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Review

Detection Technology for Battery Safety in Electric Vehicles: A Review

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Abstract: The safety of electric vehicles (EVs) has aroused widespread concern and attention. As the core component of an EV, the power battery directly affects the performance and safety. In order to improve the safety of power batteries, the internal failure mechanism and behavior characteristics of internal short circuit (ISC) and thermal runaway (TR) in extreme cases need to be tested and studied. The safety of lithium ion batteries (LIBs) has become a research hotspot for many scholars. With unreasonable misuse or abuse of lithium ion batteries, it is easy to cause internal short circuits, resulting in thermal runaway, which poses a great threat to the safety of the whole vehicle. This comprehensive review aims to describe the research progress of safety testing methods and technologies of lithium ion batteries under conditions of mechanical, electrical, and thermal abuse, and presents existing problems and future research directions.

Keywords: EV; LIB; mechanical safety test; environmental safety test; electrical safety test; detecting technology

1. Introduction

With the increasing number of automobiles, air pollution caused by automobile exhaust is becoming more serious, and the contradiction between energy and environmental development is becoming increasingly prominent. In the absence of new policies, automobile energy consumption and related exhaust emissions are projected to increase by nearly 50% by 2030 [1]. Although some alternative fuels have been commercially applied, such as natural gas [2], biodiesel [3], and ethanol, the scales are small, and the effects on saving energy and reducing emissions are unremarkable. In order to meet the challenges of energy shortages and environmental pollution, many countries in the world have recognized the important role of new energy vehicles in saving energy and reducing emissions from a strategic perspective, and the development of electric vehicles (EVs) has become the consensus of all countries in the world [4–6].

EVs are considered to be the most promising alternative to internal combustion engine vehicles toward a cleaner transportation sector [7,8]. Zero tailpipe emissions of EVs are helpful in achieving the goal of energy saving and emission reduction with regard to driving. Especially in China, with a large population, as the share of coal-based electricity decreases and the application of advanced electricity technologies widens, the energy saving and emission reduction of EVs and the mitigation of the greenhouse effect are more obvious [9,10]. If renewable energy accounts for 80% of the power structure, the greenhouse gas (GHG), SO2 and NOx, and particulate matter (PM) emissions of EVs could be reduced by more than 85%, 75%, and 40%, respectively [11].

Many countries have made EVs the development direction of the automobile industry [12]. China, European countries, Japan, the United States, and other countries have raised the new energy automobile industry to the level of national strategy and issued a series of policies and measures to ensure its rapid development. By the end of 2018, the global fleet of EVs exceeded 5.4 million [13]. In 2019, global sales of EVs reached 2.21 million, an increase of 10% compared with 2018 [14], with the market share also rising year by year, as shown in Figure 1.

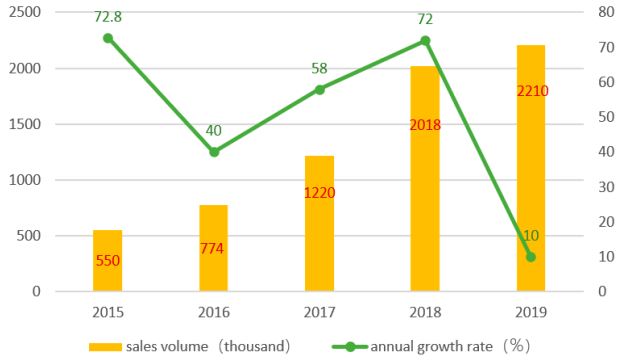


Figure 1. Global electric vehicle (EV) sales, 2015–2019.

The global EV market is developing rapidly and the industry scale is growing, but the problems of power stability, endurance mileage, and battery life are still prominent, and especially safety issues have become the focus of social attention [15,16]. According to incomplete statistics, in the first eight months of 2019, there were 40 fire accidents in the world, and among them, Tesla models suddenly ignited violently without being charged and in a static state, and users had serious doubts about the safety of EVs. The power battery is the core component of an EV, which directly affects the performance and safety of the vehicle. As the energy storage device, a lithium ion battery (LIB) can be very dangerous under unreasonable misuse or abuse conditions [17,18]. The safety of lithium ion batteries has been a key factor in curbing the development and promotion of the EV industry. In particular, fire and explosion of lithium ion batteries caused by thermal runaway (TR) has greatly affected the confidence of EV owners [19]. Therefore, in order to ensure safe, efficient, and stable driving of EVs under various traffic and weather conditions, it is necessary to test and evaluate the safety and performance of power batteries [20–22].

Improving lithium ion battery safety has become the top priority in the development of the EV industry. Safety is still the key factor in restricting the application of LIBs in the field of high energy/high power [23–25]. How to solve the hidden dangers of LIBs and how to effectively carry out safety tests and evaluations of power batteries has been a hot topic in the industry [26–32]. In order to improve the safety and performance of lithium ion batteries, many international organizations and committees have formulated and promulgated authoritative test standards and specifications which require safety tests and evaluations of batteries in harsh environments or abuse conditions, such as overcharge, high temperature, short circuit, and collision [33–42]. According to the characteristics of the test items, safety tests can generally be divided into mechanical, environmental, and electrical safety tests, as shown in Figure 2 [43].

The objective of this review is to describe and summarize the safety testing methods and research status of LIBs for automotive applications under mechanical, electrical, and thermal abuse conditions. According to international abuse testing standards and regulations for LIBs, the detection methods under different abuse conditions are summarized and elaborated, and the limitations and deficiencies of the current research on internal change mechanism, internal short circuit (ISC), and TR of LIBs by safety testing are noted. Finally, existing problems are described and future research directions for lithium ion battery safety detection technologies are proposed.

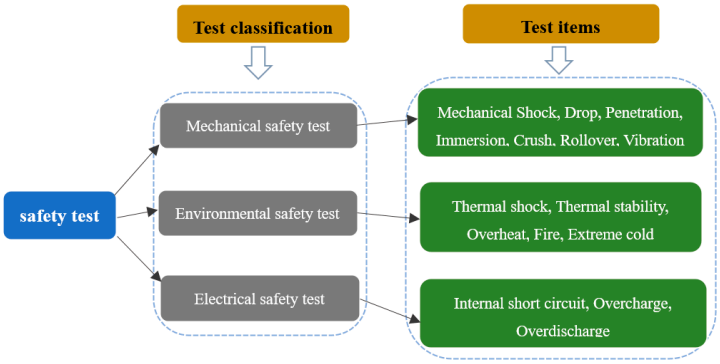


Figure 2. Safety test classification.

2. Mechanical Tests

When a lithium ion battery is impacted by external forces, the battery case can be either deformed or penetrated by sharp objects, resulting in mechanical damage. Due to rising safety requirements for lithium ion batteries, detecting mechanical abuse is becoming increasingly important [44]. Testing the mechanical abuse of lithium ion batteries mainly involves mechanical shock, drop, penetration, immersion, crush, rollover, vibration, and other methods to test the safety of the battery under the influence of external mechanical force. Common methods include extrusion, nail penetration, and vibration tests.

2.1. Crush/Crash Test

The crush/crash test is used to simulate the safety of the battery when it encounters external force extrusion. Wang et al. [45] used steel balls with different diameters to carry out transverse extrusion tests until ISC occurred, and studied the battery's TR mechanism. The internal structure of the LIB changed under the extrusion test, and the collector fluid of the positive and negative electrodes broke and tore with increased compression and the multilayer electrode layer cracked and slid, resulting in increasing deformation of the separator in the battery, and finally broke through the separator, resulting in short circuit. The short circuit of positive and negative poles caused by extrusion was mainly a point short circuit, and a large current discharge was formed at the short circuit point. The battery generated a large amount of heat, which led to a sharp increase in temperature, and eventually to TR. Cai et al. [46] conducted an ISC test on Li ion cells and Li ion polymer cells with standard and specialty separators by a multiparameter controlled extrusion test. It was found that the probability of TR caused by ISC was related to the state of charge (SOC) and capacity of the battery, which can be evaluated by the pinch test. Joseph et al. [47] carried out mechanical tests on three types of lithium ion pouch cells (small, medium and large), ranging from small consumer electric cells with LiCoO2 cathodes to EV size cells with nanophosphate chemistry. Under several local and global compression scenarios, the test mainly included compression between two flat plates and local indentation with a flat cylindrical punch, a conical punch, and three hemispherical punches. In the test, the relationship among voltage, temperature and load, and displacement was studied and analyzed. It was found that a drop in force and voltage of the cell and a rise in temperature indicated the onset of short circuit, which corresponded with peak load. Wierzbicki et al. [48] proposed a hybrid experimental/analytical method for extracting the average mechanical properties of cylindrical LIBs. Based on the principle of virtual work and the mechanism of internal load transfer of the battery, the stress–strain relationship of the cots when the cell was crushed between two plates was calculated. At the same time, the finite element model of the battery was established by using crushed foam material in LS Dyna, and the model accurately predicted the load displacement curve, the peak load magnitude, and the corresponding indentation depth caused by the failure. Through simulation, the load and displacement in the deformation process as well as the starting point of the short circuit observed experimentally were predicted.

Elham et al. [49] conducted a comprehensive test on indentation by a hemispherical punch, lateral indentation by a rigid rod, compression between two rigid flat plates, and three-point bending of commercially available 18,650 cylindrical cells. The relationship among force, displacement, voltage, and temperature with time was analyzed, and a finite element calculation model of homogenization and isotropy was established. The model captured the overall response of the single cell under four loading conditions; at the same time, it better predicted with good accuracy the onset of short circuit. It was found that local failure was detected by the local peak drop of resistance, and the onset of ISC was judged by the voltage drop. Xu et al. [50] established an efficient and accurate computational model of a commercially available 18,650 cylindrical battery with a nickel cobalt aluminum oxide system, which predicted mechanical deformation, short circuit onset, and failure properties of the cell under radial compression, indentation, bending, and axial compression. Moreover, two short-circuit criteria based on stress state and strain state were established. When the LIB was squeezed by the external force, the internal structure changed, resulting in an internal short circuit of separator rupture, accompanied by obvious changes in electrical and thermal characteristics; by establishing a finite element model, the occurrence of short circuit could be more accurately predicted.

For safety testing of Li ion cell extrusion, many extrusion methods were adopted in the current experiment. There is no unified conclusion on the causes and influencing factors of ISC and TR caused by extrusion. The starting position of ISC caused by extrusion needs to be further studied; further understanding of the safety evolution and short circuit prediction of lithium ion batteries in the case of extrusion is expected through existing experimental methods, combined with a reasonable finite element model, and using the response information of battery voltage, capacity, and temperature.

2.2. Penetration Test

The penetration test was used to evaluate ISC caused by lithium deposition, manufacturing defects, or other reasons, or the situation where a nail penetrated the lithium ion battery. Cheon-Soo et al. [51] used infrared technology to study the ISC of a polymer LIB with ceramic membrane during a nail penetration test. Based on the analysis of temperature, voltage, and burr state of different SOC batteries, it was considered that the burr connection between the copper foil and aluminum foil caused by the nail penetration test led to ISC. Three failure modes were put forward: model A, the aluminum burrs melt and no longer have contact with the copper burrs; model B, the aluminum burrs do not melt and have contact with copper burrs to form ISC; and model C, the aluminum burrs do not melt completely. It was found that the LIB with high SOC was more prone to TR and explosion than one with low SOC, and the safety of the penetration process was worse. Yokoshima et al. [52] developed an ISC observation system based on X-ray detection, as shown in Figure 3. The system can observe the internal structure change in the LIB; capture dynamic change images of positive and negative electrodes during penetration testing at high speed; and observe the boiling of electrolytes, the generation of gas, and the change in interlayer distance clearly and intuitively. It has a great promoting effect on the analysis and early warning of TR and improving the safety of LIBs.

In the above research, changes in the internal mechanism and ISC of LIBs were studied by penetration experiments, but there was no mature model or theoretical support. Electrochemical–thermal coupling models of the penetration safety of LIBs can more accurately analyze the factors that cause ISC in the puncture process, which plays a significant role in early warning of TR and improving LIB safety. This can be explained by the following research. Chiu et al. [53] established a numerical electrochemical model based on voltage changes in a nail penetration test by using porous electrode theory. The model simulated the temperature distribution of the cell in the state of TR, accurately predicted the temperature change in the battery before and after nail penetration, calculated the output current of a short-circuited battery, and predicted the heat production rate of the battery under different electrochemical parameters. Zhao et al. [54] established an electrochemical thermal coupling model and combined it with the equivalent circuit to study the nail penetration process of lithium ion batteries. The effects of battery capacity, short-circuit internal resistance, and pin

diameter on the electrochemical and thermal behaviors of LIBs during the nail penetration test were studied by using the model. It was found that the internal resistance and pin diameter of the cells had significant effects on the thermal behavior. When the battery capacity was large, it was easy to cause TR.

Increasing contact resistance is one of the most effective methods to prevent runaway heat. Yamanaka et al. [55] developed a new electrochemical–thermal coupled model to quantitatively evaluate the risk degree of TR in a penetration test, and found that the nail penetration test speed had a significant impact on combustion degree. Liu et al. [56] established an integrated mechanical–electrochemical thermal behavior computation model of LIBs in the process of nail penetration. The model was composed of a 1D battery model, a coupled 3D mechanical model, and a short circuit model, and could accurately predict the changes of battery voltage, temperature, and mechanical properties with time, as shown in Figure 4. The shape, size, displacement, penetration speed, and SOC value of nails were quantitatively analyzed by using the model. For different shapes, the order of short circuit display and heating rate were different; a large penetration distance led to a sharp rise in temperature, which was more likely to lead to runaway heating; within a certain range, the penetration speed had little impact on the safety of the battery; and the higher the SOC value, the greater the short-circuit displacement. The model has important guiding significance for the safe use of LIBs under various conditions.

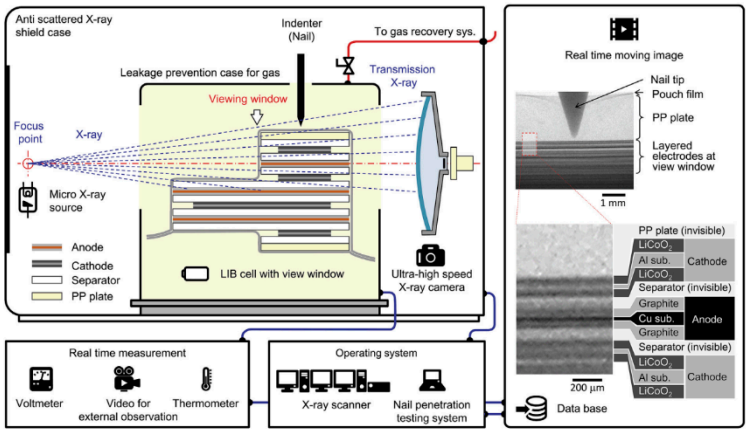


Figure 3. Schematic illustration of nail penetration system with internal short circuit (ISC) and X-ray scanners for laminated lithium ion batteries. Image on the right is an atypical X-ray transmission image of a laminated LIB cell recorded through the viewing window [52].

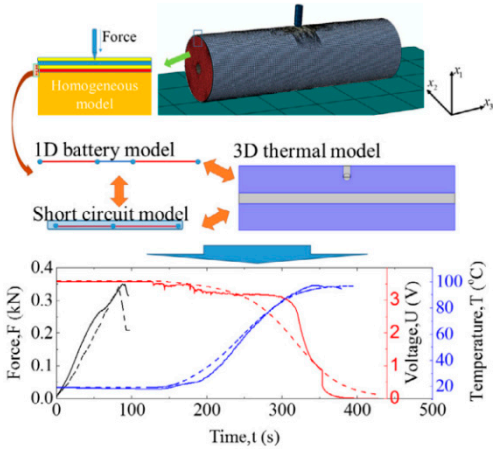


Figure 4. Geometry of 1D battery, short circuit, and 3D failure models [56].

2.3. Vibration Test

The vibration test of lithium ion batteries can be divided into sinusoidal and random vibrations according to the loading properties. Since safety and lifetime are especially important in electric mobility, automotive random vibration is the most tested kind of vibration in the scientific literature, as presented in [57]. Berg et al. [57] carried out tests of random vibration on a variety of 18,650 lithium cells, and studied its effect on the internal structure by using computed tomography. It was found that the inner mandrel was helpful to prevent or delay the cycle aging of the cell, but it became the weakest link under the vibration load, which increased the risk of ISC.

At the same time, the packaging design of the battery pack is important for vibration durability and stability. Hooper et al. [58] studied the electromechanical attributes of nickel cobalt aluminum oxide (NCA) lithium ion 18,650 battery cells when subjected to vibration commensurate with that experienced by EVs through road-induced excitation. The vibration durability of commercially available cells was tested in six degrees of freedom (6-DOF) using a multi-axis shaker table. The test method employed in the study is summarized in Figure 5. The experimental results highlight that both the electrical performance and mechanical properties of the commercially available NCA 18,650 Li ion cells employed in this study typically showed no statistically significant degradation. However, the natural frequency amplitude of the cell and a change in electrical performance had a degree of correlation. Kim et al. [59] evaluated Li ion cell failure under vibration tests. Vibration and shock tests were carried out in the x-, y-, and z-axes for six lithium ion batteries, and discharge capacity and internal resistance were analyzed and compared before and after the tests. Brand et al. [60] studied the effects of vibrations and shocks on pouch and cylindrical lithium ion cells. The influence of load distribution on the battery was studied by capacity measurement, impedance spectroscopy, micro-X-ray computed tomography, and post mortem analysis. Mechanical stress had no effect on the investigated pouch cells. The mandrel of cylindrical cells stressed in a vertical position struck against internal components, causing bruising of active materials, short circuits, and a damaged current collector and current interrupt device. It was found that the mechanical cell design, especially the fixation of the internal components, plays a decisive role in the capacity of lithium cells to withstand vibrational load.

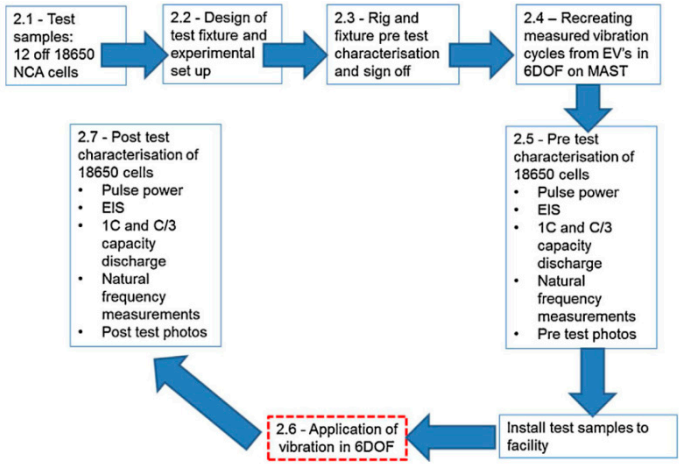


Figure 5. Schematic of test process for cells [58].

At present, random vibration testing mainly focuses on the performance of a single battery, and there is less research on battery packs connected in different series and in parallel. The influence of random vibration on the internal structure of the cell needs further study. The internal structure of the cell and the internal connection of battery packs have important research value in terms of its lifetime and structural stability, but there is no mature, reliable research model. Based on an understanding of the influence of the internal structure and connection relationship on lifetime and structural stability,

a reasonable design of the internal structure of the cell and optimization of the internal structure layout of the battery pack are important for high safety and long lifetime operation of battery systems.

3. Environmental Tests

Environmental testing is aimed at evaluating the safety performance of battery systems under conditions of temperature change, such as thermal stability, thermal shock cycling, overheating, immersion, extreme cold temperature, and fire [43]. The main detection methods are overheating and fire tests.

3.1. Overheating Test

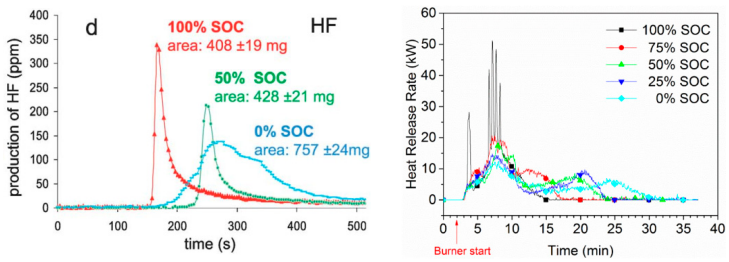
For different material systems, the heating test of lithium ion cells is mainly used to simulate the safety of cells under the condition of high-temperature abuse. Wang et al. [61] investigated the TR and fire behavior of large-scale LIBs under different heating methods, using a cylindrical heater and an electric furnace. The accumulation of heat inside the battery caused by external heating can lead to runaway temperature rise and chemical reaction, thereby increasing heat and causing TR and subsequent fire. Different heating factors, such as location, area, and power, have different effects on the surface temperature, heat release, gas emission, and mass loss of the battery. A battery heated with a cylindrical heater produced more sparks and gas/smoke ejection, while a larger explosion and more jet fire could be observed for a battery heated with an electric furnace. Compared with electric furnace heating, the onset temperature of TR of a battery heated with a cylindrical heater was lower. With increased heating power or area, heat release, CO_2 production, and mass loss increased. Nevertheless, compared to heating power and area, the heating position had a slight influence on battery burning. The results show that the battery had a high thermal abuse hazard with higher heating power or larger heating area.

Ouyang et al. [62] conducted several tests to study the thermal failure propagation and fire hazard of 18,650 LIBs under heating by a cylindrical heater. It was found that thermal failure of the battery pack was greatly affected by the distance between the battery and the heater and the initial failure position, and the SOC of the battery also had a certain influence on thermal failure. The higher the SOC, the greater the thermal hazard of the battery pack. The more heaters there were, the earlier thermal failure occurred. If the center of pack underwent thermal failure, its propagation was intensified, and the thermal failure time of the whole battery pack was shortened. Wu et al. [63] studied the thermal runaway characteristic of a soft-pack commercial cell by using an accelerating rate calorimeter (ARC) with internal and external heating modes. During external heating, the time to thermal runaway decreased with increased SOC. Using discharge to simulate internal heating, thermal runaway was accelerated with increased discharge current. Both onset temperature and critical temperature in external heating mode were larger than in internal heating mode. Through the internal and external heating experiments, the thermal runaway was divided into three stages: (1) normal operation of lithium cell; (2) anode heat release is detected, and thermal runaway is prevented by effective heat dissipation; and (3) the cathode reaction and separator melt cause cell voltage drop and thermal runaway. Li et al. [64] investigated the impact of SOC, heater power, and cell spacing on the thermal behavior of LIBs in side-heating condition. The thermal runaway behavior of LIB was significantly alleviated with decreased SOC. At SOC of 50%, the LIB was in an unstable state, and at higher than 50%, a strongly ejected flame occurred frequently. Additionally, the increased spacing and lower heating power both contributed to mitigate the severity of thermal runaway behavior.

Through lithium ion battery safety testing, it was found that different heating methods have different effects, but there has not been a unified and effective conclusion on the influence of heating position. At the same time, the mechanisms of and reasons for ISC and TR caused by heating with different SOC need to be further studied. Based on the existing research, an accurate thermal model was developed, and response information such as voltage and temperature were used, and it was possible to realize accurate judgment of TR, which can play a positive role in early safety warning.

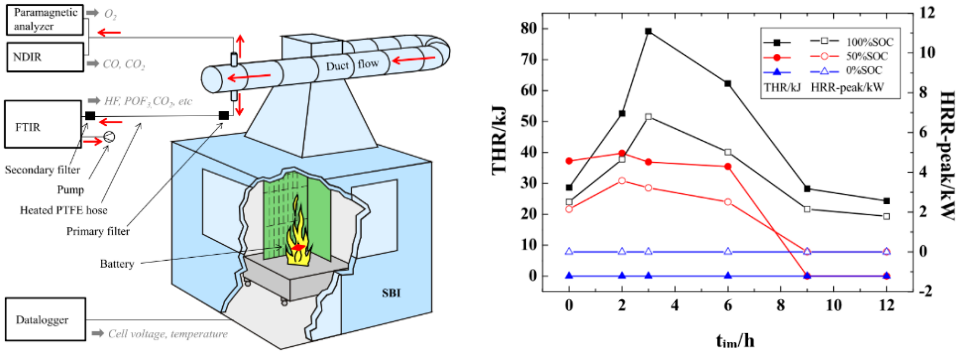
3.2. Fire Test

The external fire test of lithium ion batteries mainly observes various conditions that may occur due to sudden temperature rise in a short period of time. Ribiere et al. [65] used the Tewarson calorimeter to test the combustion of a battery at different SOC levels. Through the mass loss of combustion, the heat release rate (HRR), heat release, and emission gas in the combustion process were analyzed. For the tested pouch cells, the maximum temperature during the combustion test reached 660 °C to 1083 °C, more than 50% of the heat of combustion came from the polymer, and the mass lost in the ignition was about equivalent to the mass of organic matter. HRR increased with increased SOC. The reaction rate was the highest when the battery was fully charged, which makes it easy to explode, but the battery was relatively safe at 0% charge. The concentration of gas produced during combustion depended on the state of charge of the battery, and the emission and concentration of HF were the highest at 100% SOC, as shown in Figure 6. Carbon oxide and nitrogen oxide are direct products of combustion. The lowest yield of HCl had little to do with SOC. Larsson et al. [66] tested the combustion of a large LIB and studied its safety in fire. In the fire test, the HRR of the LIB was related to the SOC: the higher the SOC, the faster HRR increased, as shown in Figure 6. However, total heat release (THR) has little relationship with SOC. At the same time, toxic gas emissions of HF were measured at 100%, 50%, and 0% SOC; the highest was at 50% and the lowest at 100%. Ping et al. [67] conducted a full-scale burning test on large-size and high-energy LIBs to evaluate the safety of the battery pack. When the temperature was about 175–185 °C, ISC was caused by melting of the separator, which caused TR. The cell combustion behavior can be described by the following stages: battery expansion, jet flame, stable combustion, second cycle of jet flame, third cycle of jet flame, stable combustion, abatement, and extinguishment. The maximum temperature of flame combustion can reach 1500 °C, which appeared in the area beyond 100 mm from the surface of the cell. The highest HRR was 49.4 kW, and the combustion heat reached 18,195.1 kJ. The highest HRR, mass loss, and calorific values all increased with increased SOC of the battery. Fu et al. [68] obtained similar conclusions. Andersson et al. [69] conducted combustion tests on commercial lithium ion batteries using propane combustion units (Figure 7) to evaluate HHR, changes in cell temperature and voltage, and HF emissions under combustion conditions. Under different states of charge, the reaction activity and energy burst of LIB are different. The higher the state of charge, the stronger the thermal reaction, the faster the temperature rises, the earlier the voltage drops, and the more active the battery reaction. THR per battery energy capacity was determined as 28–75 kJ/wh and the maximum HRR was 110–490 w/wh. HF was found in the gas released by the combustion test; the highest production rate was at 50% SOC and the lowest at 100%. Tao et al. [70] used 3.5 wt% NaCl solution as surrogate seawater to study the fire behavior of LIBs with different immersion times (tim). The fire hazards of LIBs were evaluated by parameters such as tim, surface temperature, mass loss, HRR, and THR. The battery ignition time first decreased and then increased with increased tim, and reached a minimum value at 3 h. THR and HRR reached peak value when tim was 3 h for 100% SOC and 2 h for 50% SOC, as shown in Figure 7. The combustion time, HRR, and THR remained unchanged when the time exceeded 3 h.



(**a**) (**b**)

Figure 6. (**a**) Mass flux of HF [d] as a function of time at different state of charge (SOC) [65]; (**b**) heat release rate [66].



(**a**) (**b**)

Figure 7. (**a**) Schematic illustration of experimental setup [69]; (**b**) change in total heat release (THR) and heat release rate (HRR) peak with different immersion times (tim) [70].

At present, the combustion test of lithium ion cells mainly studies the influence of different SOC on HRR and emission gas, but the conclusions are different. HRR and emission gas directly affect the explosion possibility and safety. Therefore, it is necessary to further strengthen the research on the mechanism of TR triggered internally, and even explosion, clarify the influencing factors, establish an accurate electrothermal model, realize accurate judgment of LIB thermal runaway, and improve the reliability of LIB safety warning information.

4. Electrical Tests

There are inconsistencies among the individual cells inside the EV battery pack, including in voltage, capacity, and internal resistance. During normal charging and discharging, serious abuse problems of overcharge and overdischarge are likely to occur, which cause internal structural changes and ISC, resulting in TR. There is a safety hazard of fire and even explosion. Abuse tests to evaluate the electrical safety of the battery mainly include overcharge protection, overdischarge protection, and short circuit protection tests.

4.1. Overcharge Test

Overcharge is one of the most serious and common safety problems in the use of LIBs [71]. Overcharge occurs when the battery reaches its nominal cutoff voltage or SOC limit [72,73]. When there is overcharge abuse of LIBs, a lot of energy will be generated, which can cause internal structural changes, electrolyte decomposition, and performance degradation, and even lead to TR. Ren et al. [74] studied the overcharge behavior and mechanism of TR through a series of overcharge experiments. The influences of charging current, restraining plate, and heat dissipation on battery overcharge behavior were evaluated on a pouch LIB. The overcharge performance of the LIB was less affected by the charging current. The restraining plate combined with pressure relief design reduced the internal pressure in the overcharge state and delayed TR, which had a positive effect on improving the overcharge performance of the LIB. The onset SOC of TR increased significantly and the maximum temperature of TR decreased under the nonadiabatic condition. The cathode suffers from electrolyte oxidation, transition metal dissolution and phase transition during the overcharge process. Serious lithium deposition will occur on the anode surface, which could reduce its thermal stability and raise its temperature. Rupture of the pouch and melting of the separator are the two key factors for the initiation of TR during the overcharge process. Wang et al. [75] studied the degradation mechanism of cells overcharged to different cut-off voltages with incremental capacity curve analysis, a prognostic and mechanistic model, and scanning electron microscopy/X-ray energy dispersive spectrometry tests. The study found that the reduction/oxidation of electrolyte caused by the abnormal electrode potential was the main cause of battery degradation. When the battery's overcharge voltage exceeded

3.2 V, the electrolyte decomposed during the degradation process, and an SEI film formed on the surface of the $Li_4Ti_5O_{12}$ anode, causing the degraded cells to generate gas and expand, as shown in Figure 8. Belov et al. [76] used differential scanning calorimetry and scanning electron microscopy to study the overcharge behavior of an $LiCoO_2$ LIB. When the overcharge capacity reached 150%, the internal structure of the battery changed dramatically and irreversibly. As the SOC reached 200%, the catalyst film peeled off from the current collector. It was found that dendrite particles grew from the cathode, the separator was penetrated, the side reaction of the anode was accelerated, and a micro short circuit formed, finally leading to TR. Ohsaki et al. [77] studied the thermal behavior of overcharged cathodes and anodes of an $LiCoO_2$ cell. They believed that TR caused by overcharging of the battery could be divided into four stages: lithium precipitates from the cathode and deposits on the positive electrode, the voltage increases continuously as the cathode precipitates lithium, and the battery impedance increases as the cathode resistance increases; then the liquid undergoes an exothermic reaction, the temperature of the battery rises significantly, and a large amount of gas is generated. The overcharged anode (deposited lithium) reacts violently with the electrolyte solvent at high temperatures, causing TR and even explosion. Huang et al. [78] conducted an experimental study on the internal failure mechanism and TR behavior of lithium ion batteries with different packaging modes during overcharge. According to the evolution trend of voltage and temperature, the TR caused by overcharge of the LIB could be divided into five stages, as shown in Figure 9. The pouch battery cell exhibited better thermal behavior and stronger overcharge tolerance compared to the prismatic battery cell in stages I to III. However, the prismatic battery cell had better TR buffering, smaller deformation, and longer early warning time. The above research mainly focused on overcharge experiments and TR research of a single cell, which is different from the failure mechanism and TR in the overcharge process of an EV battery pack, but it has important reference significance for overcharge safety research of battery packs.

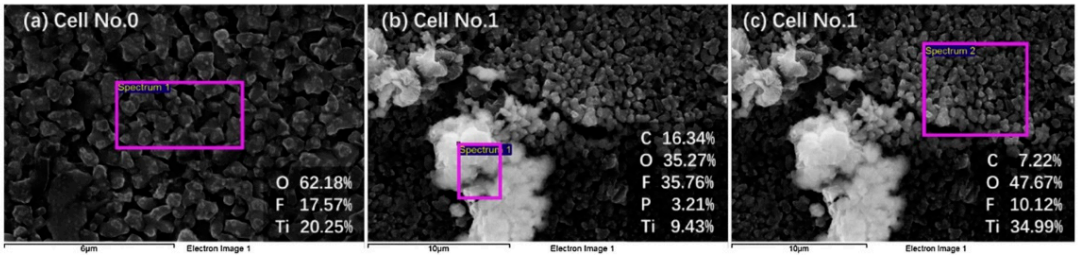


Figure 8. Energy dispersive spectrometer results. (**a**) Fresh cell anode; (**b**) degraded cell anode deposits; (**c**) degraded cell anode [75].

There are many reasons for TR caused by overcharge, such as separator melting, electrolyte decomposition, abnormal electrode potential, etc. The relationship between the causes and the internal failure mechanism need to be further studied. Experimental research on overcharge should be combined with precise control models; make full use of voltage, temperature, resistance, and other state information; accurately grasp the change rule of overcharge; and improve the judgment and warning of TR in advance.

4.2. Overdischarge Test

Overreaching a certain minimum allowable voltage region upon discharge of an LIB is considered to result in irreversible degradation of cathode materials, up to their complete destruction [79]. Overdischarge poses a significant threat to the safety and reliability of LIBs. Maleki et al. [80] investigated overdischarge effects on the cycle life and thermal stability of a Li ion cell. After they were cycled 100 times between 4.2 and 3.0 V at 0.8 A, the cells lost between 8 and 26% more capacity. Overdischarging cells between 2.0 and 0.5 V can lead to permanent capacity loss of 2–16%. Overdischarging to 0.5 V resulted in considerable swelling of the cells, but had minimal effects on thermal stability, overcharge

performance, and AC impedance of the cell. When the cell is overdischarged to 0 V, Cu2+ ions can migrate through the separator from the anode side to the cathode side and cause an internal short. Lai et al. [81] studied the electrical behavior of overdischarge-induced ISC and the self-repair capability of NMC cells with different degrees of overdischarge by an experiment. The degree of ISC was found to increase nonlinearly with the depth of discharge (DOD). When the cell was overdischarged to approximately 118% DOD, the maximum ISC occurred. More than 120% DOD showed a higher capacity decay rate. ISC occurred when the DOD of cells did not exceed 125%, and normal charging could be restored after a long rest. The cells with DOD of more than 130% could lead to irreversible ISC. ISC could be identified and predicted by its electrical characteristics. Ouyang et al. [82] studied the effects of cycle, charge, and discharge rates on the degradation behavior of lithium batteries in overdischarge conditions. In the process of overdischarging, the battery produced severe electric heating behavior, causing inconsistent battery packs, serious temperature rise, substantial increase in internal resistance, performance degradation, and accelerated aging. Wu et al. [83] obtained the same conclusion through an overdischarge experiment. Guo et al. [84] studied the failure mechanism of ISC of LIBs in the process of overdischarge. The variation of voltage and resistance with SOC was analyzed by scanning electron microscopy and X-ray diffraction, and the overdischarge was terminated before 12% SOC. Neither ISC nor capacity attenuation occurred, the cell overdischarged to SOC < −12%, and copper ions dissolved in the electrolyte and deposited on the cathode through the separator, making the positive and negative electrodes conductive to form ISC, leading to battery failure, as shown in Figure 10. Overdischarge of lithium batteries causes irreversible capacity loss and ISC, which leads to TR in severe cases. Through experimental studies of overdischarge to different degrees, the relationship between the battery failure mechanism and internal short circuit evolution with the degree of overdischarge was analyzed, and was shown to have a positive effect on TR early warning of the overcharge process.

Overdischarge could lead to fading and gradual failure of battery capacity and increased internal resistance; on the other hand, it could cause sudden failure risk of ISC and TR. The experimental study of LIB overdischarge is still limited to single parameter changes. The mechanism of LIB failure caused by overdischarge needs further study with respect to multiple parameters, such as voltage, SOC, temperature, cycle times, and discharge rate. Therefore, on the basis of recognizing the influence of overdischarge on battery performance, it is of great significance to develop accurate battery management systems to prolong the lifetime and increase the thermal stability of LIBs.

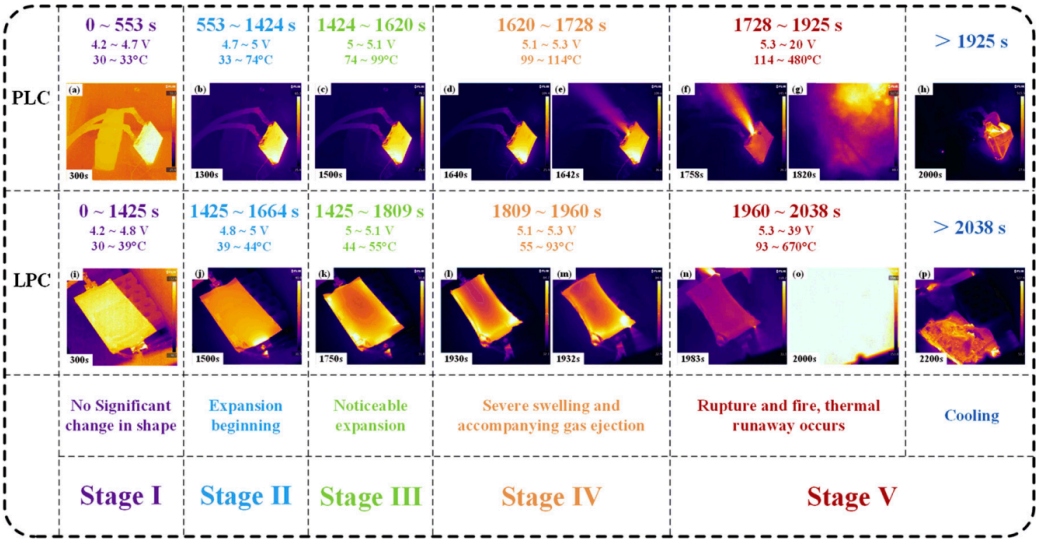


Figure 9. Thermal infrared images of thermal runaway (TR) behavior of battery cells during 1 C current overcharge: (**a**–**h**) prismatic cell; (**i**–**p**) pouch cell [78].

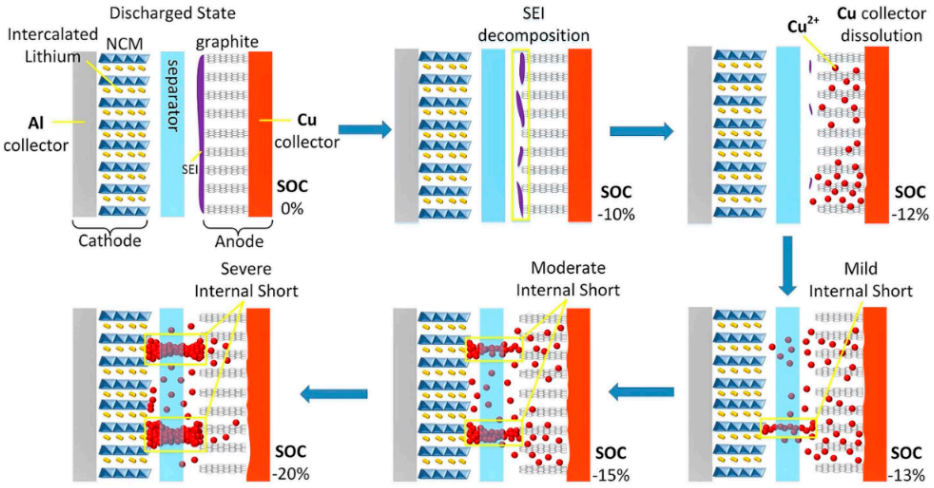


Figure 10. Copper dissolution and deposition during overdischarge and formation of ISC [84].

4.3. ISC Test

Almost all abuse conditions are accompanied by ISC, as shown in Figure 11, which is also one of the main causes of TR accidents of lithium ion batteries [31,85]. Manufacturing imperfections, the presence of impurities in the cells, and dendritic growth of lithium inside the battery can trigger the occurrence of ISC, which seriously affects the safety performance of the battery [86–88]. With the increased specific energy of the battery system, the electrode material of the LIB becomes thicker and the separator becomes thinner, and the probability of ISC increases; therefore, it is important to study the triggering mechanism and detection method of short circuit in LIBs [89].

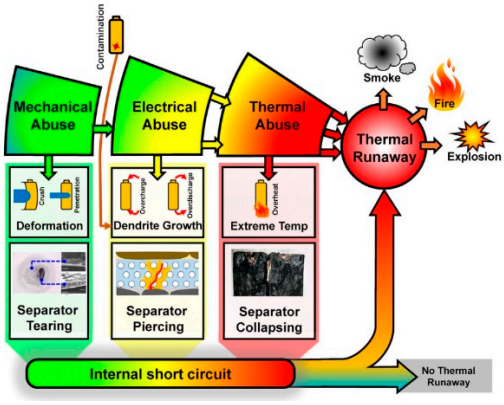
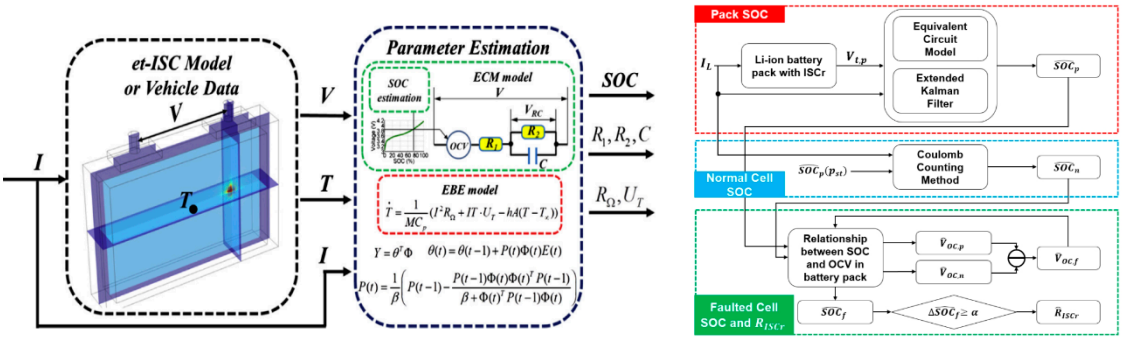


Figure 11. ISC, the most common feature of TR [31].

ISC detection of a battery is critical for preventing TR and enhancing electrical vehicle safety. Feng et al. [90] proposed a model-based internal short circuit inspection measuring method for a large-format LIB, and the scheme is shown in Figure 12. The detection problem is transformed into a key parameter estimation problem. By establishing a three-dimensional electrochemical thermal ISC coupling model of a large-capacity LIB, the relationship among the ISC state and measured voltage, current, and temperature data was studied. The abnormal loss of SOC and excessive heating of ISC will affect the voltage and temperature changes, which can be reflected in the parameterized model. It was found that real-time parameter tracking based on the model can track ISC latency or detect instantaneous ISC triggering; at the same time, the physical position of ISC in the battery can be determined by detecting the surface center temperature. Seo et al. [91] proposed a detection method to estimate early ISC of lithium ion batteries by terminal voltage and load current, and the overall scheme is depicted in Figure 12. By extracting the open circuit voltage (OCV) of the faulty battery to reflect

the self-discharge phenomenon caused by ISC in the battery pack, the ISC resistance of the battery pack was estimated accurately. Finally, the effectiveness of the algorithm under different soft ISC fault conditions was verified by simulation and experiment. In the experiment, the error of resistance estimation was less than 31.2%, which enabled the battery management system to detect the ISC early. Zhao et al. [92] conducted internal and external short circuit tests on different capacity lithium ion batteries. It was found that the external short circuit of a small-sized battery with high internal resistance was more serious; in the ISC test experiment, the battery with large capacity generated more heat and led to a higher failure rate when the current increased. An improved electrochemical thermal coupling model was proposed, which could accurately predict the occurrence and start time of temperature change and TR. Based on the self-discharge current of LIBs, Sazhin et al. [93] proposed a new method to detect the nascent ISC of LIBs. The ISC test used a constant DC voltage source in parallel with the detected LIB, and at the same time, the current measuring device was connected. The DC source voltage was slightly less than the OCV of the battery. The detected LIB discharged to the constant voltage power supply until the voltage was equal. In the case of ISC, the constant voltage source in turn charged the battery. Through the change in current direction detected by the current detection device, short circuit could be accurately measured in a few minutes so as to realize early warning of catastrophic failures. This method has good operability and convenience. Ouyang et al. [94] used the equivalent circuit model to analyze the electrical characteristics of the ISC of a large-format LIB. The ISC detection method was developed based on equivalent parameters and battery consistency, which conducted parameter estimation with the mean-difference model and the recursive least square. According to the basic parameters of mean-difference model, characteristic parameters such as the voltage differential and the fluctuation function of the internal resistance were calculated, and the obvious change in this parameter was used for ISC detection. The method could effectively help the battery management system to detect the internal short-circuit problem of the onboard vehicles battery system, and at the same time, the detection threshold of ISC could be reduced by improving the battery consistency in the battery pack, thus reducing the detection time.

Most of the research on ISC detection methods focused on cell or simple series battery packs, and the detection accuracy has been constantly improved, but the type and location of ISC cannot be accurately determined. At the same time, there is less research on ISC of battery packs and battery systems. Therefore, based on in-depth study on the mechanism of short-circuit triggering in battery packs, it is necessary to strengthen the testing and conduct accurate model research so as to improve the accuracy of identifying ISC and safety warnings.



(**a**) (**b**)

Figure 12. (**a**) Scheme of ISC detection algorithm [90]; (**b**) scheme of proposed algorithm [91].

5. Summary and Outlook

The increasing sales volume of EVs has led to a trend of accelerated growth in the demand for lithium ion batteries. However, safety accidents such as fire and explosion caused by lithium batteries are also increasing year by year. The safety problems with lithium batteries have become one of the key

factors restricting the rapid development of EVs. Safety testing of LIBs is not only a direct reflection of the safety problems of the batteries, but also an important means to understand and analyze the failure behavior and mechanism of TR. Research on ISC detection and the TR mechanism of LIBs under abusive conditions is of great significance to improve the application safety. In general, great progress has been made in battery detection technology, ISC mechanism and detection, and early warning of TR in EVs, but some problems still need to be solved.

(1) Comprehensive research on safety detection of LIBs

At present, most of the research on the safety of LIBs is mainly focused on single cells or battery series under one or two abuse conditions, while there is less research on the safety of multiple abuse conditions and complex parallel battery series. Therefore, it is necessary to strengthen comprehensive safety testing of LIBs under multiple abuse conditions. According to the actual vehicle application scenario, safety tests should be carried out under various abuse conditions. At the same time, safety testing and research on the three levels of single cell, module, and battery system should be carried out to find the logical relationship between the different levels and comprehensively evaluate the safety performance of batteries.

(2) Optimization and improvement of detection methods

Different detection methods according to different safety testing requirements need to be adopted for LIBs. However, many methods are used in individual safety tests, the test links and technology are not mature enough, the test cycle is insufficient, the correlation is not strong, and it is difficult to evaluate the advantages and disadvantages. Therefore, it is necessary to continuously enhance the detection technology of safety testing and optimize the test links and procedures. According to different test items, a standard, mature, and advanced test method should be formed to improve the consistency, rationality, and accuracy of test results.

(3) Accurate positioning of ISC and early warning of TR

ISC is a common problem in the case of mechanical, electrical, and thermal abuse and a common reason for TR [31]. Different abuse cases correspond to different types of ISC, and the positions of the ISC are not consistent, so the process of TR is more complex and it is easily concealed before it occurs. Determining how to accurately locate ISC and increase the effective warning time faces many difficulties and challenges. Therefore, in the face of the continuous improvement of energy density and the continuous emergence of new materials for lithium batteries, it is necessary to further study the detection technology, the failure mechanism of ISC, and the prediction model of TR under the condition of abuse so as to determine the type and position of ISC and effectively improve the warning time of TR.

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Abbreviations

EV	Electric vehicle
SOC	State of charge
HRR	Heat release rate
THR	Total heat release
LIB	Lithium ion battery
TR	Thermal runaway
ISC	Internal short circuit
DOD	Depth of discharge
OCV	Open circuit voltage
tim	Immersion time

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