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Welding Technology Options for EV Battery Assembly

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Content

01 Executive Summary

Minimal contact resistance between the cell and the connection tab via proper linkage is the prime deliverable for welding processes used for electric vehicle (EV) battery assembly. Such resistance has the most decisive effect on the performance and safety of EV batteries [1].

Hyper energy densities of EV batteries escalate the hazard of thermal runaway and other unsettling developments [2]. Improper linkage escalates cell-to-tab electrical resistance, increasing the possibility of a thermal runaway that can create safety challenges such as electrode melting or sparks [3].

Welding is a preferred joining process because it connects materials right down to their molecular level. Weld joints, therefore, have a strength comparable to that of the parent material [4].

Various weld technology options are available and the decision to choose between laser beam welding (LBW), resistance spot welding (RSW), and ultrasound welding – ultrasonic metal welding (UMW) or ultrasonic wire bonding (UWB) – depends primarily on the production scale, battery cell geometry, and cost factors [1].

Road transport emits 16% of the total global greenhouse gases (GHGs) [5]. EVs are important because they offer a way to decarbonize transport, an area that has been conventionally tough to make carbon-free. Electricity and heating are the other two applications of energy that can be decarbonized with relative ease [6].

As per the Paris Agreement, an international and legally binding pact, temperature rise needs to be limited to 1.5°C [7] above the pre-industrial levels if the world is to avoid facing the horrendous consequences of runaway Climate Change. This calls for Net Zero Emissions i.e. elimination of emissions by 2050 [7].

Demand for portable gadgets and machines such as electric vehicles (EVs), mobile phones, and tablets has expanded the market for batteries that power these [1]. Improvement in range of EVs, combined with policy support and public spending, have seen the demand for EVs explode in recent times.

BNEF forecasts 26 million EVs (including hybrids) on roads across the world by end-2022 [8].

Global EV sales picked up in 2021 and totalled 6.6 million units, garnering a 9% share in sales. This marked a 4 percentage point rise over corresponding figures in the lean and COVID-affected 2020 [5].

To put the EV growth story in perspective, only 120,000 EVs found buyers in 2012 over the world. The number falls short of international weekly sales figures for 2021 [9]! Yet, this is not enough. For achieving Net Zero Emissions by 2050, there needs to be a total of 300 million electric cars by 2030, amounting to 60% of the total new cars sold [5].

China accounts for 46% of global EVs at present. Europe is second on the list at 34% followed by the United States at 15%. Europe has the most number of plug-in hybrids on its roads. These may soon decline as policymakers cut subsidies [8].

Eventually, these markets will saturate, leaving India, Southeast Asia, Brazil, Japan, and Mexico to drive the EV demand. These have low EV adoption at present but are showing good potential. More than 50% of new sales of India’s 3-wheelers are electric. Latin America is rapidly electrifying taxis. And Vietnam is fast migrating to electric bikes [8].

Apart from technological advances that increase the EV range, the availability of charging and/or swapping infrastructure will strongly influence the speed at which people accept EVs. Welding assumes significance since it strongly affects EV battery performance, safety, and throughput.

02 Importance of Welding in EV Battery Assembly

Contact resistance between the individual cell and the connection tab is the most crucial factor determining the performance and safety of EV batteries. Welds are the bottleneck in the EV battery's electrical circuit. A sufficiently large weld area is essential to ensure the least possible resistance and the flow of required current without undue heating [1].

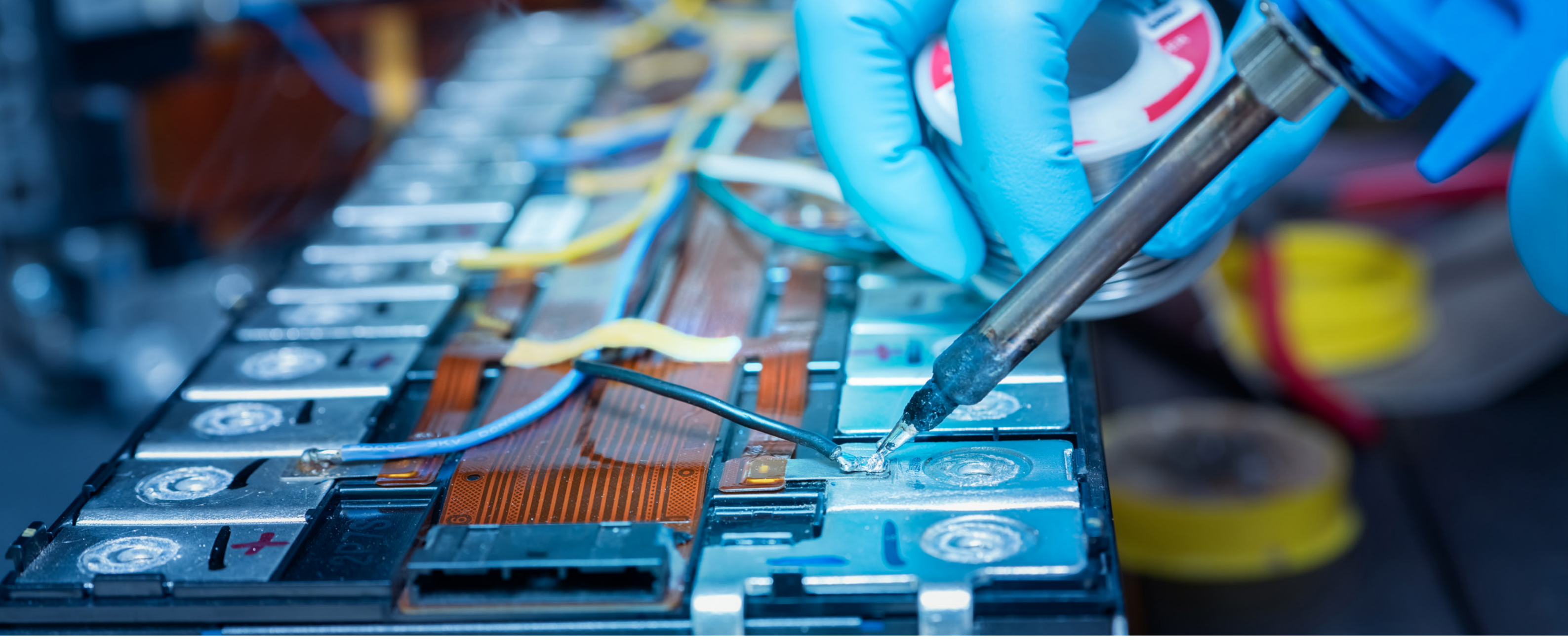
Welding technology used for EV battery assembly must deliver:

- Least contact resistance between the connection tab and the cell to cut energy loss via heat generation [10].
- Least inter-cell electrical resistance to reduce electrical losses which deliver higher torque via larger peak current for the EV [11].
- Establish strong inter-cell mechanical connections to withstand vibrations [11].
- Use minimal weld energy to prevent excessive heating of the internal separator in the cell [11].

High quality welds are of uniform width and have no gaps. Thin welds are more suited for EV battery packs because the thicker ones can penetrate the casings. Good welds ensure that the following challenges associated with welding are duly addressed [1] & [10]:

- Thermal & Electrical
    - Contact Electrical Resistance is low via high connection efficiency that optimizes energy flow rate, minimizes heat generation during operation and charging-discharging, and lowers the probability of power blowout.

- Thermal Fatigue is minimal so as have cells with high reliability and durability.
    - Thermal Input is reduced to avoid the possibility of melting.
- Metallurgical & Material
    - Variable Surfaces are robustly connected despite these possessing high levels of reflectivity, conductivity, joint stack ups, oxide layers, or surface coatings.
    - Dissimilar Materials are properly joined regardless of intermetallic layers that are brittle and have elevated electrical resistance.
- Mechanical
    - Strength of Joint is adequate to shoulder the design load and prevent separation due to vibrations, which are inevitable in automobiles. Large joints successfully counter mechanical and thermal stresses.
    - Join without Vibrational Energy or Residual Stress as both affect joint strength and cell performance.



03 Technologies for EV Battery Welding

Lithium ion batteries are a multilayer, intricate structure with a large number of weld joints. Metals inside the pack have varying thicknesses. Their makes also differ, and they can be nickel, stainless steel, aluminium, or nickel plated with copper [10]. Welding operations for EV batteries are, therefore, equally complex.

Welding technologies used for EV battery welding are:

- Resistance Spot Welding (RSW)
- Laser Beam Welding (LBW)
- Ultrasonic Welding: Ultrasonic Metal Welding (UMW) & Ultrasonic Wire Bonding (UWB)

Before getting into the details of each technology, a general understanding of the welding process within the context of EV battery assembly is worthwhile. Following factors affect weld quality, which, in turn, influences performance and safety [12]:

- Welding technology
- Joint geometry
- Material
- Cycle time
- Weld access
- Budget

Components or features of EV battery welding set up that determine weld quality are [12]:

- Overall process management
- Loading and unloading
- Process data management
- Fixtures
- Weld quality checks

Conventional data management tools such as machine monitoring and Statistical Process Control cannot provide the transmission speed, processing capability, storage space, and networking that Industry 4.0 solutions demand. This is why equipment or system designers prefer the following communication protocols [12]:

- PROFINET
- EthernetIP
- Modbus TCP/IP

Secure and easy to integrate, the hardware for these protocols is readily available. The networks for these are simple to configure [12].

3.1. Resistance Spot Welding (RSW)

Elihu Thomson devised this procedure in 1877. Today, it is one of the most popular joining methods for sheet metals. Resistance spot welding utilizes [1]:

- Pressure in combination with electric current for welding without shielding gases or filler material.
- An inverter to convert input current from AC to square wave DC, which is amplified and filtered subsequently.
- Dual pulse current with the second pulse joining the metals after the first has eliminated oxides and contaminants on the metal surface.
- Optimized applied current levels.

Micro-TIG or tungsten inert gas welding is not used at present for EV battery pack assembly. The reasons for mentioning it in the present discussion are its potential in EV battery welding as brought out by [1]:

- Uses short pulses to limit heat input of the arc.
- Is compatible with welding dissimilar materials as well as copper, nickel, and steel.
- Has flexible current options viz. AC and DC. AC delivers better results when welding aluminium as it removes oxide layers before initiating the weld action.

Metallic strips that connect cells are made from nickel, steel, aluminium, and copper. Joining the last two via RSW can present challenges because of their elevated conductivity. Three main process parameters for spot welding are [1]:

- Welding time
- Electrode force
- Welding current

RSW welding time can range from microseconds to a few milliseconds. Deficient welding time and force produce a poor weld. Higher values of these parameters cause deformation.

The resultant metal flame can generate a burn mark between spots and impair the electrode. Similarly, metal sparking results from low welding force and deformation follows excessive force [1].

Excessive welding current lowers the tensile strength of the joint by fostering weld voids and cracks. Low applied current fails to counter stray current from battery sources while excessive levels cause electrode sticking. Too much heat during welding can alter cell chemistry undesirably. Little heat will produce a weld with low strength [1].

Weld current flow is critical to weld quality, and is affected by [11]:

- Electrode resistance and contact area
- Material interface between parts
- Current control

In RSW, weld current needs to be focused. Following relevant points are important [11]:

- Dome shaped projections on the tab serve as points of high resistance where heat is concentrated in the initial welding phase. More material available at the projection focuses heat in them. The projections heat up and collapse in a specific zone when current flows.
- When bifurcated, the strip that links successive cells lowers electrode-to-electrode initial current flow, so more cur rent flows through the tab. It is this current that carries out the welding operation.
- Flat ended electrodes are preferred be cause they:
  - Spread pressure uniformly and, therefore, last longer.
  - Are easier to regrind.
  - Are less costly.

Pros	Cons	Compatibility with Battery Types
Automation friendly	Limitations in joining high conductivity materials	Small Prismatic
Does not require shielding gas or filler	Limitations in dissimilar metal welding	Cylindrical
Contact process enables excellent quality control	Electrode sticking to base metal	
Contact process eliminates need for fixtures	Quality variance between different welds	
Low capital requirements	Slower	
Compatible with thin sheets		

Table 1: Resistance Spot Welding (RSW) Features [1], [10] & [12]

- Electrodes with dome-shaped ends are used to focus weld current if tab projetions cannot be used. Flat electrodes of small diameter in conjunction with high pressure can also serve the same purpose by simulating a reverse projection.

Monitoring electrode wear is the chief quality-related concern for RSW after process optimization [12]. Quality monitoring tools measure multiple weld parameters independently of the weld head and power supply. These include [12]:

- Variations in the force, electrical properties (resistance, current, and voltage), and displacement of the weld across the pulse duration.
- Overall weld collapse and its rate.

Factors that improve resistance weld quality are:

- Sensors for force and displacement measurement [12].
- Rapid rise in squeeze times.
- Polarity switching [12].
- Closed loop control over feedback [12].

AI is being integrated into RSW to map the relationship between weld parameters and quality. The same will be then used for programming. Apart from decreasing quality variations, automation slashes RSW's operational expenses related to [1]:

- Energy by optimizing power use.
- Labour by saving on wages, training, and non-productive employee costs.
- Material by ensuring lesser wear of electrodes.

Welding guns and power sources form the main capital expenses of RSW, making it less costly than others. Inverters are known to cut RSW expenses by improving [1]:

- Uptime via boosting power output.

- Quality by delivering more consistent DC supply vis-à-vis AC.
- Yield through more uptime.

Weld electrodes need greater thermal and electrical conductivity than that of the metals being welded. This is why RSW cannot weld metals with high conductivity. Copper alloys are the most popular electrode material [1]. As mentioned, monitoring electrode wear is the chief quality-related concern for RSW after process optimization [12].

RSW also does not make a good process for dissimilar metal welding as temperature control maintains a constant level. Dissimilar materials with different melting points are not suited for such control [1].

3.2. Laser Beam Welding (LBW)

Highly focused, minimally diffracted beam with a tiny spot size is preferred for laser beam welding. The procedure is performed in the keyhole mode that delivers a weld with greater depth-to-width ratio [1].

Metal atoms evaporating from the surface due to the beam's intense power density create vapour pressure that acts against further evaporation. The same pressure generates a keyhole i.e. a depression in the molten material.

In combination with beam reflections inside the cavity, the keyhole boosts the energy efficiency of the LBW process

Pros	Cons	Compatibility with Battery Types
Automation friendly, being a non-contact, simple-to-imitate process	Complex execution requires dedicated experience and training	Prismatic
Low electrical resistance joints	Excellent joint fit-up essential	Cylindrical
Fast	Tough to weld high reflectivity metals	Pouch
Accurate	Capital intensive	Ultra Capacitor
Suitable for narrow areas with low accessibility		
Limited heat affected zone		
Minimal/zero post weld processing		
Easier control over depth and width		

Table 2: Laser Beam Welding (LBW) Features [1], [10] & [12]

Vaporized metal atoms form a plasma that envelops the weld area. Shielding gas is essential to prevent the plasma from affecting the laser beam [1].

Two primary lasers used for EV battery pack welding are [1]:
- Pulsed Nd:YAG i.e. Yttrium Aluminium Garnet doped with Neodymium
- Fibre Laser

Both these types are available in pulsed and continuous variants. The pulsed type supplies energy in short pulses while the other supplies energy continuously. The former makes a better choice for reflective and heat sensitive metals for they lower the total heat input [1].

Pulse rate, welding speed, and laser power influence [1]:
- Geometry of the weld bead.
- Weld quality.
- Weld dimensions that increase with rising laser power but fall with climbing speed. Parameter control enables modifications in weld thickness.

Other influences on LBW quality include:
- Gap between the parts being welded. Minimal gap provides better quality.
- Material coating.
- Surface finish.

Thin welds are more suited for EV battery packs for the thicker ones can penetrate thin casings. Close parameter and process control prevent the high power density of the laser from causing unintended damage [1].

Although the laser pulse initially generates a large amount of heat, it is limited to the cell terminal [1]. Welding speeds depend on the materials being welded and their thicknesses [12]:
- Maximum speed is 20 welds per second.
- Typical speed range extends from 100 milliseconds/weld for mass production to 1-2 seconds/weld for low quantity production.

ANSI 136.1 dictates the use of a non-light-transparent enclosure for laser welding. LBW quality improves with proper selection of [12]:
- Spot weld size
- Equipment
- Weld path
- Weld parameters

Chief concerns for laser weld quality after optimisation are the maintaining of proper [12]:
- Interface between the part and the weld at the focus of the laser
- Part fit up

Being a non-contact process, LBW utilizes light wavelength analysis for quality monitoring [12]:
- Infrared emitted by the high temperature areas.
- Ultraviolet emerging from the keyhole and welding plume.
- Laser’s back reflection.

3.3. Ultrasonic Welding: Ultrasonic Metal Welding (UMW) & Ultrasonic Wire Bonding (UWB)

While the mechanism for UMW is not completely understood, high frequency oscillations are believed to shear the metals, thus facilitating plastic deformation at the interface. A combination of 20 kHz oscillation and pressure form the joint via [1]:
- Micro melting
- Metallic interlocking
- Chemical bonding

Sheets and foils of diverse metals and varying thicknesses can be seam and spot welded using ultrasonic welding. UMW is automation friendly, its parameters can be monitored via software for data analysis, and fits into existing manufacturing lines [1].

UMW is a solid state process that does not melt the metals. It provides joints with the required strength while minimizing or avoiding the formation of brittle intermetallic zone along the joint. Such features make it suitable for connecting metals with high reflectivity and conductivity [13]. The nullification of melting makes it a low energy process [14].

A variant of UMW, UWB is used widely in microelectronics where access is available from one side only. A sonotrode welds a continuously fed wire to successive substrates via pressure and vibration. Low energy use and production expenses are the two main economic benefits of UMW [1].

UWB provides the same positives as UMW. On the downside, it requires tight fixtures as lateral movement slashes the amplitude of ultrasonic vibration so essential for producing robust joints. And because it can weld only small gauge wires, UWB can deal with low currents only [1].

Pros	Cons	Compatibility with Battery Types
Particularly compatible with dissimilar, thin, and numerous layers of metals with high conductivity	Requires access from both sides with anvil on one side and sonotrode on other	Pouch
Suited for welding high reflectivity materials	Error prone when welding materials with high surface roughness	
No filler metal or shielding gas required	Requires excellent fixtures as vibrations can damage battery cell structure	
Joints free from typical metallurgical issues viz. hot cracking, porosity, and bulk intermetallic compounds	Unsuited for hard materials as these do not vibrate much	
Solid state welding enables lower energy inputs and shorter weld times	Cannot weld think joints as these do not vibrate much	
Lower production cost	Can only weld lap joints as it requires access from both sides	
Low energy usage	Sonotrode is prone to sticking as built up metal on its surface bonds with workpieces of same metal	

Table 3: Ultrasonic Metal Welding (UMW) Features [1] & [13]

Determinants of UMW and UWB weld quality [1]:

- Machine Parameters
  - Oscillation amplitude
  - Welding energy transferred
  - Welding force
- Material Quality
  - Top part geometry affects weld energy absorption.
  - Bottom part roughness influences friction.

Excessive roughness creates numerous hot spots. In turn, these generate a temperature gradient that causes fractures in brittle materials. Slippage due to low roughness prevents strong weld formation.

04 Welding Technology Selection for EV Battery Pack Assembly

A June 2019 study by Harald Larssan et al. at Uppsala University compared RSW, Micro-TIG, UMW, and LBW from the perspective of Manufacturing Readiness Level (MRL) and reached these conclusions [1]:

- LBW has highest MRL for cylindrical cell welding, followed by Micro-TIG, UWB, and RSW.
- The order for prismatic cell welding is same as for cylindrical.
- LBW and UMW are tied at first spot for pouch cell welding. MicroTIG and RSW come later in that order.

Criteria employed for the comparison were [1]:

- Resistance of joints for similar and dissimilar materials.
- Durability and current capacity of the joints.
- Heat transferred by the procedure.
- Repeatability, ease of automation, and adaptability.
- Possible damage from mechanical and vibrational factors.
- Capital investment and cost for every battery connection.
- Safety and cycle time.

Manufacturers choose the welding technology based on [1]:

- Cell Geometry is the prime consideration.
- Overall Cost is related to production levels as large volume production can more than offset the high capital investment via greater yields as is the case with LBW, for example.
- Material Properties become particularly important when cells need to deliver large currents. Significant energy losses result from tiny electrical resistance increases when large currents are involved.

Following guidelines help select the most compatible method [1]:

- Except for UMW, which is unsuited for cylindrical cells, other methods are broadly ok with all cell geometries.
- LBW is best when high weld strength is required.
- RSW's low overall costs and simplicity make it useful for smaller scale productions.
- UMW and UWB are most suited for joining dissimilar metals.
- LBW and UMW deliver good welds on high conductivity (thermal and electric) materials while RSW does not.
- RSW and UMW do a good job with materials of large surface reflectivity. LBW is least suited for these.
- LBW transfers a great quantity of heat on the substrate metal.
- Micro-TIG and RSW involve elevated heat transfer levels.
- For cylindrical cell welding:
  - LBW and UMW are more automation friendly than RSW or Micro-TIG.
  - RSW and Micro-TIG are least expensive per battery connection.
  - LBW has the same cost for each battery connection as that of UWB despite having the highest investment cost.
  - LBW is the fastest with the shortest weld time.

05 Final Comments

Production scale, battery cell geometry, and budget have the strongest influence on the selection of welding technology. A host of parameters then determine the overall efficiency and throughput of the chosen welding technology.

With Industry 4.0 technologies unleashing the boundless benefits of data analysis, the speed of EV battery manufacturing and their quality are bound to appreciate.

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