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Evaluation of mechanical abuse techniques in lithium ion batteries

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HIGHLIGHTS

- We examined mechanical techniques to generate internal short circuits in Li-Ion cells.
- Multiple test conditions and cell constructions were evaluated.
- Post-mortem analysis was performed using CT imaging.
- Results were found to vary significantly with test conditions and cell construction.

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ABSTRACT

Mechanical tests are a commonly used method for evaluating the safety performance of batteries. The mechanical blunt rod testing method, as well as sharp nail penetration, was performed on commercially available cells. Evaluation was carried out on different cell constructions as well as varying test conditions. Results obtained at ambient conditions were found to differ little from traditional sharp nail penetration testing. When tested at elevated temperatures it was observed that the results became heavily dependent upon the internal construction of the cell. Computed Tomography (CT) imaging confirmed this, showing differences in behavior depending on whether or not a solid core was used in the cylindrical cell construction. Pouch cells were tested as well, showing that a full penetration of the cell was necessary to initiate a failure event within the cell.

1. Introduction

Lithium ion batteries have been in use in the consumer electronics industry for well over a decade. Further, they are increasingly being applied to vehicular and stationary energy storage applications. In this time awareness of potential safety issues has increased dramatically [1–4]. Field failures of lithium ion batteries in consumer electronics devices have been well documented and prompted several large scale recalls of product. In nearly all cases, field failure was the result of an internal short circuit developed over the course of normal use. Several causes have been identified including mechanical defects introduced during manufacturing, small impurities trapped between the electrode layers and dendritic growth of lithium or other metallic particles bridging the electrodes [2,5,6]. Because these develop and progress over time, and are extremely rare, quality control at the point of manufacture is generally unable to detect these faults. This leaves the option of understanding and mitigating the consequence of internal short circuit failures. Traditionally, mechanical intrusion of a cell, such as through nail penetration, has been used as a method to simulate an internal short circuit. However, recent work has shown that these methods are not entirely representative of most spontaneous internal short circuits [7–10]. However, while significant work has been performed to develop more appropriate testing methods, a general consensus on methods to initiate internal short circuits has not been reached. Because of this, many testing laboratories continue to use mechanical methods as a substitute for a broadly accepted internal short circuit test. Further, the usage conditions of lithium ion batteries are continually evolving. Testing and evaluation of batteries for consumer electronics devices has typically focused on the impacts of spontaneous failure of the cells, or the impacts of electrical and thermal abuse as severe mechanical damage was unlikely. Physical damage to a cell that is relatively unlikely in a consumer electronics device is an eventuality that

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must be prepared for in mass produced electric vehicles. This leads to an importance to more fully understand the nature and impacts of mechanical testing. The work presented here is to better understand the nature of mechanical abuse testing, such as its reliability, the impact of varying test conditions and the impact of differing cell constructions. It does not attempt to make an evaluation of the suitability of mechanical testing as an internal short circuit test.

Nail penetration tests of Li-Ion cells, where the cell is rapidly punctured with a sharp nail, have long been used as an abuse test [11]. Further, without a strong standard for internal short circuit tests, they are used as a stand in to simulate an internal short as well. This is considered problematic due to the fairly complex nature of battery internal short circuits. Internal short circuits have been observed to occur from anode to cathode, anode to Al current collector, cathode to Cu current collector, and between the Al and Cu current collectors, with varying results [9,10,12–15]. Nail penetration creates a relatively large shorting volume with multiple electrode layers brought into electrical contact with one another as well as shorting through the nail, plus significant immediate damage to the cell. This creates a very non-localized electrical pathway, with the failure caused by the nail occurring over a fairly large volume. Other forms of mechanical abuse, such as flat crushing and three point bend tests have been studied by Greve and Fehrenbach [16] as well as Sahraei et al. [17], finding that failures in these conditions typically arise from macroscopic damage to the electrodes, such as large cracks through the electrode jelly roll or delamination of electrode layers. Typical field failures, meanwhile, rise from relatively small defects and begin as a very localized process. Among other effects, this leads field failures to have a relatively high impedance (at least initially) and concentrate the related heat generation in a very small volume when compared to the failure caused by a sharp nail penetration [10,12,13,15]. This has led to the development of various tests to try and simulate internal short circuits within Li-Ion cells.

Several tests have been developed that use some sort of mechanical deformation to damage the cell, the most well-known of which being the aforementioned nail penetration test. Other mechanical techniques attempt to deform the cell enough to cause a failure without causing significant physical damage to the cell. Researchers at Oak Ridge National Laboratory and Motorola [7,8] have developed such a test for prismatic pouch cells that attempts to create a short circuit between the anode and cathode by compressing a point of the cell between two spheroids. Some attempts have been made to generate internal shorts using more representative non-mechanical methods. Orendorff et al. [9] at Sandia National Laboratories have proposed using an insert of a low melting point metal to generate a controllable short circuit by slightly elevating the temperature of a cell. Researchers at TIAX LLC have reported a method of generating shorts by depositing metallic defect particles in a cell and growing them dendritically through battery cycling [10]. Such testing methods represent the ongoing work to develop a true internal short circuit test applicable to lithium ion cells.

The method used in this work was first developed by Underwriters Laboratories and NASA [12,18] and creates a failure by mechanically deforming a cell with a blunt rod. This attempts to simulate an internal short circuit by applying force normal to the axis of a cylindrical cell sufficient to cause the outer electrode layers to come into contact with one another and short but without doing significant damage cell itself. The objective of this work is to evaluate this method under different test conditions and battery constructions as well as expand on the method by evaluating its applicability to different cell orientations and cell types. Testing was performed on commercially available 18650 and pouch cells.

2. Experimental

Experiments were performed on commercially obtained 18650 Li-Ion batteries and pouch cells. Cell A is a LG 2200 mAh cell, model ICR18650 S3. Cell B is a Panasonic 2200 mAh cell, model CGR18650CG. The pouch cells used are 3000 mAh cells from AA Portable Power Corp (model PL-7035130-10C), purchased at www.batteryspace.com. These cells use collocated current tabs and have dimensions of 7.4 mm × 35.5 mm × 130 mm. Computed Tomography (CT) scans were used to evaluate the internal structures of the cells before testing and can be seen in Fig. 1. The most prominent difference observed between the two cells is that type B (Fig. 1 right) has an easily observed solid core present in the center of the spiral wound cell. Both cell types at 100% state of charge have a nominal capacity of 2200 mAh and cell voltage of 4.2 V. Cell type A (Fig. 1 left) used proprietary mixed metal oxide cell chemistry, while cell type B as well as the prismatic pouch cell evaluated used $LiCoO_2$ based cell chemistry. Computed tomography imaging was performed with a Northstar Imaging CT X50 with microfocus capability.

Blunt rod indentation and puncture was performed using a 3 mm diameter (nom.) stainless steel blunt rod. The blunt rod is mounted to a hydraulically driven actuator with a stroke of 9 inches and a maximum applied load of 10,000 lbf. Tested batteries were held in place with brass fixtures, insulated to prevent electrical contact from the cell can to the fixture and fitted with cartridge style heaters to allow testing at elevated temperatures. Two fixtures

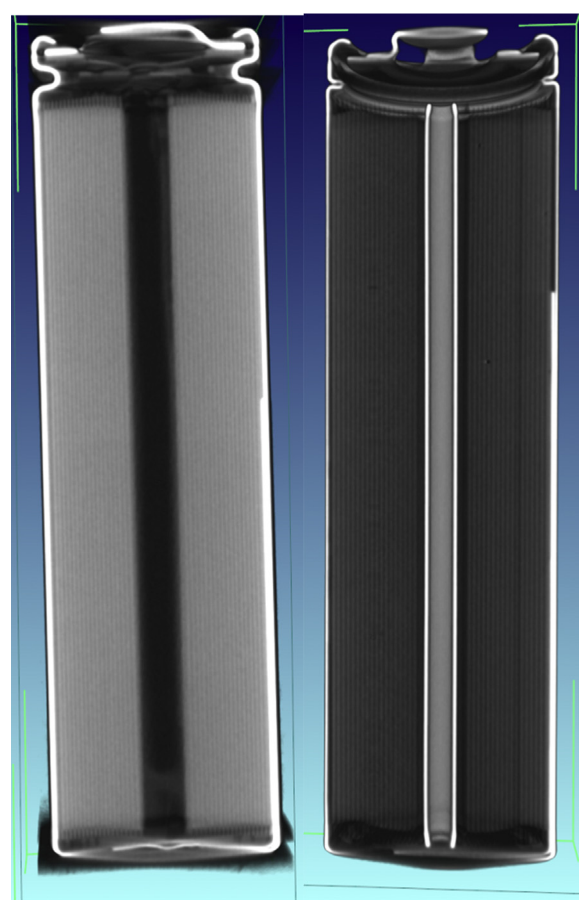

Fig. 1. CT imaging showing the internal construction of cell type A (left) and B (right). The primary observable difference is the presence of a solid core in type B, while in type A the center of the cell is left empty.