CHAPTER 1

LITHIUM-ION BATTERY MANUFACTURING FOR ELECTRIC VEHICLES: A CONTEMPORARY OVERVIEW

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1.1 INTRODUCTION

During the last few decades, environmental concern about the petroleum-based transportation has led to renewed and stronger interest in electric vehicles (EV). In an EV, energy storage devices (such as batteries, supercapacitors) or conversion devices (such as fuel cells) are used to store or generate electricity to power the vehicle. The first highway-capable EV with mass production in the modern age was GM's EV1 [1], which used lead-acid-based batteries as onboard energy storage. With the advancement of newer generations of high-density energy storage batteries such as the metal-hydride batteries and most recently the lithium-ion (Li-ion) batteries, battery electric vehicles (BEVs) have seen tremendous growth in the past decade. Batteries used as the power and energy sources to drive BEVs are called traction batteries.

A BEV falls into one of the following four categories: hybrid electric vehicle (HEV), plug-in electric vehicle (PHEV), extended range electric vehicle (EREV), and pure BEV. An HEV is generally powered by an internal combustion engine and a battery pack. The internal combustion engine is the primary source of energy during medium or high-speed driving conditions with the batteries serving as the main power source in stop-and-go traffic as well as power assist in vehicle acceleration, where the batteries are also called power batteries. The battery pack is relatively small and recharged by the internal combustion engine and regenerative braking. An exemplary vehicle is Toyota's Prius (2015 model year), offering an EPA-estimated 50 mpg fuel

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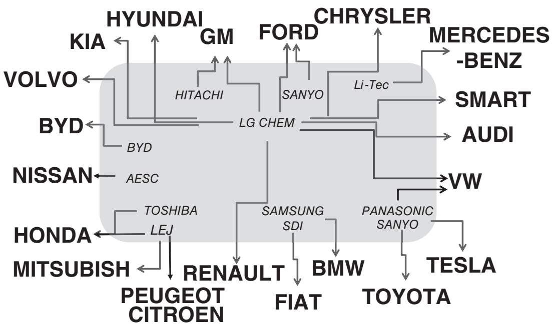


FIGURE 1.1 Major BEV manufacturers and Li-ion battery suppliers (2015 landscape).

economy using a small 4.3 kWh of Li-ion battery pack [2]. A PHEV operates under either the battery mode, the internal combustion engine mode, or a combination of the two modes. The battery pack, however, can be charged via an external electrical power grid. An exemplary vehicle is Toyota's Prius Plug-in [2]. Depending on the design intent and the size of the battery pack, the traction batteries in PHEV can be either power or energy batteries. An EREV differs from a PHEV in that the battery pack is relatively large and the vehicle operates primarily under the electric mode. The internal combustion engine in the vehicle is used exclusively or primarily to charge the traction batteries (although the internal combustion engine can also be used to assist the battery mode driving in special circumstances). An exemplary vehicle is GM's Chevrolet Volt [3]. A pure BEV is powered entirely electrically by an onboard battery pack through the traction motors. The battery pack is typically recharged via an external electrical power grid. Although many automakers are mass-producing BEVs in the marketplace, the most notable models are Tesla Model S [4], Nissan LEAF [5], and BMW i3 [6,7]. Figure 1.1 shows a complete landscape of major BEV manufacturers and their Li-ion battery cell suppliers. A comparison with reference [8] immediately finds significant industry evolution during the past 5 years. While every single global automotive manufacturer is now producing BEVs, a few BEV start-ups and many traction battery joint ventures have been reorganized or even gone out of business during the past few years. At the end of 2014, Panasonic, AESC, LG Chem, and BYD were the top four largest manufacturers of traction battery cell in the world, supplying batteries to Tesla Model S (pure BEV), Nissan LEAF (pure BEV), GM Chevrolet (EREV), and BYD (pure EV and PHEV), among others [9]. Table 1.1 lists some key technical data for several major BEVs in the marketplace.

1.2 LI-ION BATTERY CELLS, MODULES, AND PACKS

This section reviews different formats and structures of Li-ion battery cells, modules, and packs as seen in BEVs. The focus is on the characteristics relevant to the joining, assembly, and packaging rather than the battery chemistries, functions, and performances.

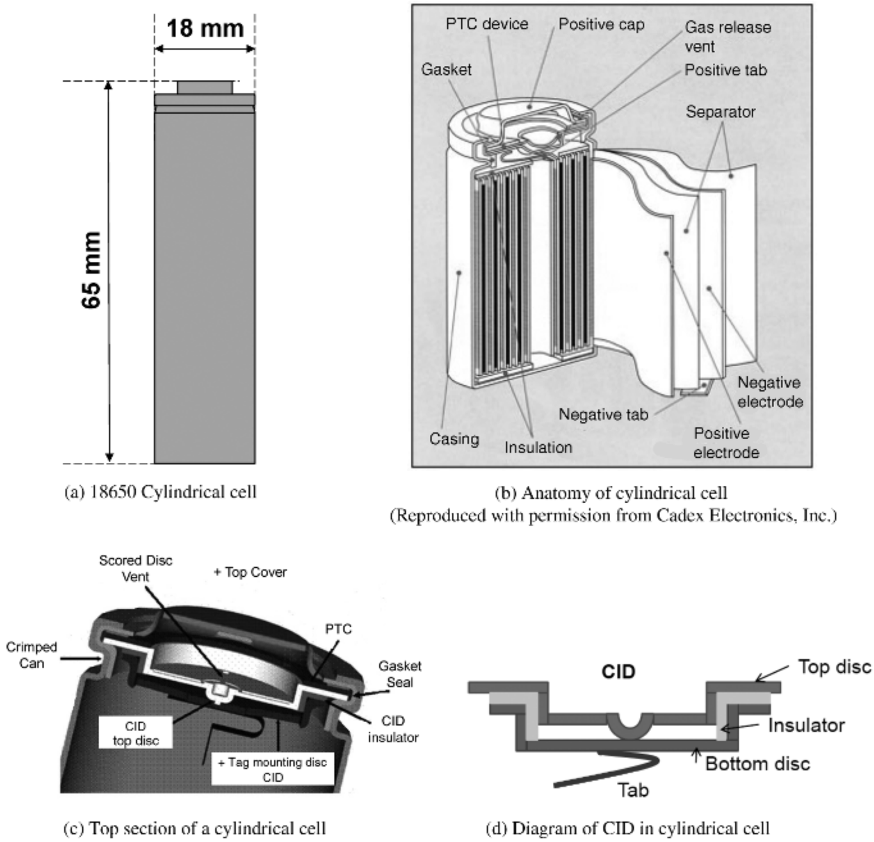
TABLE 1.1 Selected technical data for major BEVs

	Toyota Prius Plug-in [2]	GM Chevy Volt [3]	Tesla Model S [4]	Nissan LEAF [5]	BMW i3 [6,7]
Model Year	2012–2015	2015	2012–2015	2013/2014	2014
Energy Storage (kWh)	4.4	16	85	24	18.8
Fuel Economy (MPGe)	58	62	89	115	124
Pure Electric Driving Range (miles)	11	39	265	75	81
Cell Manufacturer	Panasonic	LG Chem	Panasonic	AESC	Samsung SDI
# of Cells	56	288	7104	192	96
Cell Format	Prismatic	Pouch	Cylindrical	Pouch	Prismatic
Cell-to-Cell Joining	Bolting	Ultrasonic welding	Wire bonding	Ultrasonic welding	Laser welding
# of Modules	3	9	16	48	8
Module-to-Module Joining	Bolting				

1.2.1 Formats of Li-Ion Battery Cells

A battery cell is the most basic and fully independent operating unit in a storage battery. It is primarily composed of positive and negative electrodes, separators, electrolytes, and a container. In the current marketplace, there exist primarily three different cell formats for a traction battery cell: cylindrical, prismatic, and pouch. Due to legacy reasons, the cylindrical format has been the mainstream ranging from alkaline (such as AA cells) to NiMH to Li-ion (such as 18650) cells. However, when rechargeable batteries such as NiMH or lithium-ion batteries have been considered for automotive battery applications, other formats of battery cells such as prismatic and pouch types have been developed to improve the volumetric efficiency [10], accommodate thermal management, and/or packaging requirement.

1.2.1.1 Cylindrical Cells Figure 1.2a shows an 18650 cylindrical cell (i.e., 18 mm in diameter and 65 mm in height) as used in Tesla's EVs. Figure 1.2b is an anatomy of a representative cylindrical cell [11], although the exact structure varies



(a) 18650 Cylindrical cell

(b) Anatomy of cylindrical cell (Reproduced with permission from Cadex Electronics, Inc.)

(c) Top section of a cylindrical cell

(d) Diagram of CID in cylindrical cell

FIGURE 1.2 Cylindrical format Li-ion battery cells.

for different manufacturers. The cylindrical cells are known to be less volumetric efficient than prismatic cells. However, the commercial production lines for many cylindrical cells allow for some advanced passive safety features such as positive temperature coefficient (PTC) and current interrupt device (CID) (Figure 1.2c and d) to be built in reference [12]. PTC is a type of material that demonstrates significantly high electrical resistivity at high temperatures so as to melt the PTC itself to break the circuit at higher electrical current [13]. CID is another passive device that breaks when the pressure inside a cell reaches high levels. Normally, when the cell is overheated, such as in a thermal runaway, the pressure increases to a level to break the CID and thereof the circuit [13]. Although manufacturers make cylindrical cells of many different dimensions, 18650 cells are the most produced cells due in part to Tesla's needs.

1.2.1.2 Prismatic Cells For a prismatic Li-ion battery cell, the current collectors (after anode and cathode coatings) and separators are either wound, as shown in Figure 1.3 [14], or laminated (not shown), and then inserted into a prismatic shaped container and sealed all together after filling in the electrolyte. The container is normally made of steels or aluminum alloys (although can be plastics too) and offers rigidity for dimensioning, handling, and protecting the cell. No standard exists as to the size of prismatic cells.

1.2.1.3 Pouch Cells A number of BEV manufactures use pouch cells for light-weighting, better volumetric energy density, and high spatial efficiency. Inside the cells (Figure 1.4) [15], multiple layers of precut positive/negative electrodes and

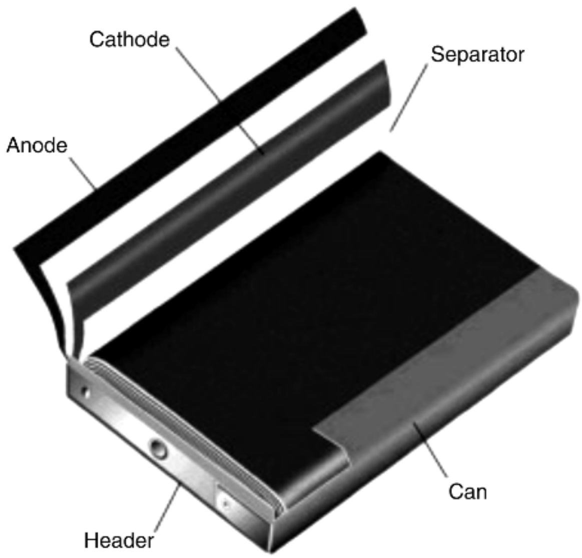


FIGURE 1.3 An anatomy of a prismatic Li-ion battery cell. (Reproduced from Ref. [14] with permission from Cadex Electronics, Inc.)

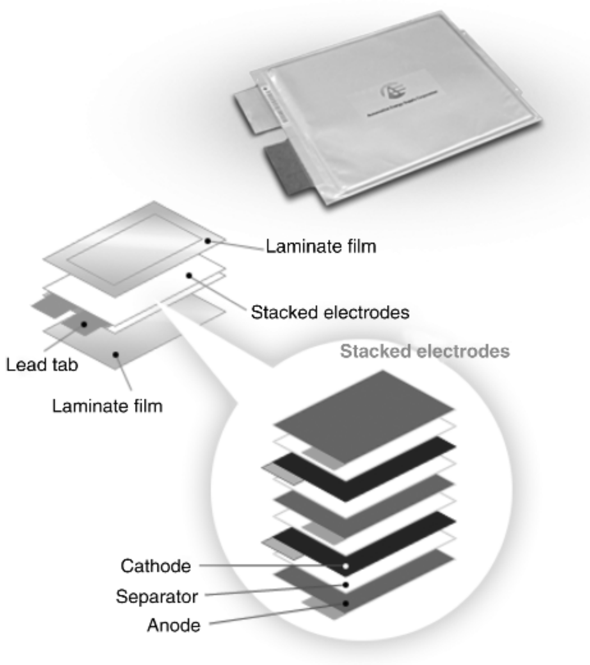


FIGURE 1.4 Schematics of pouch-type cells. (Reproduced from Ref. [15] with permission from Automotive Energy Supply Corporation.)

separators are stacked with electrode leads (or tabs) and then welded. Then the edges of the aluminum-laminated films (i.e., the pouch materials) are heat sealed. Similar to prismatic cells, no standards exist as to the size of pouch cells.

1.2.2 Battery Modules and Pack

A module is a group of two or more battery cells joined together that can be replaced in maintenance and repair without impacting the rest of the battery pack. A module is also typically the minimum unit installed with safety components, power and heat management electronics. Modules can vary in their sizes, see Table 1.1. A pack is a collection of all battery modules in the BEVs. The enclosure of a battery pack is sealed and watertight; it can protect the modules inside in the event of vehicle impact or crash. Due to excessive flexibility and softness of the pouch cells, holding components are generally needed to prevent pouch cells from having dimension and alignment issues. Such holding components can include frames, rigid cases, and supporting trays.

1.3 JOINING TECHNOLOGIES FOR BATTERIES

This section reviews a few selected joining technologies that are most pertinent to Li-ion battery cell and pack manufacturing, that is, ultrasonic welding, resistance welding, laser welding, wire bonding, and mechanical joining. The advantages and limitations are discussed. The applications in major BEVs will be discussed in Section 1.4.

1.3.1 Ultrasonic Metal Welding

1.3.1.1 Overview Ultrasonic metal welding (USMW) is a process in which a high frequency, usually 20 kHz or above, of ultrasonic energy is used to produce relative lateral motions to create solid-state bonds between two or multiple metal sheets clamped under pressure. The high-frequency shear forces induce alternating metal surface friction and heat to produce a weld. A schematic of the USMW system is shown in Figure 1.5 [16]. It can be used to join a wide range of metal sheets or thin foils, see Figure 1.6 [17].

USMW is considered a solid-state welding. In contrast to fusion welding processes, USMW has several inherent advantages. The main advantage of USMW lies in its excellent welding quality for thin, dissimilar, and multiple layers of highly conductive metals (such as Cu and Al), which is crucial in battery cell joining and for battery tab joining [18]. Another advantage is the low heat-affected zone. USMW also produces a very thin layer of bonding interfaces (typically a few microns) and therefore eliminates metallurgical defects that commonly exist in most fusion welds such as porosity, hot-cracking, and bulk intermetallic compounds. Therefore, it is often considered the best welding process for Li-ion battery applications.

1.3.1.2 Ultrasonic Welding Physics The bonding mechanisms for USMW are not completely understood. A combination of the following four mechanisms may attribute to the bonding: (a) micromelting (e.g., a few microns of thin interface layer melting), (b) metal interlocking (due to plastic deformation, particularly the severe deformation caused by sonotrode knurls), (c) diffusion, and (d) chemical bonding (such as covalent and metallic bonding). To better understand different phases generated at the bonding interfaces, an Al-Cu phase diagram such as the one in reference [19] should be consulted.

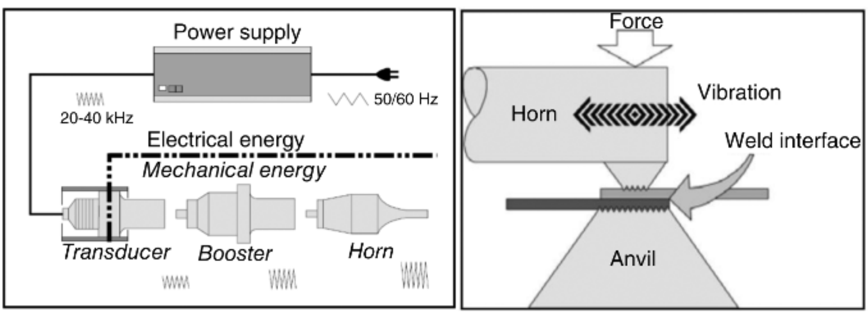


FIGURE 1.5 A schematic of USMW system. (Reproduced from Ref. [16] with permission from Cadex Electronics, Inc.)

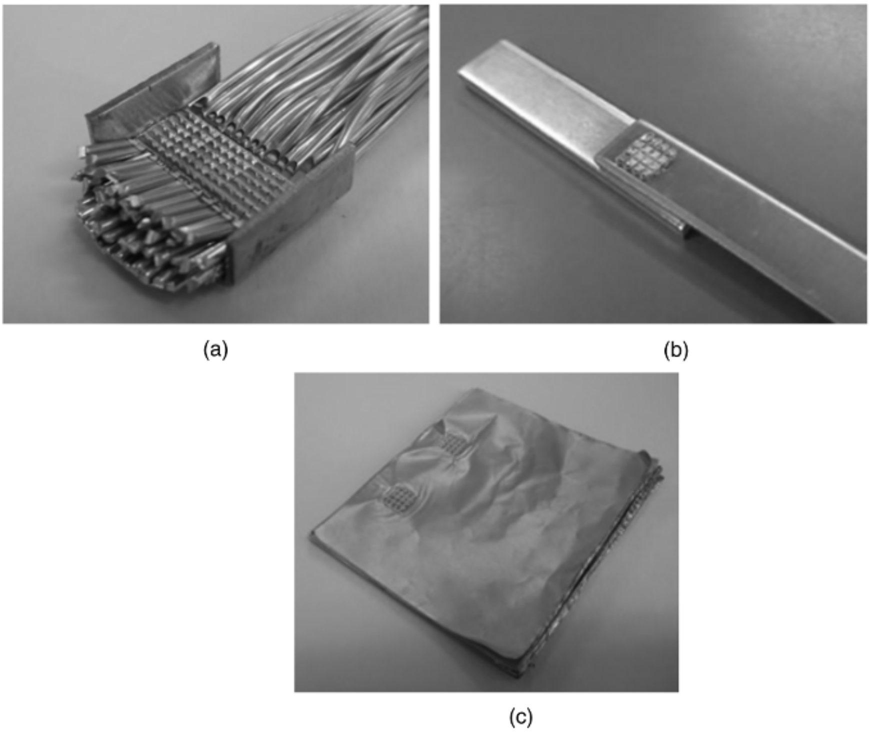


FIGURE 1.6 (a) Aluminum wire welding onto copper. (b) Copper and aluminum welding. (c) Multilayered copper foil welding. (Reproduced from Ref. [17] with permission from Nippon Avionics Co., Ltd.)

Figure 1.7 [20] illustrates how the joints of multiple metal sheets are generated in ultrasonic welding. It is believed that the propagation of the welds is through the top layer (i.e., the layer in contact with the sonotrode) to the bottom layer (i.e., the layer in contact with the anvil) [20].

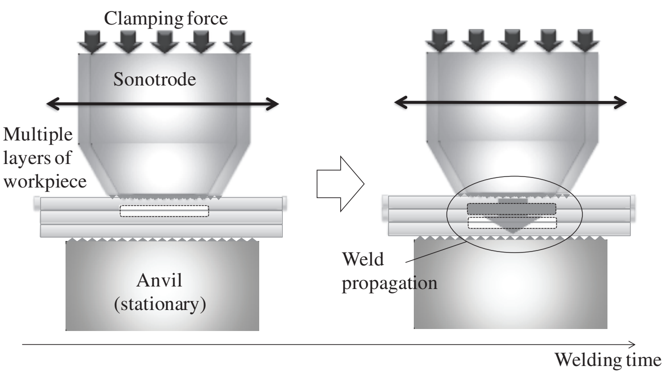


FIGURE 1.7 Weld propagation in USMW of multiple sheets.

There are three important physical attributes pertaining to the quality of an ultrasonic weld:

1. The temperatures at the bonding interfaces.

   Recent researches [21,22] were able to measure in situ the welding temperatures using the self-developed thin-film thermocouples and thermopile sensors. Although it was found that the measured temperature is 660°C for Cu-Cu ultrasonic welding at 1 mm away for the weld spot, it was uncertain whether melting actually occurred at the weld spots. According to the Fick's laws of diffusion [23], temperature is the most critical factor in diffusion bonding to ensure proper rate of solid-state atomic diffusion between the interfacing metals. Therefore, from both melting and diffusion points of view, higher temperature will be beneficial to the welding quality. In this respect, research has been performed to predict the welding temperature [24]. Higher welding temperatures and more uniform welding temperature distribution can also be achieved via a number of innovative methods shown in Figure 1.8 [24]. According to reference [18], in USMW, if the welding parameters (e.g., vibration amplitude, welding pressure, and welding time) are set too low, low temperatures at the weld interfaces result in low bonding strength.

2. Fracture and perforation of the metals at the weld spots.

   The second attribute critical to the weld quality is the fracture and perforation of the metals. Figure 1.9a is a sketch of a two-layered circular ultrasonic weld whose size is dictated by the sonotrode knurl area as shown in Figure 1.9b. According to reference [18], if the welding parameters (e.g., vibration amplitude, welding pressure, and welding time) are set too high,

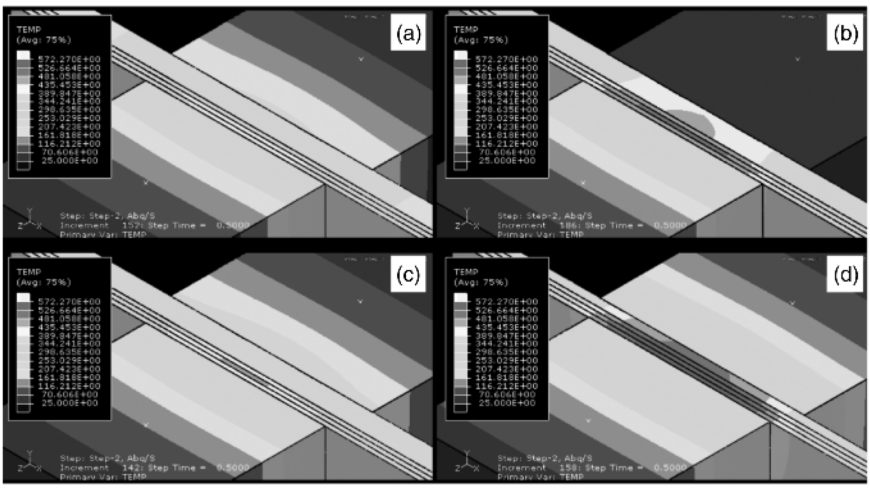
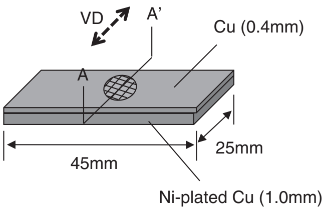
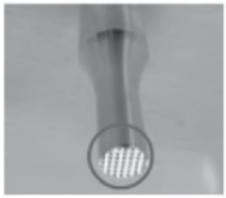


FIGURE 1.8 Temperature contours at the end of a 500 ms ultrasonic welding for (a) baseline model, (b) insulated anvil, (c) 100°C preheating, and (d) 0.6 mm thick busbar instead of 0.9 mm. (Reproduced from Ref. [24] with permission from ASME.)



(a) Cu-Cu stack up [18]

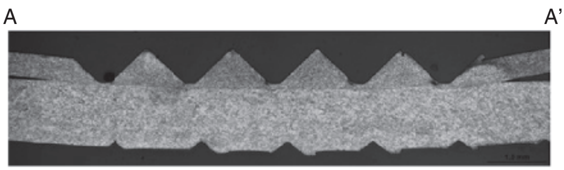


(b) A sonotrode [25]

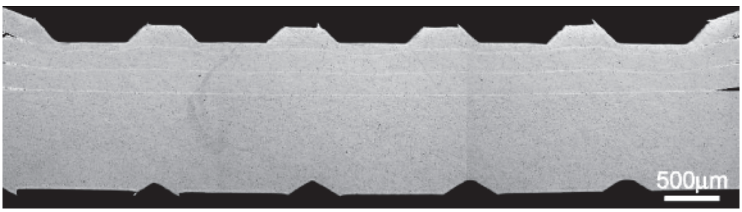
FIGURE 1.9 (a) Two layers of metals with sonotrode knurl marks. (b) A sonotrode (with knurls on the tip).

excessive plastic deformation and/or higher temperatures can result in metal fracture and perforation at the weld spots and consequently poor joint strength, although the interfacial bonding strength can be higher. Figure 1.10 shows micrographs of several ultrasonic welds including a Cu-Cu weld (Figure 1.10a), where the top Cu layer is fractured/perforated fairly severely.

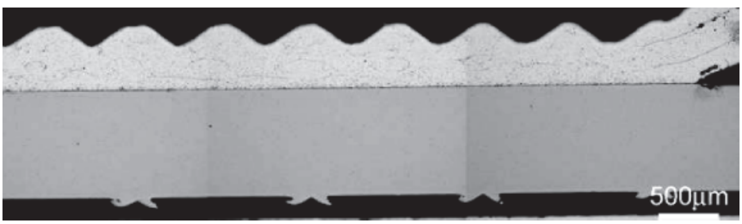
3. Structural stress and failure induced by USMW.



(a)A Cu-Cu USMW with fracture/perforation on the top layer
(Reproduced from Ref. [18] with permission from Cadex Electronics, Inc.)



(b) Optical micrograph of a four-layer copper USMW
(Reproduced from Ref. [26] with permission from Elsevier.)



(c) Optical micrograph of a four-layer USMW (Al-Al-Al-Cu)
(Reproduced from Ref. [26] with permission from Elsevier.)

FIGURE 1.10 Micrographs of ultrasonic welds.

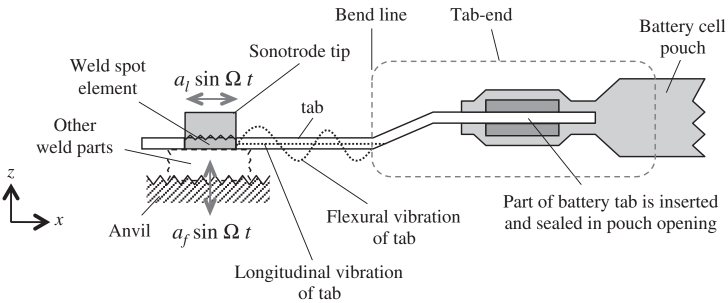


FIGURE 1.11 A pouch battery cell assembly (with the pouch partially shown) under ultrasonic vibration. (Reproduced from Ref. [27] with permission from ASME.)

Since the ultrasonic vibration is a mechanical wave that can propagate to cause stresses throughout the entire system, it is important to ensure that the structure (under specific boundary conditions) does not have a natural frequency at or near the ultrasonic frequency. As an example, paper [27] studied the distribution of stresses in the battery tab during ultrasonic welding using an analytical mechanistic model, as shown in Figure 1.11. The main focus of the study was to assess the effects of the elastic vibration of the battery tab on the stress development near the weld spot area during welding. It was found that the natural frequencies of the tab depend on the length between the weld spot and tab-end (interface between the battery tab and cell pouch), boundary conditions of the tab-end, the cross-sectional area, and the material of the tab. Therefore, it is important to design the weld position on the tab such that the tab's natural frequencies stay away from 20 kHz as much as possible to minimize tab stresses. Further, the stresses near the weld area could exceed the tab material's yield strength and cause fatigue fracture.

For larger and complex structures, modal analyses using finite-element analysis should be performed to extract the natural frequencies of a welding system under different design options in order to optimize the system to move away from resonance at the ultrasonic welding frequency. Further, steady-state dynamics analysis should also be performed to investigate the field outputs such as the stress/strain/displacement under the ultrasonic welding vibration input (such as +/–20 μm of sinusoidal input of 20 kHz) to assess the soundness of the design. As another example, Figure 1.12 depicts one welding configuration on a battery interconnect circuit board, consisting of a positive and a negative battery tab welded with a U-shaped interconnect busbar [28]. Welding of the tabs is performed on one side (i.e., the left-hand side Cu tab welding with the interconnect) followed by the subsequent welding on the other side of the interconnect. The joint made by the first welding is termed as "existing weld," and the joint made by the subsequent welding action is called "active weld." The ultrasonic vibration generated during the active weld welding may place enough stresses on the system and

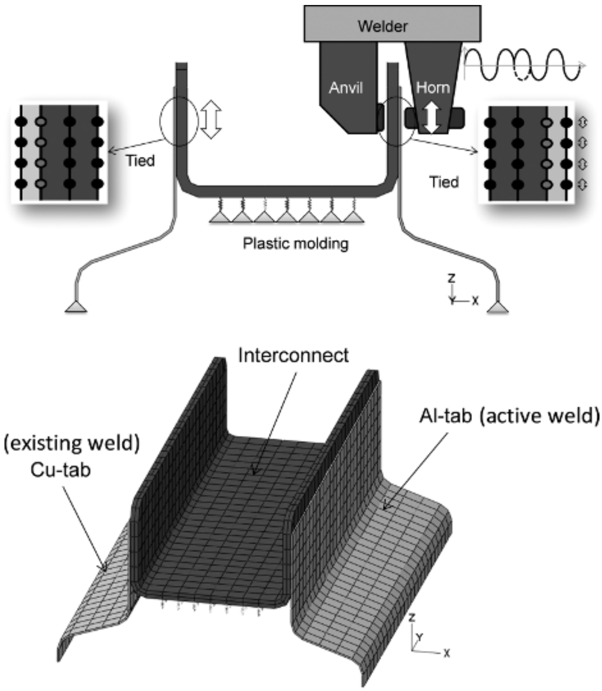


FIGURE 1.12 Modeling of battery welding system: (top) boundary conditions and (bottom) finite-element mesh.

destroy the existing weld on the left-hand side [28]. Therefore, the system (including the choice of materials and boundary conditions) should be designed to avoid resonance under ultrasonic welding.

1.3.1.3 Ultrasonic Welding Quality Evaluation Standards and guidelines for destructive, postweld quality evaluation are well established [29] for many types of welds, including ultrasonic spot welds [30,31]. They generally prescribe the quality evaluation and testing procedures. As for nondestructive evaluation (NDE), a variety of methods are developed using ultrasonic probes, eddy current, X-ray/CT, electrical resistance, etc. Success of any of the methods largely depends on the nature of the weld and defect types, and significant challenges exist in interpreting the test data. Jia et al. [32] reported that stereography method has the potential for accurate NDE for ultrasonic welds. In terms of real-time, online welding process monitoring and NDE, no standard or guideline exists, although many sensors such as temperature sensors (including thermocouples, infrared (IR)), force/pressure sensors (such as load cells), displacement (such as linear variable differential transformer (LVDT), accelerometers, and acoustic sensors are reportedly used [33]. In particular, online monitoring and quality assurance methods were developed for GM's Chevy Volt [34] and Cadillac ELR [35].

1.3.2 Resistance Welding

Resistance welding relies on a higher contact resistance at the joint interface to induce a localized joule heating and fusion of materials when the electrical current is applied through two electrodes. Resistance welding process is fast and generally automated. It has wide applications in sheet metal industries, particularly for steels welding. Although resistance welding has also been used in the battery welding for decades, its usage was primarily limited to low current-carrying applications and faces challenges in high-power BEVs:

1. Li-ion battery metals use highly electrically and thermally conductive materials such as aluminum and copper. These metals are difficult to weld using the conventional resistance spot welding technology, particularly when the contact resistance(s) at the metal interface(s) becomes low. It hence requires very large electrical current density (i.e., current vs. weld size) to be applied in the welding circuit to generate enough joule heat at the intended weld interfaces. A steady stream of recent advances has given users much improved capabilities to control various aspects of the process. For example, projection resistance welding method can sometimes be used where a small metal projection is introduced at one of the metals to reduce the total contact area of the metals and hence increase the current density. Another solution is to increase the current density by using a special type of resistance welder called capacitive discharge welder [36] to provide very high welding current (such as 10–100 kA) in a very short period of time (such as 10 ms). Nevertheless, it is still very difficult to produce a large-sized weld nugget for battery metals because of the extremely high electrical current density required.
2. As is the case for all fusion welding technologies of dissimilar materials, welds are difficult to form due to different melting temperatures; in addition, a large amount of intermetallics is typically produced, making the weld brittle with very high electrical resistivity.
3. When welding multiple layers, it is very difficult to ensure homogenous melting at all the interfaces.

Figure 1.13 [37] and Figure 1.14 [38] shows the resistance welding/welds using single-side welding electrodes, that is, two electrodes are on the same side of the metals to form a closed current conducting circuit instead of the more conventional process of two-sided resistance welding (not shown) with the two electrodes on each side of the metals. As early as 2004, NASA [37] set process specifications for the resistance spot welding of battery and electronic assemblies, where battery assemblies are considered to be nonstructural without load-carrying requirement.

1.3.3 Laser Beam Welding

Laser beam welding (LBW), or simply laser welding, is a welding technique to join workpieces through the use of the high power beam of laser. The process has been

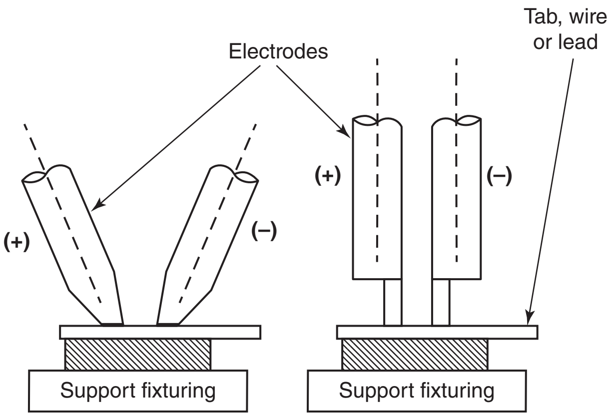


FIGURE 1.13 Resistance spot welding of battery and electronic assemblies. (Reproduced from Ref. [37]. Public domain.)

frequently used in high-volume applications, but recently it has also been used in electronics and battery industries. Figure 1.15 shows laser welding of busbars to cylindrical battery cans [39]. Figure 1.16a shows a laser seam welding of an aluminum can [39]. In battery tab welding, as described in Figure 1.16b, weld

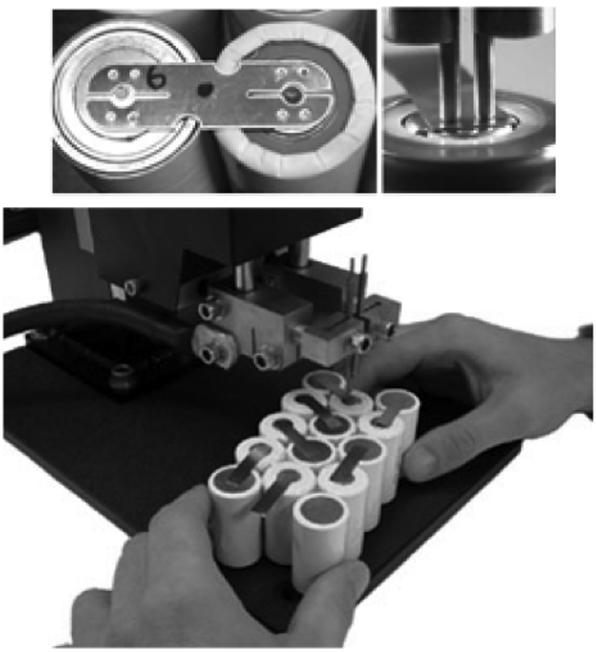


FIGURE 1.14 Battery cell resistance spot welding by (a) Amada Miyachi (reproduced from Ref. [36] with permission from Amada Miyachi) and (b) Sunstone Engineering (reproduced from Ref. [38] with permission from Sunstone).

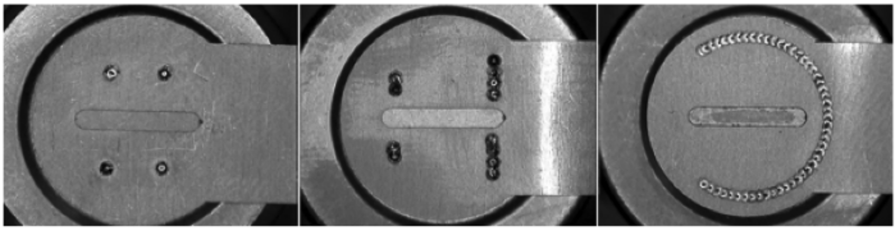


FIGURE 1.15 Laser welding of busbars to cylindrical battery cans. (Reproduced with permission from Amada Miyachi.)

penetration must be controlled accurately so that the weld nugget does not penetrate into the can [39].

Laser welding can offer significant advantages in process precision, throughput, and noncontactness. It also produces a small heat-affected zone, resulting in low weld distortion and low residual stress. Low heat input and low weld penetration can also reduce the adverse effect of heat flux on the structure and the chemistries of battery

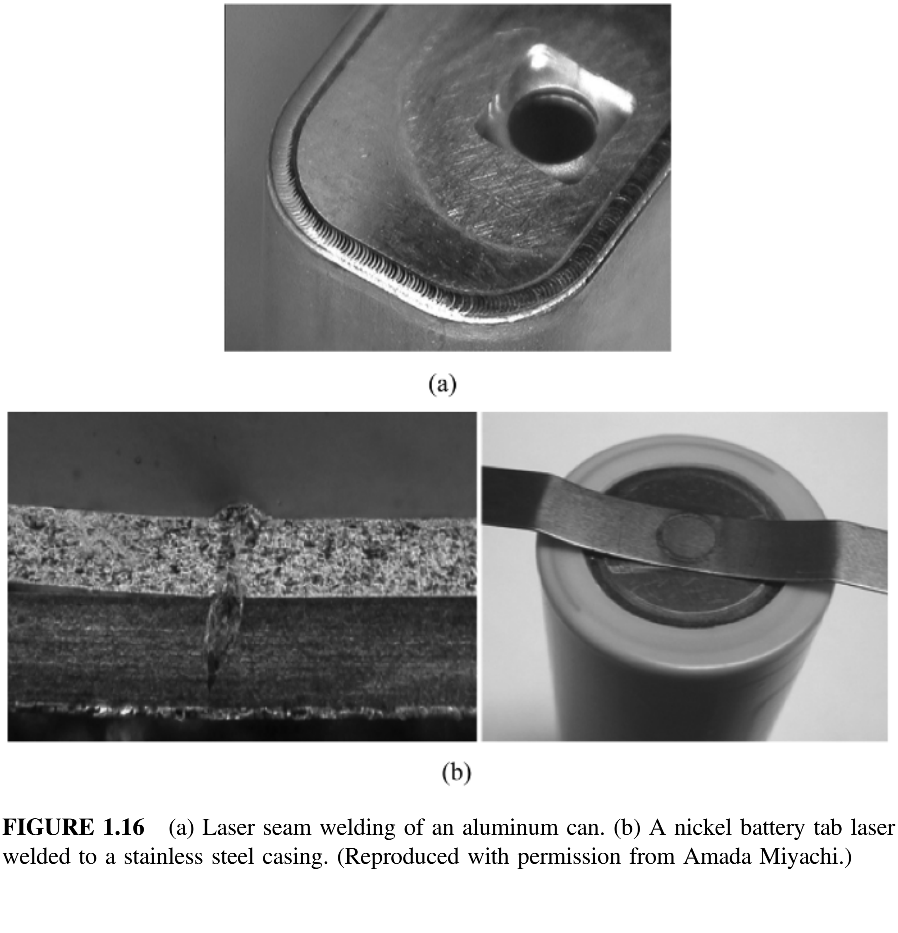


FIGURE 1.16 (a) Laser seam welding of an aluminum can. (b) A nickel battery tab laser welded to a stainless steel casing. (Reproduced with permission from Amada Miyachi.)

cells. However, the need of precise joint fit-up and the high reflectivity of the battery materials (e.g., Cu and Al) make laser welding challenging in battery applications. More critically, due to the large amount of intermetallics from the fusion welding process, weld defects such as porosity and hot cracking can be significant [40]. Recent research (Figure 1.17) demonstrated superior joining quality using a laser braze-welding process. This process uses a very small laser beam diameter (such as 50 μm), very high beam quality (i.e., high M^2 factor) in conjunction with high-speed beam scanning to precisely control the melting of aluminum layer only so that the Al and Cu welding is essentially a brazing process (without filler materials) [41].

1.3.4 Wire Bonding

Wire bonding [42] is a single-sided ultrasonic welding that bonds an auto-fed small diameter (typically 0.01–0.500 mm) Ag, Cu, or Al wire to one substrate first (called the first bond) and then to the second or more substrates in sequence (i.e., the second bond, the third bond, etc.) to establish an interconnect between the substrates through the bonding wire. Wire bonding is widely used in microelectronics industry and generally considered the most cost-effective and flexible interconnect technology. Figure 1.18 is a photo of wire-bonding process [43].

For high-power applications such as BEVs, heavy gauges of feed wires (either Al or Cu) are needed. For example, Tesla Model S uses 0.381 mm diameter of Al wires as interconnects between its 18650 Li-ion battery cells and the bus plate, as shown in Figure 1.19 [44].

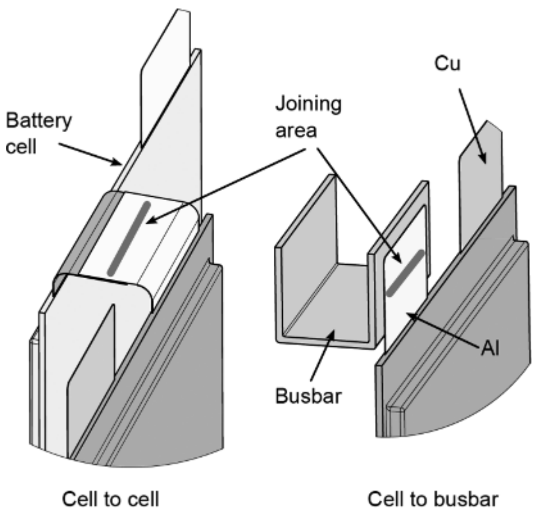


FIGURE 1.17 Laser braze welding of pouch type of battery tabs with U-shaped busbar. (Reproduced from Ref. [41] with permission from Elsevier.)

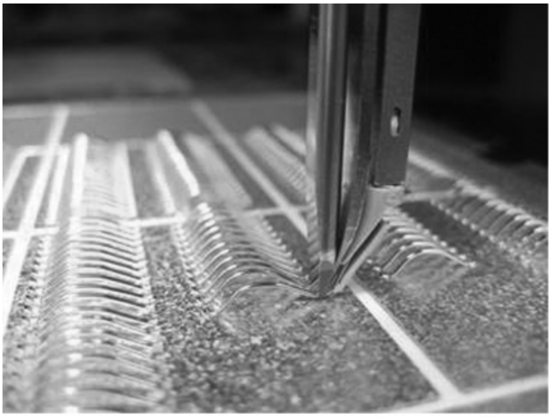


FIGURE 1.18 Wire bonding: the bond head is finishing the second bond on a Cu substrate. (Reproduced from Ref. [43] with permission from Hesse Mechatronics.)

1.3.5 Mechanical Joining

Mechanical joining [45] can be categorized by two distinct groups: fasteners and integral joints. Fasteners include nuts, bolts, screws, pins, and rivets. Integral joints include seams, crimps, snap-fits, and shrink-fits that are designed into the components to be connected. For example, snap-fit is a mechanical joining method in which part-to-part attachment is accomplished with locating and locking features (constraint features) [46]. For battery module-to-module connection, mechanical joining is preferred for the ease of disassembly for maintenance and repair.

1.3.6 Summary

The key characteristics of the selected battery-joining technologies are summarized in Table 1.2.

1.4 BATTERY MANUFACTURING: THE INDUSTRIAL LANDSCAPE

This section discusses the battery manufacturing processes and particularly the joining processes. Depending on the design specifics of cells, modules, packs, and the battery management system, the manufacturing processes vary. The section hence focuses on the manufacturing processes most relevant to BEVs in today's marketplace.

1.4.1 Cell Manufacturing

At the high level, Li-ion battery cell manufacturing processes are common for all three different cell formats [47,48], although processes vary according to different cell

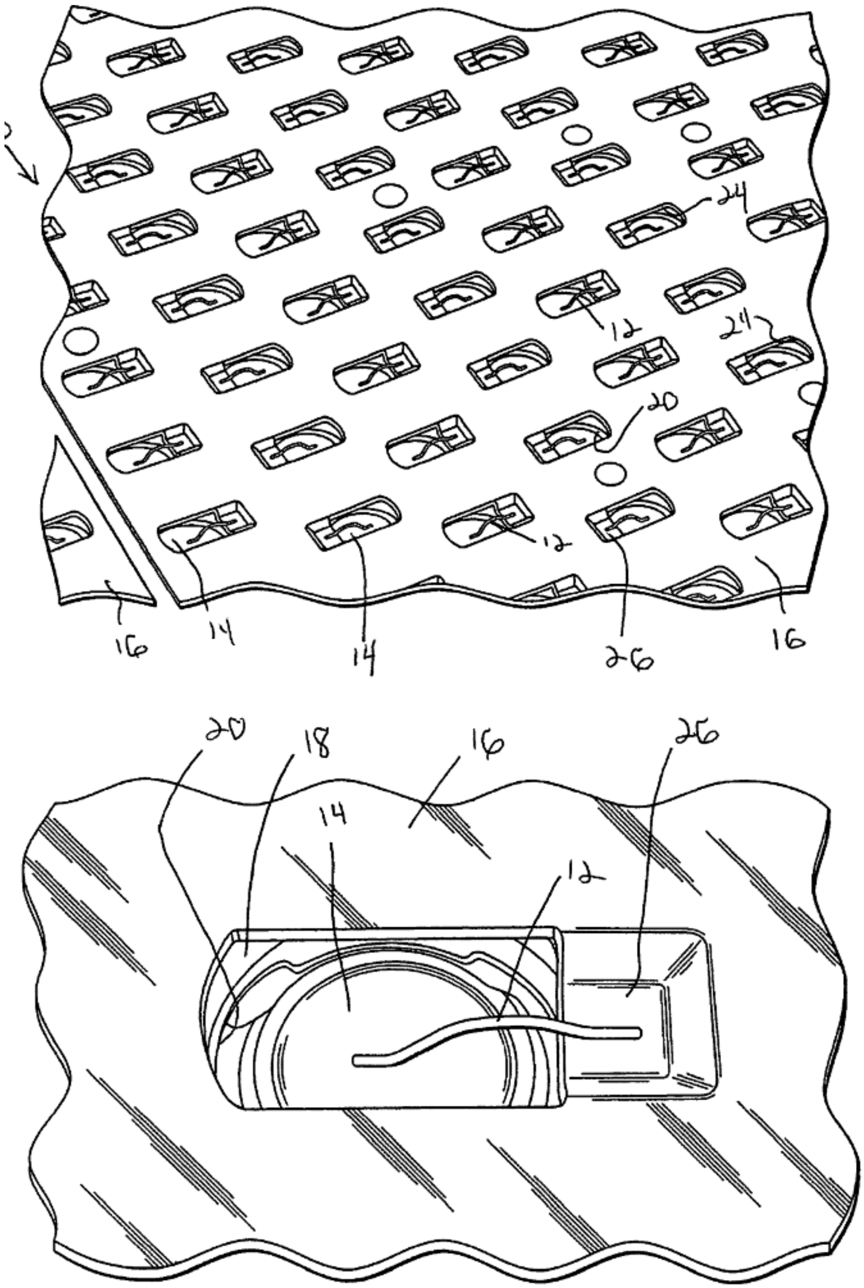


FIGURE 1.19 Tesla Model S battery joined by wire bonding. (Reproduced from Ref. [44]. Public domain.)

TABLE 1.2 Summary of battery-joining technologies

Joining methods	Advantages	Disadvantages
Ultrasonic welding	• Excellent for dissimilar materials due to minimal intermetallics • Low heat-affected zone: low thermal distortions and low residual stresses • Excellent for highly conductive materials • Excellent for thin sheets or wires • Excellent for multiple wires or multilayered sheets	• Double-sided • May have severe knurl perforation at the top and/or bottom weld surface • May cause structural vibration • Has an upper limit in total joint thickness • Most suitable for soft materials
Resistance welding	• Can be single-sided welding • Relatively mature technology with established weld quality monitoring and/or control methods • Low cost	• Large heat-affected zone: large thermal distortion and residual stresses • Large amount of intermetallics for dissimilar materials • Difficult for highly conductive materials • Difficult for multiple layers • Difficult to produce large welds • Electrode sticking/wear
Laser welding	• Relatively small heat-affected zone: small thermal distortion and residual stresses • Single-sided and noncontact • High throughput	• Large amount of intermetallics for dissimilar materials • Porosity and hot-cracking • Requiring very tight sheets fit-up • High initial cost
Wire bonding	• Excellent for dissimilar materials due to minimal intermetallics • Low heat-affected zone: low thermal distortions and low residual stresses • Excellent for highly conductive materials • Single-sided • Built-in bond strength testing	• Only light gauges of wires can be bonded onto the substrates (such as the busbars or bus plates) and thus the electrical current carrying capability is limited • Most suitable for soft materials • Substrate needs to have rigidity to sustain the bonding force
Mechanical joining	• Joint strengths can be very high • Easy disassembly	• Added parts and mass • Labor-intensive • Corrosion

designs (such as PTC/CID), materials used (such as the container materials: aluminum alloys or steels), and the supplier's design preferences. In particular, the manufacturing processes for cylindrical [49] and prismatic cells are substantially the same but somewhat different for pouch-type cells [50], as shown in Figure 1.20.

The following is a list of battery cell components requiring joining:

For all cell formats	
Cathode current collector (i.e., foil):	commercial grade pure Al (e.g., 1100)
Anode current collector (i.e., foil):	commercial grade pure Cu (e.g., CDA 110)
Positive electrode lead (i.e., tab):	commercial grade pure Al (e.g., 1100)
Negative electrode lead (i.e., tab):	commercial grade pure Cu (e.g., CDA 110), or Ni
For cylindrical and prismatic cells only	
Enclosure case (i.e., container):	steels, stainless steels, aluminum alloys
Enclosure cover (i.e., top plate):	steels, stainless steels, aluminum alloys

Welding occurs for the following four scenarios in a battery cell:

1. (For all cell formats): between an electrode lead/tab and multiple (such as 10–100) layers of current collectors [51]. Thickness of each layer ranges from 10 to 30 μm [51] depending on the design and materials used, and the cathode foils are thicker than the anode foils when Al and Cu are used. The thickness of the lead/tab is 0.1–0.2 mm. Ultrasonic welding is commonly used.
2. (For all cell formats): for multiple layers of foils themselves. This welding operation is optional. Ultrasonic welding is commonly used.

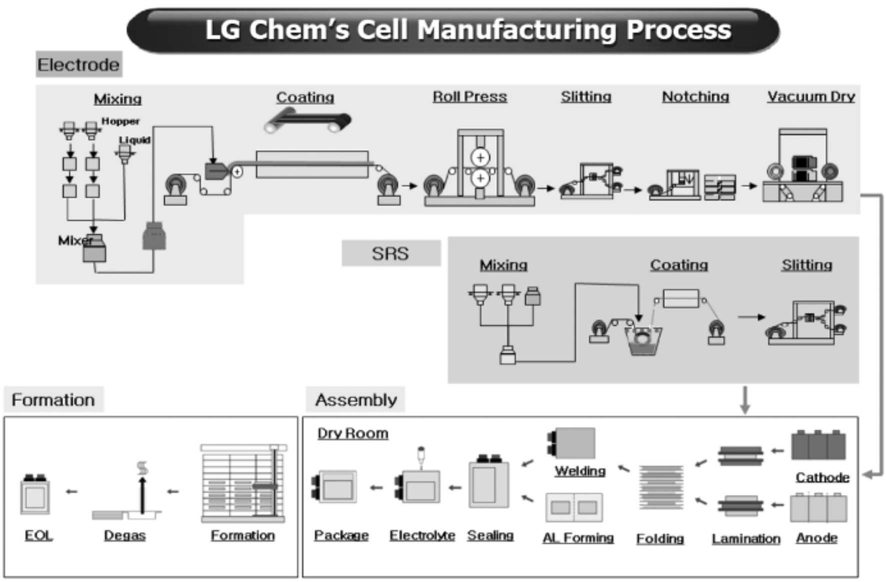


FIGURE 1.20 LG Chem's Li-ion battery cell (pouch-type) manufacturing process. (Reproduced from Ref. [50] with permission from LG Chem.)

3. (For cylindrical cells only): between a positive tab and a positive terminal, or a negative tab and the bottom of the enclosure case. Laser welding or resistance spot welding is commonly used.
4. (For prismatic cells only): between the enclosure case and the cover. Laser welding is commonly used.

1.4.2 Module Assembly (Cell-to-Cell)

A number of battery cells are normally grouped together, either in parallel or series, to form a module. Often, circuitry sensors and safety devices, along with busbars or conduction plates are also joined together with the cell tabs or terminals. The busbars or conduction plates are made of Cu or Al. On the contrary, busbars are usually much thicker than battery cell tabs. Therefore, tab-to-busbar joining is a high-gauge ratio's joining, which may limit the choice of joining method. In addition, for pouch cells,

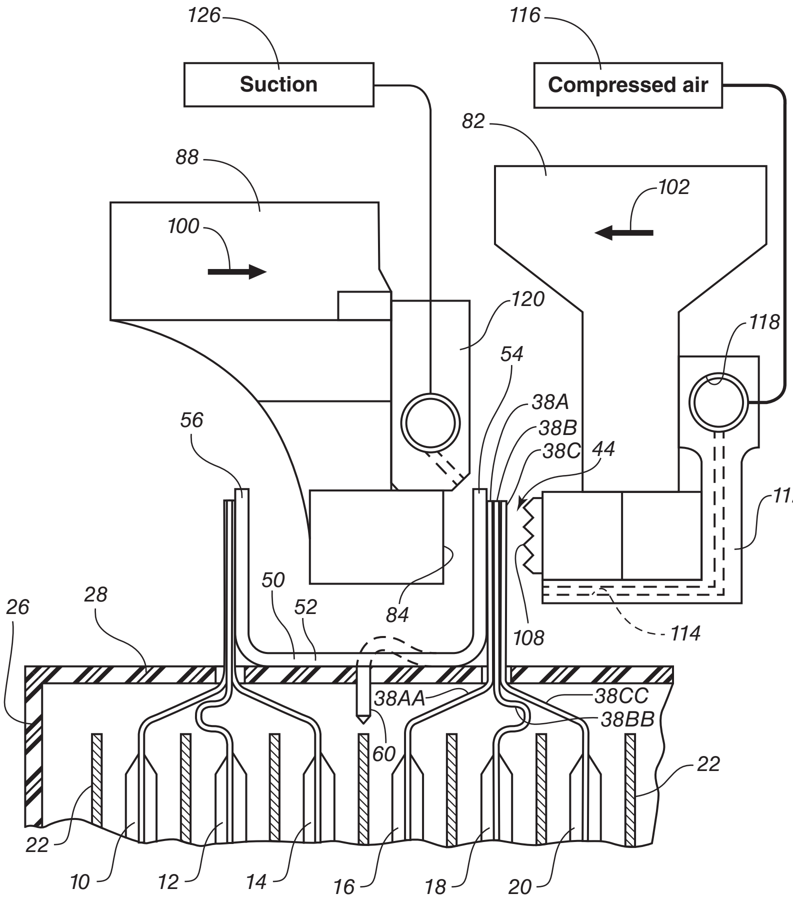


FIGURE 1.21 GM Chevy Volt: a part of battery module under ultrasonic welding.

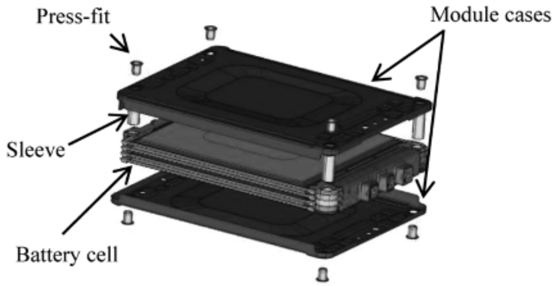


FIGURE 1.22 Nissan LEAF's battery module. (Reproduced from Ref. [53] with permission from SAE.)

positive battery tabs are typically made of aluminum, while negative tabs are made of copper, thus requiring dissimilar materials joining. Figure 1.19 shows the Tesla Model S pack [44] in which each 18650 cylindrical cell is wire bonded to the Cu bus plate. Figure 1.21 shows a schematic of GM's Chevy Volt battery module (partial view) in which three pouch cells are ultrasonically welded to the Cu busbar for each weld [52]. Figure 1.22 shows a Nissan LEAF battery module consisting of four battery cells [53], two of which are connected in series and two in parallel. BMW i3 battery module design and manufacturing process can be found in reference [54].

1.4.3 Pack Assembly (Module-to-Module)

Module-to-module assembly is normally mechanically joined via bolts/nuts with busbars. In fact, welding is not recommended at this stage due to the need of disassembly of battery packs. Figure 1.23 shows Nissan LEAF's battery pack [55].

FIGURE 1.23 Nissan Leaf battery cell, module, and pack. Upper left: a laminated battery cell; upper right: a battery module set of four laminated battery cells; bottom: a battery pack made up of 48 modules. (Reproduced from Ref. [55] with permission from IEEE.)

1.5 CONCLUSIONS

This chapter provides a comprehensive overview on the state-of-the-art of BEV manufacturing, with emphasis on the joining, assembly, and packaging of lithium-ion battery packs.

1. Li-ion battery and BEV marketplace are growing and evolving rapidly. In 2014, Panasonic, AESC, LG Chem, and BYD were the four largest manufacturers of traction battery cells in the world, supplying batteries to Tesla Model S (pure BEV), Nissan LEAF (pure BEV), GM Chevrolet (EREV), and BYD (pure EV and PHEV), respectively.
2. There are three major cell formats for Li-ion traction batteries, that is, cylindrical, prismatic, and pouch. The manufacturing processes for cylindrical and prismatic cells are substantially similar but deviate meaningfully for the pouch-type cells. The exact manufacturing process for any format is determined by the designs, materials, and cell and BEV manufacturers' preferences.
3. The traction Li-ion battery joining is an important manufacturing process at three different levels, that is, cell level (inside cell joining), module level (cell-to-cell joining), and pack level (module-to-module).
4. Ultrasonic welding, Laser beam welding, resistance welding, wire bonding, and mechanical joining are the commonly used joining techniques for Li-ion battery cells, modules, and packs.

REFERENCES

1. GM EV1. http://en.wikipedia.org/wiki/General_Motors_EV1.
2. Toyota Prius PHEV. http://en.wikipedia.org/wiki/Toyota_Prius_Plug-in_Hybrid.
3. Chevy Volt. http://en.wikipedia.org/wiki/Chevrolet_Volt.
4. Tesla Model S. http://en.wikipedia.org/wiki/Tesla_Model_S#Battery.
5. Nissan LEAF. http://en.wikipedia.org/wiki/Nissan_Leaf.
6. BMW i3. http://en.wikipedia.org/wiki/BMW_i3.
7. BMW i3 — Batteries and Charging Solutions. http://www.bmwblog.com/2013/04/18/bmw-i3-batteries-and-charging-solutions/.
8. Lee, S.S., Kim, T.H., Hu, S.J., Cai, W., and Abell, J.A. (2010) A state-of-the-art review on lithium-ion battery joining, assembly and packaging in battery electric vehicles, in *25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition, Shenzhen, China*, Nov. 5–9, 2010.
9. 2014 Global Traction Battery Market. (2014) http://m.d1ev.com/37935.html?from=timeline&isappinstalled=0.
10. Buck, D.S., Fattig, R.N., and Silk, B.J. 2008. *Battery Pack with Integral Cooling and Bussing Devices*, Enerdel, USA.
11. EV World. Panasonic 18650 Lithium-ion Cell, the Heart of Tesla Motor's Battery Pack. http://evworld.com/news.cfm?newsid=34408.

12. Jeevarajan, J. (2010) Safety Limitations Associated with Commercial 18650 Lithium-ion Cells. Lithium Mobile Power and Battery Safety, November 3, 2010.
13. Augeard, A. Singo, T. Desprez, P. Perisse, F. Menecier, S. and Abbaoui, M. (2014) Arc analysis to the CID of Li-ion battery cells in high-current applications. *IEEE 60th Holm Conference on Electrical Contacts (Holm)*, Oct. 12–15, 2014, New Orleans, LA, USA.
14. Battery University. http://batteryuniversity.com/learn/article/types_of_battery_cells.
15. Laminated Cells. http://www.eco-aesc-lb.com/en/randd/laminatecell/.
16. Choi, S., Zhang, G. Fuhlbrigge, T.A., and Nidamarthi, S. (2012) Vibration analysis in robotic ultrasonic welding for battery assembly. *8th IEEE International Conference on Automation Science and Engineering*, Aug. 20–24, 2012, Seoul, Korea.
17. Nippon Avionics Co., Ltd. Ultrasonic Metal Welder SW-3500-20/SH-H3K7. http://www.avio.co.jp/english/news/141216.html.
18. Lee, S.S., Kim, T.H., Hu, S.J., Cai, W., Abell, J.A., and Li, J. (2013) Characterization of joint quality in ultrasonic welding of battery tabs. *ASME Journal of Manufacturing Science & Engineering*, 135(2), 021004 13 pp.
19. Villars, P. *ASM Alloy Phase Diagram Database*, ASM International, Materials Park, OH, 44073, USA, 2006–2013.
20. Lee, S.S., Kim, T.H., Hu, S.J., Cai, W., and Abell, J.A. (2015) Analysis of weld formation in multilayer ultrasonic metal welding using high-speed images. *ASME Journal of Manufacturing Science & Engineering*, 137(3), 031016 8 pp.
21. Li, H., Choi, H., Ma, C., Zhao, J., Jiang, H., Cai, W., Abell, J.A., and Li, X.C. (2013) Transient temperature and heat flux measurement in ultrasonic joining of battery tabs using thin-film microsensors. *ASME Journal of Manufacturing Science & Engineering*, 135(5), 051015 8 pp.
22. Zhao, J., Li, H., Choi, H., Cai, W., Abell, J.A., and Li, X. (2013) Insertable thin film thermocouples for in situ transient temperature monitoring in ultrasonic metal welding of battery tabs. *SME Journal of Manufacturing Processes*, 15(1), 136–140.
23. Callister, W.D. Jr. (2007) *Materials Science and Engineering: An Introduction*, John Wiley & Sons, Inc.
24. Lee, D.K., Kannatey-Asibu E. Jr., and Cai, W. (2013) Ultrasonic welding simulations for multiple layers of lithium-ion battery tabs. *ASME Journal of Manufacturing Science & Engineering*, 135(6), 061011.
25. Nippon Avionics Co., Ltd. Rib Shape and Knurling of Horn. http://www.avio.co.jp/english/products/assem/principle/ultrasonic/rib.html.
26. Wu, X., Liu, T., and Cai, W. (2015) Microstructure, welding mechanism, and failure of Al/Cu ultrasonic welds. *SME Journal of Manufacturing Processes*, 20 (Part 1), 321–331.
27. Kang, B.S., Cai, W., and Tan, C.A. (2014) Dynamic stress analysis of battery tabs under ultrasonic welding. *ASME Journal of Manufacturing Science & Engineering*, 136(4), 041011.
28. Lee, S.S., Kim, K., Cai, W., and Abell, J.A. (2014) Parasitic vibration attenuation in ultrasonic welding of battery tabs. *International Journal of Advanced Manufacturing Technology*, 71(1–4), 181–195.
29. American Welding Society. (2007) AWS B4.0 Standard Methods for Mechanical Testing of Welds.

30. MIL-STD-1947. Ultrasonic Welding of Aluminum and Aluminum Alloy Materials. US Department of Defense Military Standard, 1985.
31. SAE/USCAR-38, Performance Specification for Ultrasonically Welded Wire/Cable Termination, December 2009.
32. Jia, S., Hong, E., Katz, R. Lev, L.C., Smyth, S., and Abell, J. (2012) Nondestructive testing of ultrasonic welding joints using shearography technique. *ASME Journal of Manufacturing Science & Engineering*, 134(3), 034502 6 pp.
33. Cai, W., Abell, J.A., Tang, J., Wincek, M., Boor, P., Spacher, P., and Hu, S.J. Method and system for online quality monitoring and control of a vibration welding process. US Patent 8,702,882.
34. University of Michigan Record Update. GM, CoE Create Technology to Maximize Volt's Battery Weld Quality. http://www.ur.umich.edu/update/archives/110624/battery, January 24, 2011.
35. Green Car Congress. (2013) Ultrasonic Welding in the Battery Pack for the Cadillac ELR. http://www.greencarcongress.com/2013/08/elr-20130802.html, August 2, 2013.
36. Amada Miyachi America. http://www.amadamiyachi.com/products/resistance-welding/rw-power-supplies/adp-series.
37. NASA, PRC-009 REV D. (2004) *Process Specification for the Resistance Spot Welding of Battery and Electronic Assemblies*. NASA Johnson Space Center, February 2004.
38. Sunstone Engineering. Battery Tab Spot Welders. http://sunstoneengineering.com/applications/batteries/battery-tab-spot-welders/.
39. Industrial Laser Solutions. (2015) Battery Welding: Selecting Laser, MicroTIG, and Resistance Technologies. http://www.industrial-lasers.com/articles/print/volume-30/issue-1/features/battery-welding-selecting-laser-microtig-and-resistance-technologies.html, January 26 2015.
40. Mys, I. (2006) Laser Micro Welding of Copper and Aluminum. *Proceedings of the SPIE 6107, Laser-based Micropackaging*, 23 Feb, p. 610703
41. Solchenbach, T., Plapper, P., and Cai, W. (2014) Electrical performance of laser braze-welded aluminum-copper interconnects. *SME Journal of Manufacturing Processes*, 16(2), 183–189.
42. Wire Bonding. http://en.wikipedia.org/wiki/Wire_bonding.
43. Wire Bonding. http://www.smtnet.com/media/images/hmi-heavy-copper-wire-bonding.jpg.
44. Kohn, S., Berdichevsky, G., and Hewett, B.C. Tunable Frangible Battery Pack System. US Patent 7923144 B2.
45. Lee, S.S., Kim, T.H., Hu, S.J., Cai, W., and Abell, J.A. (2010) Joining technologies for automotive lithium-ion battery manufacturing — a review. *Proceedings of the ASME International Manufacturing Science and Engineering Conference, Erie, PA*.
46. Bonenberger, P.R. (2000) *The First Snap-fit Handbook*, Hanser.
47. Electropaedia. Lithium Battery Manufacturing. http://www.mpoweruk.com/battery_manufacturing.htm.
48. MTI Corporation. Li-ion Cylindrical Battery Fabrication & Equipment. http://www.mtixtl.com/xtlflyers/Cylinder-cell-flyer.pdf.
49. Chris Hillseth Enterprises. About Lithium-ion Battery Manufacturing. http://chrishillsethenterprises.com/battery/about-lithium-ion-battery-manufacturing/.

50. Koo, R. (2012) Advanced Li-ion polymer battery cell manufacturing plant in USA. *DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting*, May 16. http://energy.gov/sites/prod/files/2014/03/f10/arravt001_es_koo_2012_p.pdf.
51. Massey, S. (2013) Ultrasonic Metal Welding for Lithium-Ion Battery Cells. http://ewi.org/ultrasonic-metal-welding-for-lithium-ion-battery-cells/. January 17.
52. Scheuerman, R.J. and Rourke, R.F. Method and Apparatus for Ultrasonic Welding of Terminals, US Patent Application US20100224671 A.
53. Kinoshita, Y., Hirai, T., Watanabe, Y., Yamazaki, Y., Amagai, R., and Sato, K. (2013) Newly Developed Lithium-Ion Battery Pack Technology for a Mass-Market Electric Vehicle. SAE Technical Paper 2013-01-1543.
54. Autoevolution. Watch how BMW i3 Batteries are Made - Video. http://www.autoevolution.com/news/watch-how-bmw-i3-battery-cells-are-made-video-76279.html#agal_0.
55. Fleming, B. (2010) Battery switching, driving dynamics, and touch-screen control input. *IEEE Vehicular Technology Magazine*, 5(4), 4–7.