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Internal configuration of prismatic lithium-ion cells at the onset of mechanically induced short circuit

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HIGHLIGHTS

- Cross-sectional areas of mechanically deformed Li-ion cells were studied.
- Tearing of current collectors, kinking and fault lines were observed.
- Internal short circuit occurs under complicated mechanical deformation conditions.
- New mechanical models are needed to simulate the soil-like behavior.

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ABSTRACT

The response of Li-ion cells to mechanically induced internal electrical shorts is an important safety performance metric design. We assume that the battery internal configuration at the onset of electrical short influences the subsequent response and can be used to gauge the safety risk. We subjected a series of prismatic Li-ion cells to lateral pinching using 0.25″, 0.5″, 1″, 2″ and 3″ diameter steel balls until the onset of internal short. The external aluminum enclosure froze the internal cell configuration at the onset of short and enabled us to cross-section the cells, and take the cross-section images. The images indicate that an internal electric short is preceded by extensive strain partitioning in the cells, fracturing and tearing of the current collectors, and cracking and slipping of the electrode layers with multiple fault lines across multiple layers. These observations are at odds with a common notion of homogeneous deformation across the layers and strain hardening of electrodes that eventually punch through the separator and short the cell. The faults are akin to tectonic movements of multiple layers that are characteristic of granular materials and bonded aggregates. The short circuits occur after extensive internal faulting, which implies significant stretching and tearing of separators.

1. Introduction

Li-ion batteries have been widely used to power portable electronic devices. Recently, Li-ion batteries have transitioned from prototype to commercial electric vehicles [1], where vehicle crashworthiness and safety are major design considerations. Vehicle crash can expose batteries to intense deformation and accelerations so that battery response under dynamic loading must be included in the overall safety assessment [2]. Unlike portable electronics devices which use a small number of low capacity cells, electrical vehicles can use hundreds of large-format, tightly-packed, high-capacity cells. As the numbers of electric vehicles increase on the road, the chances of accidents proportionally increase. Li-ion batteries and the supporting structures must be designed to remain safe when subjected to high-speed impacts. Lacking an in-depth understanding of how the batteries fail under mechanical deformation, the current approach is to protect the batteries by heavy, armor-like enclosures [3]. This adds significant weight to the vehicle and reduces its range and energy efficiency. Even with a heavy protection, batteries can still deform under extreme crash conditions and understanding of the safety risks associated with deformation is needed.

Various tests have been developed to evaluate the safety of Li-

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ion cells under mechanical deformation. The techniques to induce internal short circuit on fully assembled cells are nail penetration [4], indentation [5,6] and pinch [7,8] tests. The purpose of these tests is to create a small break in the separator mimicking the very rare internal short circuit events in Li-ion cells. Mechanical abuse tests of the Li-ion cells include dropping [9,10], and crushing [11]. These tests focus on the overall cell response to mechanical deformations and the subsequent thermal events. No experiments have been reported in the literature for investigating the detailed mechanisms of internal cell deformation and configuration leading to internal shorts due to lateral mechanical deformation. Crush and impact tests have also been carried out for cells, modules and packs used in electric vehicles [11]. These tests focus on battery response and safety risks after mechanical deformation. The test results, safety outcomes and ranking of thermal events are usually based on the USABC tables [12].

The main reasons for the lack of mapping of the kinematic processes of internal mechanical deformation of the battery cells are the destructive nature of the mechanical abuse tests and the difficulties associated with freezing the battery state. Since the final outcome is usually a short circuit, thermal runaway or fire, there is often very little evidence left to examine. Even for tests that do not end with thermal runaway, local heating can melt the separator(s) making post-mortem interpretation of the samples very difficult. Jellyrolls are kept under compression in cells and have significant spring-back when the cell casing is removed. Opening the cells after mechanical deformation and peeling each layer to find and expose the origin of failure eliminates much of the in-situ deformation information. For most pouch cells, the original deformation cannot be retained as soon as the applied force is removed because of the combination of the spring back of the jellyroll and the flexibility of the pouch enclosure.

Li-ion cells have been studied non-destructively using X-ray tomography [13,14] and neutron imaging [15,16]. The cost, setup constraints and interpretation of the data limit their effectiveness and practicality.

In this paper, we report on a procedure to study the internal configuration of Li-ion cells at the onset of electrical short due to mechanical loading. Commercially available $LiCoO_2$ prismatic Li-ion cells with 800 mAhr capacity in aluminum cans were subjected to lateral mechanical pinch. The cell capacity was kept at minimum to avoid thermal damage and a voltage drop was used as the indicator of the onset of internal short circuit. The aluminum enclosures of the cells froze the internal mechanical deformation after the removal of external load. The deformed cells were discharged and cut using a slow-speed diamond saw at the center of indentation. The cross-sectional areas were then imaged using optical microscopy. This technique allowed us to investigate the actual kinematic processes of deformation inside the Li-ion cells. This study gives the first-hand information about the prevailing internal kinematic deformation mechanisms of Li-ion cell and suggests directions for modeling of the jellyroll response and the onset of short circuit.

2. Experimental setup

The pinch test configuration was similar to previously reported tests [7] for internal short circuit simulation. The Li-ion cells used are commercially available $LiCoO_2$ batteries with dimensions of $34 \times 42 \times 4.3$ mm and capacity of 800 mAhr. Fig. 1(a) shows a schematic of the pinch test setup. The two steel spheres shown in Fig. 1(a) were used to apply concentrated coaxial loading on both sides (top and bottom) of a prismatic cell. The spheres were connected with rigid rods to the actuator and load cell of a servo hydraulic mechanical testing machine (MTS Systems with model 407 controller). Stainless steel spheres of diameters between 0.25 inch and 3 inch were used. Internal short circuits were typically detected at > 60% reduction of the total thickness. A polycarbonate box was used to contain fragments in case a cell went into thermal runaway during the test and was connected to the laboratory's ventilation system. The tests were carried out under constant speed controlled by the machine's actuator. The cell open circuit voltage (V_{ocv}) was used as feedback to a computer controlling operation of the servo hydraulic testing machine. Whenever the cell open circuit voltage V_{ocv} dropped below a preset threshold value, i.e. 0.10 V, the motion was stopped and the moving sphere (the other sphere was stationary) returned to its initial position. Various control parameters, such as sphere size, loading speed, stroke response mode (hold or return when the V_{ocv} of a cell drops below a preset threshold voltage), and the preset threshold voltage, can be adjusted. The picture in Fig. 1(b) shows a Li-ion cell after pinching with 0.5″ diameter spheres. Fig. 2 shows the results of a typical pinch test using 1-inch diameter steel balls. The battery was charged to 4.0 V and short circuit occurred at 64.2 s with maximum load of 1947 pounds and displacement of −0.064 inch (−1.65 mm).

3. Results and discussion

3.1. Mechanical deformation of Li-ion cells using 0.25″, 0.5″, 1″, 2″ and 3″ diameter spheres

Mechanical deformation of the internal layers of Li-ion cell after pinch tests using 0.25″, 0.5″, 1.0″, 2.0″ and 3.0″ diameter spheres are shown in Fig. 3(a)–(e). The following kinematic features of deformation were observed:

- *Tearing of current collectors*: Current collectors under the indenter are discontinuous, showing evidence of cracking and tearing.
- *Through layer cracking (fault lines)*: In Fig. 3(a)–(c), shear-type faults span multiple-layers and are oriented at approximately a 45° angle.
- *Kinking of layers*: Correlated kinking extending for multiple layers from the indenter can be seen in Fig. 3(a)–(e).
- *Local melting*: Small black voids without the original materials were observed in Fig. 3(e).

Fig. 4 shows close-up views of the Li-ion cell after a pinch test using 0.25″ spheres. The current collectors beneath the aluminum can in Fig. 4(a)–(b) are torn apart by several 45° angle faults. The cross section images show the current collector fragments between 200 μm and 700 μm indicating multiple, possibly radial, cracks from the center of the indentation. In Fig. 4(b), the copper and aluminum foils on opposite sides of shear faults are separated by a significant amount. Electrode materials previously contained between the current collectors were able to “flow” into the faults pushing the torn current collectors to deform along with the separators. The distribution and curvature of the current collector act as tracers of deformation and movement. Folding of the layer and kinks are shown clearly in Fig. 4(c).

The kinking of the electrodes near the edge of the cell-can, in Fig. 4(b) and (c), shows cell edge deformation under mechanical abuse. It is one of the main modes of internal short circuit under soft mechanical deformation (e.g. drop on the edge), in which the separator tends to fold back into itself causing anode–cathode micro-shorting. This failure mode often shows a latent effect (battery self-discharge).

Fig. 5 shows close up images of a cell after a pinch test using 0.5″ diameter spheres. The smaller curvature of the spheres caused more homogeneous deformation of the electrode material layers. However, shear faults still dominate the global deformation, as