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Characterization of penetration induced thermal runaway propagation process within a large format lithium ion battery module

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HIGHLIGHTS

- Thermal runaway (TR) propagation test on large format Li-ion battery pack is done.
- TR propagation mechanism in a large format Li-ion battery pack is analyzed.
- TR propagates from the nail point to the 1st battery, then to adjacent batteries.
- Side heating in TR propagation leads to a lower TR onset temperature around 100 °C.
- The heat transferred through battery shell dominates the TR propagation process.

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ABSTRACT

This paper investigates the mechanisms of penetration induced thermal runaway (TR) propagation process within a large format lithium ion battery pack. A 6-battery module is built with 47 thermocouples installed at critical positions to record the temperature profiles. The first battery of the module is penetrated to trigger a TR propagation process. The temperature responses, the voltage responses and the heat transfer through different paths are analyzed and discussed to characterize the underlying physical behavior. The temperature responses show that: 1) Compared with the results of TR tests using accelerating rate calorimetry (ARC) with uniform heating, a lower onset temperature and a shorter TR triggering time are observed in a penetration induced TR propagation test due to side heating. 2) The maximum temperature difference within a battery can be as high as 791.8 °C in a penetration induced TR propagation test. The voltage responses have a 5-stage feature, indicating that the TR happens in sequence for the two pouch cells packed inside a battery. The heat transfer analysis shows that: 1) 12% of the total heat released in TR of a battery is enough to trigger the adjacent battery to TR. 2) The heat transferred through the pole connector is only about 1/10 of that through the battery shell. 3) The fire has little influence on the TR propagation, but may cause significant damage on the accessories located above the battery. The results can enhance our understandings of the mechanisms of TR propagation, and provide important guidelines in pack design for large format lithium ion battery.

1. Introduction

Lithium ion battery is a promising choice to power today's electric powertrains, given its high energy density and extended cycle life. However, accidents associated with lithium ion battery failure have been reported from time to time [1–5], raising concerns and motivating research and development. The safety of lithium ion batteries, particularly associated with thermal runaway (TR) hazards, has received much attention.

The failure modes of lithium ion battery in field applications can be classified into 3 categories based on the major failure mechanism: mechanical failure, electrochemical failure and thermal

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failure [6,7]. All three modes may trigger a severe thermal hazard in a lithium ion battery system. Therefore compulsory test standards, i.e., SAE-J2464 [8], IEC-62133 [9,10], QCT-743 [11,12] and others [13–19], have been established. Safety risk still exists, although all the batteries in market can pass these test standards [20]. For example, small impurities mixed in the electrode active materials, which cannot be eliminated during the manufacture of batteries [6], may lead to short circuit defects after a long time of incubation [21] and therefore cause TR at some unpredictable point of time.

Internal short circuits (ISC) can cause severe TR of lithium ion batteries. Many researchers have studied the mechanisms of ISC [20–28] and four major approaches have been used to simulate an ISC [21]: (1) Inserting metallic particles into a battery [23]; (2) Making a battery with phase change material, which is activated at preset temperature, between the active materials [24]; (3) Indenting a battery with a blunt rod [21,25]; (4) Penetrating a battery with a nail or spike [25–28]. Nail penetration tests have long been used to simulate severe ISC induced by mechanical impact [8,11,12]. Nail penetration always leads to TR and is regarded as one of the most difficult tests for a lithium ion battery to pass.

Once a TR is initiated, TR propagation to neighboring cells is important as it can lead to violent thermal hazards. Several models have been developed to investigate TR propagation in a pack of 18,650 cells [29,30]. Simulations show that the TR propagation happens when the triggering battery is in good contact with others [29]. Experimental data is analyzed for the TR propagation behavior in a pack of 18650 cells [31]. However, little model validation work has been done.

For TR research, large format batteries are of special interest. On one hand, large format helps to reduce the number of cells, thereby reducing system complexity [32]. On the other hand, a large format battery is more vulnerable to TR because it contains more stored energy and has larger variation in its temperature distribution. A hot spot can cause local meltdown of the separator, leading to ISC. ISC could propagate to the whole battery resulting in a severe thermal hazard [33]. For large format lithium ion batteries, a TR model for a single cell was established a few years ago [33,34], followed by a model for TR propagation within a battery pack [35]. However, experimental validation has not been provided in literature to the best knowledge of the authors.

The goal of this paper is to analyze the mechanisms of a penetration-induced TR propagation within a large format lithium ion battery module, including both TR initiation and propagation processes to understand the mechanisms and gain insights to the thermal hazards of a battery pack system. The TR behavior of single battery is based on the work reported in Refs. [36,37]. In our experiments, the TR was triggered by nail penetration of the first battery, which might trigger TR propagation to subsequent batteries. Temperature distribution and voltage variation were used to characterize the mechanisms of TR propagation. Moreover, the physical damages caused by TR propagation were analyzed by disassembling the battery module after experiments. We choose $LiNi_xCo_yMn_zO_2$ (NCM) as the cathode of the battery because NCM cathode material demonstrates higher capacity, good thermal stability and lower toxicity among the family of Li-ion batteries [6,38,39].

2. Experiments

2.1. The battery

The 25Ah battery used in this paper is manufactured by the AE Energy Co. Ltd. with NCM/graphite as its electrodes [36,37]. The battery consists of two pouch cells in an aluminum shell, which are connected in parallel, as shown in Fig. 1a. A micro-thermocouple was inserted between the two pouch cells to measure the internal temperature of the battery.

Six batteries formed a battery module in a penetration induced TR propagation test. Fig. 1b shows the definitions of cell, battery and battery module in this paper. To avoid misunderstanding, we call the two pouch cells “cell” and the battery cell “battery” in the following sections. In other words, two cells formed a battery, and six batteries formed a battery module.

2.2. EV-ARC test of a battery

The battery was heated into TR using an extended volume-accelerating rate calorimetry (EV-ARC), as reported in Ref. [36]. An EV-ARC test follows the heat-wait-seek method and provides an adiabatic calorimetric environment for thermal analysis. The EV-ARC test result is used for further analysis in this paper. Fig. 2 shows the EV-ARC used in Refs. [36,37] and this paper.

2.3. Thermal runaway propagation tests of battery modules

Penetration induced TR propagation tests on a battery module were conducted using the penetration test bench (Fig. 3a) inside an explosion-proof room at the Battery Test Laboratory of China Automotive Technology and Research Center (CATARC). Six batteries were clamped together using two pieces of steel holder, as illustrated in Fig. 3b. Bat *i* ($i \in \{1,2,3,4,5,6\}$) is used to describe the *i*th battery towards the direction where the nail came in, e.g., Bat 1 was penetrated by the nail, while Bat 2 was heated to TR by Bat 1. Kapton tape of 0.6 mm thickness was used to wrap the batteries to avoid short circuits through the shell and to hold the thermocouples. Thermal resistant layers (made by asbestos) were inserted between the battery module and the steel holder to avoid excessive heat transfer to the holder.

Given the explosive nature of the testing, extra care had been paid to assure safety of the people and equipment involved. Cameras were employed to monitor the experiment so that the testers could stand outside the explosion-proof room to guarantee safety. Disassembling work after tests was performed after the toxic gases were exhausted by the air-blower inside the explosion-proof room.

Three tests were performed under different settings, as listed in Table 1. For experiment No. 1 and No. 2, the batteries were connected in series using connectors, while for experiment No. 3 the batteries were not connected. The battery voltage was monitored, and flame retardant layers were introduced to protect the voltage monitoring circuit from fire for experiment No. 2 and 3 but not for experiment No. 1.

47 Thermocouples (TC_1–TC_{47}) were placed at selected points within the battery module, as marked in Fig. 3b and summarized in Table 2. The internal temperature of the batteries were monitored by inserting TC_1–TC_8 inside the battery as described in Fig. 1. TC_1–TC_6 were placed at the center of each battery. In addition, two more TCs were placed inside Bat 1 (TC_7) and Bat 2 (TC_8) 20 mm away from the center to observe the temperature difference away from the battery core. The pole temperatures were monitored using TC_9–TC_{18}. TC_{19}–TC_{29} were placed on plane A (in red in the web version) and plane C, while TC_{30}–TC_{47} were located on plane B (in blue), as well as at the centers of the battery surfaces. TC_{19}–TC_{47} were used to analyze the temperature distribution within a battery.

Bat 1 was penetrated using a nail with 8 mm diameter at a speed of 10 mm/s. After Bat 1 was penetrated, TR propagated to adjacent batteries sequentially, as shown in Fig. 4. The TR propagation behavior, including the temperature and voltage responses, will be described in the following sections.