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Effects of electrolyte, loading rate and location of indentation on mechanical integrity of li-ion pouch cells

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HIGHLIGHTS

- Analyzed effects of electrolyte presence on material properties of lithium ion cells.
- Examined effects of punch location on mechanical response of lithium-battery cells.
- Studied changes in cell response at various loading rate.
- Investigated repeatability of mechanical punch testing .

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ABSTRACT

The safety of lithium-ion batteries under mechanical abuse conditions is an essential feature where these cells are used in mobile applications such as electric vehicles. In recent publications, punch testing has been used as a benchmark to study the mechanical abuse tolerance of the cells. What has not been studied in depth is how various test conditions such as the loading rate or the location of indentation affect the response of the cell. This paper quantifies the effects of four important test variables on the results of mechanical indentation tests. The first factor studied was to what degree tests on dry dummy cells without electrolyte can predict the response of a production cell. Then the effects of loading location, center versus on the edge, was evaluated. The speed of the test, at quasi-static rates, was the third variable. The last test characteristic studied was the repeatability of punch loading experiments. After completing the test program, a finite element model was developed to simulate the response of all studied cases. The model showed good predictability of load-displacement response and the onset of short circuit under all loading scenarios studied in this research.

1. Introduction

Lithium-ion batteries have a high energy density and no memory effect, making them attractive for a variety of applications from small electronics to electric vehicles and airplanes. The safety of lithium-ion batteries is extremely important due to their widespread use in consumer products including vehicles. While much is understood about lithium-ion batteries, no comprehensive computational models exist to predict their safety and optimize these batteries before manufacture.

The battery research of the Impact and Crashworthiness Laboratory (ICL) at the Massachusetts Institute of Technology has been focused on understanding the lithium-ion battery's mechanical properties so that individual battery cells and battery packs can be characterized during crash events. This work began in 2010 with the mechanical testing of small cylindrical and pouch cells to develop a finite element model of a lithium-ion cells using representative volume elements (RVE). The first RVE models used an isotropic homogenized foam model to represent the interior of the battery [1–5], but subsequent models incorporated the characteristics of the individual layers [6–8]. Mechanical testing of batteries by the ICL included compression, indentation, and three-point bending of different sizes and types of batteries and at different states of charge (SOC). Tensile, biaxial punch, compression and other tests were performed on battery interior components, including individual anode, cathode, separator, and multilayer samples [7,9–12]. All test results were incorporated into new or existing computational models to further refine and validate them. A summary of the above research is published in a recent review paper by Kermani and Sahraei (2018) [13].

Studies on the mechanical properties of lithium-ion batteries has been conducted by other research groups as well. Researchers from the University of Michigan have studied the mechanical properties of large

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lithium-ion cells and modules under compressive loading scenarios and developed relevant computational models [14–16]. The mechanical properties of large cylindrical cells have been studied by Volkswagen [17] and researchers from the University of Wisconsin [18]. Additional research on 18650 cells and the effects of state of charge and dynamic loading on mechanical properties of these cells has been reported by researchers from Beihang University [19,20]. Despite the recent advances in research on the mechanical behavior of lithium-ion batteries, there are still many unknowns in understanding the complete properties of these cells. In this research, authors have focused on answering three major questions posed by industry: the effects of electrolyte, loading rate, and location of indentation on the mechanical integrity of lithium-ion pouch cells. In addition, the repeatability of punch tests was explored.

In many studies, researchers use a dry cell with no electrolyte or cut out a sample of a cell, allowing the electrolyte to evaporate resulting in a dry sample, to study the material properties of lithium-ion batteries [16,18]. However, there have not been any systematic studies to understand how the behavior of a dry cell replicates or differs from the response of a cell with electrolyte. This study sheds light on the points of similarity and differences between the two. Additionally, no investigation on how material properties may change when the indentation location changes from the center toward or at the edges of the cell has been conducted. In all publications focusing on the indentation of batteries, loading has been applied to the center of the cell. This research investigates the changes in material properties from center to edges of a pouch battery cell.

The effects of loading rate on the response of the cell is also explored in this research. Few recent studies report on the dynamic response of cylindrical and pouch cells [19,21]. Most previous research and modeling work used quasi-static loading scenarios [2,14,17,22] without analyzing effects of quasi-static loading rates on the response of the cell. Finally, repeatability of punch testing was studied. Punch testing is used as a benchmark to determine mechanical abuse tolerance of lithium-ion cells, but this testing is destructive, expensive, and poses safety concerns. Therefore, the testing is sometimes limited, making repeatability an important factor. To study the above topics, a series of experimental tests were completed. In each series, one factor was varied, and all other variables remained constant. The results were then used to develop a Finite Element model for the subject pouch cell to further analyze the changes in material properties due to changes in the specific cell or loading conditions.

2. Experiments

Commercially available pouch cells were used for testing with and without electrolyte (live cell and dry cell). The cells had Lithium Nickel Cobalt Oxide chemistry, a nominal capacity of 52 A h, and a volumetric energy density of 280 W h/l. Shape and dimensions of the cell are shown in Fig. 1. The live cells were discharged to 0% SOC for safe testing. Both dry cell and discharged live cells were used for compression and hemispherical punch testing with the MTS Loading Frame as shown in Fig. 1.

2.1. Test equipment

The primary test equipment used for this research was a displacement-controlled 200 kN MTS Loading Frame with a crosshead speed range of 0.1 mm/min to 1000 mm/min. The MTS machine was fitted with flat cylindrical punches for compression tests and hemispherical punches for indentation, or punch tests. Testworks© 4 software measured the force and recorded the displacement. In addition, an Imaging Retiga 1300i digital camera and Vic-Snap™ and Vic-2D™ digital image correlation (DIC) software recorded and calculated the displacement from test equipment that was marked. A RadioShack© 46-Range Digital Multimeter and Meterview software recorded voltage and resistance. In order to ensure safety during cell tests, a ventilated enclosure and an extension rod for the MTS machine were also used.

Tape with markings was attached to the MTS fixtures, and the DIC camera tracked the markings for comparison with the MTS displacement results. The voltage and resistance of the cells were recorded using a multi-meter. For the discharged live cells, a short circuit was detected in the cell when the voltage started to drop.

The experiments were designed to study effects of five variables on test results. First parameter studied was effects of electrolyte. For this purpose dry and live discharged cells were subjected to flat compression and punch indentation loads and the differences in the response of these cells were investigated. The tests were conducted on cells with pouch cover. However, previous research has shown that pouch cover, which is a thin foil of fused aluminum/polyester, do not add any strength to the cell under these loading scenarios [2], and the measured data directly reflects the properties of the electrode/separator stack. The second factor was the location of loading. For this purpose, hemispherical punch loading was applied to a matrix of points starting from center of the cell and moving toward the edges and the results were compared. The third factor studied was quasi static rate of loading, tests were performed at speeds of 0.2–20 mm/min. The last item was the repeatability of test results. For this purpose, indentation tests with three different punch diameters were conducted and the range of variability of repeated identical tests were identified.

3. Finite element modeling

Two types of models have been used to simulate through thickness behavior of pouch lithium-ion cells, using isotropic and anisotropic crushable foam materials [2,4,6]. The observation of an isotropic separator failure from the indentation tests of the pouch cells in this study indicates that the isotropic crushable foam model available from the library of LS Dyna software will be suitable for the simulation of this cell. This material model works in the plane of principal stresses and behaves differently in tension and compression. The behavior in tension is elastic until reaching a tensile cut-off value σ_{YT}, which caps the highest stress the material can tolerate in tension. A hardening stress-strain curve is defined in compression. Here the compressive hardening curve is calibrated from the flat cylinder punch shown in Fig. 1. A transition area between the compressed and free section of the cell have minimal contribution to the total force and can be neglected in calculation of stress-strain curves [4]. Therefore, compressive hardening stress (σ_{YC}) can be directly calculated by dividing total force (F) by punch cross sectional area (A), i.e. $\sigma_{YC} = \frac{F}{A}$. Compressive stresses for live and dry cells are shown in Fig. 2. The tensile response of the cell cannot be directly calculated from any of the punch cells. Therefore, tensile coupon tests were performed on all components of the cell, and the aggregated tensile curve was calculated as a weighted average of the system of layers undergoing same strain ($\sigma_{avg} = \frac{\Sigma\sigma_i t_i}{\Sigma t_i}$) where σ_i and t_i are the stress and thickness of each layer. The aggregated tensile curve was used to calculate the Young's Modulus (4200 MPa) and tensile cut-off stress, (18 MPa). Cell density was calculated from the mass and dimensions of the cell (2.530e-009 tonne/mm3).

A finite element model of the pouch cell was developed in LS Dyna explicit finite element code, using 31416 solid elements. All components of the pouch cell, including the cover were homogenized into a single part. A multi-step mesh was used to reduce number of elements and accelerate simulations. The mesh size used under the punch was 1.2 × 1.2 × 1 mm and was increased to 2.5 × 2.5 × 1 mm and 10 × 10 × 1 mm when moving outside the loading area, as shown in Fig. 5.

4. Results and discussion

First set of results presented here are from variety of experimental