mechanical assembly and resistance spot welding are schematically presented in Fig. 5 for joining interconnectors to both cylindrical and pouch/prismatic cells.

Ultrasonic welding

Fig. 5(a) and Fig. 5(b) show schematically how a cylindrical and a pouch or prismatic cell, respectively, may be joined to an interconnector by ultrasonic welding. Brand et al. (Brand et al., 2015) employed amongst others ultrasonic welding to interconnect cylindrical battery cells. The connection resistance was measured, and dependency between the weld area and the resulting resistance was found. The resistance increased with decreasing joint area and was evaluated to be acceptable and comparable to resistance welding. Brand et al. (Brand et al., 2015), furthermore, point out that ultrasonic welding has a higher heat generation than laser and resistance welding. However, they evaluated the heat input to the battery as not critical.

Zhao et al. (Zhao et al., 2013) and Li et al. (Li et al., 2013) employed thin-film thermocouples and thermopile sensors to measure heat generation in situ. Temperatures of up to 660 °C have been measured 1 mm from the weld area. This indicates a high heat generation.

Das et al. (Das et al., 2019) found that aluminium tabs resulted in a higher heat generation at the tab-busbar joint than copper tabs, which appeared to be independent from the busbar itself. Das et al. (Das et al., 2019) investigated electrical and thermal characteristics of ultrasonic joints during current flow. It was observed that the connection resistance increased with increasing joint temperature caused by electrical currents between 150 and 250A. They measured for aluminium-copper joints an increase in resistance of 31% due to a temperature rise of 50 °C at 250A over 60 s and for copper to copper 16% due to a rise of 26 °C.

Shin and de Leon (Shin and de Leon, 2017) investigated the mechanical and electric performance of different joining partner setups made by copper and aluminium sheets while the copper interconnector consisted of multiple layers. They found for multilayer configuration that the presence of unbonded interfaces increased the connection resistance, whereas the resistance was found to be lower than measured values for solder joints. McGovern et al. (McGovern et al., 2019) measured the electrical connection resistance of two copper sheets welded to a copper busbar as part of a quality assurance methodology for varying welding conditions and configurations.

Raj et al. (Raj et al., 2019, Mohan Raj et al., 2018) investigated joint aluminium and copper wires in terms of joint resistivity and connection resistance in dependence of different process parameters while taking intermetallic compounds into consideration.

Choi et al. (Choi et al., 2012) note that the inherent process vibrations may propagate into the battery and subsequently damage it. Kang et al. (Kang et al., 2014) and Li et al. (Lee et al., 2014) found in numerical studies of interconnected pouch or prismatic cells, that an already

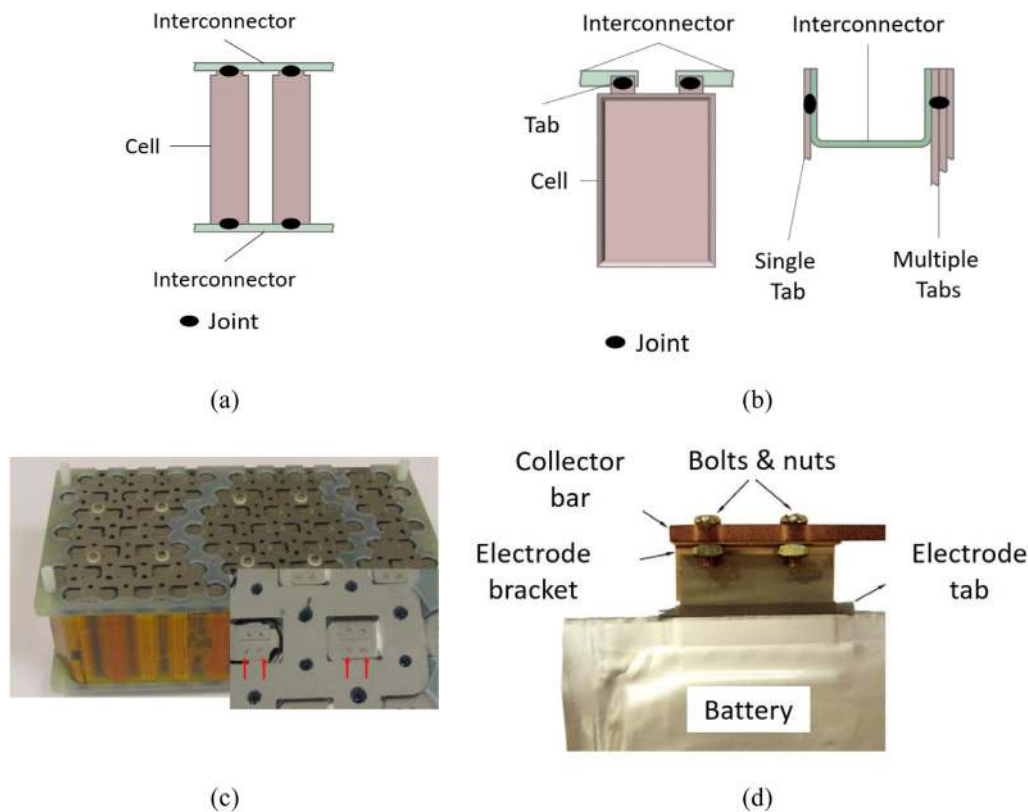


Fig. 4. Overview of joining tasks in battery applications: schematic depiction of the joining location (a) if cylindrical cells or (b) if pouch cells or prismatic cells are interconnected; (c) battery module consisting of cylindrical cells which are directly connected by one large busbar (interconnector) (joints indicated with red arrows) (Martinez et al., 2015), (d) single pouch cell interconnected to a copper collector bar (busbar/ interconnector) (Taheri et al., 2011).

existing weld can be damaged while creating a second weld on the same interconnector. During the second weld, vibrations of the connector are induced, which in turn causes stress in the first weld. This can be comprehended in Fig. 6.

Zhao et al. (Zhao et al., 2014) found that fatigue increases the connection resistance of ultrasonically welded aluminium copper samples. Characteristic progress of the connection resistance throughout fatigue life could be identified which offers the possibility for weld fatigue life prediction.

In relation to ultrasonic welding of battery tabs, much research is conducted as the technology itself is challenging and not fully understood yet, due to its inherent multi-physical nature. Those studies, dealing with process monitoring and improvement, quality assurance, power dissipation during welding etc., are beyond the scope of this paper as we intend to provide an overview on battery interconnections in sense of the joint being an electric conductor.

Wire bonding

Wire bonding, schematically depicted in Fig. 5(c) and Fig. 5(d), is a frequently employed joining technology in semiconductor device technology. Here, a wire is joined onto an integrated circuit board in order to create connections. Those connections are most commonly manufactured by means of thermo-compression bonding, ultrasonic (wedge) bonding, and thermo-sonic bonding (Charles, 2017). The reader is referred to (Charles, 2017) for more information. No scientific literature about wire bonding in relation to battery module manufacturing was found, but it is frequently stated as a process in the automotive field. This is most likely as Tesla Inc. filed several patents using wire bonding for battery modules (Straubel et al., 2010, Barton et al., 2018, Kohn et al., 2011) and is applying the joining process in its Model S (Ruoff, 2016). Tesla's patent US7923144B2 (Kohn et al., 2011) claims the bat-

tery interconnection depicted in Fig. 7. Here number 14 is the battery cell and 12 the connector wire joined onto the battery, which is in turn connected to the collector plate 16. The joints are recommended to be made by ultrasonic wedge bonding, but any other process may be used. The wires shall be of aluminium and have a diameter of 0.28 - 0.41 (mm). The collector plate shall be of any electrically conducting material, preferably metal.

Force fitting and mechanical assembly

Fig. 5(e) and Fig. 5(f) depict schematically two cases of battery applications employing force fitting as joining method, namely connecting an interconnector to a prismatic or pouch cell and the clamping of a cylindrical cell. Both Bolsinger et al. (Bolsinger et al., 2017) and Brand et al. (Brand et al., 2016) conducted comprehensive studies on electrical connection resistance in force fitting joints. In both studies, a test setup was employed which is a combination of a press to adjust force or pressure, respectively, between two joining partners and an ohmmeter to measure the electrical contact resistance. This enabled to test different materials under different surface conditions and different process forces/contact pressures. Both found that the applied force/contact pressure and material properties are crucial to the electrical contact resistance. Surface roughness was found to be negligible, while oxidation layers or other films do have a strong, increasing influence on contact resistance, particularly for aluminium and its oxidation layer. Bolsinger et al. (Bolsinger et al., 2017) concluded from their study that the contact area has no noticeable influence, whereas Brand et al. (Brand et al., 2016) state a decreasing connection resistance with increasing contact area for brass. It may be stated, that Bolsinger et al. (Bolsinger et al., 2017) employed a rather realistic set up as they used a real battery terminal of a Panasonic NCR18650B Li-Ion cell and investigated different material combinations with it, whereas Brand et al. (Brand et al., 2016) paired the same ma-

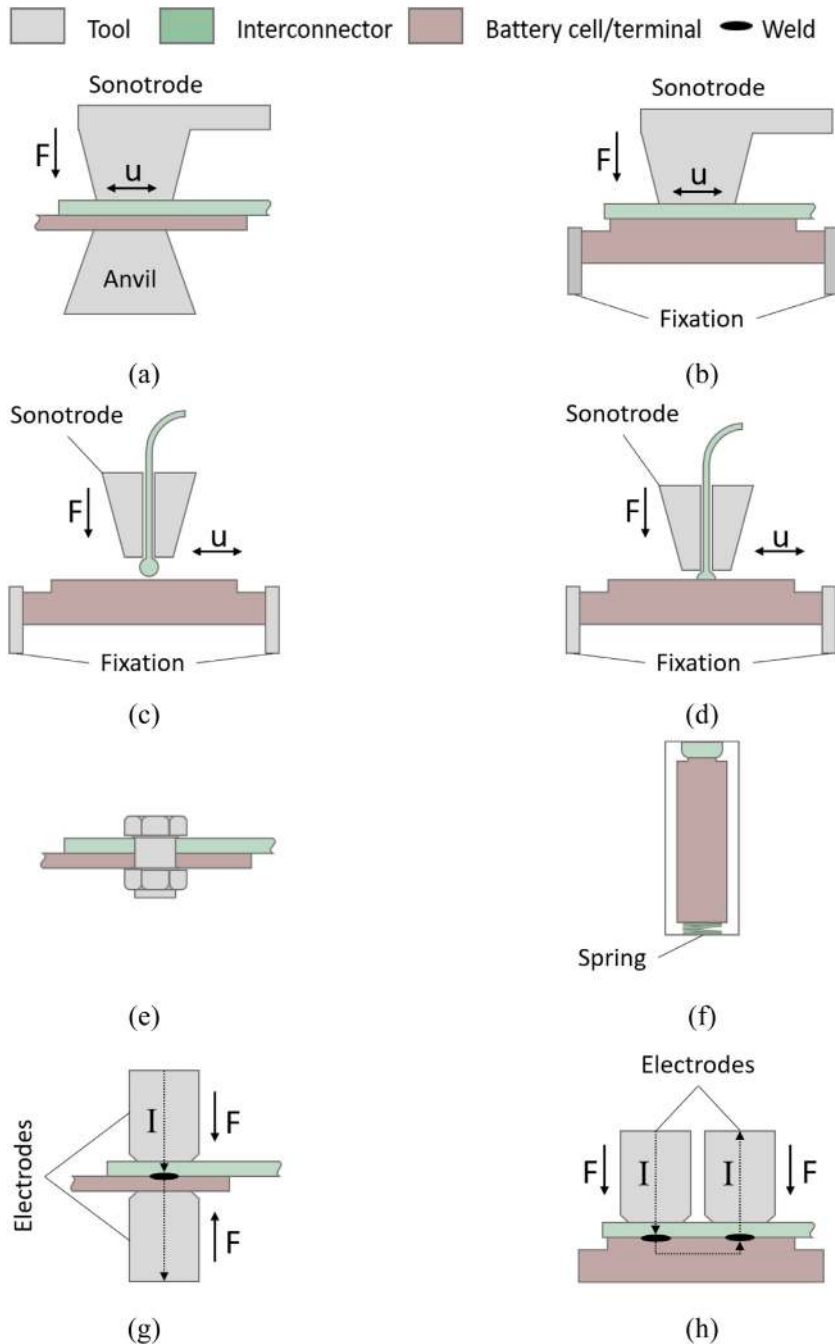


Fig. 5. Overview of manufacturing processes in the field of battery manufacturing: ultrasonic welding of (a) a pouch/prismatic cell or (b) a cylindrical cell to an interconnector; wire bonding (c) before and (d) during the process; (e) mechanical assembly of an interconnector and a pouch/prismatic cell; (f) clamping of a cylindrical cell (force fitting); (g) two-sided resistance spot welding for joining pouch/prismatic cell and an interconnector, (h) single-sided resistance spot welding of an interconnector onto a cylindrical cell.

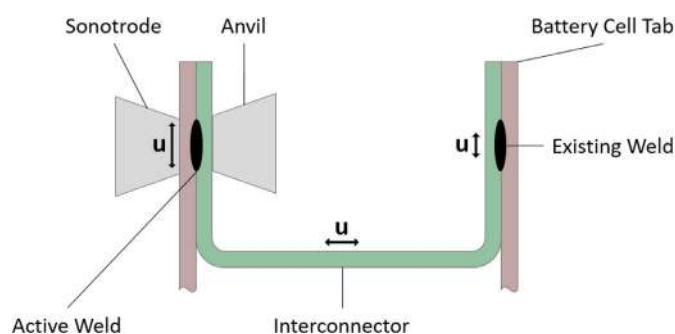


Fig. 6. Schematic depiction of existing welds being damaged due to vibrations caused by creation of the active weld.

materials and thus conducted a more general study on contact resistance of joined materials being identical. Taheri et al. (Taheri et al., 2011) investigated pouch cells being connected to copper bars utilising bolted joints. They confirm the dependency of the electrical contact resistance on applied pressure but recommend for the specific case of bolt joints polishing of the surface to decrease the connection resistance. Moreover, they conclude that in the case of low-pressure joints, interfacial electrically conductive materials may be used to decrease the electrical contact resistance, which is not needed for high-pressure joints. Füssel et al. (Füssel et al., 2018) investigated different bolted connections, namely nut and bolt, flow drilling screw, and thread-forming screw connections, for electrical connections. They extensively tested those joint types and measured the connection resistance, where, amongst others, the connection resistance was found to tend to increase over time. For bolted and screw connections the influences on the connection resistance are

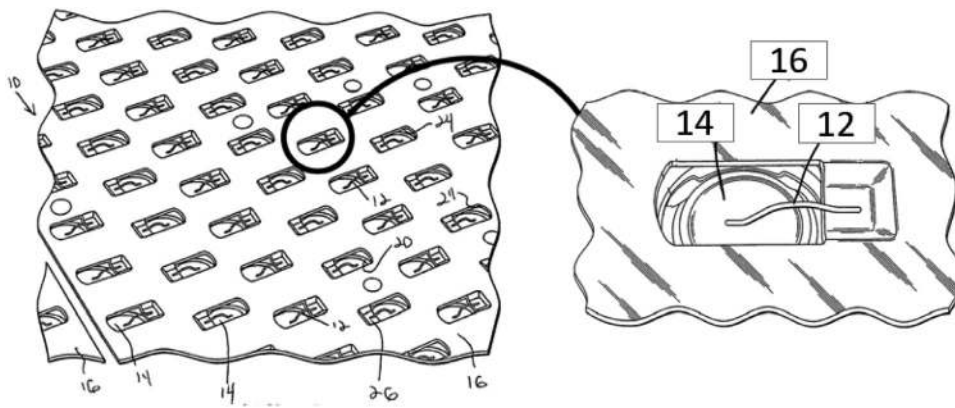


Fig. 7. Patent US7923144B2 battery interconnections, where 14 is the battery cell, 12 the to the battery welded wire, and 16 the collector plate (Kohn et al., 2011).

the resistivity of the joining partners, contact geometries of the joining elements, coatings of both joining partners and joining elements, and the variation of the process parameters.

Fu et al. (Fu et al., 2012) investigated the influence of vibrations on the electrical connection resistance in high power plug-in connections used in hybrid vehicles. They observed that vibrations lead to an increase in resistance and consequently the temperature in the contact region due to high current flows of up to 220 A. Fretting corrosion only occurred after the silver coating were worn out.

Soldering and brazing

Brand et al. (Brand et al., 2017) investigated in their study the suitability of soldering for battery interconnections. The study employed iron soldering for joining cylindrical cells and varied different solder materials with different liquidus temperatures, when joining brass or Nickel-plated steel samples, respectively. It was found that the liquidus temperature of the solder material should not exceed 150 °C to avoid extensive heat input into the battery and consequently damage it. Moreover, they compared their current study to previously published studies, namely Brand et al. (Brand et al., 2015, Brand et al., 2016), and concluded that soldering gives the lowest connection resistance. Soldering a brass sample with varying connection area to a 26,650 battery cell format was compared to laser, resistance, and ultrasonic welding as well as force fitting. Solchenbach et al. (Solchenbach et al., 2014) investigated laser brazing of dissimilar aluminium–copper battery interconnections, where the aluminium directly acted as brazing material. They found a direct connection between the size of intermetallic compounds in the joint and the connection resistance, i.e. the smaller the compounds, the lower the resistance. Solchenbach et al. (Solchenbach et al., 2014) investigated the thermal and electric ageing effects of the same joints. They found that direct current of 200 A for 1 to 24 h led to a distinctly higher formation of intermetallic compounds than thermal ageing. The formation depended strongly on the polarity of the current. However, as they (Solchenbach et al., 2014) considered large prismatic cells and the joint is far from the cell chemistry, the heat input was not analysed. Fig. 8 shows cross-sections for aluminium to copper laser brazing. In case of a good joint, the copper layer remains in solid-state, whilst the aluminium melts. The heat input, in this case, cannot ultimately be evaluated, but it may be assumed, if the brazing time is rather short, to be acceptable. Similar to laser welding, an inverse correlation between joint configuration, namely area, and resulting connection resistance was found (Brand et al., 2017, Solchenbach et al., 2014).

Laser beam welding

As an industrially commonly used joining technique laser welding can be employed for interconnecting batteries. Fig. 9(a) shows different

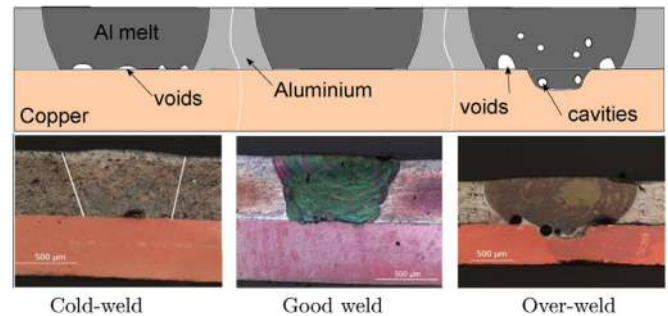


Fig. 8. Laser brazing of aluminium and copper where the aluminium melts and the copper remains in solid state during the brazing process (Solchenbach et al., 2014).

weld seams which are produced by laser beam welding. The example shows connector strips being welded to cylindrical battery cells.

Brand et al. (Brand et al., 2015) and Schmidt et al. (Schmidt et al., 2014) found direct relations between the weld seam configuration, namely size, area, and shape, and the resulting connection resistance. Brand et al. (Brand et al., 2015), furthermore, found in their study laser welding to have the lowest connection resistance compared to resistance and ultrasonic welding and evaluated the heat input to be not critical if laser welding parameters are optimised. Shaikh et al. (Shaikh et al., 2019) investigated the electro-thermo-mechanical behaviour of laser welded copper to nickel-plated steel. They found a relatively small difference between connection resistance and parent metal resistance. When exposing the joint to 75A for 120 s at temperature, the temperature at the weld region rose roughly 6 °C and was measured by a thermal camera. An increase in joint strength was found to be accompanied by the increase in connection resistance, where metallurgical behaviour of the two materials is suspected to give rise to the resistance.

Schmitz (Schmitz, 2016) deployed a similar set up as in (Brand et al., 2015) when investigating the influence of different pulsed laser strategies on resulting connection resistance. He found, unlike the other authors, no direct connection between electrical connection resistance and the total joint area.

Mehlmann et al. (Mehlmann et al., 2014) and Brand et al. (Brand et al., 2015) recommend spatial power modulation, i.e. a linear feed with circular laser rotation of the laser beam, to control the penetration depth. Fig. 9(b) shows a decreasing penetration depth with an increasing spatial power modulation a (from left to right), whereas other parameters are kept constant. This avoids damage of the battery chemistry as the chemistry is directly located underneath the housing and damaged if the laser penetrates the housing. Furthermore, Schmitz (Schmitz, 2016) recommends a pulsed welding strategy with discretely pulsed weld seams in order to minimise heat input and maximise flexibility.

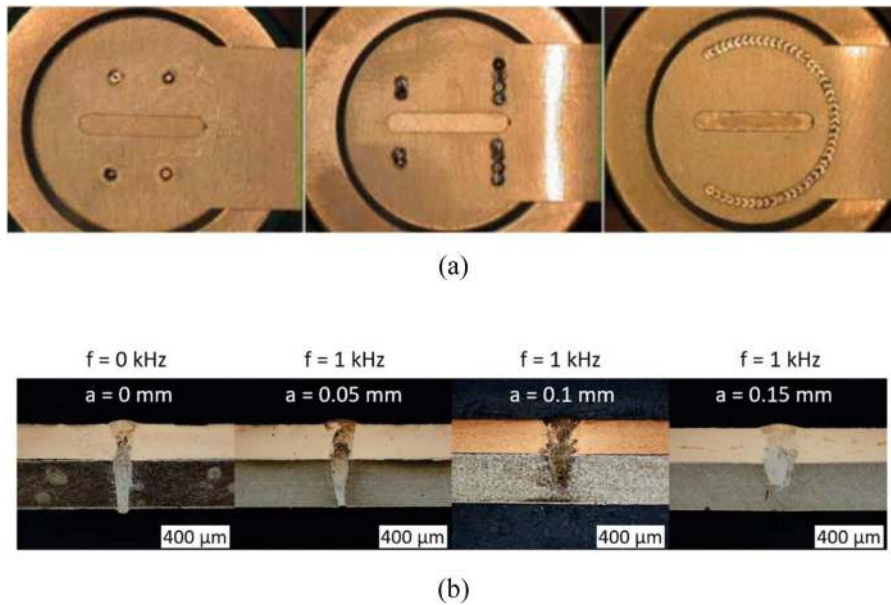


Fig. 9. Laser beam welding of battery application: (a) Different seam shapes on bus-bars welded to cylindrical battery cells (Kundrat and Alexy, 2018); (b) Variation of spatial power modulation a (left to right) for CuSn6 on top and DC04 steel on the bottom resulting in smaller penetration depth (for all applied: $P = 170$ W; $v = 100$ mm/s) adjusted from (Mehlmann et al., 2014).

Pantsar et al. (Pantsar et al., 2018) proposed the application of pulsed green lasers or nanosecond pulsed infrared lasers to improve process stability and spatter formation and to suppress the formation of intermetallic compounds to improve weld strength and conductivity.

Helm et al. (Helm et al., 2019) found that the mechanical properties were reduced if copper connector ribbons in a combined wire bonding-laser welding process were oxidised and subsequently roughened in order to improve weldability by decreasing reflectance, whereas the electrical characterisation is subjected to further investigations. Helm et al. (Helm et al., 2020), furthermore, investigated the application of surface structures produced by ultrashort pulse laser radiation to reduce the surface reflectance of copper. They could achieve a faster transition to deep penetration welding and increased energy input throughout the entire process.

Franciosa et al. (Franciosa et al., 2019) developed a method for closed-loop in-process quality control for laser welding in battery assembly lines.

Resistance welding

Resistance welding is an applicable process for battery welding. Depending on the battery cell type, different process variants are applied as schematically presented for prismatic or pouch cells and cylindrical cells in Fig. 5(g) and Fig. 5(h), respectively. Both process variants can be combined with projections. Brand et al. (Brand et al., 2015) found in their study that single-sided resistance welding is suitable for welding partners having a low conductivity. Moreover, the number of spot weld points was varied and subsequently the connection resistance measured. The more weld points are produced, the lower was resulting connection resistance. Additionally, resistance welding has a considerably lower heat input than laser and ultrasonic welding. Godek (Godek, 2013) found that with increasing energy input the connection resistance dropped and the weld diameter increased. Masomtob et al. (Masomtob et al., 2017) and Martinez et al. (Martinez et al., 2015) conducted further studies, whereas none of the crucial factors as connection resistance or heat input were investigated. Campestrini et al. (Campestrini et al., 2016) deployed resistance welding but gives no further information regarding the welding process. Das et al. (Das et al., 2019) investigated the weldability and weld performance of aluminium and nickel-coated copper. Liu et al. (Liu et al., 2020) investigated the thermal performance of secondary cells of type 18,650 with and without spot-welded interconnectors. They found for welded samples an increasing heat generation

and impaired performance of the battery with an increase of the current rate at which the cells are discharged.

Friction stir welding

Friction stir welding is a solid-state welding process, where a rotating tool generates frictional heat to join parts. Grimm et al. (Grimm et al., 2015) stated friction stir welding as an alternative process for automotive batteries due to the capability of joining dissimilar materials, like aluminium and copper for instance, without the formation of undesired intermetallic compounds. Mypati et al. (Mypati et al., 2020) investigated copper-aluminium pouch cell tab to tab welding with a respective sheet thickness of 0.3 mm and 0.2 mm. They investigated the resistance of the welded samples and found an increase of 9–16% compared to the resistance of copper.

TIG welding

Tungsten inert gas (TIG) welding is an arc welding process employing a non-consumable tungsten electrode to create an arc and operates under inert shielding gas. It was not found applied to interconnect batteries. However, it was stated by Kundrat and Alexy (Kundrat and Alexy, 2018) and Das et al. (Das et al., 2018) as a possible technology, and Das et al. (Das et al., 2019) investigated the weldability and weld performance of aluminium and nickel-coated copper of pulsed TIG spot welding.

Joining by forming

Joining by forming may be used for the electrification of vehicles. Pragana et al. (Pragana et al., 2020) successfully produced copper-aluminium hybrid busbars by a recently developed combined partial cutting and bending process with compression form-fit joining. They could overcome well-known material challenges in copper-aluminium joining systems as the formation of brittleness due to intermetallic compounds as seen in fusion joints for instance.

Füssel et al. (Füssel et al., 2019) investigated the application of clinching, functional elements and self-piercing riveting in electrical circuits and considered the mechanical strength and electrical connection resistance of the joints in mint and aged conditions, where the latter was exposed to constant temperatures with and without the exposure to constant or cyclic current.

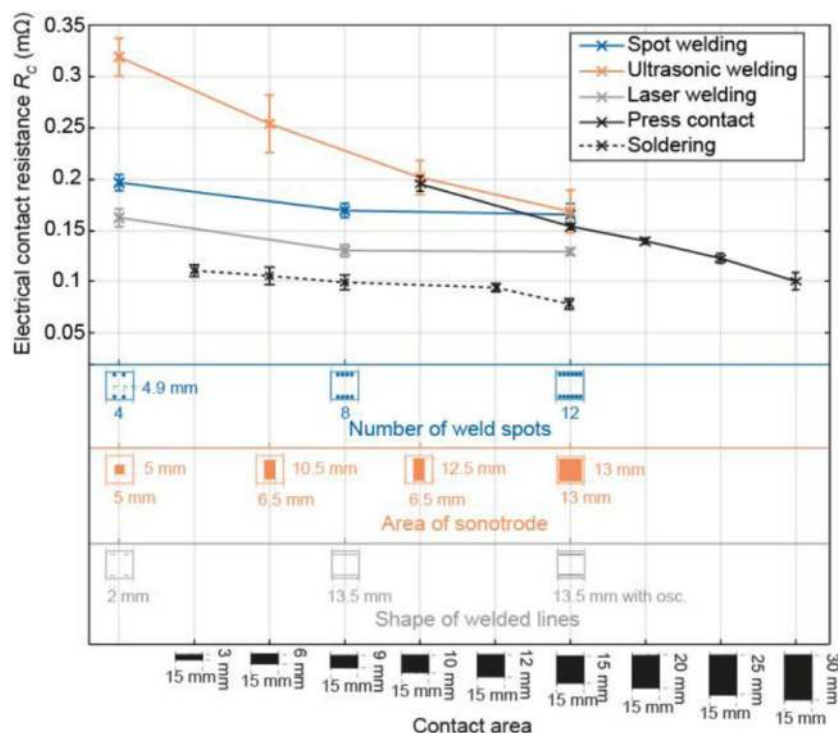


Fig. 10. Comparison of joining technologies in terms of connection resistance including scattering range (90% confidence interval) as function of the joint/contact area. Results have been obtained by the same methodology by Brand et al. (Brand et al., 2015, Brand et al., 2016, Brand et al., 2017) and comparatively published in Brand et al. (Brand et al., 2017).

Concerning clinching, copper-copper, aluminium-aluminium and copper-aluminium joining were considered and process parameters were optimised against the connection resistance while maintaining mechanical performance, which was realised by increasing the contact area while maintaining satisfactory traction. For the aluminium containing connections, they found that temperature-induced softening led to an increase in connection resistance over time and consequently to joint failure. The effect was further promoted due to a decreased temperature limit for softening onset by the high degree of deformation. The copper-copper systems showed constant resistance behaviour over time, where the connection resistance could be further reduced by the application of tin-plating. The latter effect was not observed for all aged cases. Clinching results were also partly published in Füssel and Kalich (Füssel and Kalich, 2018) and Kalich et al. (Kalich et al., 2019).

Füssel et al. (Füssel et al., 2019) also considered the electrical and mechanical performance of functional elements, namely riveting nut and punching bolt. For riveting nuts, it was found that shear cut pre-holes yielded a lower connection resistance than drilled pre-holes, where the latter was found to be the best around their minimum dimension. Punching bolts in aluminium sheets showed an increasing connection resistance during thermal ageing, where the softening of the material is suspected to impair the connection between functional element and sheet. Lastly, Füssel et al. (Füssel et al., 2019) investigated self-piercing riveting of steel-aluminium and aluminium-aluminium sheets. They optimised the rivet length against the electric connection resistance, while maintaining mechanical performance, and obtained better results when applying shorter rivets. Here both the connection resistance and the scattering range could be reduced.

Adhesive bonding

Adhesive bonding was found to be applied for structural or temperature management purposes in battery pack or module manufacturing rather than battery cell interconnecting (Oehl, 2019, Lutz et al., 2019). However, Zhang et al. (Zhang et al., 2019) applied solder-reinforced adhesives to pouch cell tab-to-tab joining and investigated the mechanical and electrical performance in comparison to ultrasonic welding. They

found the employed Eutectic SnPb (Sn₆₃Pb₃₇) solder balls in commercially available epoxy-based structural adhesive to result in a lower connection resistance than in ultrasonic welding.

Evaluation of joining technologies

When studying literature on battery joining it becomes apparent that the electrical characterisation of the joints, namely the analysis of the resulting connection resistance, is not commonly performed. It is done in a series of publications, whereas the experimental tests and the applied methods vary greatly and so do the results. Differences in analysed parameters are also apparent.

Electrical characterisation of connections is not yet standardized. The specimens, therefore, vary greatly in terms of geometry and overlap. They also vary in terms of the joint area. It is, for instance, possible to join the entire overlap by laser welding but not by resistance spot welding. Meaningful comparison of the joints is therefore difficult in terms of electrical properties.

The applied technology for measuring the electrical connection resistance is almost exclusively the four-point-probe measurement technique (Miccoli et al., 2015). The connection resistance has to be isolated from the bulk resistance of the sheets, as for example proposed by Brand et al. (Brand et al., 2015). It is, however, not always apparent how this is done. Some researches considered joining of more than two sheets, which may require a different testing procedure than for only two sheets. Another difference is that some researchers apply a constant current when measuring the resistance, while others apply different currents in order to reach a higher accuracy.

The way results are presented is also different, while most studies present the connection resistance, the scattering range is not always clear. A few studies present their results in relative numbers or performance factors, which is, however, only meaningful if done in the same manner across joining technologies as by Füssel et al. (Füssel et al., 2018, Füssel et al., 2019), Füssel and Kalich (Füssel and Kalich, 2018) and Kalich et al. (Kalich et al., 2019) for instance.

Brand et al. (Brand et al., 2015, Brand et al., 2016, Brand et al., 2017) compared force fitting, resistance spot welding, ultrasonic weld-

Table 3

Overview of advantages and disadvantages of presented joining technologies in general and with focus on battery welding.

Manufacturing technology	Advantages	Disadvantages
Ultrasonic welding	<ul style="list-style-type: none"> → Self-tooling → Joining of dissimilar materials → Solid state process → No filler metals or gases → Good for thin sheets, wires, or multi-layer sheets → Low energy consumption → Excellent for highly conductive materials → Fast process 	<ul style="list-style-type: none"> → Clamping battery may be critical → High heat generation can damage batteries → Expensive consumables → Restricted to lap joints → Limited joint thickness (<3 mm) (Lee et al., 2010) → Challenging on high strength and hard materials → Sonotrode sticking → Sensitive to surface conditions → Possible audible noise → Large weld indentation
Wire Bonding	<ul style="list-style-type: none"> → Joining of dissimilar materials → Widely applied in electronics industry → Easy automatable 	<ul style="list-style-type: none"> → Only suitable for thin wires → Low wire and joint strength → Clamping battery may be critical → Complex manufacturing
Mechanical assembly (Force fitting)	<ul style="list-style-type: none"> → Easy dismounting and recycling → Easy repair → Cold process 	<ul style="list-style-type: none"> → Potential mechanical damage and loosening → Additional weight due to additional parts → High connection resistance → Expensive
Soldering and Brazing	<ul style="list-style-type: none"> → Joining of dissimilar materials → Widely applied in electronics industry 	<ul style="list-style-type: none"> → Labour intensive → Need for solder material → Joint strength → Debris → Labour intensive → Challenges in dissimilar joining
Laser beam welding	<ul style="list-style-type: none"> → High speed → Low thermal input → Non-contact process → Easy automatable → High precision 	<ul style="list-style-type: none"> → High initial costs → Material reflectivity → Need of shielding gas → Needs good joint alignment → Quality control is difficult → Process monitoring is difficult → Challenges in dissimilar joining
Resistance welding	<ul style="list-style-type: none"> → Low cost → No filler metals or gases → Efficient and fully automatable → Self-tooling → Low heat input (Brand et al., 2015) → Existing technology for weld quality control 	<ul style="list-style-type: none"> → Risk of expulsion → Electrode sticking/wear → Difficult for highly conductive materials → Difficult to produce large joints → Difficult for joining more than two layers → Challenges in dissimilar joining
Friction stir welding	<ul style="list-style-type: none"> → Solid-state process → Joining of dissimilar, conductive and reflective materials → Non-consumable tool → No filler metals or shielding gases → Different process variants available (spot, lap, butt welding) 	<ul style="list-style-type: none"> → Exit hole left unfilled → Clamping required → Sensitive to joint clamping → Expensive machine technology
TIG welding	<ul style="list-style-type: none"> → Low cost → Fusion joint → Joining of conductive and reflective materials → Easy automatable → Mechanical joint performance 	<ul style="list-style-type: none"> → High thermal input → Large heat affected zone → Need of shielding gas → Challenges in dissimilar welding → Difficult to join more than two layers
Joining by Forming	<ul style="list-style-type: none"> → Joining of dissimilar, conductive and reflective materials → Automatable → Cold process 	<ul style="list-style-type: none"> → Temperature induced softening in case of aluminium (Füssel et al., 2019) → Additional weight due to joining elements → Accessibility of parts

ing, laser beam welding and soldering of battery interconnects in all cases deploying the same testing methods, specimen geometry and material. The connection resistance as function of the joint/contact area is shown in Fig. 10 for the different processes. It is seen that the connection resistance strongly depends on the joint area which is useful when optimising a joint against the resulting connection resistance but makes the comparability somewhat difficult.

General discussion on battery joining technologies

The presented joining technologies are briefly discussed qualitatively in the following. Advantages and disadvantages of each process are summarised in Table 3. Ultrasonic welding has advantages as it is self-tooling, is a solid-state process, and having excellent suitability for joining highly conductive materials. However, it may be less suitable for the particular application, battery welding, as it was found to have a high heat generation and thus substantial heat input into the battery. Furthermore, connection resistance was reported to be largest compared to

other process technologies and having the broadest scattering range. Therefore, the ultrasonic welding may be evaluated as not ideal for welding of cylindrical battery cell but usable for pouch and cylindrical cell interconnecting.

Wire bonding is an already applied technology by Tesla Inc. and has thereby proven to be suitable. It is, however, limited to thin wires, which need to be joined with both the bus-bar and the battery cell. This increases complexity during the manufacturing process. Additionally, a module must be designed such that the bonds between wire and battery as well as wire and bus-bar do not experience high loads during operation as the joint strength is low. No information about connection resistances could be found, but the following may be stated. The considered system would have two occurring resistances at both contacting points, which would add up as they are connected in series. Moreover, each of the thin wires is a resistor itself, whereas the noticeability would depend on the magnitude of the current (cf. Joule's law of heating). This also implies that the charging/discharging current cannot not be too high, and therefore, the system might not be suitable for large prismatic or

pouch cells. In conclusion, wire bonding may be suitable, but there are aspects as connection resistance of the joining area, which cannot be stated.

Mechanical force fitting stands out as it joins merely by applying force and has therefore low heat generation. Additionally, connection resistance and its scattering range was reported to be low and narrow, respectively. However, additional parts are required causing an increase in weight and increase in manufacturing complexity as well as is a limitation to automation. Loosening of the connection over time was reported, too. Given these points, mechanical force fitting may not be a suitable process for automotive battery manufacturing.

Soldering appears to be a suitable process based on connection resistance and its scattering range. However, the process requires an additional solder material yielding an increase in process complexity. The insertion of the solder may be impaired by for instance battery modules as shown in Fig. 4(c). Here the entire bus-bar covers the batteries and thus the joining area after the first joint was made. Therefore, it may be difficult to place and control the solder material accurately as it is placed between the battery and the bus-bar. Therefore, the process seems suitable for battery joining in general, but not for manufacturing large modules with a high number of cells.

Both laser beam welding and resistance welding result in low connection resistance with low scattering and comparable high mechanical strength. Additionally, the heat input was in either case not evaluated as critical, whereas resistance welding was reported to yield the lowest heat input of all presented process technologies. Both provide the opportunity for high and easy automation. Laser welding, however, is an expensive process, requires in many cases shielding gas and is not self-tooling, and a good joint alignment is needed. Also, process and quality control are challenging. In contrast, resistance welding is a cheap and most mature process, as it is applied for many decades in highly advanced industries. On the contrary, it is more difficult to stabilise the process as a complex interplay of many influencing parameters is apparent. However, if the process is stabilised for a specific weld task, it is highly feasible to maintain quality. Therefore, it is suitable for a standardised weld task with a large number of repetitions as the case for battery module manufacturing. Resistance spot welding has, furthermore, the inherent advantage that welding occurs locally at the faying surfaces, which makes it an appropriate candidate for either weld task. Laser beam welding must melt through the entire interconnector in order to join it to the cell. Hence, the larger the connector, as in the case of large prismatic or pouch cells, the larger the volume which needs to be melted. Both processes are suitable for battery welding, whereas resistance welding appears to be more applicable due to advantages as low price, less prone to environmental influences as well as maintainable process stability, once achieved.

Friction stir welding was not found to be commonly applied in battery interconnecting so far. However, it appears to be beneficial from a metallurgical point of view since especially in dissimilar material combinations the formation of intermetallics can be avoided. Friction stir welding is generally a welding technology with a low heat generation compared to fusion joining, whereas it was not investigated whether or not the frictional heat may damage battery cells. In the case of cylindrical cells, it remains open whether or not welding might thermally or physically damage the cells. Clamping of the joining partners may be a challenge if battery-connector joint designs get rather complicated, as in the case of multiple pouch cell tabs to busbar welds for instance. At this point, it may be concluded that the technology has the potential to be used in battery interconnecting but more research is necessary.

TIG welding of battery interconnects was reported in the sense of being an option rather than an applied technology in the field. It might be applicable for interconnecting pouch cell tabs or external terminals of prismatic cells as the heat input is considerably high, which makes it less applicable for cylindrical cells due to potential damaging of the cell chemistry. Due to fusion joints, TIG welding could potentially lead to low connection resistance. However, the authors did

not find further research and information on the applicability of this technology.

Joining by forming may be impractical during interconnecting cylindrical cells directly as it could penetrate the battery cell. It may, however, be used for the interconnection of both prismatic and pouch cells, if in the former case the tabs/terminals are externally located. Also interconnection busbars is an option for this technology. Challenges as softening of aluminium when ageing progresses might be a problem and need to be properly investigated for the particular application. Overall, joining by forming seems to be an applicable method if accessibility of the joining partners is given and application related challenges are solved.

Adhesive bonding is applied for joining structural parts of battery packs or modules as the module casing for instance. One study investigated the applicability of adhesives for pouch cell interconnecting and achieved good results in terms of connection resistance and mechanical performance (Zhang et al., 2019). However, the fact that the adhesive needed to be cured at 200 °C (Zhang et al., 2019) makes it less applicable as the batteries would be likely to be damaged during the process. Additionally, adhesive bonding may be outcompeted by other joining technologies in terms of speed due to the requirement for curing. However, the authors did not find further research and information on the applicability of this technology. It was, therefore, excluded from Table 3.

Conclusions

An interdisciplinary approach for battery pack manufacturing is necessary due to the inherent multiphysical nature of the application to satisfy an increasing demand for electric cars. The connection resistance in battery packs is a dependant variable and thus a crucial factor, which needs to be addressed in terms of magnitude and repeatability as it influences the battery pack lifetime. Here, a standardised measurement methodology needs to be developed for connection resistance. This would enable comprehensive comparability across joining technologies and the field of production engineering to develop methods for creating long-lasting joints with lowest connection resistances and narrow scattering ranges. When comparing joining technologies for battery welding, it is realised that the applicability of a technology depends not only on the connection resistance and its scatter but also on the specific joining task, i.e. the battery cell type. Ultrasonic welding appears to be suitable particularly for joining pouch cells. Wire bonding is suitable for large modules containing small cylindrical cells, but not for connecting prismatic or pouch cells. Laser welding is also applicable for cylindrical cells but may be less applicable when joining large cells with geometrical large interconnectors. Resistance spot welding and its process variants is a flexible technology that can be deployed for all battery cell types as the welding occurs at the contacting surfaces locally, unlike laser welding where an entire melting of the connector regardless its size is necessary.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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