Analysis of Li-Ion Battery Joining Technologies*

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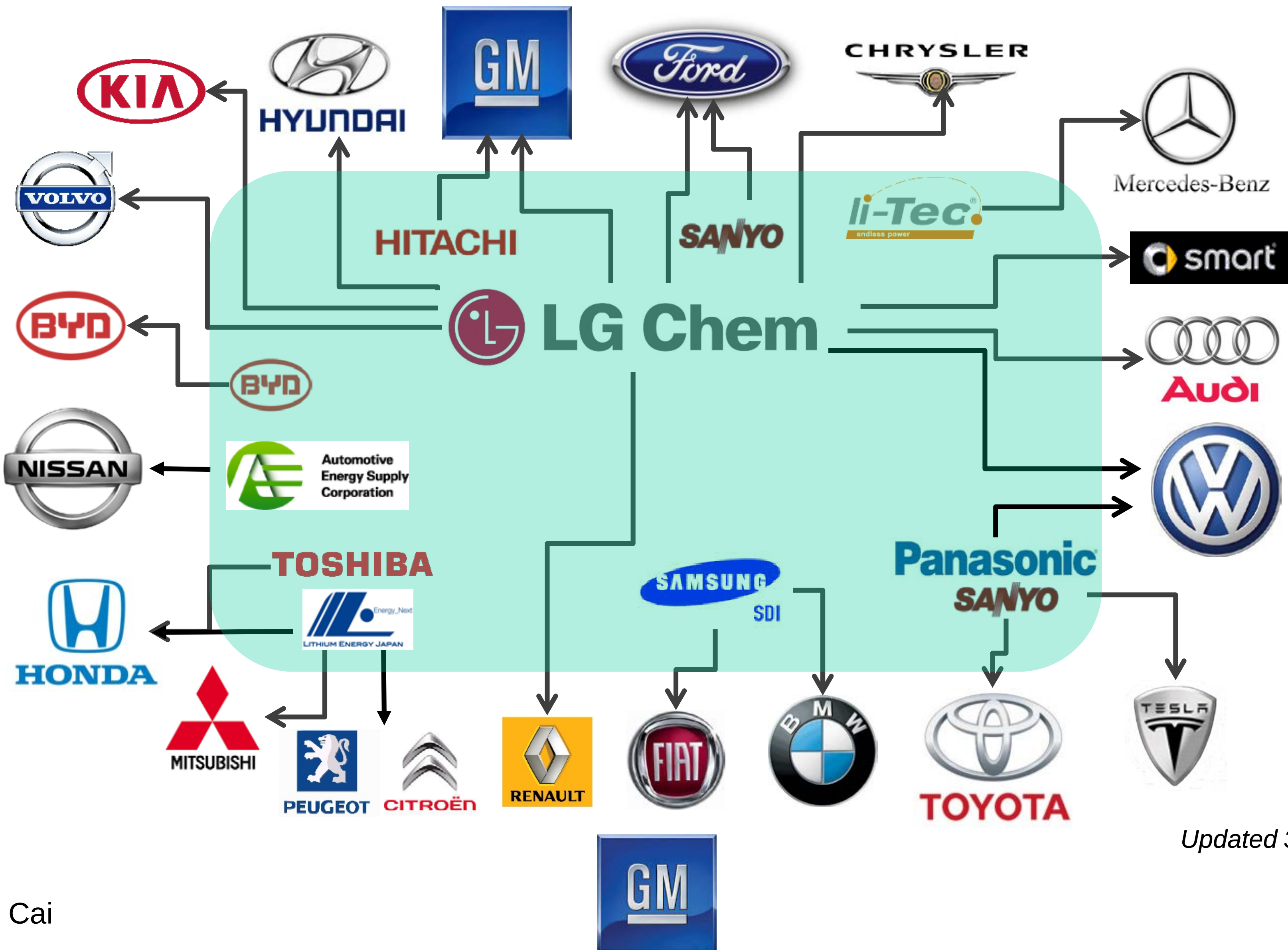
** W. Cai, B. Kang, and S.J. Hu, (2017), Ultrasonic Welding of Lithium-Ion Batteries, ASME Press*
** W. Cai, (2016), Lithium-ion Battery Manufacturing for Electric Vehicles: A Contemporary Overview, in Advances in Battery Manufacturing, Service, and Management Systems (eds J. Li, S. Zhou and Y. Han), John Wiley & Sons, Inc., Hoboken, NJ, USA.*

Outline

1. **BATTERY ELECTRIC VEHICLES**
2. **LI-ION BATTERY CELLS, MODULES AND PACKS**
   1) Formats of Li-ion Battery Cells
   2) Battery Modules and Pack
3. **JOINING TECHNOLOGIES FOR BATTERIES**
   1) Ultrasonic Metal Welding
   2) Resistance Welding
   3) Laser Beam Welding
   4) Wire-bonding
   5) Mechanical Joining
4. **BATTERY MANUFACTURING: THE INDUSTRIAL LANDSCAPE**
   1) Cell Manufacturing
   2) Module Assembly (Cell-to-Cell)
   3) Pack Assembly (Module-to-Module)
5. **CONCLUSIONS**

1. Battery Electrical Vehicle Landscape



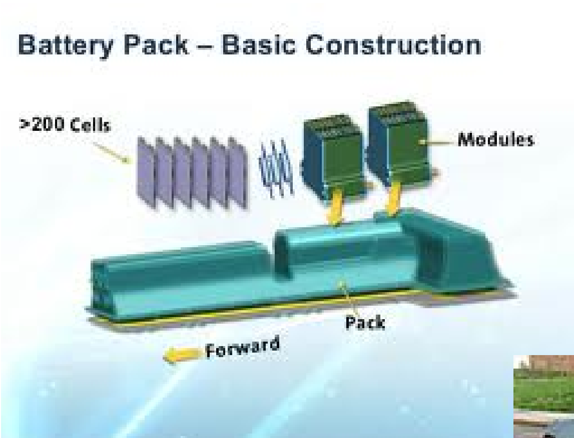
Updated 3/30/2015

1. Battery Electrical Vehicles

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 [7][8]
Model Year	2012-2014	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	288	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				

Chevy Volt

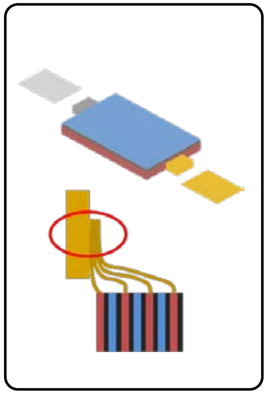
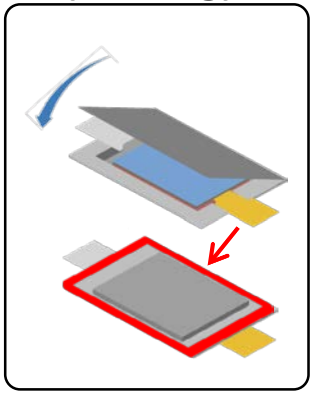
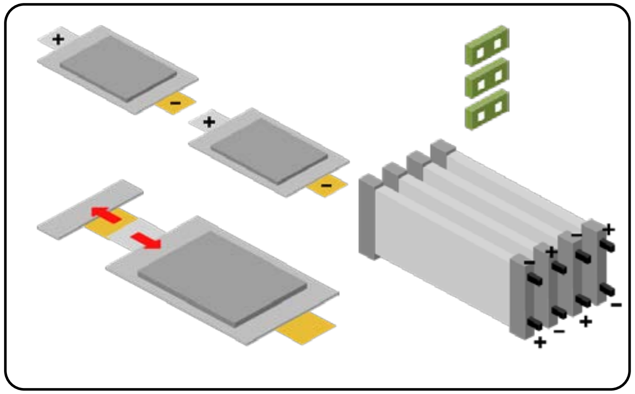
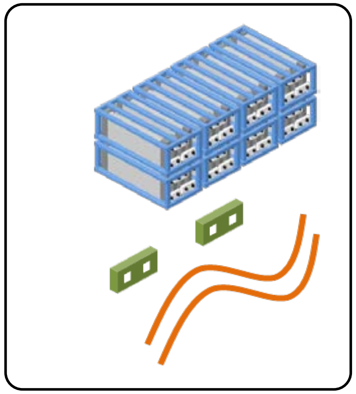


Source: Google images

Hierarchy of Battery Pack Manufacturing

Joining Processes of Battery Pack

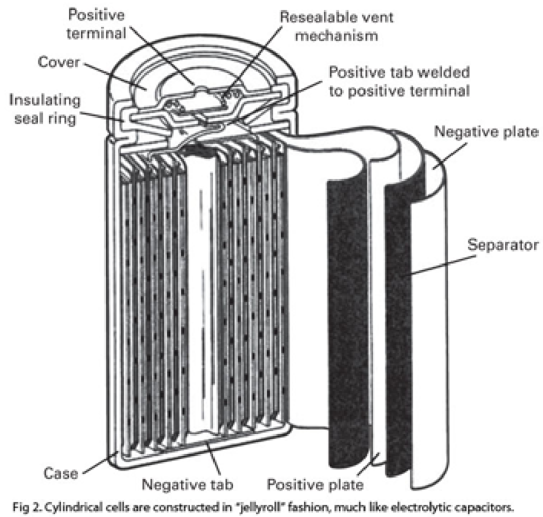
- **Cell Level**
  - Electrodes-to-Tab
  - Case (Sealing)
- **Module Level**
  - Cell-to-Cell
- **Pack Level**
  - Module-to-Module

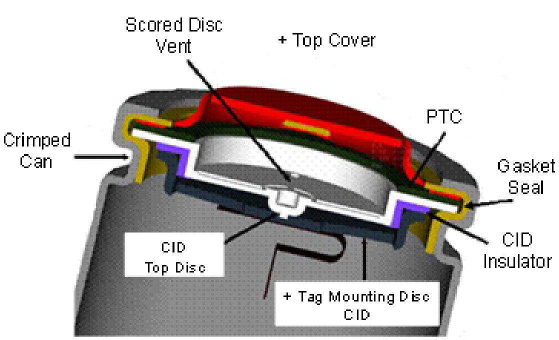
2. LI-ION BATTERY CELLS, MODULES & PACKS

Cylindrical Cells

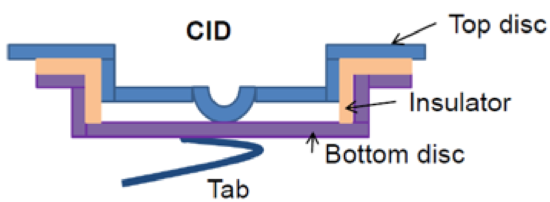
(a) 18650 Cylindrical Cell



(b) Anatomy of Cylindrical Cell



(c) Top Section of a Cylindrical Cell



(d) Diagram of CID in Cylindrical Cell

FIGURE 1.2 CYLINDRICAL FORMAT LI-ION BATTERY CELLS.

(1) The cylindrical cells are known to be less volumetric efficient than prismatic cells, but were the first format of li-ion cells

(2) 18650 cylindrical cells are used in Tesla's electric vehicles

(3) PTC, or Positive Temperature Coefficient, 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.

(4) CID, or Current Interrupt Device, 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-away, the pressure increases to a level to break the CID and thereof the circuit.

Prismatic Cells

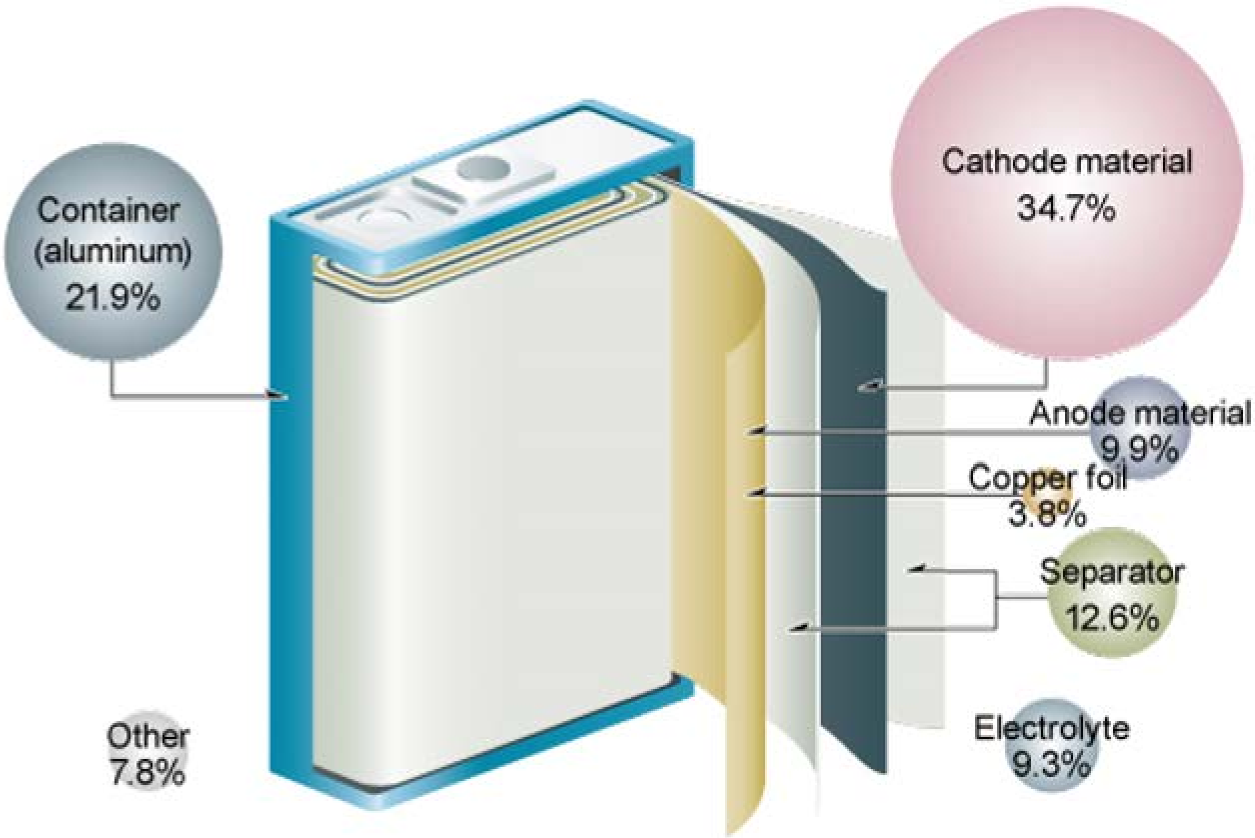


FIGURE 1.3 AN ANATOMY OF A PRISMATIC LI-ION BATTERY CELL, WHERE THE % INDICATING THE ESTIMATE COST

Pouch Cells

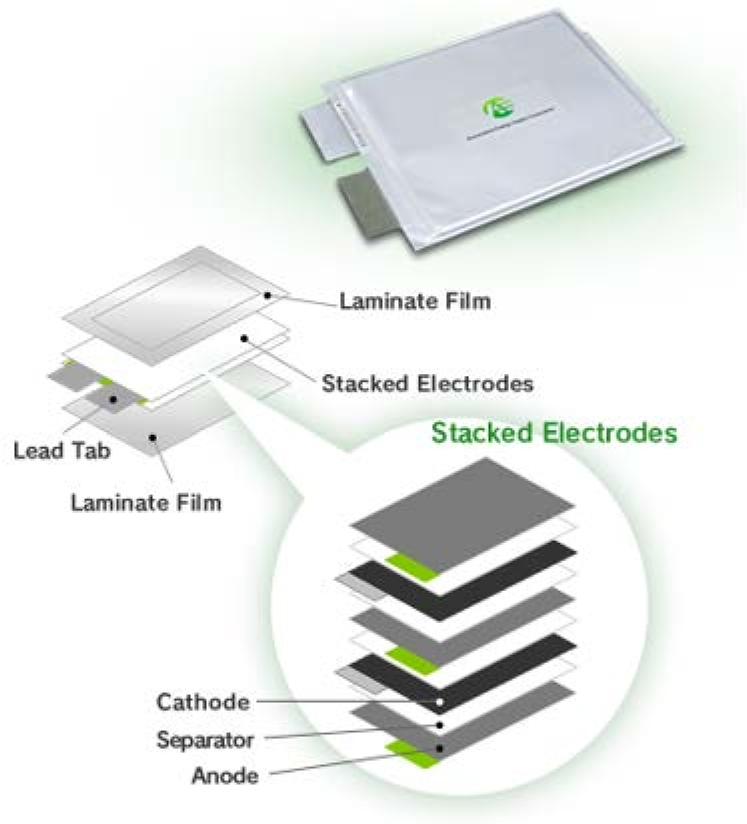
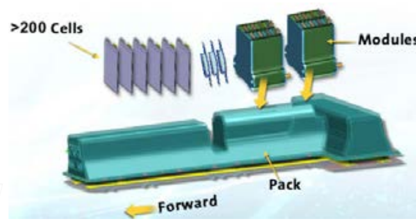


FIGURE 1.4 SCHEMATICS OF POUCH TYPE CELLS

highly conductive materials

dissimilar materials



thin, multi-layer materials

100% reliability

Ultrasonic Welding

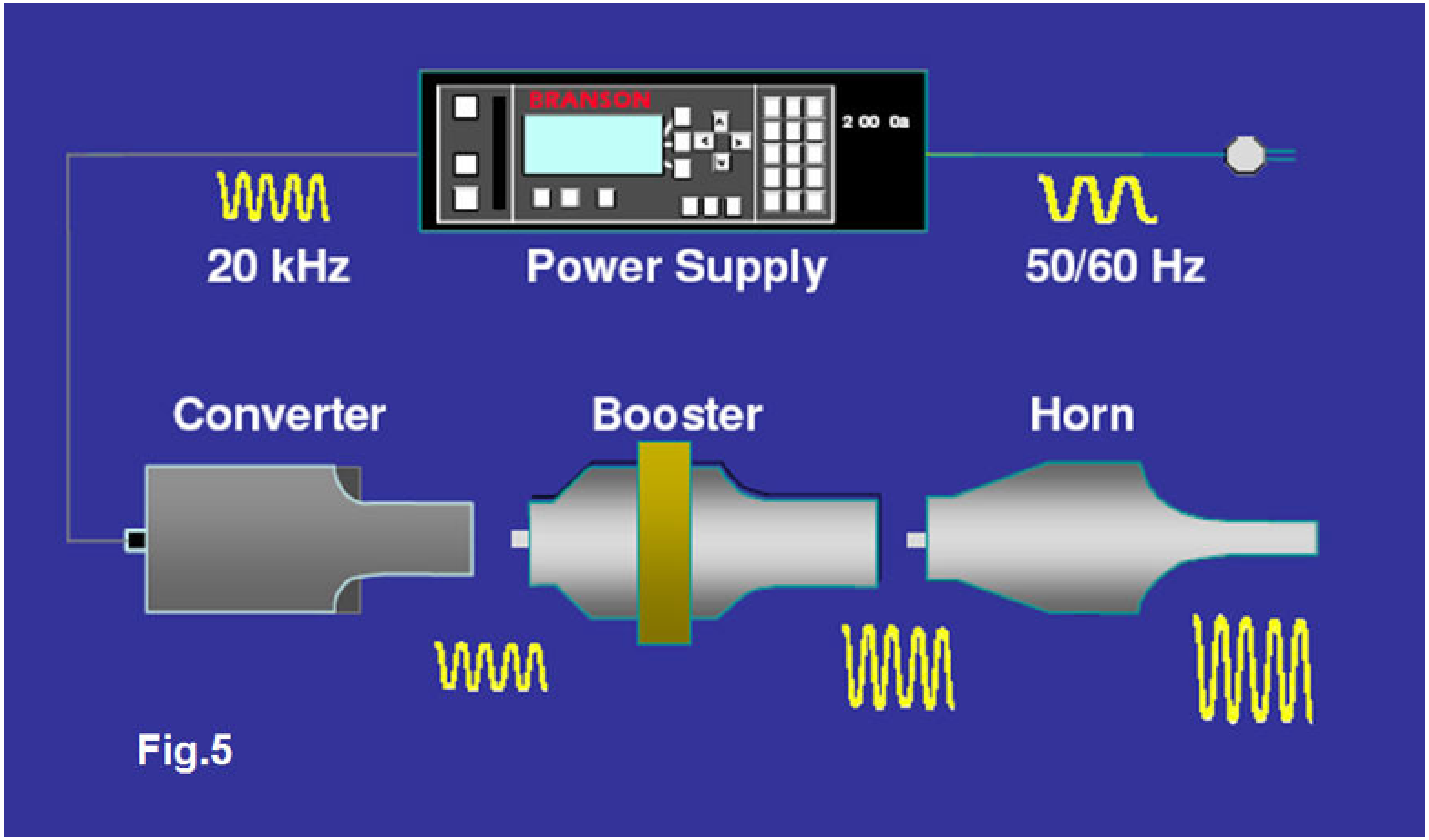


FIGURE 1.6 A SCHEMETIC OF ULTRASONIC METAL WELDING SYSTEM

Ultrasonic Welding

Ultrasonic Welding

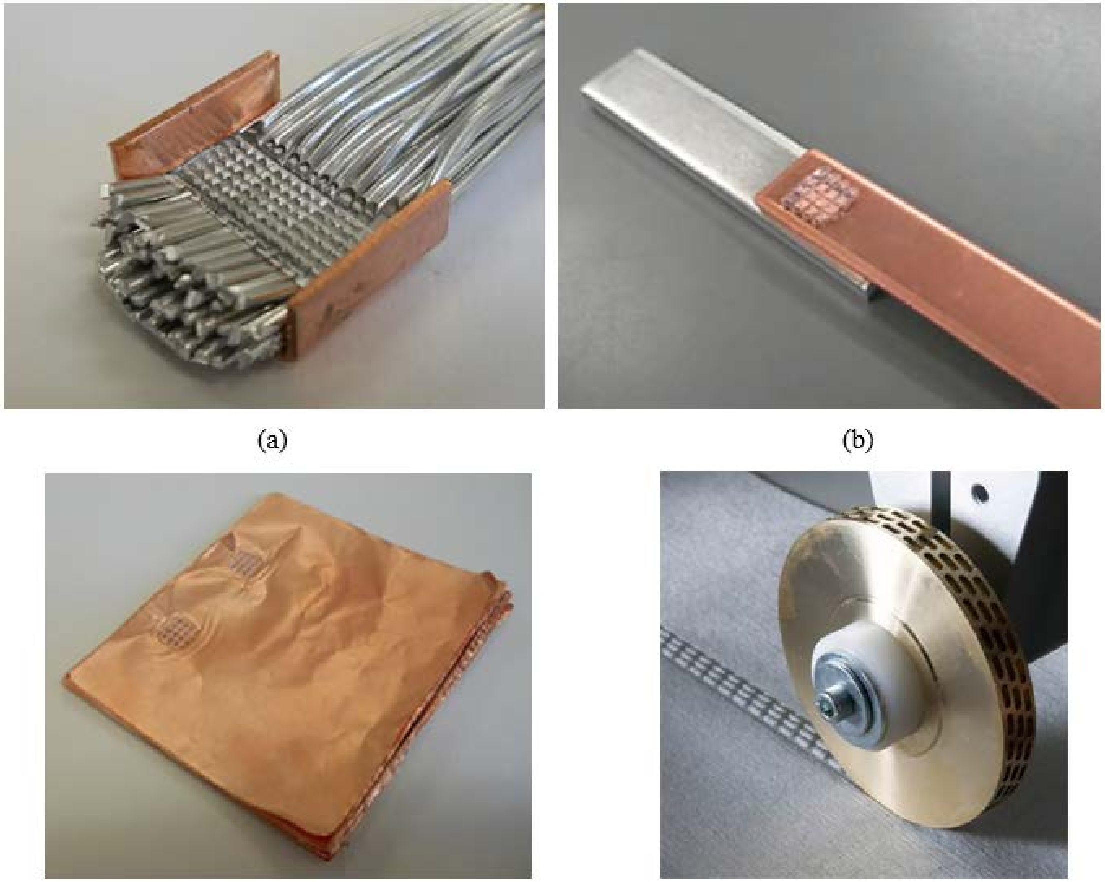


FIGURE 1.7 (A) AL WIRE WELDING ONTO CU; (B) CU AND AL WELDING; (C) MULTI-LAYERED CU FOIL WELDING; (D) ULTRASONIC SEAM WELDING

The Ultrasonic Bonding Mechanisms

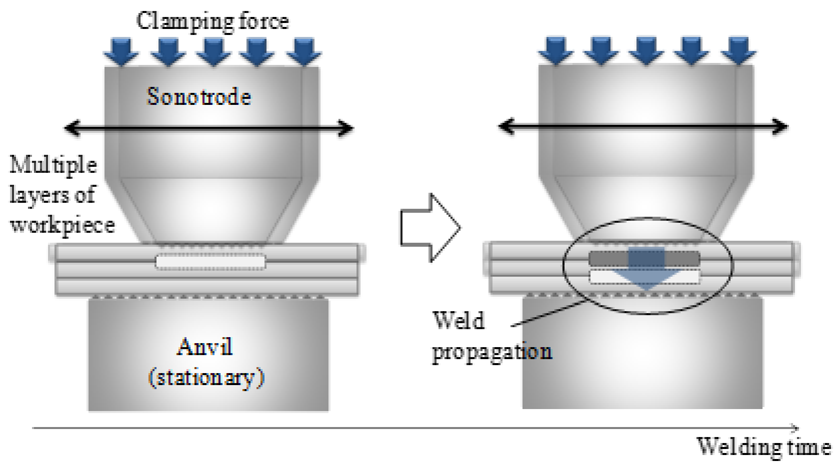
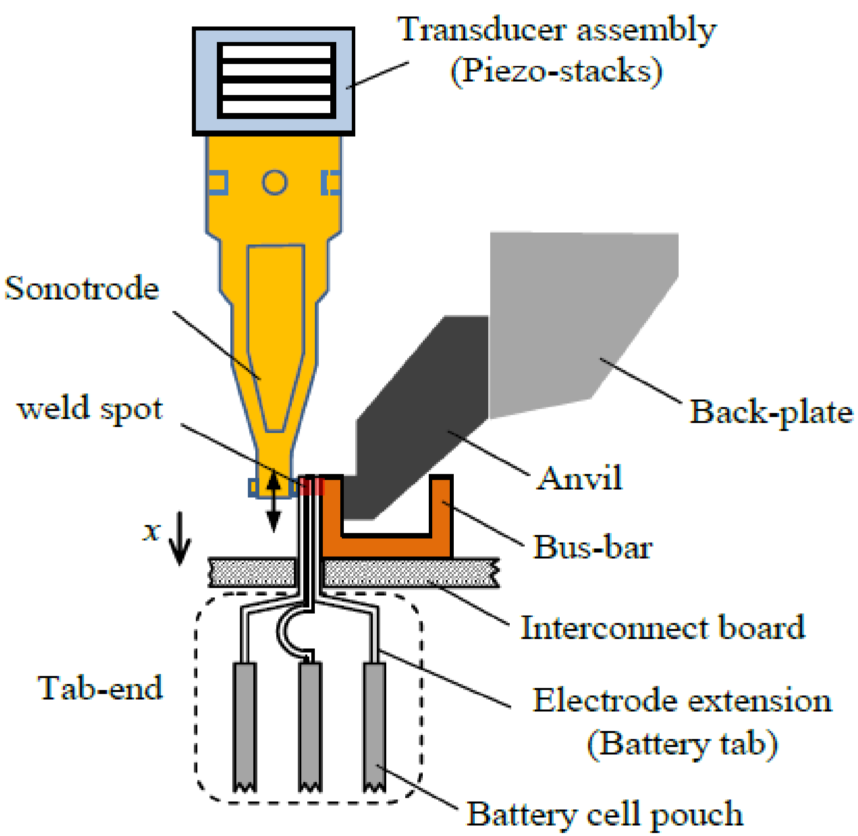


FIGURE 1.8 WELD PROPAGATION IN ULTRASONIC METAL WELDING OF MULTIPLE SHEETS

A combination of the following four mechanisms may attribute to the bonding:
(a) micro-melting (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) atomic diffusion, and
(d) metallic bonding

Chevy Volt Ultrasonic Welding:

between battery tabs and the interconnect bus bar



B.S. Kang, W. Cai, and C.A. Tan, "Dynamic Stress Analysis of Battery Tabs under Ultrasonic Welding," ASME Journal of Manufacturing Science & Engineering, 136(4), 041011 (May 21, 2014).

http://insideevs.com/2013-chevy-volt-battery-pack-and-drivetrain-disassembly-video/

Ultrasonic Welding Quality Prediction #1: Temperatures and Bonding Quality

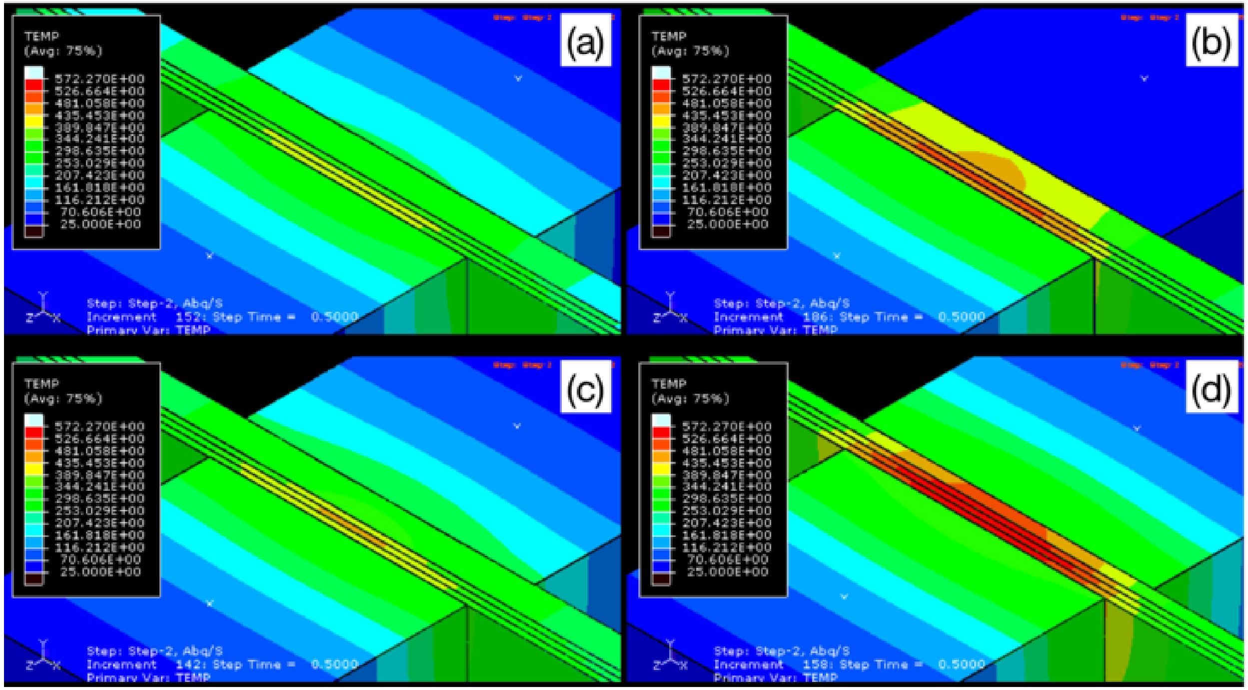
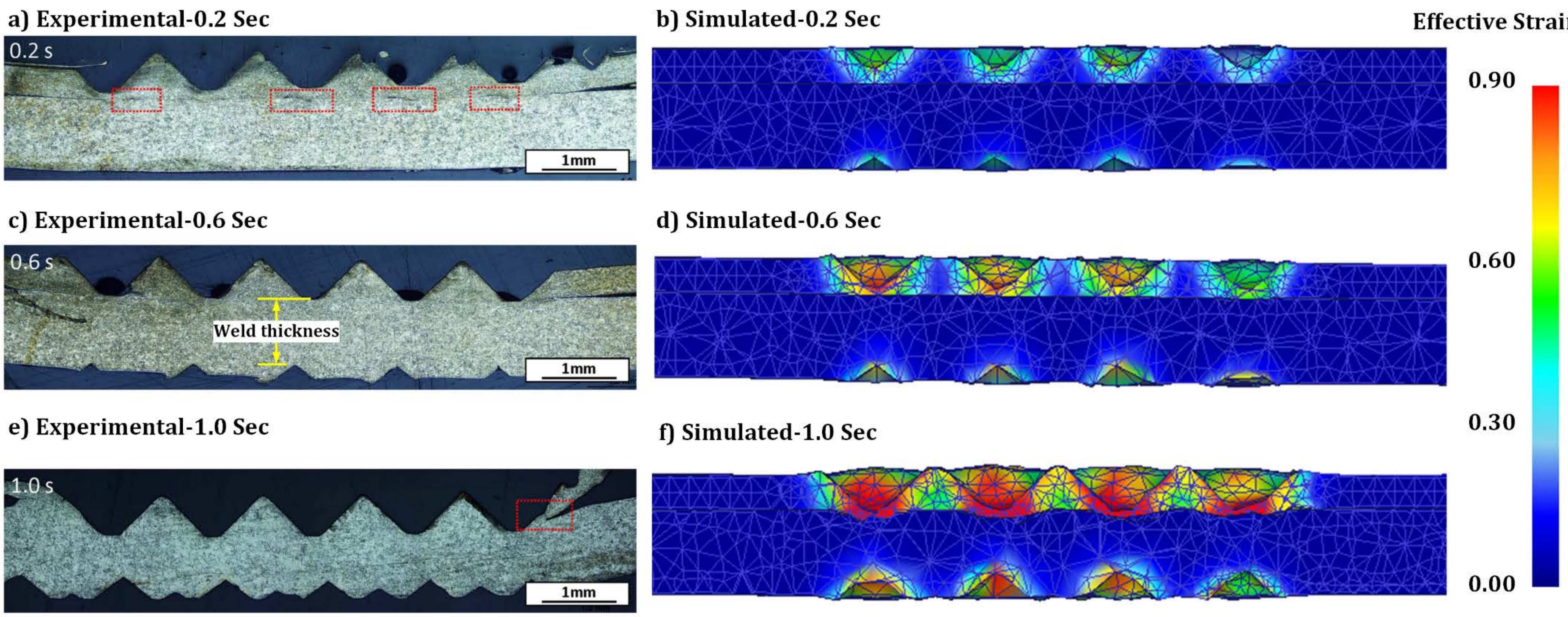


FIGURE 1.9 TEMPERATURE CONTOURS AT THE END OF A 500 MS ULTRASONIC WELDING FOR (A) BASELINE MODEL, (B) INSULATED ANVIL, (C) 100°C PREHEATING (D) 0.6 MM THICK BUSBAR INSTEAD OF 0.9 MM

The finding: preheating enhances the bonding quality

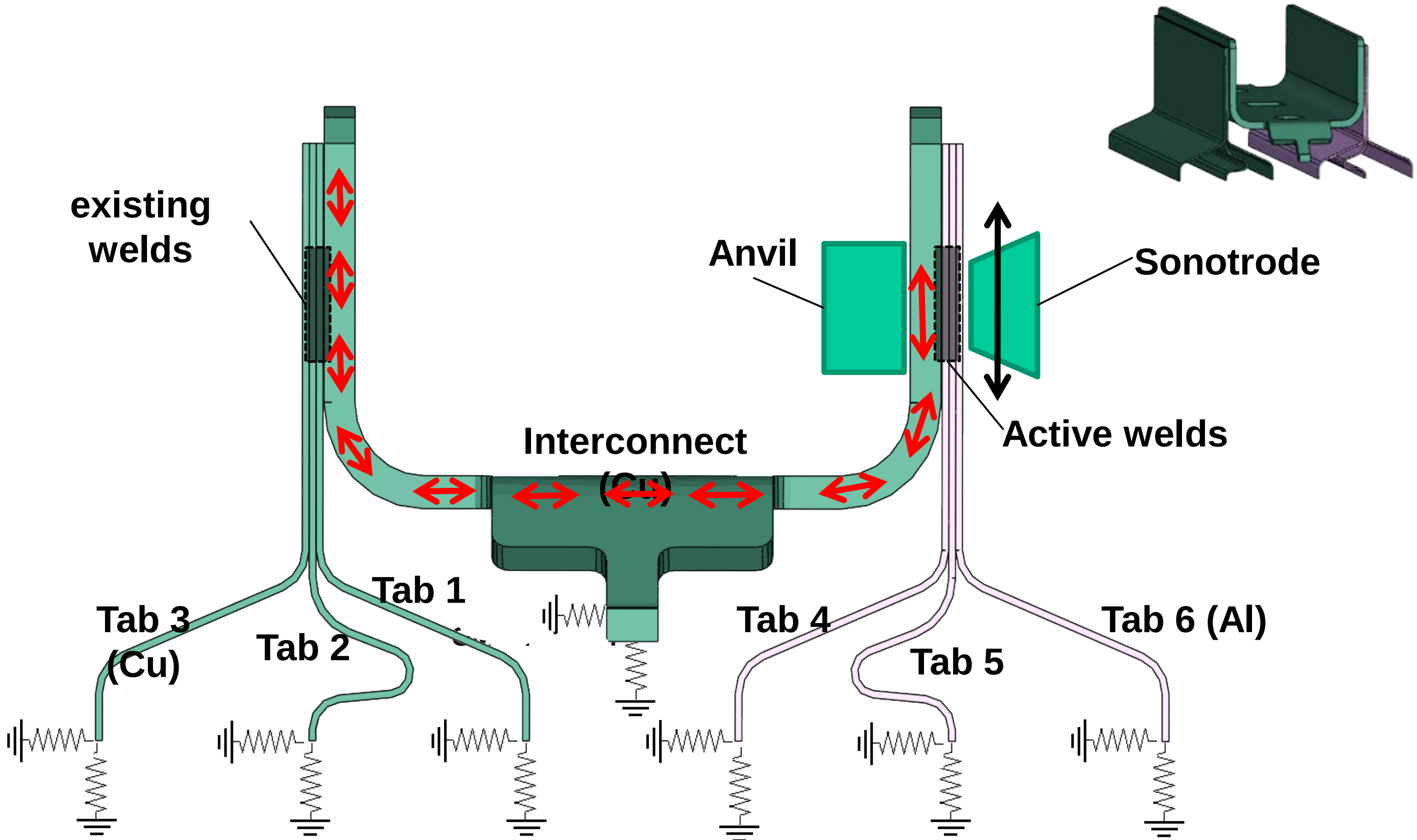
Ultrasonic Welding Quality Prediction #2: Fracture



Simulated deformation as compared with the experimental results

Fractures of the top layers should be avoided

Ultrasonic Welding Quality Prediction #3: Vibration



Cautions should be exercised to void damage from vibrations

Resistance Spot Welding

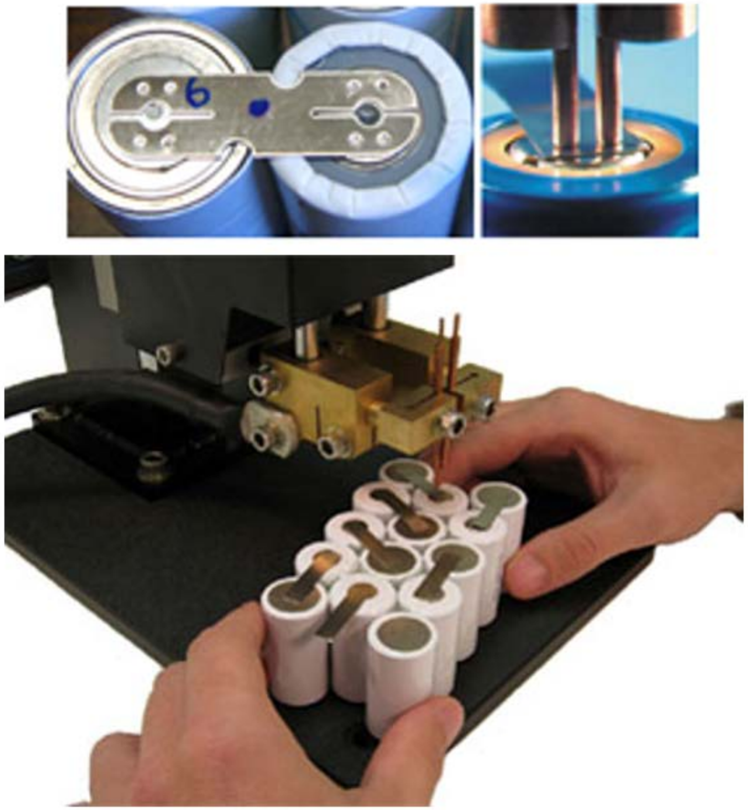


FIGURE 1.15 BATTERY CELL RESISTANCE SPOT WELDING BY AMADA MIYACHI, AND (BOTTOM) SUNSTONE ENGINEERING

Laser Beam Welding

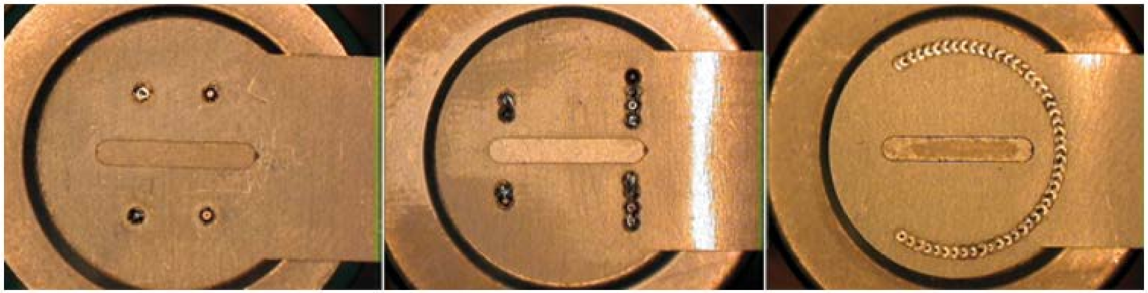
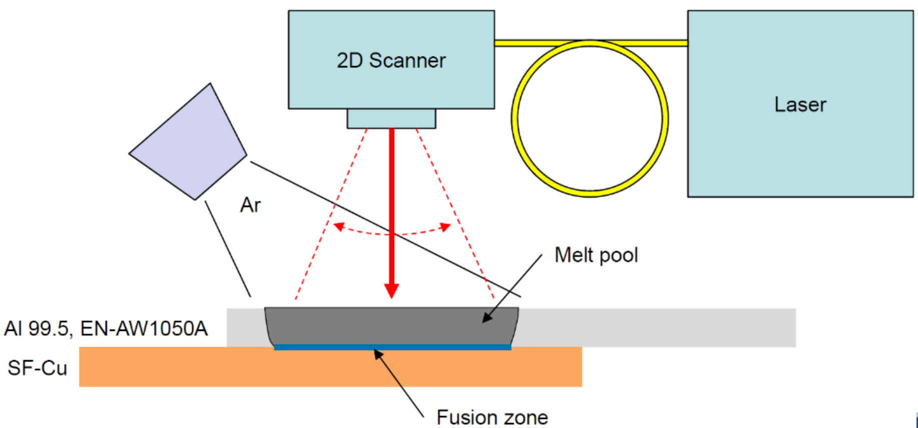


FIGURE 1.16 LASER WELDING OF BUSBARS TO CYLINDRICAL BATTERY CANS

Laser Braze-Welding



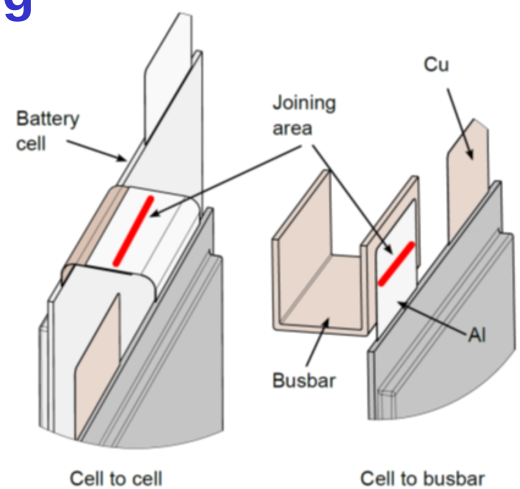
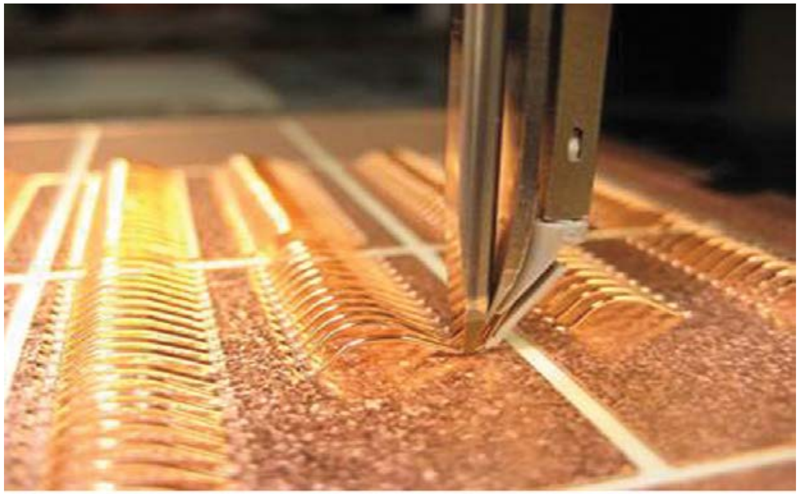


FIGURE 1.18 LASER BRAZE-WELDING OF POUCH TYPE OF BATTERY TABS WITH U-SHAPED BUSBAR

BMW i3: Laser Welding

3. JOINING TECHNOLOGIES FOR BATTERIES

Wire-bonding



Heavy Copper (Cu) Wire Bonding
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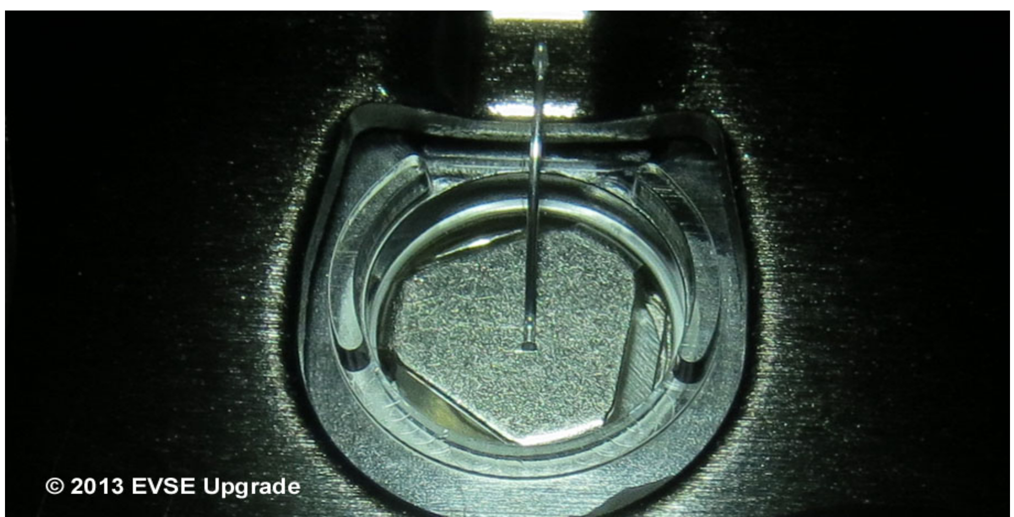

3. JOINING TECHNOLOGIES FOR BATTERIES

TABLE 3.2 SUMMARY OF BATTERY JOINING TECHNOLOGIES

Joining methods	Advantages	Disadvantages
Ultrasonic welding	• Excellent for dissimilar materials due to minimal intermetallics • Excellent for thin sheets or wires • Excellent for multiple wires or multi-layered sheets • Low heat-affected zone: low thermal distortion and low residual stresses • Excellent for highly conductive materials	• 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

3. JOINING TECHNOLOGIES FOR BATTERIES

TABLE 3.2 SUMMARY OF BATTERY JOINING TECHNOLOGIES

Joining methods	Advantages	Disadvantages
Laser welding	• Relatively small heat-affected zone: small thermal distortion and residual stresses • Single-sided and non-contact • High throughput	• Large amount of intermetallics for dissimilar materials • Porosity and hot-cracking • Requiring very tight sheets fit-up • High initial cost
Wire bonding	• Low heat-affected zone: low thermal distortion and low residual stresses • No or very little intermetallics for dissimilar materials • Excellent for highly conductive materials • Single-sided • Built-in bond strength evaluation	• Only light gauges of wires can be bonded onto the substrates (such as the bus bars 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

Cell Manufacturing

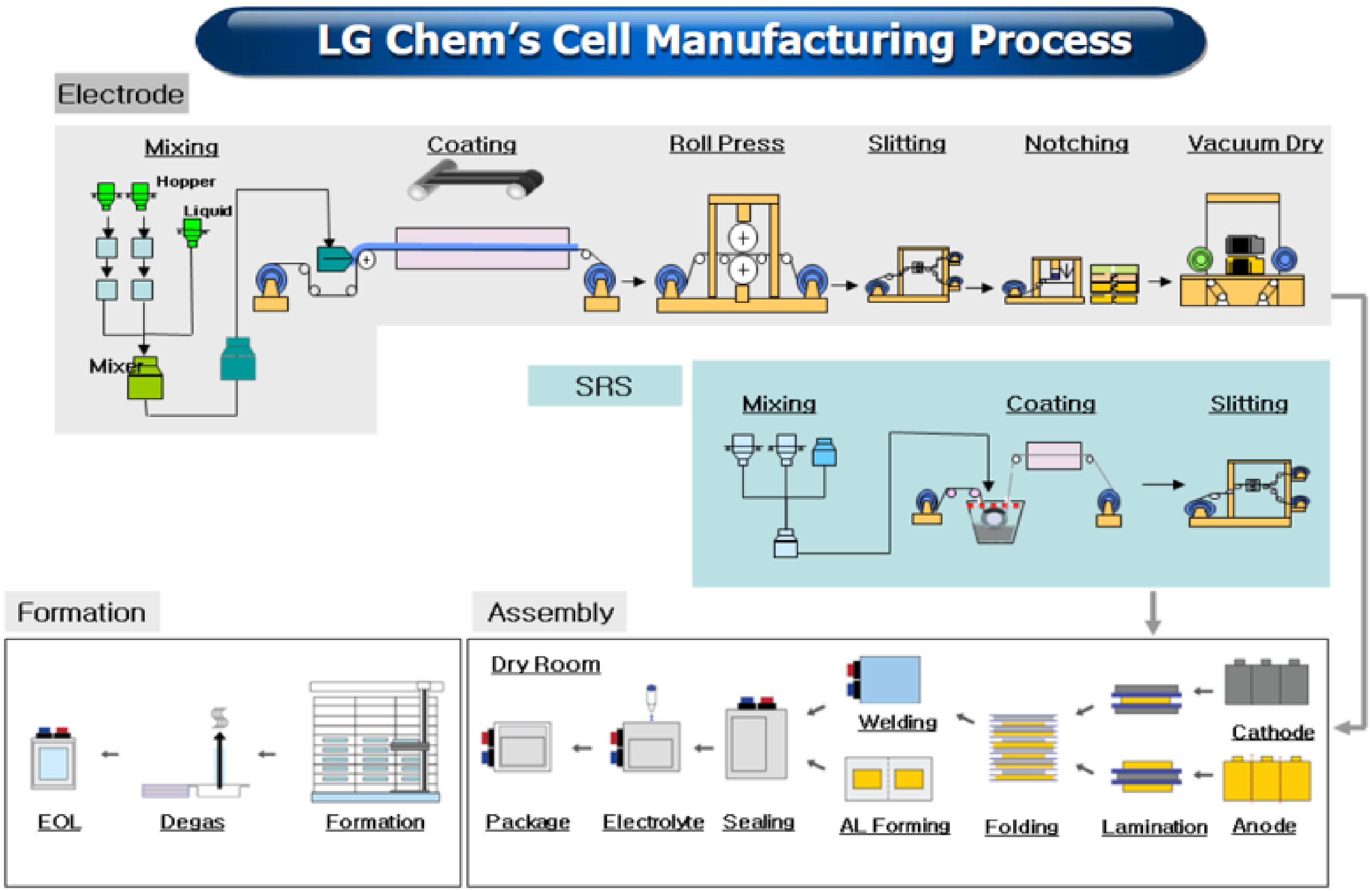

FIGURE 1.22 LG CHEM'S LI-ION BATTERY CELL (POUCH TYPE) MANUFACTURING PROCESS

List of battery cell components requiring joining

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

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. Thickness of each layer ranges from 10 - 30 microns 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.
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.

Module Assembly (Cell-to-Cell)

FIGURE 1.23 TESLA MOTOR'S BATTERY PACK, CONSISTING OF MORE THAN SEVEN THOUSAND OF 18650 CYLINDRICAL CELLS

FIGURE 1.24 GM CHEVY VOLT: BATTERY MODULES WITH ULTRASONIC WELDS

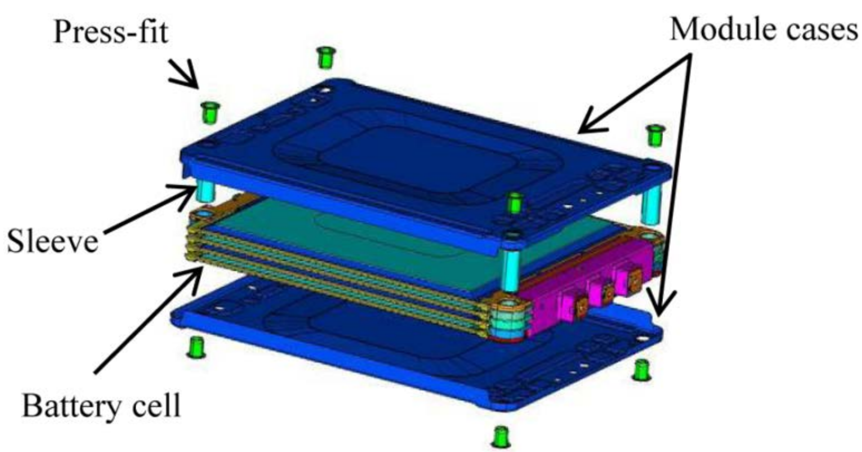

FIGURE 1.25 NISSAN LEAF'S BATTERY MODULE

FIGURE 1.26 BMW I3 BATTERY MODULE

Conclusions

1) Li-ion battery and battery electric vehicle marketplace are growing and evolving rapidly. As of 2014, Panasonic, AESC, LG Chem and BYD are the four largest traction battery cell manufacturers 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, i.e., cylindrical, prismatic, and pouch. The manufacturing processes for cylindrical and prismatic cells are substantially similar, but deviate meaningfully from that 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, i.e., 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.

Thank You!