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Thermal runaway risk evaluation of Li-ion cells using a pinch–torsion test

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HIGHLIGHTS

- A pinch–torsion test is designed to evaluate Li-ion cell safety under simulated internal short-circuit conditions.
- The torsion component can trigger internal short-circuit at a lower load with smaller short spot size.
- TRR (thermal runaway risk) scores are proposed to rate cell safety performance.
- This method can distinguish commercial cell safety performance in a wide range of state of charge.

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ABSTRACT

Internal short circuit (ISCr) can lead to failure of Li-ion cells and sometimes result in thermal runaway. Understanding the behavior of Li-ion cells in ISCr condition is thus critical to evaluate the safety of these energy storage devices. In the current work, a pinch–torsion test is developed to simulate ISCr in a controlled manner. It is demonstrated that the torsional component superimposed on compression loading can reduce the axial load required to induce ISCr with smaller short spot size. Using this pinch–torsion test, two types of commercial Li-ion pouch cells were tested under different state of charge (SOC). Based on the severity of the cell damage, a series of thermal runaway risk scores were used to rate the thermal stability of these cells. One of the cell types showed significantly increased hazard as the SOC increased while the other type exhibited relative uniform behavior among different SOC. Therefore, this novel pinch–torsion test seems to be an attractive candidate for safety testing of Li-ion cells due to its abilities to consistently create small ISCr spots and to differentiate cell stability in a wide range of SOC.

1. Introduction

In recent years, safety issues of Li-ion batteries have received much attention due to their increased applications in consumer electronics, transportation, and power grid energy storage. Internal short circuit (ISCr), which can occur due to manufacturing imperfection, operational abuse, or mechanical abuse, is believed to be a major cause of field incidents associated with commercial Li-ion batteries [1,2]. If a large amount of energy is released during ISCr, local temperature rise could trigger various chemical reactions [3], which may lead to thermal runaway and in some extreme cases fires and explosions [4].

Various testing methods have been developed to simulate the ISCr events, including forced ISCr test [5], nail penetration [5–7], small indentation [7,8], and cell pinch test [1]. While these methods face difficulties in introducing small, isolated ISCr spots in a reproducible manner, an improved pinch test developed by Cai et al. [2] demonstrated good repeatability in creating ISCr with controllable size in Li-ion and Li-ion–polymer cells. The size of the ISCr spots was varied by changing the stroke-return voltage; and ISCr spots as small as 1–2 mm were easily reproduced [2].

However, this test experienced difficulties in testing cells with a high state of charge (SOC). For example, when comparing three different cell types, 100% of each type went thermal runaway at a charged voltage of 4.2 V [2], making it impossible to distinguish the thermal stability of these cells. Similar results were observed when applying this pinch test to large-capacity cells (15–25 A h) during which thermal runaway was often encountered. After careful examination of puncture locations in the failed cells, it was believed the areas experiencing higher percentage of tension failed much earlier than areas under compression. In order to demonstrate this observation a simple anode/separator/cathode sandwich structure was tested on an MTS machine that can apply a “twist” in the *X–Y*

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plane during compressive loading in the *Z*-direction. When a small rotation was applied during the compression, the separator failed at a smaller loading force. When the same tests were repeated on small pouch cells, ISCr could be induced (as indicated by a voltage drop) without causing severe thermal runaway. These preliminary results suggested that a combined pinch and *X*–*Y* torsion could generate smaller ISCr spot size than the pinch only.

Although it is hard to confirm after a field thermal runaway event, it is believed that the actual spot size of ISCr is usually very small. Possible sources for ISCr are Li dendrites formed during cell operation and machining debris/metal particles introduced in the manufacturing process. Therefore, generating smaller ISCr size can better simulate the field conditions. Furthermore, reducing the short size could induce ISCr without causing catastrophic damage, making it possible to distinguish safety behavior under high SOC.

The hypothesis that torsion can reduce the ISCr size during pinch test was demonstrated through two series of experiments. Comparison between the pinch-only and pinch–torsion tests was first performed on a three-layer (anode-separator-cathode) dry cell mentioned above, and then extended to multi-layer Li-ion pouch cells. Using the new pinch–torsion test, two types of commercial Li-ion pouch cells were then examined. These cells exhibited different thermal responses under various SOCs. The combined pinch–torsion tests were able to distinguish ISCr behaviors of fully charged (4.2 V) Li-ion cells. A thermal runaway risk (TRR) scoring system was also proposed to evaluate the thermal stability of Li-ion cells based on the changes of cell temperature and voltage under ISCr testing.

2. Experimental method

Pinch–torsion tests were performed on a commercial axial/torsional servo-hydraulic testing machine (Model 809, MTS, Eden Prairie, MN, USA). Two steel loading rods were aligned to pinch the Li-ion cells from both directions. The ends of the loading rods were hemispheres with a diameter of 12.7 mm. The test set-up is shown in Fig. 1a. Displacement control was used in all tests.

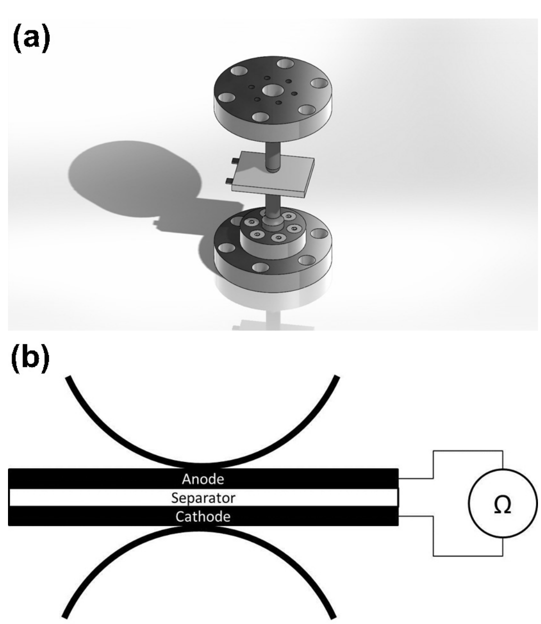

Fig. 1. Schematics showing the (a) pinch–torsion test setup and (b) the three-layer dry cell configuration.

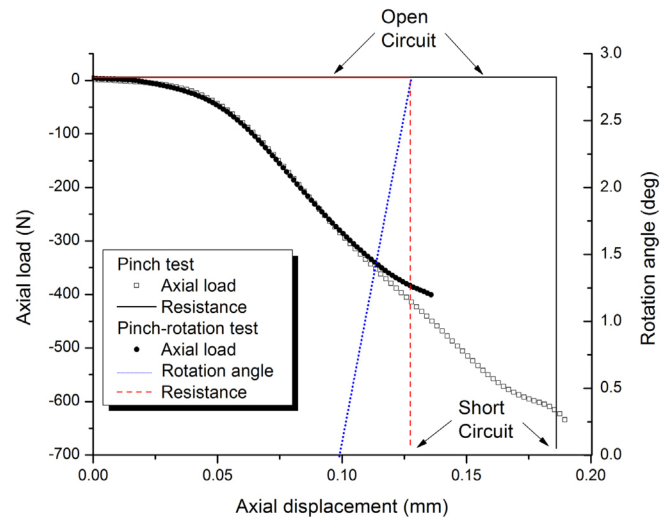

Fig. 2. Comparison of loading curves during pinch and pinch–torsion tests of the prototype cells. The abscissa shows the movement of the testing rod in the direction parallel to the cell thickness (the axial direction). The ordinate on the left hand side shows the force in the axial direction and the ordinate on the right hand side shows the measured angle of rotation (pinch torsion test only).

For the prototype dry cells, the resistance between the positive and the negative electrodes was monitored. When ISCr occurs, this resistance would change from infinity (open circuit) to a definite value (typically a fraction of Ohm). For the pouch cells, the voltage between the positive and negative electrodes was monitored. The occurrence of ISCr was determined when a voltage drop of 0.1 V was detected [2]. Temperature on the outside surface of the cells was recorded using thin film thermocouples. For commercial Li-ion cells testing, an enclosure box connected to the exhaust and filtering systems was used.

While the original pinch test can be applied to pouch cells and prismatic cells in aluminum cans, the pinch–torsion test only applies to pouch cells since our preliminary results suggested additional torsion did not prompt earlier failure when testing the latter. It is because the effective torsion force depends on not only the normal compressive force but also the friction between the contact surfaces. It was likely that the friction between the steel loading rods and the aluminum can was too small to be effective in transferring the torsion force.

After testing, cells were opened and damaged separators were examined using optical microscopy.

3. Pinch test versus pinch–torsion test

This section will discuss pinch-only and pinch–torsion tests performed on the dry cells as well as multi-layered pouch cells.

3.1. Prototype cells

To explore the effect of torsional component on creating ISCr during pinch tests, dry cells (Fig. 1b) were constructed from common materials used in commercial Li-ion batteries. A graphitic anode layer, a polymeric separator, and an LCO-coated aluminum cathode layer were stacked and encapsulated without electrolyte using polymeric pouch material. Metal tabs were attached to the electrodes for the measurement of electrical resistance. The lateral size of the dry cells was approximately 50 mm × 80 mm. Since no electrolyte was used, the electrical resistance between the anode and the cathode was monitored and used to determine the occurrence of ISCr (Fig. 1b). The axial loading rate in pinch-only and