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Experimental study of internal and external short circuits of commercial automotive pouch lithium-ion cells

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ABSTRACT

In order to develop a deeper understanding of the behaviour of commercial automotive lithium-ion pouch cells under short-circuiting conditions, two scenarios were experimentally investigated and compared. Firstly, experiments were conducted by internally shorting 15 Ah cells by full nail penetration using three different nail materials; copper, steel and plastic. A second set of experiments involved externally shorting the cell tabs using an external circuit with a range of resistance values. In both scenarios the cell electrical and thermal response were determined by the shorting resistance. In the case of nail penetration there was a clear distinction between the outcome of the conducting and non-conducting nails, although the outcome using conducting nails suffered from poor reproducibility. The poor reproducibility was attributed to the variation in the contact resistance between the nail and the cell layers. Correlating the outcome of both tests can be used to estimate the shorting resistance and construct the current profile during nail penetration test.

1. Introduction

Currently, large-format lithium-ion batteries are the main battery technology used for hybrid and electric vehicles, primarily because of their high energy and power densities [1,2]. Their use is expected to rise - it is predicted that hybrid and electric vehicles will account for at least 50% of the total light duty vehicles sales worldwide by 2050 [3]. The use of high-capacity batteries in these vehicles comes with risks that must be understood and mitigated if possible to improve safety. There are a number of safety standards that mandate abuse tests to be conducted without failure in order for the battery cells to be approved for use in a specific application [4]. These abuse tests simulate the failure process and are used to develop a deeper understanding of the root cause of failure and its associated mechanisms. This work is aimed at investigating the cell response in more detail.

A short circuit is an event in which both electrodes are connected by a very low resistance path, resulting in a high current followed by rapid Ohmic heat generation. Short circuits can occur externally or internally: An external short circuit occurs when the tabs are connected by a low resistance path; an internal short circuit occurs when the insulating separator layer between the electrodes fails. In the case of nail penetration a metallic nail punctures the separator and connects the positive and negative current collectors, causing an internal short circuit. An internal short circuit can also occur when impurities or lithium dendrites puncture the separator, providing a low resistance shorts between electrodes. High capacity cells are at a higher risk of thermal runaway from internal short circuits [5].

Whether or not a cell will undergo thermal runaway is often related to heat build-up from the short circuit, which is the net effect of heat generation and heat dissipation. If heat generation is sufficiently greater that heat dissipation then the cell gets hotter and a critical temperature is reached where exothermic reactions form a chain reaction, leading to uncontrollable thermal runaway causing fire, gassing and explosion [6,7]. Heat dissipation is dependent on the thermal properties of the cell and cooling system [8]. Short circuits often result in an exponentially increasing rate of heat generation whilst the rate of heat dissipation increases linearly [9].

For automotive applications, nail penetration test is an important safety test and is compulsory in a number of safety

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standards. For example, at a cell level the FreedomCAR Abuse Test Manual for Electric and Hybrid Vehicles Applications requires the cell to be fully penetrated by a conductive pointed rod with a diameter of 3 mm and at a speed of 8 cm/s [10]. The Society of Automotive Engineers' (SAE) J2464 abuse test standards also specify the same test parameters [11]. Nail penetration with lithium-ion batteries are used to simulate abuse conditions such as penetration of the pack by a foreign object during a crash. An example of this is Tesla Model S battery pack catching fire after impact with a metallic object on the road [12]. Nail penetration is also used to simulate internal shorting from field failures, such as imperfections in the cell manufacturing process, although it is recognised that it may not be fully representative. Both scenarios can result in large short circuits and high rates of heating.

This paper experimentally investigates internal and external short circuits of commercial automotive-grade pouch cells. The ultimate aim of this work is to develop more representative and reproducible testing procedures, understand abuse mechanisms and make cells safer and more abuse tolerant for the automotive industry.

1.1. Nail penetration

As shown in Fig. 1, when the nail penetrates a battery cell it internally connects the anode and cathode current collectors. This means that a current flows between the nail and the electrodes. It is assumed that when the nail fully penetrates the cell each electrode is shorted independently by the nail.

The discharge process of the cell takes place as follows; electrons and lithium-ions are produced by delithiation reactions at the anode active material. Electrons then travel to the anode copper current collector where they converge towards the short circuit contact spot created by the nail. The electrons are then conducted along the nail to the cathode aluminium current collector. The lithium-ions on the other hand are transported from the anode to the cathode through the electrolyte and separator. The lithiation reaction takes place at the cathode active material when the electrons transported by the nail meet the lithium-ions transported through the separator. Heat is generated in both the nail and the cell primarily by current flowing through them [13].

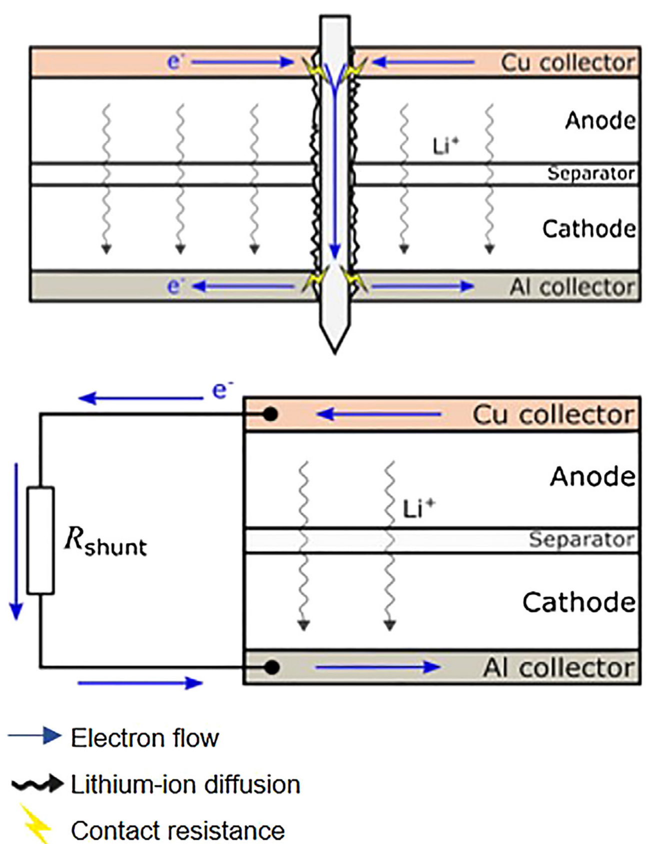

Fig. 1. Schematic diagram comparing electron flow, lithium-ion diffusion and contact resistance during nail penetration and external short circuit.

The initial shorting current is influenced by the shorting resistance, contributed primarily by the contact resistance of the electrical interface between the nail and the current collectors of the cell, as well as the resistance of the nail. After an initial surge of high current, lithium ion is depleted in the cathode active material; the movement of ions through the electrolyte and separator limits the replenishment of lithium ions and in turn limits the shorting current and the Ohmic heating [7,14]. Assuming the ionic conductivity is efs>]. Assuming the ionic conductivity is unchanged between the cells, the different shorting resistance caused by the inherently random contact interfaces formed between the nail and the damaged cell layers is responsible for the resulting current and heating profiles.

The shorting resistance (R_s) is determined by the nail resistance (R_{nail}) and how well the contact between the nail and the current collectors known as the contact resistance (R_{cnt}) is. Zhao et al. [15] describe the contact resistance as extra series resistance to the electron flow between the nail and the electrodes as shown in Fig. 1 and can be mathematically expressed in Eq. (1).

$$R_s = R_{nail} + R_{cnt} \tag{1}$$

It is expected that the nail properties would affect the nail resistance and hence the outcome of the nail penetration test. But this is only the case if the contact resistance is the same every time which does not occur, because of the randomness of the interaction between the nail and the bilayers. Modelling work shows that for the same penetration test the cell can respond very differently because of the difference in shorting resistances [15].

1.2. External short-circuit

During an external short circuit the current path is similar to normal discharge as shown in Fig. 1. Lithium-ions and electrons are liberated at the anode. Lithium-ions travel across the electrolyte towards the cathode where they are intercalated into its structure, while electrons travel from the anode to the cathode through the external circuit resulting in an electrical current. As with the case of nail penetration, the shorting current is determined by the combined resistance of the current path. For the external short circuit scenario this resistance combines the resistance of the external circuit elements, the wiring and the connections, the tabs and the internal cell resistance. The current is also limited by the ionic movement of lithium-ions in the electrolyte.

1.3. Comparison of nail penetration and external short circuit

Both internal and external short circuit scenarios can result in excessive discharge rates of the energy stored in the cell resulting in heat generation. In both cases the initial response depends on the shorting current, which is determined by the resistance of its path (shorting resistance). To correlate the outcome of both tests the variables that determine the electrical and thermal response should be compared.

In both cases, current is determined by the shorting resistance, but the current flow path is different. As shown in Fig. 1, during external short circuits electrons move through the current