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Tab Design and Failures in Cylindrical Li-ion Batteries

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ABSTRACT Lithium-ion (Li-ion) batteries play a vital role in today's portable and rechargeable products, and the cylindrical format is used in applications ranging from e-cigarettes to electric vehicles due to their high density and power. The tabs that connect the electrodes (current collectors) to the external circuits are one aspect of the cylindrical battery design that plays a role in reliability and safety. This paper overviews various tab materials, structures, and welding methods and then discusses failures in commercial 18650-type Li-ion batteries due to the tab defects. The recommendations for tab design and manufacturing are given.

INDEX TERMS Lithium-ion battery, tab design, tab location, tab manufacturing, computed tomography (CT) scan.

I. INTRODUCTION

Cylindrical Li-ion batteries are one of the most popular low-cost types of Li-ion batteries since they are mechanically stable for multi-protection devices and can store significant energy in a small volume. They are widely used in everything from e-cigarettes to smartphones and computers, to electric vehicles. However, battery fires and explosion incidents have created challenges for the industry. For example, there have been over 195 separate battery-related fire/explosion incidents of electronic cigarettes in the United States between January 2009 and December 31, 2016 [1]. Several Tesla Model S vehicles caught fire after they were damaged by road debris in 2013 [2]– [4]. In August 2016, a Tesla electric car caught fire during a promotional tour in France. Although Tesla strengthened the battery shield on their new model vehicles, in December, 2018, a Tesla Model S caught fire twice in a day. The Tesla engineers said the heat generated by the batteries was the root cause result in this incident [3].

The cylindrical battery (cell)*, is one of three types of Li-ion batteries: cylindrical cells, pouch cells, and prismatic cells. Flat batteries, including pouch cells and prismatic cells, are sandwich structures made up of many positive and negative electrodes. This sandwich structure increases the possibility for short circuit, inconsistency, and deformation. Compared with flat cells, cylindrical batteries mainly consist of a jellyroll including anode, cathode, separator, and a cap located on the top of the positive terminal, as shown in Figure 1(a). Safety valves facilitate the release of gases that have accumulated inside the cell due to thermal runaway. Some cylindrical lithium-ion batteries include a center pin to help release the gases. A typical 18650 cap structure is displayed in [4, Fig. 1(b)]. The arrows in Figure 1 (b) are the pathways of gas released from the positive cap during thermal runaway. The tab bonded to current collector is used to connect the electrodes to the external circuits. The current flows from the cathode through the tab to the electrical connection and terminal contact, and finally out to an external circuit. If the pressure increase inside the cell is not controlled as in abusive operations, the electrical connection between the terminal contact and a cell electrode may be broken by breaking the tab to ensure the cell's safety.

The Li-ion cell's jellyroll structure gives it good mechanical stability, long calendar life, and cycling ability. Moreover, cylindrical cells are easy to manufacture, are lower cost than other batteries, and can withstand high internal pressures due to their steel case. Hence, cylindrical cells are preferred for electric vehicles. However, the increasing vehicle fires/explosions caused by Li-ion batteries highlight the safety issues of cylindrical batteries [5].

The tab on the top of the Li-ion battery's positive terminal can further ensure the battery safety and reliability

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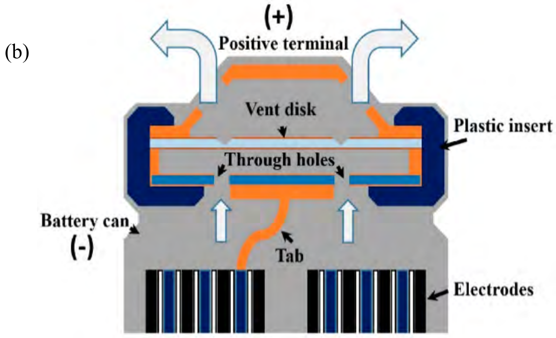

FIGURE 1. Cylindrical Li-ion battery. (a) Structure of 18650 Li-ion battery. (b) Typical 18650 battery cap structure [4].

by disconnecting the electrical circuit to reduce the risk of fires or explosions. However, failures that can lead to fires and explosions can be caused by defects during the manufacturing process, especially associated with tab defects, such as welding burrs and improper tab locations. The electrode tabs are the small metallic strips that are welded onto the current collectors without active materials. When the battery is charged or discharged, the temperature around the electrode tabs is much higher than other places inside the cell due to the current concentration [6]. This high temperature can affect the performance, cycle life, and safety of the battery.

This paper overviews the manufacturing process of cylindrical Li-ion batteries, with a focus on the electrode tab design, including tab materials, shape, size, and location. Failures due to the electrode tabs are investigated in two case studies. Recommendations are then presented.

II. MANUFACTURING OF CYLINDRICAL BATTERIES

The Li-ion battery manufacturing process for cylindrical cells consists of five major steps [7, Fig. 2]: (1) mixing and coating the positive electrode and negative electrode materials on thin metal foils; (2) winding the positive electrode, negative electrode, and separator; (3) inserting the wound center pin into the battery case and filling it with the electrolyte; (4) sealing the battery case; and (5) formation and aging.

The first step is mixing and coating [7]. The anodes and cathodes in the Li-ion cell are made by similar processes with similar or the same equipment. The cathode electrode active material is usually a Li-metal oxide, and the anode electrode material is carbon or graphite. The active electrode materials are coated onto both sides of metal foils and calendared during the electrode fabrication process. The electrode materials are mixed by a conductive binder mixer to form a slurry that is distributed on the surface of the foil when it passes into the slitting machine. A knife edge is positioned above the foil. The gap between the foil and the knife edge can be adjusted to control the coating thickness and make sure all the components fit into the case during sealing and final assembly. Furthermore, the coating thickness ranges from nanometers to many hundreds of micrometers and can be measured by machines such as X-ray reflectivity (XRR) to keep the energy storage per unit area consistent between the anode and cathode electrodes. The coated foil is put into a drying oven to bake the active materials onto the metal foil and remove the solvent. Singh et al. reported that the electrode thickness can be preferred ranging from 70 μm to 350 μm for high energy Li-ion batteries [8], [9]. Subsequently, the coated foil is sent into a slitting machine to be cut into the cell designed dimensions (length, width, and thickness) of strips by a cutting method such as laser foil cutting. Since any burrs on the edges of the foil strips can result in short circuits in the cells, the slitting process should be extremely precise.

The second step is to feed the cut anode and cathode strips into the winding machine to form a reel with a cylindrical mandrel [7]. The separator is used to keep the anode and cathode apart and avoid short circuit. The winding machine works automatically until the strips are used up. To simplify the cell construction, only two electrode strips are fabricated in the cylindrical cells. Each electrode terminal is connected with a single tab, which is welded to the bare part of the anode and cathode electrodes, separately. To obtain a high current for high-power cells, some batteries may have several tabs attached by welding along the edges of the strips. To ensure a uniform current distribution in the cell, the tension on the coil during the winding process should be constant. Otherwise, a malfunction may result from the gap between the separator and electrode, and the cycle life of the cell may be shortened. Then a center pin is inserted into the reel to protect the battery from mechanical abuse such as dropping, shock, or vibration [10]. The center pin is used to fix and support the electrode assembly. Moreover, the center pin serves as a passage to discharge gas generated as a result of internal reaction when charging/discharging and operating the battery [11]. It is worth noting that some cells do not have a center pin that can dissipate the temperature inside the cell. A welding electrode is inserted through the hole of the center pin to weld the anode tab to the cell case. The electrode structure is connected to the terminals together with safety devices such as vents, positive temperature coefficient (PTC) thermistor, or current interrupt devices (CIDs), and this subassembly is then inserted into the case.

The third step is to fill the electrolyte in the cell by a vacuum. The filling process is carried out in a dry room or dry box to prevent water reacting with the electrolyte. Any moisture contamination can result in the decomposition of the electrolyte by toxic gas emissions. A precision pump is used first to fill the electrolyte, then a vacuum is employed to make sure the pores of the separator and electrodes are permeated and filled completely with electrolyte. After the filling process, the cap is positioned with any safety devices as mentioned above.

In the fourth step, polymer compression is used to seal the cell. The vent on the top of the positive terminal can be assembled using heat welding processing. The fifth step is to inspect and age the cell (e.g., calendar and cycle aging) to identify any manufacturing defects such as misalignment during the winding process or bending of the tabs. Afterwards, a label

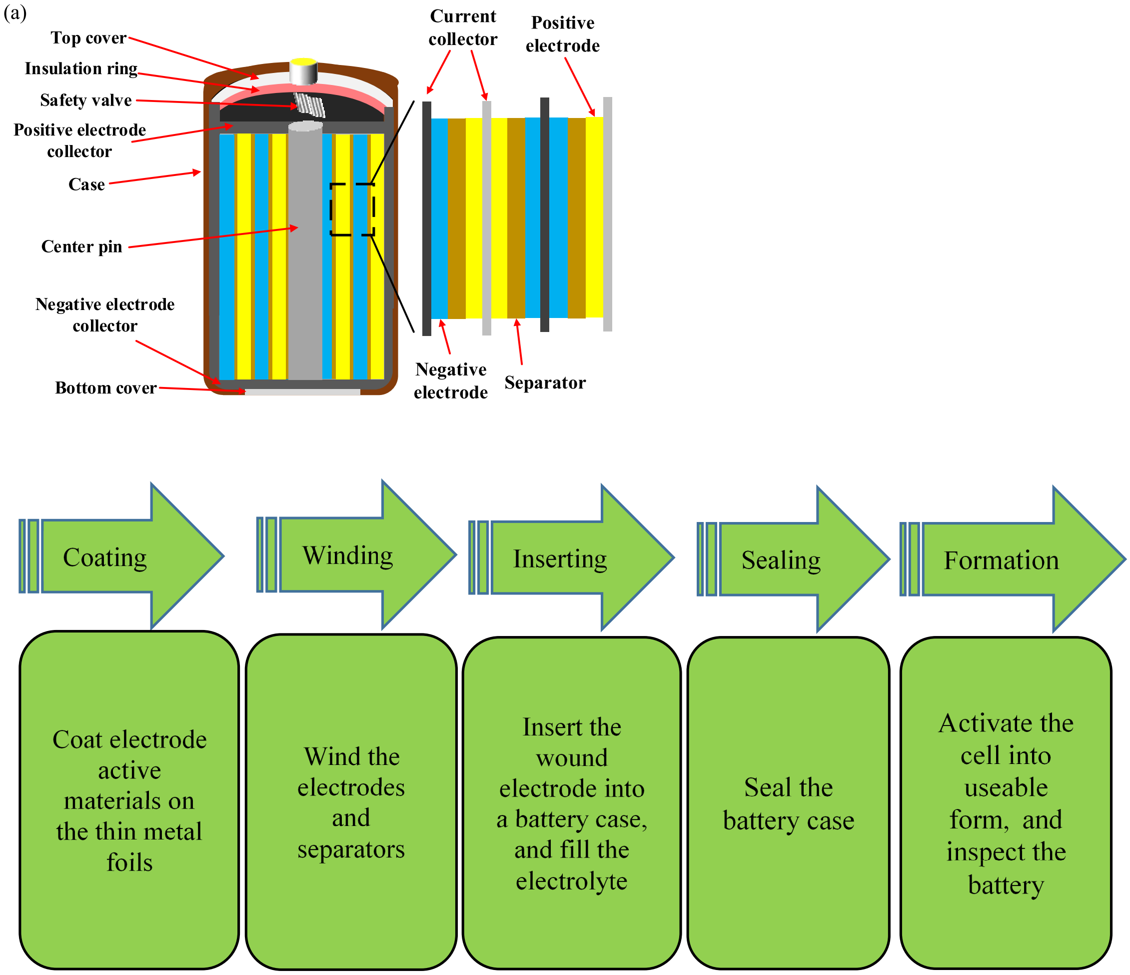

FIGURE 2. **Manufacturing process for Li-ion battery parts.**

with a serial number is attached to the case to identify the cell and provide detailed information of the manufacturing process. The aging process removes cells with defects and categorizes cells by capacity to form battery packs with high power.

III. ELECTRODE TAB

Li-ion batteries are a type of rechargeable batteries in which the lithium ions move from the cathode to anode during charging, and from the anode to cathode during discharging. A typical Li-ion battery consists of cathodes, anodes, separators, and current collectors or tabs coupled to the cathode and anode, respectively. A Li-ion battery uses a jellyroll structure for the cathode or positive electrode, the anode or negative electrode, and the separators. The positive electrode is a compound of materials coated on aluminum foil. The negative electrode is usually graphite with some binder and conductive additives. The positive and negative electrodes are insulated by a thin porous plastic sheet, which is the separator.

The battery tab is a bridge that connects the electrode and external circuit. Tab design and manufacturing have significant influence on the battery performance. To ensure battery reliability and safety, it is necessary to figure out the tab issues. The following section discusses the electrode tab materials, structure, numbers, welding methods and locations.

A. MATERIAL

The tabs bonded to current collectors in the Li-ion battery are made by using metallic foils attached to each of the positive and negative electrodes. The current during charge and discharge flows in each of the tabs. The tab materials determine the discharge performance of the Li-ion battery especially at high C-rates [12].

Traditionally, the anode tab is made of a single material. The cathode current collector is connected to the Al tab, and the Ni tab is used for the anode current collector. The electrical conductivity of Ni is poor at ∼14,0000 S/cm, and the electrical conductivity of Al is ∼36,9000 S/m. When batteries are discharged at high C-rates, the surface temperature of the battery will increase due to the poor electrical conductivity of the anode tab. Therefore, the output voltage of the battery and the current flowing through the tab are reduced.

To overcome the heat generation problem, one solution is to use a lower-resistance material than Ni, such as Cu. Mao et al. [13] and Jang *et al.* [11] proposed a Cu-Ni alloy anode tab. The Cu-Ni alloy has higher electrical conductivity (∼584000 S/cm) than an anode tab made of Ni. Therefore, the anode tab resistance is reduced based on the same area and length. In this way, battery safety would be improved by reducing the heat generated from the anode tab during operation. Due to the anode reduced tab resistance, the current flow in the secondary battery would be prevented, and the operation efficiency of the battery can also be improved [13]. This patent also suggested that Si and Sn can be added to the Cu-Ni alloy to improve the mechanical strength of the anode tab. Moreover, Si exhibits lower resistance than Ni. When the temperature of Sn increases, its resistance decreases.

Sometimes a battery tab is also coated with a thin layer of material to improve the corrosion resistance and welding quality, e.g., Cu tabs can be coated with Ni, and the anodization layer can be coated on Al tabs [14].

B. STRUCTURE

Li-ion battery tabs usually have a square structure. The square structure is easily penetrated by the adjacent cell. Zhang et al. [15] proposed an arc structure for the Li-ion battery tab with a spherical shape at the terminal of tab as shown in Figure 3. The arc structure tab with a pole shown in Figure 3 could protect the nearest cells from penetration and improved battery safety and reliability. Moreover, the outer side of the elastic layer was fixed to the locating slot, and the other side was slip-connected to the locating slot. The elastic layer was evenly located on the surface of the battery body to ensure a stable connection for the tab. In this structure, the elastic layer with locating slot and pole on both sides of tabs was an electrical connection that ensures the reliability of the tab connection.

Generally, the smaller the blank foil (the current collector without active materials) of the current collector on the tab, the higher the energy density. If the tab can protect the battery from overcurrent or overheating, and the connection between the battery and external circuit can be cut off by the tab. Therefore, the battery's useful life can be extended and safety can be improved.

To improve energy density, Wei *et al.* [16] presented an electrode with a single buried tab. The effective area of the electrode was increased by reducing the blank foil, as shown in Figure 4. The blank foil of the electrode was reduced by keeping the local area in the electrode, which the local area was the same size as the tab welding zone. In this way, the energy density was improved by increasing the effective area of the tab and reducing the polymer battery thickness. Considering the tab welding, the width of the blank foil was 1 to 4 mm larger than that of the tab. And the tab was also protected by a tape around the tab in this patent.

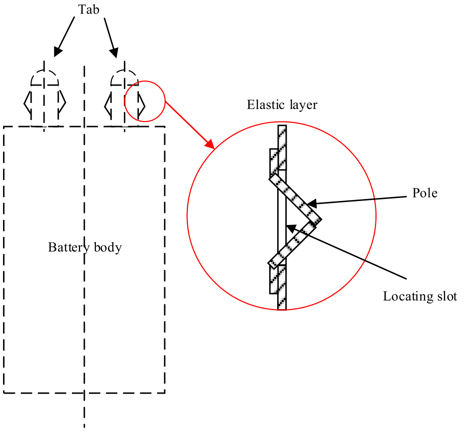

FIGURE 3. **Li-ion battery with arc tab [15].**

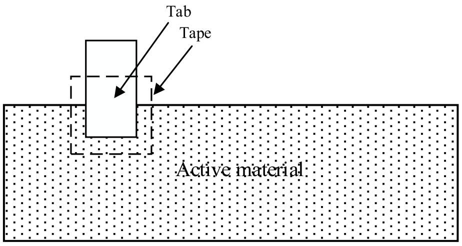

FIGURE 4. **Li-ion battery with arc tab [15].**

Even though this buried tab improved the energy density to some extent, the polarization around the tab became intense when the cell was discharged by a large current, which could result in overheating and even fire and explosion. Therefore, Yao [17] presented an electrode with double tabs, as shown in Figure 5. A metal foil was sequence welded to the first tab, blank area without active materials, the active area with active materials and the second tab area. The increased contacting area between the tabs and metal foil reduced the current flow through the tab. Subsequently, the heat production was reduced. Furthermore, the overheating could be avoided for the blank area without active materials.

Ling *et al.* [18] proposed a battery tab with overcurrent protection for a Li-ion battery, which included two metal strips (Figure 6). These two metal strips were overlapped and connected by positive temperature coefficient (PTC) materials. The PTC material and the two metal strips were connected in serial as a thermistor. The resistance of the PTC material was low when the Li-ion battery was normally operated. However, when the battery was overcharged or overheated, the temperature of the PTC material increased, and the resistance rapidly increased. This sharply increased resistance limit the current and protect the battery from overcurrent and overheating. Moreover, when the temperature cools down, the PTC material recover to the initial state and be reused.

If the insulating films are the same length, they can be symmetrically pasted on both sides of the tab and therefore are easy to detach from the metal strip when the tab is bent for installation in the battery. Subsequently, metal strips without insulated film are prone to short circuit.

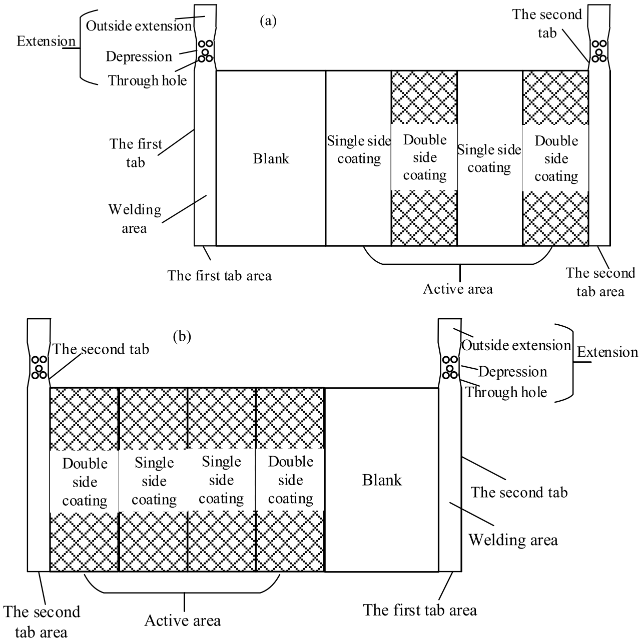

FIGURE 5. Li-ion battery with double buried tabs. (a) Front view. (b) Back view [17].

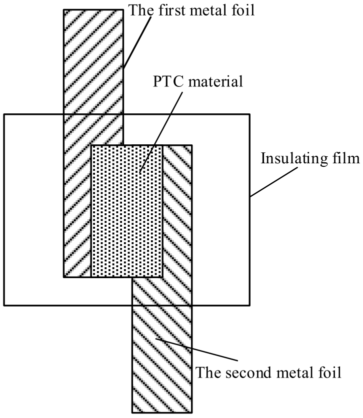

FIGURE 6. Li-ion battery tab with overcurrent protection [18].

Ling *et al.* [19] presented a tab that can prevent short circuit by using a ribbon flat conductor. Both sides of the conductor were pasted on two different-length insulating films, as shown in Figure 7. The length of the insulating film on one side of the conductor was over 1 mm more than that of the other side. In this method, the extra length of insulating film can cover the bent tab to avoid short circuit of part of the conductor. Moreover, the insulating film can also avoid to be detach by increasing the area where the ribbon flat conductor contacted with the insulating film.

To avoid tab short circuit, some researchers have proposed the methods by narrowing the tab size. For example, Ling *et al.* [20] proposed a battery tab with a through-hole in the tab ribbon strip to replace the conventional tab with the same width tab ribbon strip, as shown in Figure 8. The hole in the strip tab narrows the electrical area. The narrowed tab would fuse to protect the battery when the overcurrent flows from the tab due to the short circuit.

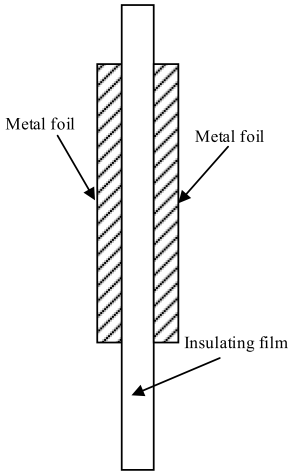

FIGURE 7. Li-ion battery tab with overcurrent protection [19].

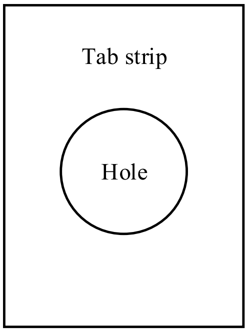

FIGURE 8. Li-ion battery tab with overcharge self-breaking [20].

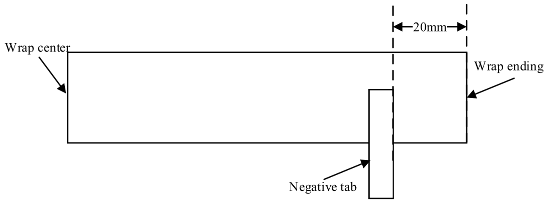

FIGURE 9. Cylindrical Li-ion battery negative tab without spot welding [21].

Welding is another essential tab manufacturing process of for Li-ion batteries. Welding burrs or incomplete welds can happen during spot welding for the tab. Consequently, Xue [21] proposed a kind of negative tab that can be manufactured without spot welding, as shown in Figure 9. The negative tab is made of an elastic conductive metal. In this way, the negative tab elastic contacts with the bottom or side of the steel case. The negative tab is 1$\sim$50 mm wide and 10$\sim$100 mm long. The distance between the negative tab and the wrap ending is 20 mm.

C. LOCATION

It has been determined that induced currents can increase power loss, thereby resulting in higher internal heating and decreased battery operation time. To reduce induced

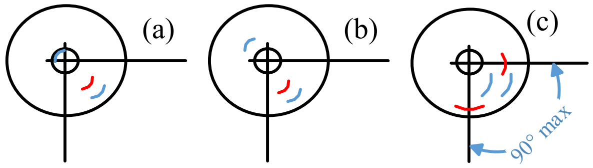

FIGURE 10. Multiple tabs with different locations [6].

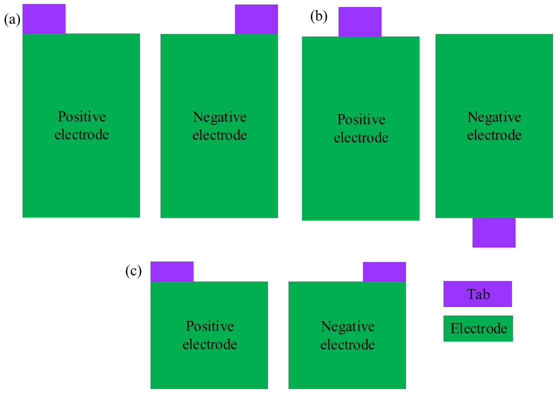

FIGURE 11. Multiple tabs with different locations. Reproduced from [19] with permission from Elsevier. Copyright (2014). Reproduced from [19] with permission from Elsevier. Copyright (2002).

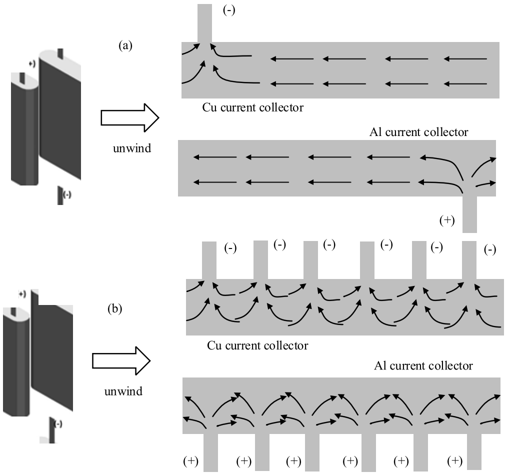

FIGURE 12. Electron transport path in the current collectors of a cylindrical cell. (a) Cell with a single pair of tabs. (b) Multiple pairs of tabs. Reproduced from [19] with permission from Elsevier. Copyright (2014).

currents in cylindrical electrochemical cells, some possible tab numbers and locations have been proposed in patents. Gozdz *et al.* [10] proposed uniformly spacing tabs along a length of the positive sheet or the negative sheet in Li-ion cells, as shown in Figure 10. At least one of the positive and negative current collectors can electrically communicate with the conducting tabs that extend from the anode sheet or cathode sheet. The conducting tabs extend from an end face of the spirally wound assembly and include 4 to 12 tabs.

To determine the temperature distribution inside the battery some researchers have focused on thermal models of electrode tabs. Shin's group [22], [23] investigated the thermal properties of a Li-polymer battery influenced by three electrode shapes of pouch cells, as shown in Figure 11. In the first two pouch cells in Figures 11a and c, the two tabs with different dimensions were placed symmetrically on the same side of the rectangular electrode. In the third pouch cell in Figure 11b, the two tabs were placed in the center on opposite sides of the rectangular electrode.

As shown in Table 1, Shin *et al.* [19] claimed that the location of tabs in the third cell (Figure 11c) is preferred to generate the lower maximum temperature during charging when the discharge rate is the same as other cells. In other words, the tab placement in the third cell is safer than the other two placements due to the lower temperature.

Figure 12 displays the electron transport path in the current collectors of a cylindrical cell [19]. If there is only one pair of the positive and negative tabs in Figure 12(a), the electrons generated in the anode electrode have experienced a long distance to be collected by the negative tab. Therefore, severe voltage loss results from the ohmic resistance of the electron flow through the current collector foils. If multiple tabs were used on the current collectors as demonstrated in Figure 12(b), the electron transport distance was divided into several small regions. The current density would be distribution.

To make full use of the theoretical material capacity under practical working conditions, Zhao *et al.* [24] proposed multiple tab positions and a plurality of tabs on the current collectors, as demonstrated in Figures 13 and 14. Tabs were evenly arranged on the current collector along the electrode length direction. In the first design (CU-design), both the positive and negative tabs were placed at the leading edge of the current collectors, whereas in the second design (CO-design) the positive and negative tabs are located at different edges of the current collectors. Namely, the positive tab was placed at the leading edge of the Al current collector, and the negative tab was placed at the trailing edge of the Cu current collector.

Zhao *et al.* [24] also established a baseline by welding a pair of tabs outward from the end edges of the long sides of the current collector as shown in Table 2. Compared with only a pair of tab positions, the discharge performance even at a high C-rate was improved by adding multiple tabs. The current density distribution and cell performance became more uniform when the number of tabs increased. The multiple tabs divide the electrode into different sections, so the electron transport losses can be reduced, and the energy density can be fully accessed in large-format cells.

The current distribution inside a battery is a major determinant of its performance, which can be significantly affected by the tab locations. As to tab design for high-power and high-energy 18650 batteries, Spotnitz *et al.* [25], [26] developed software to simulate the current distribution with different tab locations and current collector thickness. For high-energy batteries with LiNiCoAlO$_2$ cathode and graphite anode, they

TABLE 1. Maximum and minimum temperatures from the experiment and modeling for the discharge rate of 5c. reproduce from [19] with permission from elsevier. copyrigh (2014).

Model	Depth of discharge (DOD) [%]	Minimum temperature (°C)		Maximum temperature (°C)	
		Experimental	Modeling	Experimental	Modeling
Type A	30	34.4	33.5	44.5	44.5
	50	39.0	37.7	50.4	50.0
	90	47.0	40.0	57.8	58.7
Type B	30	32.9	35.3	43.7	41.9
	50	36.3	38.3	48.9	47.7
	90	42.8	43.7	57.0	55.6
Type C	30	35.7	33.6	43.0	43.1
	50	40.5	38.2	48.1	48.9
	83	45.4	38.9	53.7	55

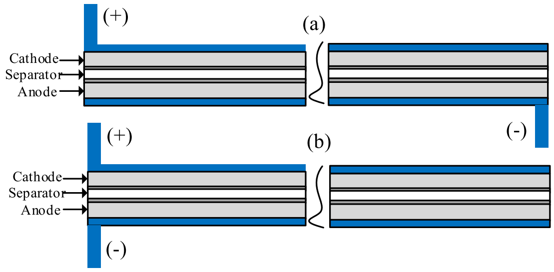

FIGURE 13. Multiple tabs with different locations. Reproduced from [19] with permission from Elsevier. Copyright (2014).

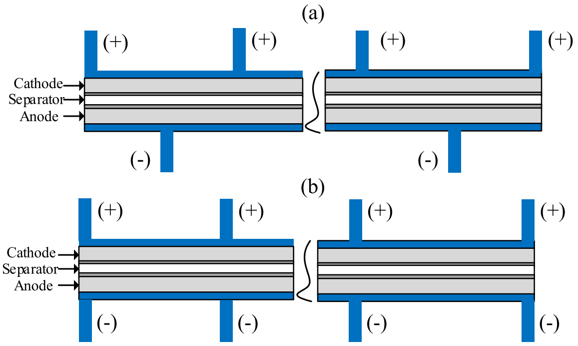

FIGURE 14. Multiple tabs with different locations. Reproduced from [19] with permission from Elsevier. Copyright (2014).

found that the current collector design was not significant, and thin collectors were preferred for the high-energy battery. The collector resistance decreased with the current collector thickness increment, which slightly decreased the cell capacity. When the high-energy cells operated at currents ranging from 0.2 C-rate to 0.5 C-rate, the ohmic drop along the length of electrodes was too small to ignore the current collector thickness increment. However, for high-power batteries with LiNiCoMnO2 (NCM) cathode and graphite anode, the tab design was critical especially when taking the thermal effect into consideration. Both the opposite-side tabs and the same-side tabs were studied. In this design, each single tab was located at one end of the positive and negative electrodes, as shown in Figure 15. The tabs were wrapped to ensure the positive tab was placed at the center of the spiral the negative tab was located at the outer radius of the spiral, or both the positive and negative tabs were at the center of the spiral. After simulation, Spotnitz *et al.* [25] found that more uniform state of charge distribution was obtained by placing the tabs at opposite ends, which produced more capacity. In this situation, they optimized the collector thickness and claim that the positive collector thickness was preferred at 20 μm by adjusting the negative collector thickness to ensure the linear resistances for both positive and negative collectors were almost the same.

TABLE 2. Comparison of calculated energy density of various cell designs. reproduced from [19] with permission from Elsevier. copyright (2014).

	1C discharge	2C discharge	3C discharge
Coin cell	100%	87%	75%
Baseline cell			
2 tabs (CO)	39%	10%	3.3%
2 tabs (CU)	52%	N/A	N/A
Multi-tab cell			
3 tabs (CU)	89%	68%	62%
4 tabs (CO)	80%	62%	44%
5 tabs (CU)	96%	84%	71%
6 tabs (CO)	97%	84%	71%
7 tabs (CU)	98%	85%	73%
8 tabs (CO)	99%	85%	73%

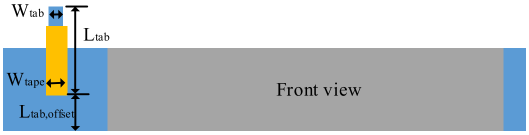

FIGURE 15. Single tab electrode design. Reproduced from [25].

Spotnitz [25] also studied the tab location for the high-power battery as shown in Figure 16. The influence of the positive tab with 20 μm thickness was investigated by fixing the negative tab with 12 μm thickness at the outer radius of the jellyroll in this cell design. The optimal tab location was at the middle of the positive electrode as seen in Figure 16.

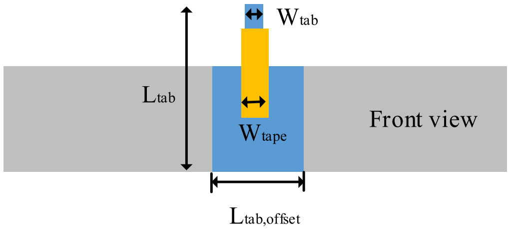

FIGURE 16. Electrode design for adjustable positive tab locations. Reproduced from [25].

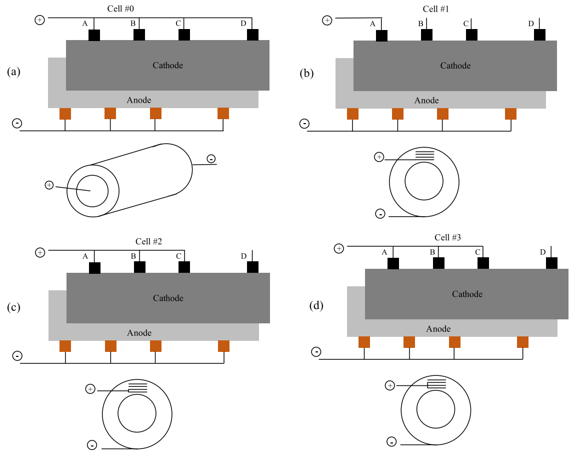

FIGURE 17. Schematic of the current collecting tabs design. (a) Non-modified closed cell #0; (c–d) modified cells #1 to #3 with one to four tabs connected on the cathode side, respectively. Reproduced from [27] with permission from Elsevier. Copyright (2016).

TABLE 3. Cell used in the [27].

Cell	Modification
#0	non-modified, NTC-type and type K thermocouples at mid-height of cell surface
#1	Modification: tab A, type K thermocouples at mid-height of cell surface and inside jelly roll
#2	Modification: tabs A + B, type K thermocouples at mid-height of cell surface and inside jelly roll
#3	Modification: tabs A + B + C, type K thermocouples at mid-height of cell surface and inside jelly roll

They observed that the tab location made a big difference to the cell especially when the simulation stopped as soon as the cell temperature was 60 °C for higher discharge currents as shown in Figure 17.

Furthermore, given the same resistance of the current collectors, Spotnitz *et al.* [26] also investigated the effect of multiple tabs on available capacity in high-power cells. They found that the configuration of two positive tabs and one negative tab in made more available capacity. However, only a marginal benefit for capacity and voltage was achieved when the number of tabs was further increased.

Waldmann *et al.* [27]. studied the effect of current collecting tab design on the performance of thermal and electrochemical for high-power 26650 cylindrical Li-ion cells without center pin by experiment as shown in Figure 17 and Table 3.

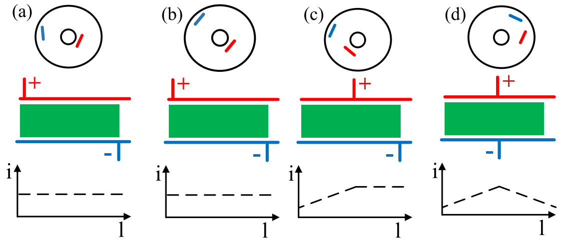

FIGURE 18. Electrical connection schemes and current distributions for cells (a)–(d). Top: positive and negative current leads are shown by red and blue. Middle: the electrode configuration for the unrolled electrodes. Bottom: expected current distribution versus position l along the length of the electrodes [28].

The $LiFePO_4$ cathodes and graphite anodes cells were modified to observe the cell surface temperature and the temperature inside the jelly roll by operando via and NTC-type sensor and a K-type thermocouple at middle height of the cell surface, respectively. They found that the less numbers of current collecting tabs, the more significant the influence of discharge C-rate on the temperature rise. And the less numbers of tabs can also weak the heat transfer and therefore lead to higher temperature rise inside the cells. The radial temperature gradients at the middle height of 26650 cells increased by decreasing the number of tabs. The increased temperature gradients easy to result in aging gradients inside the cells. They suggested that the multiple tabs are better to cell performance and temperature gradients decreasing.

By using spatially resolved neutron powder diffraction, Senyshyn et al. [28] investigated the Li concentration in the graphite anode of various charged 18650 Li-ion cells. The X-ray computed tomography and electrochemical approach were employed to disclose the non-homogeneity of Li distribution in the graphite anode. They found that the various resistive paths for the current in a cell due to different electrode tab positions can result in non-homogeneity. Four electrode tab positions were presented as shown in Figure 18. In Figures 18(a) and (b), the positive tabs in two cells were at the center of the cells corresponding to the end of the cathode current collectors, and the negative tabs were positioned at the end of the anode current collector ending at the outer cell section. Viewed as an unrolled electrode stack, the two tabs were at the two ends. These two configurations can result in homogeneous current distribution/density. Nonhomogeneous current density occurred at both locations in the other two cells in Figures 18(c) and (d), namely, the negative tab and the positive tab were at the same end.

D. WELDING

Welding the tabs is a key process during manufacturing. In the cell level, the tab should be welded to the electrode. The tabs welded to bus bar and tabs weld to tabs in the module level.

The most challenging welding method for cylindrical Li-ion cell is the negative terminal welding since the negative tab is welded directly to the case, whereas a separate platform is used to weld the positive tab. The welding of the negative

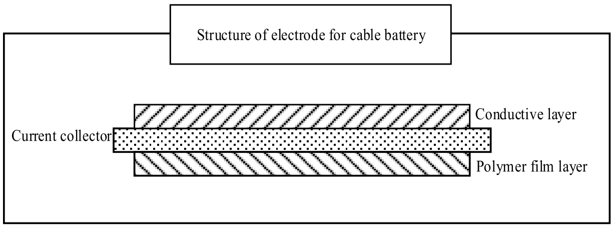

FIGURE 19. Structure of electrode for Li-ion secondary battery [30].

terminal cannot penetrate the case, which is typically 0.3 mm thickness. Therefore, the thickness of the tab should be 50-60% that of the case [29]. The case material of the cylindrical Li-ion battery is usually Ni-plated steel, and the tab material is Ni or Sn-coated Cu [30]. It is better to plate Ni than Sn since Ni is more stable.

The insulating and conductive layers formed on the electrode layer are made of a polymer material, therefore, using a typical welding method on the electrode layer may result in a poor-quality welding. Wanatha *et al.* [31] disclosed a metal tab welding method to improve the tab welding quality, as shown in Figure 19. The outer surface of the current collector was formed on a conductive layer, and a polymer film layer formed on the inner surface of the current collector. This proposed tab welding method comprised two steps: a) by using a pulse layer, a portion of the conductive layer was removed which exposed the surface of the current collector positioned below to weld the tab; b) welding a metal tab to the surface of the current collector. The metal tab is made of any one or more material groups consisting of stainless steel, aluminum, nickel, titanium, fired carbon, copper; stainless steel surface treated with carbon, nickel, titanium or silver; or an aluminum-cadmium alloy.

Mechanical fasteners such as clamps are used in tab welding owing to their low contact resistance and good electrical conductivity. Nevertheless, the electrical conductivity performance can gradually degrade if the fastener surface is contaminated [14].

Spot welding is one of the tab welding methods for Li-ion batteries and has advantages such as fast processing, low cost, and good quality control. However, it is difficult to weld the highly conductive and dissimilar materials due to the different melting temperatures.

Ultrasonic welding can be used to weld dissimilar metals and materials with different sheet thickness [30]. However, if there are more than two sheets to be welded, the ultrasonic energy cannot transfer across the sheet interfaces. The upper sheet can be welded well since it directly contacts with the ultrasonic tool with enough high ultrasonic energy source. However, the lower sheet, including the conductor bar, cannot be welded as strongly as the upper sheet due to the weak ultrasonic energy source.

For Li-ion batteries in vehicle applications, the battery tab should be welded to a conductor or a bus bar. It is difficult to weld the thin tab to the much thicker copper conductor. For example, the multiple tabs weld to one conductor, especially the thickness difference between conductor and tab is high e.g. usually the thickness ratio is over 5:1. Therefore, Sigler *et al.* [16] disclosed a solid-state weld to join multiple sheet layers made of Al or Cu by a reaction metallurgy welding method. This method can form a solid-state weld between the welding surface to produce a mobile liquid-containing reaction product, which can get rid of the oxide and any obstacles on the welding interface. During the surface process, the mobile reaction product was squeezed from the interface together with the pressing of cleaned, heated, and contacting solid surfaces to be a solid-state weld.

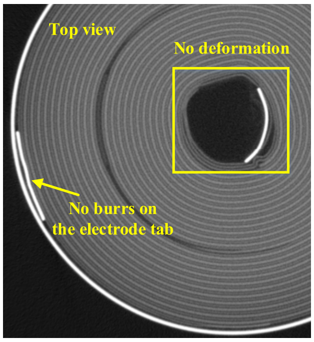

FIGURE 20. CT scan image of a cylindrical Li-ion battery.

IV. CASE STUDIES

This section discusses cylindrical Li-ion cell failures caused by improper electrode tab locations and burrs on the electrode tabs. Normal electrode tabs are first introduced, then failures resulting from tabs as shown by computed tomography (CT) scan are presented.

Figure 20 presents a CT scanned top view of a lithium-ion cell with three electrode tabs. The positive tab is depicted as a gray arc, and the negative tabs are depicted as two white arcs. One of the negative tabs is in the center of the cell, and the other one is at the edge of the case without any burrs. The layers are uniformly distributed. The three tabs have little chance to contact with each other since they are kept a certain distance apart from each other. As mentioned above, the temperature around the tab is usually higher than in other places in the cell. By placing the negative tab at the outside edge of the case, the heat generated by the negative tab can dissipate easier outside of the case compared with the location between layers in the jellyroll. Therefore, this tab location is an exemplar of good tab design and manufacturing.

A. FAILURE DUE TO TAB LOCATION

On November 29, 2016, an e-cigarette exploded after one hour of charging when the buyer was pulling the USB cord from the e-cigarette [32]. Figure 21 shows two exemplars related to the incident, Q-2-1 and Q-2-2. Q-2-1 is identical to the battery that was inside the e-cigarette battery holder which is not explode. Q-2-2 is identical to the disassembled cell from the e-cigarette battery holder.

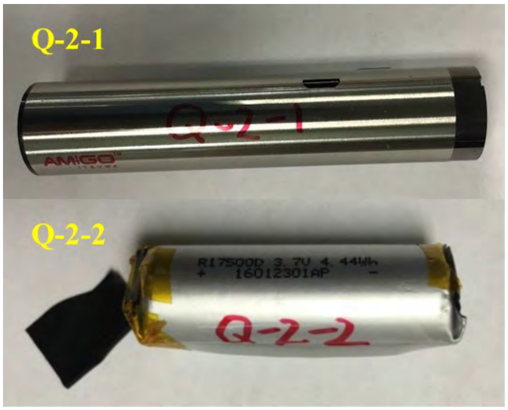

FIGURE 21. Lithium-ion battery inside e-cigarette.

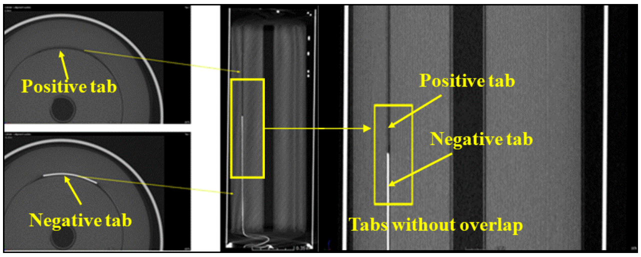

FIGURE 22. CT scan for Q-2-1.

Figure 22 shows a CT scan of the top and front view of the positive tab and negative tab of sample Q-2-1. The two left-hand figures are the top view of the battery. This battery does not have a center pin. The gray arc depicted in the top left figure is the positive tab, while the white arc in the lower left figure is the negative tab. The middle and right figures are the corresponding cross-sections. Both the positive tab and negative tab are on the same side but do not overlap. Because the temperature around the tabs is usually much higher than other parts inside the cell due to current concentrations, the electrode materials near the tabs are easy to decompose and trip [10]. However, same-side tabs will also lead to high temperature around the tab region. Hence, high temperature can make the electrode materials decompose and strip.

The CT scan image of sample Q-2-2 is presented in Figure 23. Two tabs are in the battery without a mandrel. As shown in the top view, the two ends of the electrode tabs, the gray arc and the white arc, overlap each other. To prevent electrical conduction, insulation tapes are usually placed between the tabs, but the high temperature around the overlapped tabs would make the insulation tapes melt, leading to a short circuit between these two tabs. Therefore, it is not recommended to locate the electrode tabs on the same side or especially to have them overlap each other during the design and manufacturing process.

B. FAILURE DUE TO TAB BURRS

On January 20, 2017, another e-cigarette exploded in a user's pants pocket [32]. Figure 24 shows a back-up battery of identical make and model. The top and front CT scan images of the back-up battery are shown in Figure 25. Three tabs are in this battery. One gray arc is the positive tab, and the other two white arcs are the negative tabs. Welding burrs can be clearly observed on the negative current collecting tabs. The sharp edges of welding joints can penetrate the separator and electrical contact between the negative tab and positive tab, and deform the adjacent electrode layers. Burrs also tend to penetrate the insulation tape and separator, causing electrical contact between the negative tab and the positive electrode.

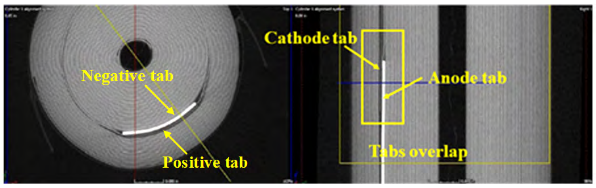

FIGURE 23. CT scan for Q-2-2.

FIGURE 24. Back-up battery of identical make and model.

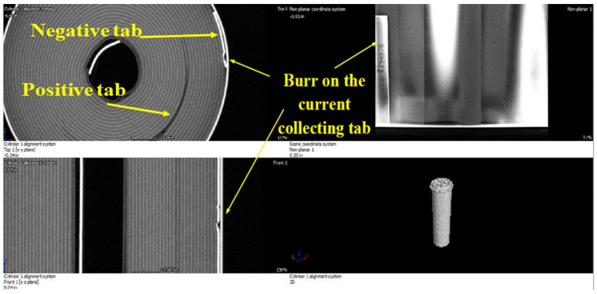

FIGURE 25. Burrs on the current collecting tab.

V. ELECTRODE TAB DISCUSSION

Electrode tabs are welded on the bare parts of the current collector, which is a pathway for the electrons from the active materials to the external power terminals. The positive electrode tab is usually made of Al, and the negative electrode tab is made of Cu, Cu-plated Al, or Ni [33]. During the manufacturing process, one of the most important issues is the electrode tab design, including the locations and numbers of tabs, which ensures uniform distribution of current density and temperature.

The length of the electron pathways in the cell is affected by the number and position of the tabs. A short electron pathway can decrease the ohmic resistance due to voltage loss [6], [24]. If only one pair of positive and negative tabs is used, the electron produced in the anode electrode has to travel a long distance to be collected by the negative tab. Likewise, the electron generated by the positive tab must travel a long distance to spread out over the area of the cathode electrode. Accordingly, the ohmic resistance of the electron transport from thin foils will lead to serious voltage loss especially in high-power batteries. In addition, in order to accurately position the tabs, the thickness of the materials which make up the jellyroll can be modeled previously or controlled during the manufacturing process to determine the method to spirally wind these materials into a jellyroll, which include the number of turns and the finished diameter of jellyroll.

Furthermore, both non-uniform current distribution and voltage loss can degrade the battery performance. Non-uniform current distribution can not only decrease the energy density expected but also lead to localized overcharge and over-discharge conditions. Therefore, some researchers [3], [19], [34] have proposed using multiple tabs in the cell. However, the tab location should be considered, particularly for multiple tabs. For one thing, the current distribution more or less depends on the relative location of the tabs even when there is only one pair of tabs as previously discussed. The position of the multiple tabs should be selected to reduce the induced magnetic field in the pulsed power compared with one pair of tabs. It has been reported that the inductance internal to a battery can interrupt the current flow from the battery and then increase the power losses [28]. As for multiple tabs, the proper tab length and tab bending should also be taken into account to avoid internal short circuit or localized high temperature around the tabs.

The possible tab locations and numbers are presented as in Figure 26 according to the previous studies and cases above mentioned. The red arc represents the positive electrode tab, and the two blue arcs represent the negative tabs. Two types of Li-ion batteries take the center pin into consideration. One type of Li-ion battery includes a center pin while the other does not. The cells with a center pin are demonstrated as follows to clearly see the relative positions of the positive tab and negative tab.

In Figures 26(a) and (b), the positive tab is placed at the center of the cell and at the end of the cathode current collector [28]. The negative tab is positioned at the end of the anode current collector ending at the outer cell section. The current densities inside the battery are homogeneously distributed. When viewed as an unrolled electrode stack, it can be seen that the positive tab is at one end and the negative tab is at the other end. In this situation, the temperature around both tabs does not easily increase dramatically in normal operations. There is little chance that these positions will lead to high temperature in the tabs region. The two tabs would avoid contact resulting in short circuit. Therefore, Figures 26(a) and (b) are examples of good-quality tab design and manufacturing.

In Figures 26(c)-(f), the negative tab and the positive tab are on the same side, and the positive tab is located in the middle of the cathode layer. In Figure 26(c), the negative tab is placed around the outer case parallel with the positive tab.

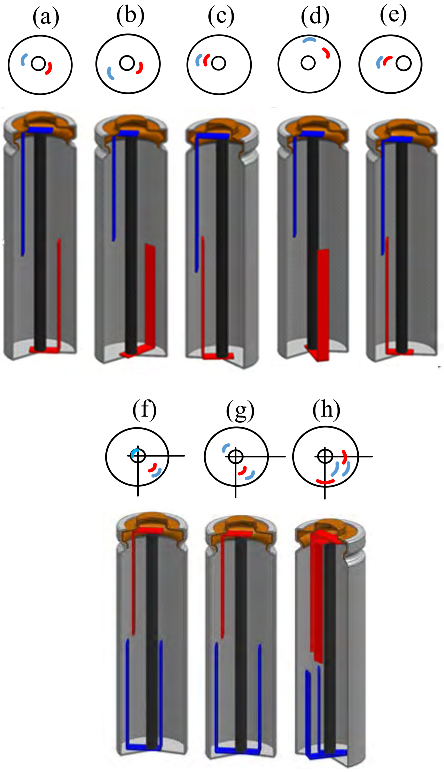

FIGURE 26. Tab locations in a cylindrical lithium-ion battery.

In Figure 26(d), the same-side tabs are placed at a certain angle, and both tabs are located in the middle of the electrode strips [6]. Both tab location designs in Figures 26(c) and (d) do not lead to high temperature, and a constant current distribution can be obtained for the left side in these two situations since the resistance is independent of the current path from the positive to the negative tab. Compared with the tab location in Figure 26(c), the configuration in Figure 26(d) seems to be the most appropriate for high-power cells since the minimum overall resistance can be obtained between the two tabs. Figure 26(e) also presents same-side tab designs, but they are poor quality. The positive tab and negative tab are close to each other without overlapping. This tab configuration is prone to high temperatures, which result in short circuit or penetration of the separator.

Figures 26(f)-(h) present three exemplars of multiple tab configurations with three electrode tabs [10]. All three tabs are kept separated at a certain distance to prevent internal shorting and high temperature. The two negative tabs are placed at the two ends of the electrode in the Figure 26(f), and one of them is close to the cell core. The positive tab is on the same side of the negative tab near the case. Compared with the tab location in Figures 26(f) and (g), the difference is that both of the negative tabs are not placed near the cell core. The function of the center pin not only can increase the strength from abuse, but also can serve as a safety device to dissipate the heat inside the battery. Therefore, the heat inside the battery is easier to dissipate at the location shown in Figure 26(f) than the location in Figure 26(g) [10]. In Figure 26(h), four tabs are placed within a 90° quadrant of an end face of the jellyroll. The four tabs can reduce the overall cell impedance compared with one or two tabs per electrode [10]. However, the increased number of tabs makes the welding process more challenging.

Welding is another critical issue related to tabs. The thickness and materials of the tabs (current collectors) and the terminals are the two most important factors during tab welding. Usually, Al is used for the positive tab, and Ni or Cu is used for the negative tab [31]. The terminal material depends on the physical size of the battery. Dissimilar materials of tabs make welding one of the challenges for battery production. The tab welding method depends on the materials and formations of the batteries.

Increasing the thickness of the electrode can improve the battery energy density and reduce manufacturing cost by cutting the number of electrode sheets. However, this improvement is usually limited to a few micrometers since a greater thickness would result in crack formation and film failure due to mechanical stress [35]. Moreover, increasing the electrode thickness also results in power limitations since the Li-ion diffusion kinetic becomes slow especially for the locations closer to the current collector. Meanwhile, along the film thickness, the Li concentration gradient would be generated. Furthermore, the capacity drop would be produced which increasing the thickness since the Li-ion of active materials which operated as lithiation or de-lithiation become smaller [35].

Tab welding in a cell consists of welding the electrode foil to the tab and the tab to the terminal. Resistance spot welding, laser welding, and ultrasonic welding are the most popular welding methods for cylindrical Li-ion batteries. Resistance spot welding is cheap and easy for rapid manufacturing, but it results in a lower-quality product. Laser welding is a non-contact welding process, but weld defects such as brittle phases and crack sensitivity are easily generated [36]. Ultrasonic welding is currently the most popular method for batteries owing to its predictable quality and performance for both thin and thick electrodes. The solid-state bonds make ultrasonic welding a good choice for joining dissimilar materials, but structural integrity is a big challenge due to high-frequency vibration (20 kHz), especially for cylindrical batteries [37].

A defective battery with bent electrode is a potential for internal short circuit, which is one of the main root causes of battery failure during the manufacturing process. Another possible defect is poor tab location, which could generate localized high temperature and result in thermal runaway, which causes explosion or fire.

VI. CONCLUSIONS

Electrode tabs are significant components that connect the internal anode and cathode layers within a cell to the external electrodes. The tab position within the cell and the manufacturing processes play key roles in the performance and safety of the battery.

The tab structure, including the size and shape, is determined by the maximum current transferring through the current collector. Tabs that are designed as a kind of switch to be fused when the current passes through them can improve the cell's safety and reliability. Otherwise, overheating generated by current concentration could result in damage of the tabs, nearby components, structures, or even the cells.

Reasonable distribution of the tabs inside the cell is a critical parameter for battery safety and reliability. Good tab position can improve battery reliability and safety by reducing the heat generated from tabs. It is generally preferred to place the two tabs on different sides of the battery to prevent overlap and short circuit. This opposite position of the tabs generates a more uniform current distribution and reduces the chance of manufacturing process defects due to overlapping tabs. However, for high-power batteries, companies often place the tabs on the same side for the small ohmic resistance. Furthermore, the two tabs should be located in the middle of the electrode strips at a certain distance to avoid shorting from deformation due to vibration or puncture.

Overlapped tabs can cause localized high temperature in a cell, which in turn can lead to internal short circuits. The tab structure, including the size, shape, and length, is essential to prevent the short circuit of the battery. The effective tab area affects the energy density of the battery. The energy density can be improved by increasing the effective area of the tab. Compared with the normal rectangular tab structure, some kinds of the arc terminal tabs and buried tabs can reduce the risk of short circuit by penetration, but they increase the cost and make the battery design more difficult. Furthermore, multiple tabs can reduce the temperature gradient inside a cell. However, the increased number of tabs could increase the manufacturing cost.

The thickness of the electrode materials affects battery performance and manufacturing cost. An electrode within order of 50-60 μm is usually used to improve the cylindrical Li-ion battery energy density. However, the electrode thicknesses are determined by both the coating and drying processes and the porosity. Thicknesses more than 320 μm are not recommended for cylindrical Li-ion batteries since the active layer would crack and delaminate from the metal foil with the small winding radii. Moreover, the power limitation could result from the increased electrode thickness due to the expansions and contractions of the active material during electrochemical cycling, and the lithium concentration gradient would be generated along the film thickness [35]. By increasing the thickness, the Li ions of the active materials, which operated as lithiation or de-lithiation, become smaller, resulting in capacity drop.

The length of the electrode tabs should be scaled to prevent short circuit. The tab closest to the center axis should be shorter than the tab farthest from the center axis (e.g., the tab near the outside case should be the longest). Thus, even if all the tabs are folded over, the different lengths enable the ends of the tabs to align the same distance away from the axis of the jellyroll. If only one pair of tabs is used on the same side of the cell, the two tabs can easily touch each other when they are long enough to overlap. The same situation occurs when using multiple tabs. However, if the total length of the positive tab and the negative tab is shorter than that of the battery, the possibility of high temperature or short circuit caused by the overlapped tabs will be eliminated.

Finally, the tab welding method should be precisely controlled to avoid generating defects, and it should also perform well made up of dissimilar materials such as Al, Cu, and other conductive materials to ensure easy to weld. This research can help to optimize tab design of cylindrical Li-ion battery to improve the safety and reliability.

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