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Dynamic impact tests on lithium-ion cells

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ABSTRACT

This paper reports on dynamic abuse tests on Li-ion cells, namely investigations on local indentation/intrusion into these cells. Two different types of cells have been investigated, pouch cells and elliptic cells. The elliptic cells were tested in two different states, with and without liquid electrolyte. The cells have been loaded by a hemispherical punch with a diameter of 12.7 mm with velocities between 0.01 mm/s and 5000 mm/s. Intrusion force, intrusion depth and velocity, and cell voltage were measured with high time-resolution during the intrusion process.

Significant changes in critical force were detected over the span of tested velocities. The critical force increased with an increase in test speed for the elliptic cells, while it decreased for the pouch cells. There were also differences associated with the presence of the electrolyte. These findings are of great importance especially for automotive applications where Li-ion battery packs are used in Hybrid or Electric Vehicles where intrusion at dynamic speeds is one of the main failure modes during a crash. The paper describes the experimental setup and test results in detail and discusses the implications.

1. Introduction

Electrical energy storage devices are gaining increasing importance for propulsion technology as well as temporary energy storage. Much effort, accordingly, is put into increasing the energy density of these systems. Yet, along with the increasing energy density and total capacity of available electrical energy storage systems, potential hazards grow more drastic as well. Uncontrolled energy release in these systems can entail combustion, development of toxic or explosive gases and dusts, or in the worst case, even an explosive failure of the whole energy storage unit. An increasing number of documented incidents with Lithium ion batteries gives evidence of this fact [1–4].

Yet, in spite of obvious safety risks of modern battery systems, an understanding of their complex failure mechanisms and loading limits is not available, for the time being. Accordingly, a systematic investigation of the perilous states of modern electric energy storage systems is highly needed.

Historically, safety studies of lithium-ion batteries were more focused on thermal and electrochemical aspects [5–7]. A series of recent studies over the past five years have investigated the mechanical deformation and onset of short circuit in lithium-ion battery cells. Punch loading has been used as a method of studying internal short circuits in batteries by focusing on thermal response of the cells [8,9]. In 2012, Sahraei et al. [10,11] and Greve and Fehrenbach [12] reported first measurements of force-displacements in mechanically induced short circuit tests of small pouch cells and cylindrical cells [10–12]. Following that, Jwo Pan and colleagues studied in-plane compressive properties of battery cells and modules of large pouch cells [13,14], while Avdeev and Gilaki [15] reported on structural analysis of large cylindrical cells. Most of the above studies and continued research on mechanical characterization of lithium-ion cells and their components were focused on quasi-static testing [16–21].

The only publication reporting on Lithium-ion cell testing at dynamic rates known by the authors is by Jun Xu et al on small cylindrical cells [22]. In vehicle applications of lithium-ion batteries, impact loading is a possible cause of deformation and mechanically induced short circuit [3]. Two common form-factors of batteries used in vehicle applications are large pouch cells and prismatic cells. For example, the Chevrolet Volt battery pack is comprised of large pouch cells [3], while the BMW i3 uses prismatic cells [23]. Therefore, the focus of this study is on experimental investigation of the deformation and subsequent onset of short circuits in lithium ion battery cells of large pouch and elliptical (prismatic) form factors under dynamic loading scenarios.

Regardless of form factor, the interior of battery cells is comprised of a multi-layer system of anode, separator, and cathode sheets, see Fig. 1. The order of thickness of those layers are less than

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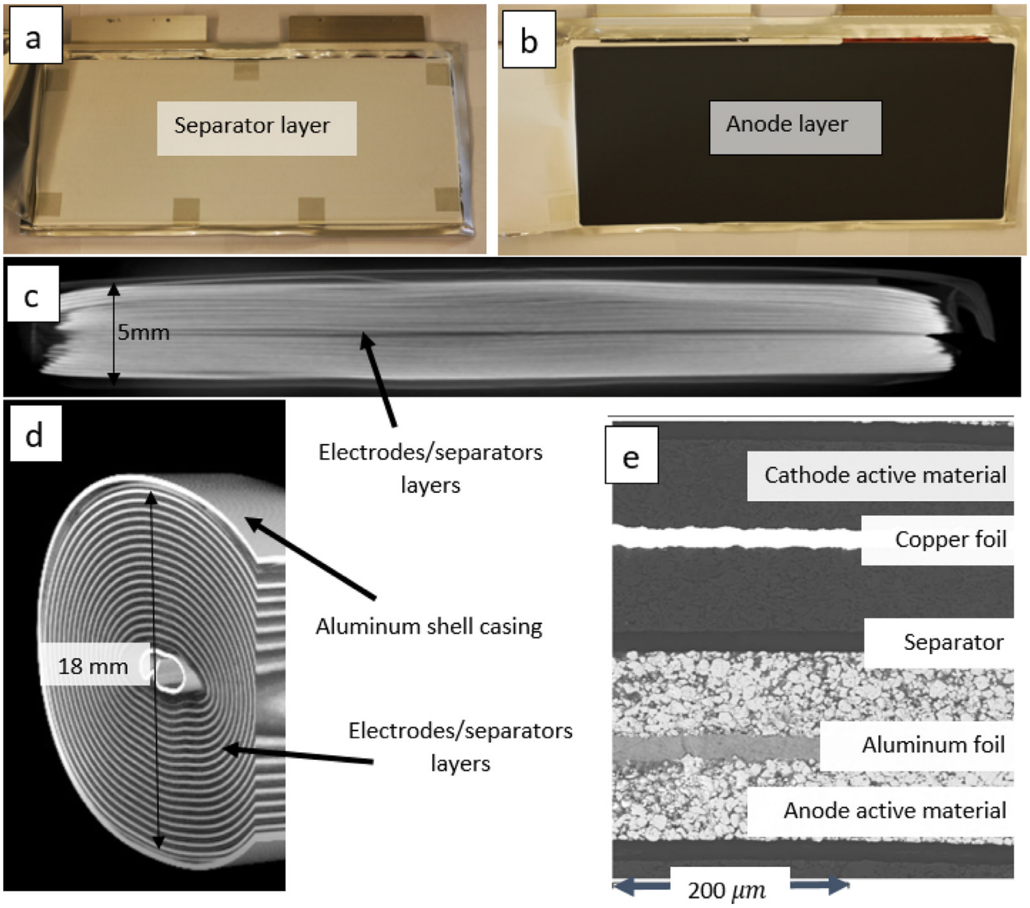

Fig. 1. Interior of battery cells, (a) after opening the cover of a pouch cell, the first layer seen is a separator layer, (b) the second layer is an anode layer, (c) a CT-scan image of a small pouch cell, (d) a CT-scan image of a cylindrical cell and (e) an SEM image of cross section of electrodes and separators. Figures c,d, and e are courtesy of Exponent Inc [19].

0.1 mm. Electrodes (anode and cathode) in turn consist of active particles mixed with polymeric binders and coated on thin aluminum and copper foils. In the case of cylindrical and elliptic (prismatic) cells, the multi-layer system is wound and protected by a hard shell casing of about 0.2 mm thickness, where the casing is commonly made of deep drawn Aluminum of H 3003. In the case of pouch cells, the layers are stacked on top of each other and then wrapped inside a Mylar-like pouch material. Active electrode coatings and separators are porous media soaked in a conductive electrolyte. The constitutive material properties of such a complex system are not easy to explain. However, previous studies have shown that at cell level, the homogenized behavior can be modeled as crushable metallic foams [10,11,19].

This paper reports on dynamic punch intrusion tests done over a wide velocity range. In Section 2, the experimental setup and the cells under test will be described in detail. Section 3 gives a description of the test results with elliptic cells and Section 4 follows with results from pouch cells. A preliminary discussion is given in Section 5.

2. Test procedure

2.1. Tested battery cells

Lithium-ion cells come in a variety of shapes and sizes. The main cell types in use are cylindrical, elliptical, pouch, and prismatic. Two of these types were tested dynamically on their susceptibility to intrusion: elliptical cells and pouch cells. The elliptical cell with a casing of thin aluminum had dimensions of 37 mm × 64 mm × 18 mm and a capacity of 5.3 Ah. This cell had a nickel oxide chemistry and contained liquid electrolyte. In addition to standard cells filled with electrolyte, inactive cells without electrolyte were tested as well. These cells will be referred to as “dry” cells, in contrast to the normal “wet” cells. Both elliptical cells are identical, apart from the missing electrolyte in the dry specimens.

Two different pouch cells were tested, which will be called pouch A and B. Pouch A had a capacity of 31 Ah, Nickel Manganese Cobalt (NMC) chemistry, and dimensions of 225 mm × 225 mm × 7.2 mm. Pouch B came with a capacity of 52 Ah, a Nickel cobalt oxide chemistry, and dimensions of 329 mm × 161 mm × 12.7 mm.

Fig. 2 shows photographs of the elliptical cell and the two pouch cells. In preparation of the tests the cells were subjected to at least one full charge/discharge cycle in order to verify its nominal capacity. All tests were done with cells fully discharged (100% depth of discharge, which means State of Charge (SOC) of 0%). Previous work of same authors have shown the mechanical behavior of batteries before short circuit is not affected by the state of charge [24]. Therefore, it is believed that the discharged state does not affect the validity of the tests while reducing hazards of thermal runaway after the test is completed.

2.2. Experimental setup and test procedure

The test stand is a commercial servo hydraulic machine (Instron 8503, see Fig. 3). The machine works with a closed servo loop for cross head velocity. It is able to be operated with cross head velocities between 0.01 mm/s and 5 m/s and a maximum force of 120 kN.

During the tests, the punch's displacement and the intrusion force had to be measured. The punch's displacement was determined from the cross head displacement which is recorded via an