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Review

Toward a Safer Battery Management System: A Critical Review on Diagnosis and Prognosis of Battery Short Circuit

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Lithium-ion batteries are commonly used as sources of power for electric vehicles (EVs). Battery safety is a major concern, due to a large number of accidents, for which short circuit has been considered as one of the main causes. Therefore, diagnosing and prognosticating short circuit are of great significance to improve EV safety. This work reviews the current state of the art about the diagnosis and prognosis of short circuit, covering the method and the key indicators. The findings provide important insights regarding how to improve the battery safety.

INTRODUCTION

Electric vehicles (EVs) are gaining wider acceptance as the transportation sector is developing more environmentally friendly and sustainable technologies (Vijayaraghavan et al., 2018; Liu et al., 2018a). Lithium-ion batteries are commonly used in EVs (Wang et al., 2018; Go et al., 2019), with advantages of high power density, high energy density, low self-discharge rate, extended cycle life, and without memory effect (Shibagaki et al., 2018; Mo et al., 2018). However, a higher energy density usually results in a higher risk of thermal instability (Liu et al., 2018b; Noh et al., 2013), where a chain exothermic reaction can be triggered (Naguib et al., 2018). Battery fire incidents of EVs have occurred continually; Table 1 lists some representative and serious accidents in recent 10 years, and the statistics of fire incidents of EVs for different external or internal cause between 2014 and the first half of 2019 is shown in Table 2 (Chen et al., 2019b). Among them, the internal short circuit (ISC) involves 52% of the accident probability, whereas the external short circuit (ESC) involves 26% of the accident probability, from which it can be explained that short circuit (SC) is one of the major failure mechanisms (Abaza et al., 2018). It is initiated by the penetration of the separator by electronic conductors, which can raise the local temperature to cause shrinkage or even melting of the separator.

Battery abuse in EVs can hardly be avoided, such as the mechanical damage caused by vehicle collision and the electrical abuse caused by battery leak, overcharge, and discharge (Ruiz et al., 2018). All of these can lead to SC, defined as unexpected and precipitous drop in electrical resistance, resulting in overheating of batteries. It has been commonly recognized that SC is the primary cause of thermal runaway (TR) (Feng et al., 2018; Liu et al., 2018; Sahraei et al., 2012a), leading to fire and even explosions (Lisbona and Snee, 2011; Meng and Li, 2019). For example, ISC resulting from mechanical abuse can directly cause TR (Deng et al., 2018a; Ren et al., 2019). In order to avoid or defeat TR, according to Table 2, although the use of high-thermal-resistant battery materials, crashworthiness design of the automobile body, and high-quality cables can reduce the probability of fire, it cannot meet the needs of cost and lightweight for EVs. So, it is of great importance to detect (diagnostics) and forecast (prognostics) SC. Efforts have been dedicated to understanding the basic mechanisms of SC. It is crucial to detect ISC before the final stage, because the TR immediately happens once ISC develops from middle stages into the final stage. Liu et al. (2018c) reviewed different triggering methods of ISC and its evolution process, i.e., the early, middle, and final stages of ISC. Zhu et al. (2018a) summarized the critical mechanical deformation to induce SC of various batteries under different mechanical abuse loading and came to the conclusion that SC of the same battery happens at different displacements under different mechanical loading. However, ESC has not attracted as much attention as ISC (Chen et al., 2018).

Different from the aforementioned studies, the contribution of this work is to provide a systematic review on both ISC and ESC, which are the most important risks to be handled in EVs. In addition, various indicators have been used to diagnose and prognosticate SC. This work will collect the existing indicators and,

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Date	Place	Accident	Brand	Cause
April 2011	Hangzhou, China	Spontaneous combustion of an electric taxi	Zotye Auto	Battery leak due to installation defects (Eric, 2011)
October 2012	New York, USA	Caught fire while being parked	Toyota plug-in hybrid	Corrosion from the salt in seawater (John, 2012)
April 2015	Shenzhen, China	Spontaneous combustion of hybrid bus	Wuzhoulong Motors	Overcharging leads to electrolyte leak (Liu et al., 2018c)
January 2016	Gjerstad, Norway	Caught fire while charging	Tesla Inc	Electrical distribution box (Steve, 2016)
June 2017	Hemberg, Switzerland	Caught fire by vehicle rollover	Rimac	Oil leaking onto hot electric wiring (Lance, 2017)
April 2019	Xi'an, China	Spontaneous combustion of an electrical SUV	Nio	Deformation of vehicle Chassis (Nio, 2019)

Table 1. Battery Safety Accidents in Recent Years

through a comprehensive comparison of their advantages and disadvantages, provide a guideline regarding the selection of indicators.

The content is organized as follows: different types of SC, the principle and characteristics of experimental studies on ISC and ESC, the indicators for SC diagnosis and prognosis, and the conclusions and suggestions regarding future work.

TYPES OF SHORT CIRCUIT

Short circuit of the lithium-ion battery can be divided into ISC and ESC depending on where it occurs, as shown in Figure 1. ESC (A) usually refers to the direct connection between the positive and negative terminals outside the battery (Zavalis et al., 2012). ISC occurs inside the battery, which can be further divided into four types according to the connection between different positive and negative components, marked as (B)–(E) (Zhang et al., 2017a; Santhanagopalan et al., 2009). In addition to the location, the changing rate of voltage, current, and temperature of ISC and ESC are also quite different. ISC normally has an incubation period (Yang et al., 2019), which is a process of gradual deterioration (Lee et al., 2018), although the final performance is consistent with the ESC.

ESC is usually caused by vehicle collision, battery leak, water immersion, and incorrect operation when assembling or disassembling batteries. Causes of ISC are more complicated. ISC is attributed to the following three issues: (1) mechanical abuse, the deformation and damage of a separator due to nail penetration or crushing, (2) thermal abuse, the collapse of a separator due to excessive ambient temperature, and (3) electrical abuse, a separator may be pierced by the dendrite growth due to overcharge or over-discharge (Feng et al., 2018a).

EXPERIMENTAL STUDIES ON SHORT CIRCUIT

Many investigations have been performed to understand the influence of SC on the performance of battery (Chen et al., 2019a), evaluate the impact on the battery safety, and provide data for model and algorithm development, such as validation and regression of empirical parameters and/or indicators. Table 3 summarizes the typical experiments on SC.

Experiments on ISC

Tests on ISC mainly include nail penetration test; indentation test; pinch test; forced internal short circuit test; overcharge, over-discharge test; and equivalent short resistance test, which are shown in Figure 2.

In addition to the tests above, ISC can also be triggered by placing special materials inside the battery, such as metallic particles (Ramadass et al., 2014), phase change materials (Finegan et al., 2017), and shape

External Causes	Spontaneous Combustion	Charging	Vehicle Collision	Cable Aging	Soaking	Other Causes
Internal causes	Internal short circuit	Overcharge	Internal short circuit and external short circuit	External short circuit	External short circuit	
2014	4	1	1	0	0	0
2015	7	1	1	1	0	1
2016	10	5	4	6	3	8
2017	6	5	4	0	1	1
2018	9	6	3	1	1	5
2019	5	3	2	0	0	2
Total	41	21	15	8	5	17
Proportion	38%	20%	14%	7%	5%	16%

Table 2. The Statistics of Fire Incidents of EVs

memory alloys (Zhang et al., 2017a). Such tests show good reliability and reproducibility (Keyser et al., 2011); however, they are excluded from this review.

Nail Penetration Test

The nail penetration test illustrated in Figure 2A refers to inserting a steel nail with an adequate diameter into the battery at a predefined speed to cause ISC (Liang et al., 2017; Zhao et al., 2015). It is widely used to simulate ISC (Zhao et al., 2017a; Liu et al., 2016) and has become the standard for battery qualification, such as GB/T 31485-2015 in China (Ouyang et al., 2019). The purpose is to imitate ISC and assess the safety of the battery in terms of occurrence probability of fire or burst upon ISC.

Mao et al. (2018) conducted such tests under different conditions such as state of charge (SOC), penetration depths, and penetration speeds. The results showed that the battery temperature in the test was not positively correlated with the depth; meanwhile, the speed affected the temperature distribution of the battery. Moreover, the mechanism of penetration was interpreted by a ''micro-short circuit cell" structure, which showed a severer TR with the nail penetrating at the battery center as the consequence of the faster speed of thermal propagation.

Although this method is easy to apply in the laboratory, it is usually dangerous to perform (Zhao et al., 2017a) and may create a large shorting volume with multiple electrode layers contacting each other and causing significant damage to the battery (Lamb and Orendorff, 2014). The nail penetration test is usually a combination of different types of ISC (Fang et al., 2014). As the consequences of each type of SC are quite different (Santhanagopalan et al., 2009), it is difficult to understand the mechanism of thermal propagation due to the uncertain electrochemical reactions (Orendorff et al., 2011). In addition, the nail penetration test can hardly give replicable results. For example, the internal current density decreases with the increase of contact area (Ramadass et al., 2014), which is decided by the penetration depth, and the contact resistance between the nail and battery is also difficult to control. Moreover, the nail as a thermal conductor will take away some heat generated. Therefore, this method cannot simulate the actual ISC accurately. Some of the actual failures are created by the lithium metal dendrite penetration (Li et al., 2019), but this test can only be used on the battery while suffering from deformation. So, it is not entirely similar to ISC taking place inside battery without physical abuse.

Indentation Test

The indentation test is commonly used to measure elastoplastic properties (Giannakopoulos and Suresh, 1999) of materials as shown in Figure 2B, which is a mechanical test used when the classical tensile test is infeasible (Amiri et al., 2016). It has been used to trigger ISC gradually (Hao et al., 2018). The indentation test was first proposed by Underwriters Laboratories (UL) and National Aeronautics and Space Administration (NASA) (Jones et al., 2010). The purpose is not only to assess the safety after ISC without damaging the cell compared with nail penetration test (Lamb and Orendorff, 2014), but also to study the mechanical properties of multi-layered structure of the battery in order to understand the mechanical integrity.

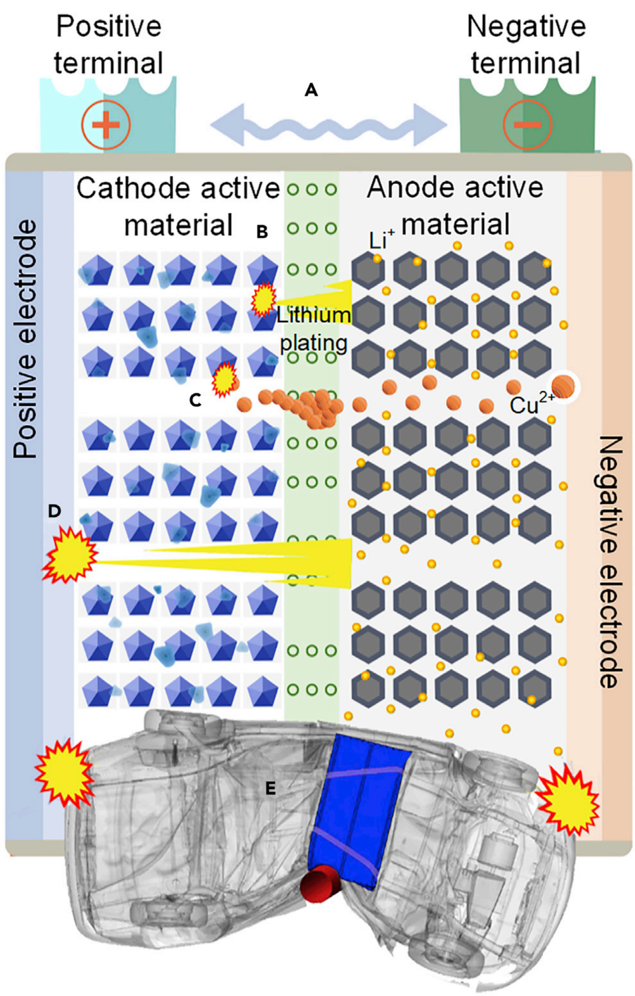

Figure 1. Types of SC

The short circuit of lithium-ion battery can be divided into five categories:
(A) External short circuit.
(B) Cathode Active Materials Layer (Ca)-Anode Active Materials Layer (An).
(C) Cathode Active Materials Layer (Ca)-Copper Current Collector Foil.
(D) Aluminum Current Collector Foil-Anode Active Materials Layer (An).
(E) Aluminum Current Collector Foil-Copper Current Collector Foil.
Credit Adapted from Hu et al. (2020) and Zhu et al. (2018a).

Lamb et al. (Lamb and Orendorff, 2014) used a stainless steel blunt rod to perform the indentation test in different directions on the batteries with two different internal structures; one had a solid core in the center of the cell, and the other one was left without and empty. According to the temperature and voltage results, the indentation results were dependent on whether a solid core was used in the cylindrical cell. It was also found that the battery without solid core tended to have a soft SC, which means the voltage first decreased but can recover to normal when unloaded, if the indentation depth was shallow. Similarly, Sahraei et al. (2014) also concluded that soft SC might occur during the early stage of the indentation test. A significant finding was that a soft SC, due to 1 mm dent caused by manufacturing accident or during service, could lead to disastrous results in the future, even though there is no obvious failure now.

Wu et al., 2013 found that the separator, the anode, and the cathode near the indentation area were deformed owing to local high curvature and the resulting high stress and strain would lead to the failure of the separator. Consequently, the anode and cathode can contact each other to induce ISC. The inflection points on the force-indentation curve could be used as an indicator of the initiation of ISC of cells under indentation (Luo et al., 2017).

Type	Method	Procedure	Purpose	Advantage	Disadvantage	Measured Parameter
ISC	Nail penetration	A steel nail with an adequate diameter is inserted into the battery at a stipulate speed	To assess the safety of battery (if the battery catches fire or explodes after nail-penetration)	Easy to operate	Poor reduplication and controllability	Temperature, voltage
	Indentation	A force is exerted to an indenter, and the resulting size or depth in the surface of the material can be measured	To reduplicate the actual ISC process	Suitable for thin and small components without damage	Probability of producing wrong results because of the dissipation of heat	Force, voltage, intrusion, temperature
	Pinch	Compressing batteries by using two opposite forces	To make ISC spot size as small as possible	Inducing smaller ISC spot size	Not suitable for flat plate batteries with large thickness	Force, voltage, displacement, temperature
	Forced internal short circuit	Compressing the battery after adding a nickel particle into jelly roll	To observe the mechanical dynamic response of the inner jelly roll structure	Precluding the endcaps from restraining the deformation of the winding structure	The process of disassembling batteries is complex and often accompanied by potential safety hazards	Force, voltage, displacement, temperature
	Overcharge and over-discharge	Charging or discharging current is forced through the battery up to a certain voltage limit	Forced to charge or discharge electricity when the battery has already reached its cutoff voltage	Good reproducibility	Not very close to the actual ISC	Temperature, voltage, resistance
	Equivalent short resistance	The equivalent short resistance is placed outside or inside the battery and connected in parallel	To imitate ISC quantitatively, obtain some indicators, and provide validation for indicator-based diagnostic algorithms	Good controllability of ISC, which can be triggered anytime due to a switch in the circuit	There is no effect on internal material of battery during test, which is different from the actual ISC	Temperature, voltage, resistance
ESC	Long-time SC	Creating ESC manually	To test whether the battery will result in fire and explosion	Simple operation	Difficult to measure and control external resistance accurately	Temperature, voltage, current
	Short-time SC		To explore the impact such as capacity fading of the battery after SC happens		The procedure is complicated as the structural characterization of battery is needed every time	

Table 3. Experimental Studies on SC

This test has advantages in studying the mechanical characters of SC. However, ISC often occurs in the outermost layer of the battery, which can dissipate a large amount of heat, and therefore, the results with indentation tests may be less serious compared with the actual situation (Cai et al., 2011).

Pinch Test

The pinch test, proposed by Oak Ridge National Laboratory (ORNL) and Motorola Mobility (Cai et al., 2011), refers to the compression of batteries by using two opposite forces as illustrated in Figure 2C.

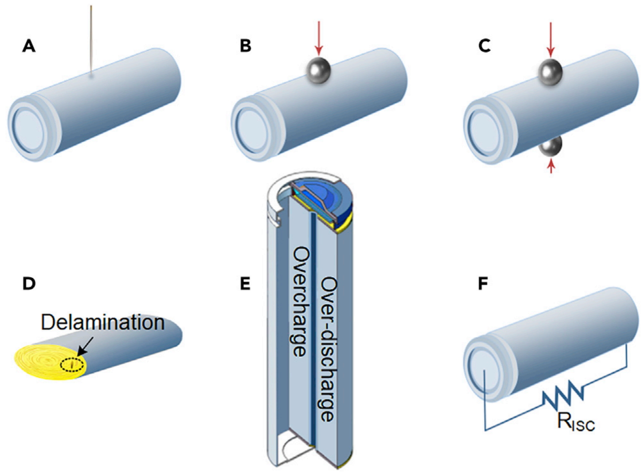

Figure 2. Classification of Experimental Studies of ISC

Generally, the ISC experiment mainly includes the above six types:

(A) Nail penetration test: inserting a steel nail with an adequate diameter into the battery.

(B) Indentation test: without damaging the cell compared with nail penetration test.

(C) Pinch test: compression of batteries by using two opposite forces.

(D) Forced internal short circuit test: disassembling the battery first and leaving only the jelly roll structure; this process may produce a delamination (Sahraei et al., 2012a).

(E) Overcharge and over-discharge test.

(F) Equivalent short resistance test: an ISC test similar to ESC.

The purpose is to make a smaller ISC spot size, because the size of the ISC spot in actual failures is tiny without heat dissipation, so as to make the test closer to the reality (Maleki and Howard, 2009).

Cai et al. (2011) stated that the experiment with a diameter of about 1 mm or less could reproduce ISC occurring in vehicles. There were two possible ways to create such a small ISC (usually 1 mm as the maximum length of the damage) under the pinch test: (1) using two spheres with small diameter to pierce a small area of separator and (2) stopping piercing immediately once a slight drop in voltage is detected. In an improved pinch test (Cai et al., 2011), a voltage threshold called stroke return-voltage was set as a cutoff condition to control the test. It verified that the 1-2 mm size ISC could be created reproducibly. The results also showed that the ISC size was determined by the voltage threshold as well. It further implied that, as the SOC and capacity of the battery increased, the risk of TR during ISC increased. Nevertheless, this test could not distinguish the thermal stability of batteries with a high SOC, because all types of tested batteries with 100% SOC led to TR under this test.

The traditional pinch test is mainly used for the batteries with small thickness. For ultra-thick batteries, a new method called ''pinch-torsion'' was developed, in which the pinch test was combined with torsion component. Ren et al. (2014) corroborated the pinch-torsion test to induce a smaller ISC spot size with a lower axial load compared with pinch test only. Triggering ISC in thick batteries requires a larger axial load, whereas the axial load applied by the equipment is limited, which can be overcome by adding torsion component. So, the pinch-torsion test is more suitable for thick batteries. Xia et al. (2014a) found that the indenter with a slight twist would introduce shear strain, which enlarged the maximum first principal strain greatly. As a result, it facilitated the failure of the polymer that could induce ISC. Maleki et al. (Maleki and Howard, 2009) compared three different ISC tests: the nail penetration, the indentation test, and the pinch test. The heat generated by the first two was concentrated on the battery shell and the nail, which diminished the probability of triggering TR. Batteries with lower capacity and charging voltage had a lower risk of TR during ISC. The results of the pinch test also showed that the SC position could influence the temperature distribution due to the limit of the heat transfer; and if the temperature was high enough to cause the separator to melt and side reactions occur, it may lead to TR.

Forced Internal Short Circuit Test

Unlike previous test protocols, the so-called ''forced ISC'' tests actually truly modify the interior cell structure/composition to better mimick ISCs in reality. The forced ISC proposed by the Battery Association of

Japan (BAJ) (Castillo, 2015; Mikolajczak et al., 2011) needs to disassemble the battery first as illustrated in Figure 2D, where the casing is removed, leaving only the circular jelly roll structure with central solid core. Then a nickel particle is placed into the jellyroll and a force is applied to compress the jelly roll at the nickel particle. The purpose is to simulate ISC caused by the metal particles mixed in the production process, observe the mechanical dynamic response of the inner structure of cylindrical batteries, and preclude the endcaps from restraining the deformation of the jelly roll structure. In the experiments (Sahraei et al., 2012a), the delamination of the jelly roll structure can be seen in the deformed cross-sectional area of the battery during the lateral crush test as displayed in Figure 2D. The anisotropy of the battery material needed to be contemplated, in order to establish a more accurate mechanical model to study ISC.

Ramadass et al. (Ramadass et al., 2014; Fang et al., 2014) disassembled the prismatic battery and fabricated a 2-mm-diameter hole at a specific location (without inserting nickel particle) to cause the ISC between An (anode-active materials layer)-Al (Aluminum current collector foil) and An-Ca (cathode-active materials layer). When comparing the maximum temperature rise during ISC with that in the nail penetration test (Ramadass et al., 2014), it was found that the maximum temperature rise in the case was reproducibly monotonically dependent on the SOC, whereas that in nail penetration tests was not. In their subsequent work, Fang et al. (2014) used the same method to create the An-Al and An-Ca ISC and estimated the contact resistances. It was found that the temperature during the ISC produced by the former was higher than that produced by the latter owing to different short resistances.

For the forced ISC test, the original structure of the battery is destroyed, making it impossible to measure the voltage when performing the crush test. Disassembling batteries is often accompanied by potential safety risks. Also, it cannot be applied to polymer lithium-ion batteries (Cai et al., 2011).

Overcharge and Over-Discharge Test

The overcharge and over-discharge tests in Figure 2E are conducted when the battery has already reached its cutoff voltage due to inaccurate estimation of battery capacity and SOC (Xiong et al., 2019; Yang et al., 2017). They can cause many side reactions in the battery and therefore result in a great amount of generated heat (Ouyang et al., 2015a). It is accompanied by gas generation or precipitation of active material, causing the separator to rupture. As a result, ISC occurs in a large area, leading to the release of all chemical energy in the form of heat and the formation of TR. The purpose of this test is to imitate actual field failures of ISC created by the lithium dendrites growth as much as possible without damaging the structure of the battery itself.

Ren et al. (2017) found that, in the last stage of overcharging, owing to the excessive internal pressure of the battery, even the cell casing might leak. ISC, hence, occurred after the separator was severely deformed by the pressure. Different from Ren's finding, Zhu et al. (2018b) considered that micro-short circuit occurred when the SOC increases from 144% to 149% due to overcharge, accompanied by a sharp rise in temperature. Once the SOC exceeded 149%, the ISC happened as a result of the structure collapse of the cathode and anode, which may lead to TR. Zhang et al. (2018) argued that ISC caused by overcharging was mainly due to the side reactions, such as lithium plating which arouse chain secondary exothermic reactions. Deng et al., 2018b) also found that the cobalt deposited on the anode pierces the separator during the overcharging process, accentuating ISC. It could bring a good shunt effect of current, thereby causing the voltage of battery not to rise anymore during the continuous charging process. It means that the battery entered a thermal equilibrium overcharge safety state. An SC path to achieve energy balance could be created due to cobalt precipitation during overcharging. Belov et al. (Belov and Yang, 2008) adopted the "soft" overcharging method, which meant that overcharged by a constant current with multiple fixed voltages, and the battery would not be damaged in this process. The scanning electron microscopy (SEM) results displayed that the microparticles from cathode were at the surface of the separator on anode side. It implied that there might be a micro-short circuit caused by the conductive growth penetrating the separator, so as to accelerate the side reaction at the anode side. Guo et al. (Guo et al., 2016) studied the over-discharge behavior of battery packs that were connected in series. A platform of the voltage was observed at "−12% SOC" (actually overdischarge by 12%). SEM and x-ray diffraction (XRD) showed that ISC was caused by the deposition of copper on the electrodes, so it was concluded that, if the terminal SOC was lower than −12%, ISC would occur inside the battery.

Equivalent Short Resistance Test

The equivalent short resistance test described in Figure 2F is structurally identical to the ESC, which consists of a battery cell and a resistor. The only difference is that the resistance of the external resistor used in such tests is much bigger than the one used in the test of ESC (below); for example, it is usually in ohm in ISC but only in milli-ohm in ESC. The purpose is not only to imitate the electrical and thermal responses of ISC quantitatively, but also to obtain some indicators and provide validation for indicator-based diagnostic algorithms.

Seo et al. did such a test in a battery cell and a battery pack (Seo et al., 2016, 2017, 2018), which aimed to validate the diagnostic algorithm, and it can be concluded that SC resistance as a diagnostic indicator can be used to detect SC early. Based on the same test, Ouyang et al. (2015b) identified an indicator of resistance difference for ISC detection, which was found to vary obviously once ISC occurred. In addition, Feng et al. (2018b, 2018c) used this test to study the thermal effect of ISC and evaluate the reliability of the diagnostic algorithm. It was found that the hazard level of an ISC can be assessed by the equivalent short resistance. However, as the manipulated SC was not caused by electric abuse or mechanical abuse, it cannot really reflect the characteristics of ISC.

Experiments on ESC

To create ESC, a resistance less than 80 $\pm$ 20 mohms according to the IEC62133 standard (Millsaps, 2012) is connected to the positive and negative terminals of the battery. Long-time test and short-time test are usually applied to understand the impacts on the performance of batteries, such as lifetime and safety.

Long-Time Test on ESC

The long-time test refers to keeping the battery short-circuited until the battery temperature drops from the highest temperature by 20% of the maximum temperature rise according to the IEC62133 standard. Kriston et al. (2017) found that the normalized external/internal resistance ratio was a main factor of peak SC current and a decrease of the ratio can be used to identify hazards such as rupture and ISC by analyzing a large number of experimental results. Conte et al. (2009) found that the peak SC current-capacity ratio is an important parameter for safety, which is the relationship between the capacity and the peak current during SC. Battery designers can forecast the peak SC current according to the capacity so as to design protection measures. Chen et al. (2016) conducted a long-time ESC experiment under different initial SOC and found that for the battery with a higher SOC the temperature rose faster, causing more damage, whereas the battery with somewhat lower SOC can survive the damage better, with lower internal leakage current, and ironically ended up having a larger external discharge capacity.

Rheinfeld et al. (2018) designed a cell that was exposed to ESC under quasi-isothermal test conditions, which permitted a distinct separation of the electrical and thermal behavior of the cell. By a qualitative postmortem analysis, copper colored contours could be observed on the cathode surface, and it is concluded that the over-discharge caused by ESC may be related to an anodic dissolution of the negative electrode's copper current collector.

Short-Time Test on ESC

The short-time ESC, normally occurring in reality by operating mistakes, may not cause immediate battery failure, but it can have long-term influence on battery capacity and internal parameters, such as the chemical and electroic transport impedances.

Zhang et al. (2016) studied the effect of the short-time ESC on long-term cycling capacity decay mechanism of batteries. The battery was tested for 1,000 cycles under different external resistances and ESC time from 1 to 180 s. The structure of the battery and the surface of the electrode were studied by XRD and SEM. It was found that high current could lead to the damage of electrodes, such as leaving voids on the surface of the active-materials layer, and could result in the decrease of cyclable lithium inventory. High temperature could cause the thickening of the SEI film to further aggravate the polarization phenomenon and increase the degradation of batteries.

Discussions

The goal of the experimental studies is to trigger SC in order to acquire the indicators about the occurrence of SC and provide validation for indicator-based diagnostic and prognostic algorithms. Key characteristics of these experimental studies are compared in Table 4.

Experimental Methods	Complexity	Reduplication	Controllability	Indicators
Nail penetration test	L	L	L	Stress and strain
Indentation test	M	M	L	Maximum indentation force
Pinch test	M	H	M	Stress and strain
Forced internal short circuit test	H	M	H	Stress and strain
Overcharge and over-discharge test	L	H	L	Internal resistance
Equivalent short resistance test	L	H	H	Internal resistance and level of battery consistency

Table 4. Characteristics of Different Experimental Methods
H, M, and L stand for high, medium, and low, respectively.

For ESC experiments, the long-time test focuses on the consequences of ESC through monitoring the change of voltage, current, and temperature, which provides a theoretical basis and indicators for the diagnosis of ESC. However, it is difficult to analyze the internal performance of batteries in ESC. Therefore, electrochemical modeling is needed to understand ESC. The short-time test lays particular emphasis on the irreversible effect on the battery during ESC that may not destroy the battery right away but nontheless can leave some permanent damage, based on which the contribution of low-temperature heating of batteries can be specified.

The future work should focus on how to improve the repeatability of trigger ISC and in a more quantitative way; moreover, non-destructive ESC needs to be explored in depth.

DIAGNOSIS

In order to avoid the negative consequences of SC, it is crucial to detect and forecast the occurrence of SC. The aim of diagnosis is to detect SC in battery in the initial stage of SC, when there is usually no obvious characteristics. Table 5 summarizes the indicators that can be used for diagnosis of SC.

Internal Resistance

The internal resistance or the internal impedance of the battery can be used as indicator of ISC. ISC resistance R_{ISC} as a part of internal resistance can reflect the level of ISC quantitatively (Guo et al., 2016), whereas the internal resistance especially the polarization resistance and ohmic resistance estimated by the detection algorithm demonstrates the ISC status (Feng et al., 2016), so internal resistance can be used as an indicator to diagnose SC. The electrical model or equivalent circuit model (ECM) (Xiong et al., 2018), including Rint-ECM and Thevenin-ECM, are commonly applied to analyze the performance of batteries. For a battery with SC, especially ISC, the Rint-ECM is shown in Figure 3A. Then, the SC resistance in ECM can be expressed by the following equation:

$$U_t(t) = \frac{U_{oc}(soc)}{R_0 + R_{ISC}} \times R_{ISC} \quad \text{(Equation 1)}$$

where $U_t(t)$ is voltage caused by R_{ISC}, $U_{oc}(soc)$ is open circuit voltage (OCV), and R_0 is internal resistance. SC resistance R_{ISC} can be estimated by genetic algorithm (GA) (Guo et al., 2016) or recursive least squares (RLS) algorithm (Seo et al., 2016, 2017). ISC can be diagnosed once R_{ISC} or internal resistance is estimated since these indicators will change significantly during period of SC (Guo et al., 2016).

Seo et al., 2016 connected a resistor with constant resistance as R_{ISC} in parallel to the battery to simulate ISC. The R_{ISC} estimated by RLS algorithm in ECM as shown in Figure 3B was in good agreement with this constant resistance. It can be concluded that once the ISC occurs, the validated diagnosis algorithm can monitor and estimate R_{ISC} online so as to detect SC effectively. In addition, The R_{ISC} can also be estimated by the whole voltage and the load current of the battery pack (Seo et al., 2018), in which a battery with ISC and normal batteries were connected in series. The results showed that R_{ISC} can be used to detect ISC effectively in a battery pack.

Indicators	Principle	Advantages	Disadvantages	Object
Internal resistance R_{ISC}	The resistance identified by the algorithm will change obviously in the incubation period of ISC. By detecting this change, the ISC can be diagnosed	Suitable for any series-parallel circuit	The estimation of resistance is rough since the actual resistance will change evidently during the SC	Battery cell and battery pack
Level of battery consistency	Compared with other batteries, the consistency of voltage and resistance of batteries suffering from ISC in battery pack will be significantly different	Convenient and rapid in diagnosing the faults in battery packs	The consistency of battery can be hardly used diagnose ISC in batteries connected in parallel circuits	Battery pack
Current, voltage, and temperature	When ISC and ESC occur, the battery is generally characterized by a sharp increase in current and temperature and a sudden drop in voltage	The most intuitive and rapid diagnostic method	It is easy to result in false positives and false negatives	Battery cell

Table 5. Comparison of the Diagnostic Indicators for SC

Feng et al. (2016) found that there was almost no difference between the voltages of the normal batteries and the batteries with ISC during the incubation period. However, it was found that the polarization resistance R_2 (used to describe the polarization characteristics of a battery) increased 355% after the occurrence of ISC with $R_{ISC} = 10\Omega$. Therefore, ISC can also be effectively diagnosed in the early stage by using estimated R_2.

The accuracy of using the internal resistance to diagnose ISC is affected by SOC, which can be further dependent on the current profiles. Meanwhile, the estimation of resistance is rough since the actual resistance will change evidently during the SC (Fang et al., 2014). Hence future research on ISC detection needs to strive to improve the accuracy and make it suitable for different current profiles.

Level of Battery Consistency

The level of battery consistency can also be used to diagnose the SC in battery pack. Usually, in the same battery pack, each of cells in the same type should maintain a high degree of consistency under the same current profile. When ISC occurs in one of the batteries, some parameters, such as voltage and internal resistance of that battery, could become significantly different, which reduces the consistency of battery packs. Based on the indicator of consistency, the SC of the battery can be diagnosed effectively.

There are two kinds of consistency indicators, the voltage difference ΔE_i and the internal resistance difference ΔR_i, which can be expressed by the following equations:

$$\Delta E_i = E_i - E_{mean} = \Delta E_{parameter} + \Delta E_{depleting} + \Delta E_{inconsistency} \quad \text{(Equation 2)}$$

$$\Delta R_i = R_i - R_{mean} = \Delta R_{parameter} + \Delta R_{depleting} + \Delta R_{inconsistency} \quad \text{(Equation 3)}$$

for serially connected batteries, where $\Delta E_{depleting}$ and $\Delta R_{depleting}$ mean the OCV change and internal resistance change due to the depleting effect of ISC, which can be obtained by the hybrid pulse power characteristic (HPPC) test; $\Delta E_{inconsistency}$ and $\Delta R_{inconsistency}$ are the independent inconsistency of SC in battery pack; and $\Delta E_{parameter}$ $\Delta R_{parameter}$ can be calculated by the following equations:

$$\Delta E_{parameter} = \frac{R_{ISC}}{R + R_{ISC}} \cdot E - E = -\frac{R}{R + R_{ISC}} \cdot E \quad \text{(Equation 4)}$$

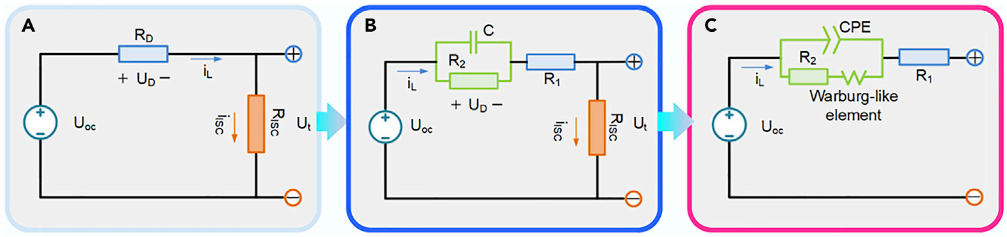

Figure 3. The Models in a Battery with ISC or ESC
(A) Rint model in a battery with ISC.
(B) Thevenin model in a battery with ISC.
(C) Fractional order model (FOM) in a battery with ESC.

$$\Delta R_{parameter} = \frac{R_{ISC}}{R + R_{ISC}} \cdot R - R = -\frac{R}{R + R_{ISC}} \cdot R \qquad \text{(Equation 5)}$$

In a circuit without ISC, $R_{ISC} = \infty$, which implies $\Delta E_{parameter} = \Delta R_{parameter} = 0$, whereas if there exists an ISC, $\Delta E_{parameter}$ and $\Delta R_{parameter}$ can be detected. It should be pointed out that Equation 4 and 5 apply to serially connected battery cells only, where the E and R of cells are simply additive.

This voltage difference and internal resistance difference have been used by Ouyang et al. (2015b) to diagnose ISC. When ISC occurred, ΔE_i and ΔR_i estimated by ECM of the cell with ISC were obviously lower than those of the normal cells. But this is a slow process, which may take up to 1 h to detect the SC with 10Ω resistance since it took about 1 h for ΔE_i and ΔR_i to change obviously. However, if it was an SC with 1Ω resistance, it can be diagnosed immediately after it occurred.

While the level of battery consistency is intrinsically a good flag of ISC in a battery pack, this consistency is easier to measure for batteries connected in serial. At present there is no good method to accurately measure the consistency for batteries connected in parallel.

Current, Voltage, and Temperature

When SC occurs, the battery is generally characterized by a sharp increase in current and temperature and a sudden drop in voltage (Chen et al., 2016; Greve and Fehrenbach, 2012), which are beyond the range of the normal operation. Therefore, if such ranges can be determined in advance, they can be used to diagnose SC.

Xia et al. (2014b, 2015) used the change rates of current, voltage, and temperature as representative indicators to determine the initial stage of SC. SC can be detected early and an inchoate warning can be realized.

However, there are many shortcomings when only using those three indicators. The circumstances of SC may vary in real situations, and SC may occur before the temperature change reaches the limits, which leads to the failure of detecting SC. Therefore, it is insufficient to diagnose SC only by thresholding. Model-based fault diagnosis can improve the accuracy of diagnosis (Chen et al., 2016; Xiong et al., 2019b). Calculating root-mean-square error (RMSE) between the predictive voltage and measured voltage can enhance the robustness of the algorithm. However, this detection method of voltage difference threshold may result in false positives due to the inconsistent SOC or states of health (SOH) (Xia et al., 2017). Xia et al. adopted the correlation coefficient of the cell voltages to prevent false-positive detections. The off-trend voltage drop in the initial stage of SC can be detected by the correlation coefficient with inconsistent SOC or SOH. But this method can only be used in the detection of battery module/pack.

Xiong et al. (Chen et al., 2016) conducted a two-layer diagnosis for ESC at the cell level based on ECM. If assuming the principle of the top layer was same as that in Xia et al. (2014b), the bottom layer with improved ECM could give a predictive voltage at the measured current. By calculating the RMSE between the predictive voltage and measured voltage, SC can be identified when the RMSE was below the threshold. Such a model-assisted diagnosis shows an improved accuracy. On the pack level, Xiong et al. (2019b) proposed a two-step equivalent circuit battery model. The diagnosis time was reduced from 5 to 3.5 s, and the RMSE was reduced to 25 mV.

Diagnostic Indicators	Diagnostic Speed	Algorithmic Complexity	Reliability	SC Application Type	Real Vehicle Application
Internal resistance	M	M	H	ISC	√
Level of battery consistency	L	H	H	ISC	√
Current, voltage and temperature	H (ESC) L (ISC)	L	L	ESC and ISC	√

Table 6. Characteristics Comparison of Diagnostic Indicators
H, M, and L stand for high, medium, and low, respectively.

However, the accuracy of using ECM is relatively low owing to not considering the electrochemical mechanism. Kuhn et al. (2004) proposed to use the constant phase element (CPE) in fractional order model (FOM) to replace ECM, which is based on electrochemical impedance spectroscopy, as shown in Figure 3C. The Warburg-like element and resistors were added to represent the ohmic resistance of electrolyte and current collectors by Wang et al. (2015) The results obtained by Victor et al. (2013) showed that CPE can better simulate the behavior of double layers in batteries. Yang et al. (2018) proposed a diagnostic algorithm based on FOM, which was consistent with that of Chen et al. (2016) Although the frequency- and history-dependent FOM had an overwhelming advantage than simple ECM (Yang et al., 2018), its iterative calculation makes it difficult to be used online, as a large amount of memory is needed and the optimization algorithm is complex.

Discussions

The diagnosis indicators can detect SC in the incubation period and provide early warning. As shown in Table 6, internal resistance and battery consistency are mainly used to diagnose ISC. The reliability of using these two indicators is high, even though the diagnosis process is relatively slow. The third category of indicators such as temperature can be used to diagnose both ISC and ESC, which can be the simplest way to fulfill purpose, but with the drawback of potential time lag (e.g. the surface temperature of a cell or pack could be very different from that of the interior hot spot) and high false-positive and/or false-negative rates. The diagnosis algorithms based on these three types of indicators can be integrated in Battery Management System (BMS) and applied in real vehicles.

PROGNOSIS

The aim of prognosis is to predict the occurrence of SC in batteries before it happens. Unlike diagnosis indicators, currently used prognosis indicators are mainly mechanical parameters. Since the essence of SC is that the separator has been damaged, it results in direct contact between positive and negative active materials in the battery. So SC prediction can be done by the detection of material failures, caused by force, stress, and strain (Greve and Fehrenbach, 2012; Sahraei et al., 2015). The prognosis indicators are shown in Table 7.

Maximum Indentation Force

According to the indentation test (Hao et al., 2018; Sahraei et al., 2014), the maximum indentation force, voltage drop, and temperature rise happen almost simultaneously in pouch battery as shown in Figure 4. The voltage drop can be considered as the occurrence of SC. Therefore, SC of pouch battery can be predicted by modeling the maximum indentation force of battery in the indentation test. Hao et al. (2018) claimed that when an indentation displacement or indentation force was given, ISC in pouch cells can be characterized. The indentation force $\bar{p}$ is determined by the normalized indentation region radius $\bar{\xi}(\bar{\xi} = \xi/R$, where ξ is indentation region radius, R is the radius of punch) and the normalized indentation displacement$\bar{\delta}(\bar{\delta} = \delta/R$, where δ is indentation displacement). It is possible to avoid triggering ISC during indentation test by adjusting $\bar{\xi}$ and $\bar{\delta}$, which are related to the punch radius. A more stable battery can be realized by optimizing the mechanical parameters of different loads and components in batteries. In Figure 4, the maximum force was directly related to many parameters, such as operating temperature, displacement due to indentation, and strain rate. It was found that displacement due to indentation was the most influential factor, followed by strain rate and temperature.

Indicator	Principle	Advantages	Disadvantages	Object
Maximum indentation force	The maximum indentation force, voltage drop, and temperature rise happen almost simultaneously, the voltage drop means the occurrence of SC. So the onset of SC can be predicted by modeling the maximum force of battery	The SC under static load can be predicted well	It not 100% verified that if the maximum indentation force can predict the SC effectively under the dynamic loading	Battery cell
Stress and strain	The fracture criterion-based stress and strain means that once the critical value is reached, failure is considered to have occurred. Hence the SC can be prognosticated by calculating the critical value	The failure time and the location of the SC both can be predicted	This method is not suitable for batteries with different electrolytes	Battery cell

Table 7. The Prognosis Indicators for SC

However, this method does not specify the relationship between the maximum force and ISC, and it is highly dependent on battery type, SOC, and loading scenarios. It was concluded that SOC will affect the maximum force of battery under the pinch-torsion test (Vijayaraghavan et al., 2018). But for the sake of safety, the existing works were carried out after the battery was fully discharged, which means SOC of battery was zero (Greve and Fehrenbach, 2012; Zhu et al., 2016). However, more tests at high SOC should be done in order to further verify the prognosis method. In addition, in the indentation test, the exact prediction of the onset of SC was determined by the coefficient of friction (Sahraei et al., 2014), and the speed of the indenter is usually fixed, which is equivalent to the static loading process. Nevertheless, the actual vehicle collision is a dynamic loading process, and it is quite different in response between dynamic and static loading (Zhu et al., 2019). Further verifications are needed if the maximum indentation force can predict SC effectively under the dynamic loading.

Stress and Strain

The battery is sensitive to external and internal mechanical loads (Zhang et al., 2017b), but the deformation of the battery is not critical in some applications. So, it is of great importance to understand the relationship between mechanical response and SC caused by deformation and to prognosticate the occurrence of SC. However, there is limited research about it. In general, the mechanical behavior of batteries includes elastic, plastic, damage, and fracture processes, and SC is caused by the development of internal cracks in battery materials under mechanical loads (Chung et al., 2018). Therefore, if the development of cracks in materials can be monitored, it is effective to predict SC. At present, many studies have conducted *in situ* analysis of battery failure by CT scanning (Sahraei et al., 2015). Moreover, the crack initiation and propagation can be prognosticated by stress-based model (Greve and Fehrenbach, 2012; Sahraei et al., 2016) and strain-based model (Sahraei et al., 2012a, 2015, 2016; Xia et al., 2014).

The ISC is initiated by the fracture of macroscopic jelly roll (Greve and Fehrenbach, 2012). Once fracture is initiated, the separated jelly roll parts can connect anode and cathode materials, leading to SC. So a fracture criterion can be used to prognosticate ISC, which could be described by the classical Mohr-Coulomb (MC) model expressed by Equation 6 (Bai and Wierzbicki, 2010). The MC fracture criterion-based stress means that once the critical value is reached, failure is considered to have occurred.

$$\max(\tau + c_1\sigma_n) = c_2 \quad \text{(Equation 6)}$$

where τ and σ_n are shear and normal stress, respectively; c_1 is material constant; and c_2 is an unknown coefficient according to the maximum shear failure hypothesis, and its relation to fracture angle θ is shown in Figure 5C. Using stress indicator to prognosticate SC can be divided into three steps: (1) finding the fracture angle (Chung et al., 2018) or the punch displacement (Greve and Fehrenbach, 2012) at the occurrence of SC according to the postmortem examination (Figure 5A), (2) estimating the stresses based on the angle

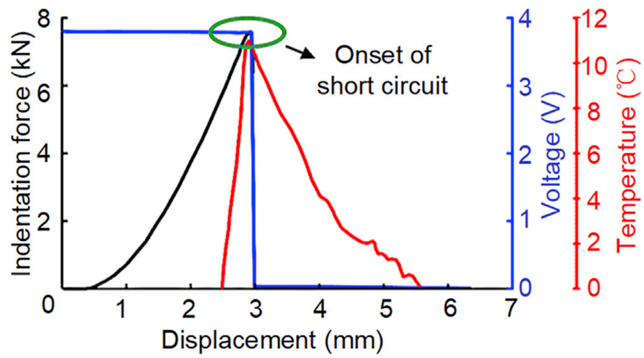

Figure 4. The Indentation Force P, Voltage Vocv, and Temperature T Response Curves During Indentation Test

or displacement by simulation, in which finite element (FE) models (Zhu et al., 2016) and representative volume element (RVE) model (Sahraei et al., 2012b, 2015) can be used (Figure 5B), and (3) determining the fracture displacement by calibrating the MC parameters according to the simulated stresses. By comparing the error between the failure displacement predicted by the MC model and the measured displacement, the stress-based model can predict the failure effectively and the location of the SC.

However, the above SC prediction was carried out without the battery shell. For the SC prediction of the battery with the shell, Zhang et al. (Zhang and Wierzbicki, 2015) used the modified Mohr-Coulomb (MMC) model to predict crack initiation and propagation in shell. Compared with the classical MC model, MMC model uses coordinate transformation to increase the accuracy of failure prediction, and it can predict the occurrence of SC more precisely. However, the MMC method did not provide a good prediction of the fracture in tension (Bai and Wierzbicki, 2010), which seldom occurred in a real vehicle collision.

Based on the MC model, the crack location under different loads is corrected to predict the SC location. However, there are still limitations due to stress indicator for ISC prognosis of the battery. Kisters et al. (2017) found that the SC behaviors of two different batteries under different impact velocities were totally different, which was attributed to the difference of the electrolyte of the batteries. MC model could not explain this behavior.

Xia and Sahraei et al. (Sahraei et al., 2015; Xia et al., 2014a) come up with the maximum strain criterion used for element failure in SC. The failure of materials and SC were detected when the maximum principal strain reached its critical value expressed by:

$$\max(\varepsilon_{ii}) = \text{constant} \qquad \text{(Equation 7)}$$

where ε_{ii} is normal strain. Sahraei et al. (2015, 2016) and Zhang et al. (2015a) argued that it was difficult to detect the failure strain from experiments, and the RVE model could be used to estimate it. In order to find the threshold of the normal strain, the strain in the material related to critical displacement at fracture keeps being changed until the measured and calculated critical displacement to fracture become coincident. Based on the maximum strain the ISC could be predicted. In order to estimate strain response of active materials and separator, Zhang et al. (2015b) applied an effective through-thickness strain to increase the accuracy of predicting failure or SC.

Xia et al., 2014a) discovered that the maximum first principal strain increased significantly by the addition of the torsion component, to meet the failure criterion readily and to predict ISC effectively. However, Chung et al. (2018) questioned the generality of the selection of the critical value of strain in inverse methods, because these values were case dependent, which were different from the actually measured strain response.

Discussions

The indicator of the maximum indentation force can be considered as a direct way for prognosticating. Stress and strain indicators can be regarded as the indirect prediction methods because of the need to

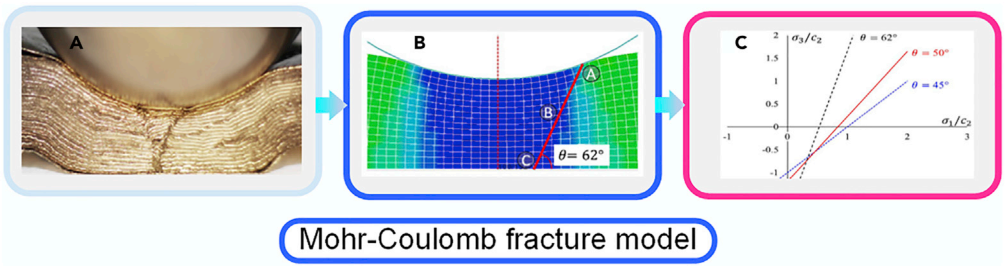

Figure 5. The Schematic Diagram of the Mohr-Coulomb (MC) Model

(A) The postmortem examination of the deformed profile and finding the fracture angle or the punch displacement at the occurrence of SC.

(B) Finite-element simulation of indentation test, according to which the stresses can be estimated.

(C) The relationship between the fracture angle and c2, to get unknown coefficient c2.

Credit Adapted from Chung et al. (2018).

use the results of FE model. Nevertheless, existing studies about prognosis mainly focus on the specific battery cell in specific loading scenario, and there is still a lack of studies investigating the battery pack in different loading scenarios (Zhu et al., 2018a). Since prognosis is to predict the SC caused by mechanical deformation when it reaches a certain extent, it is difficult to distinguish whether an ISC or an ESC will occur. In addition, owing to the huge amount of computation in FE modeling, it is difficult to apply these indicators for BMS directly at present (Zhao et al., 2017b).

Similar to other decision models (both diagnostics and prognostics), there can be false-positive and false-negative errors. The main reasons are generally due to the inauthentic sampling data, which is mainly owing to the sensor failure, or inappropriate threshold. The sensor failure can be avoided by installing redundant sensors, which, unfortunately, will increase the cost. The determination of threshold is closely related to the amount of tests and the accuracy of prediction models. To accurately determine the threshold, current profiles, battery aging, ambient temperature, and other factors need to be considered, resulting in a demand of plenty of experiments, which is both costly and time-consuming. In addition, in order to improve the prediction model, more complex frameworks consisting of more parameters are usually required, which will consequently make it more difficult to develop and implement such models. Therefore, more efforts are needed to investigate how to balance the decision errors and the model complexity. In addition, most of the current diagnosis or prognosis methods of SC are model based, and few of them are based on data-driven method for fault analysis. In the future, the data-driven method can be used to reduce the possibility of decision errors, and the fault can be captured and identified from the combination of statistics, discrete mathematics, and machine learning. With the gradual aging of the battery, the internal parameters of the battery will change. The current methods have not yet verified the diagnosis results under the battery full life cycle. So adaptive algorithm should be added to the battery diagnosis or prognosis method to ensure its accuracy.

CONCLUSIONS

Short circuit (SC) has been considered as a key issue for the safety of EVs. In order to improve the safety of batteries, this review systematically summarizes the current state of the art about the diagnosis and prognosis of short circuit.

Lab experiments show that for internal short circuit (ISC), mechanical tests have low repeatability and controllability, whereas overcharge and over-discharge tests can only trigger micro-short circuit; and for external short circuit (ESC), it is difficult to analyze the internal performance of batteries through experiments owing to the limited data that can be obtained. In addition, there have been no experimental studies considering both ISC and ESC simultaneously.

For the diagnosis of SC, internal resistance, the level of the battery consistency, current, voltage, and temperature have been identified as important indicators. Using internal resistance and the level of the battery consistency can result in a higher reliability but it takes a longer time to diagnose. The advantage of using current, voltage, and temperature is the simplicity, but they often result in false positives and false negatives. For the application in EVs, it is important to balance the complexity, the diagnostic speed, and the reliability.

For the prognosis of SC, the indicators are mainly mechanical parameters, including the maximum indentation force, stress, and strain. The maximum indentation force can be directly used to prognosticate the SC; however, the application of stress and strain need to be combined with finite element models. Currently, the challenge of prognosis is that it can only be done for one battery cell. There is still a lack of methods that can be used for battery packs.

The literature survey also highlights an urgent need for a standardalized procedure about testing short circuit, which can improve the repeatability and controllability. It is also important to develop methods that can combine diagnosis and prognosis. One of the promising way is to create an online platform to collect and share data of SC, based on which better diagnosis and prognosis methods can be developed.

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AUTHOR CONTRIBUTIONS

R.X. conceived the idea. R.X., S.M., and H.L. conducted the literature review and wrote the manuscript. R.X., S.M., H.L., F.S., and J.L. discussed and revised the manuscript.

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