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Effect of packaging and cooling plates on mechanical response and failure characteristics of automotive Li-ion battery modules☆

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ABSTRACT

When a battery pack is subjected to external mechanical load, i.e. as in the case of crash, the individual cells experience significant deformations leading to the internal short circuit and possibly fire. The current investigation looks into effects of the inactive components (i.e. cooling plates and module protective enclosure) on deformation and failure of individual pouch cells. Experiments on large spherical indentation of electric vehicle battery module with and without such components have been performed. The results show that the presence of cooling plates overall reduces the force under out-of-plane indentation by approximately a factor of 1.5. It was established however that the failure in cells occurs at the same displacement of the indenter, regardless of the presence of the inactive elements in battery module structure. This underlines the necessity for formulation of the failure criterion based on critical strain, rather than critical stress measure. The findings suggest possibility of utilizing such battery modules in impact energy absorption scenarios, due to reduction in force by the cooling components. X-Ray computed tomography (XCT) has been performed on the cells as a non-destructive analysis of internal failure and the differences of failure mode induced by introduction of structural components are discussed.

1. Introduction

Design of new electric vehicles (EV) with improved road performance relies not only on development of novel energy storage materials with higher energy density but on thorough investigation of safety of such vehicles, especially in response to crash. Principles of crashworthiness design applicable to the cars with internal combustion engine should be transferable to the case of EVs. In addition to common components for the occupant safety, which are engineered into the vehicle design regardless of the type of drivetrain, the energy storage components in EV require additional consideration. Methods of protecting the EV battery pack against external impact in great extent rely on understanding of the battery behavior under such external loading and critical conditions necessary for internal failure leading to battery pack fire.

Vast majority of modern EVs are powered by the rechargeable electrochemical cells that are based on Li-ion intercalation chemistry. In this design Li cations are responsible for the charge transport through the liquid electrolyte from one electrode to another. This ionic current is transformed into electronic current within the electrodes through redox reactions. The electrodes of opposite polarity in such cell are separated by a physical barrier, termed separator, which has porous structure thus allowing flow of electrolyte yet preventing contact between the electrodes. The electrolyte is a lithium salt dissolved in organic solvents. Such composition presents inherent safety risks due to flammability of the solvents (these are typically presented by mixtures of ethylene carbonate and diethyl, dimethyl or ethyl-methyl carbonates [1]). In the event of separator failure, the electrodes can come into

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contact and the charge stored in the electrodes can be released rapidly through the internal short circuit. Depending on the amount of charge stored, i.e. battery state of charge (SOC), such rapid release of energy can lead to the temperature rise high enough to create thermal runaway and fire. It is therefore universally accepted, that separator membrane is a critical safety component in battery. This resulted in establishment of several testing procedures and standards for the mechanical integrity of battery separators [2–4]. In addition, significant amount of research has been dedicated to investigating mechanical properties of separators either under simple uniaxial loading [5–9] or more complex loading scenarios [10–12].

Together with the investigation of mechanics of individual cell components [13,14], considerable efforts have been directed towards research of mechanical damage and failure of individual battery cells. These efforts stemmed from the need for safety certification of commercial cells and resulted in standardized procedures for drop, thermal abuse, crush, and nail penetration tests [15,16]. In typical mechanical abuse tests, pouch or cylindrical cells are subjected to indentation by a blunt rod or by penetration by a conductive nail with sharp point [17,18]. The results are usually presented by load-displacement curves, voltage measurements, and post-mortem analysis of the cells. Separately, other techniques such as pinch test [19,20], introduction of conductive particles to separator [21,22], or creating localized contact of electrodes [23] have been developed with the goal of creating controllable internal short circuit in pre-defined location within the cell.

In addition to abuse tests, where the primary goal is detection of point for internal short circuit and thermal runaway, experiments investigating mechanical response of battery cells have been performed with the goal of subsequent development of computational models for battery failure. In this case the deformation of the cell is induced by applying force to indenters of various shapes until the failure is detected by load and (or) cell potential drop [14,24–26] or by applying in-plane tension and constrained compression to the cells [13,27]. The results of indentation experiments are used as validation for finite element analysis (FEA) utilizing constitutive models built from the results of uniaxial tests of cells and cell components. The FEA can be based on completely homogenized material behavior of the cell [25–28] or it can include different components (i.e. electrodes and separator) in layer-resolved simulations with different degree of homogenization assumptions [24,29,30].

When cells are indented by cylindrical rods or punches with different sizes, as in the above mentioned studies, such indentation happens against a rigid, non-deformable surface. Such scenario does not represent well the deformation of the cell when it is placed inside a battery module and effect of other cells on the stresses and strains needs to be considered. Indeed, it is hard to expect large crushing forces, as in lateral indentation of a pouch cell resting on a rigid surface, when such cell is deformed against other compliant pouch cells. The amount of research dedicated to deformation of modules and packs, as opposed to individual cells, is rather limited to a great extent due to hazards associated with testing of such units. In a rather detailed study [31] a FE simulation of vehicle battery pack undergoing penetration from the sharp road debris represented by a conical indenter has been performed. The battery pack was similar to that in Tesla S vehicles, i.e. consisting of cylindrical cells and protected by the undercarriage armor plate. The simulation of a global deformation of a battery pack was used to impose deformation of the individual cylindrical cells. The failure criterion was based on failure of jellyroll determined from tests on individual cells crushed against rigid surface and the cell material was modeled using a crusheable foam model. In addition, Xia *et al* [32] performed impact testing of battery modules using drop tower. The exact sequence of events leading to mechanical failure in this case is hard to restore since the tests were performed on 100% charged modules and thus resulted in fire.

Compared to abundance of data on mechanical abuse of single cells, understanding of mechanics of cells when deformed in a battery module

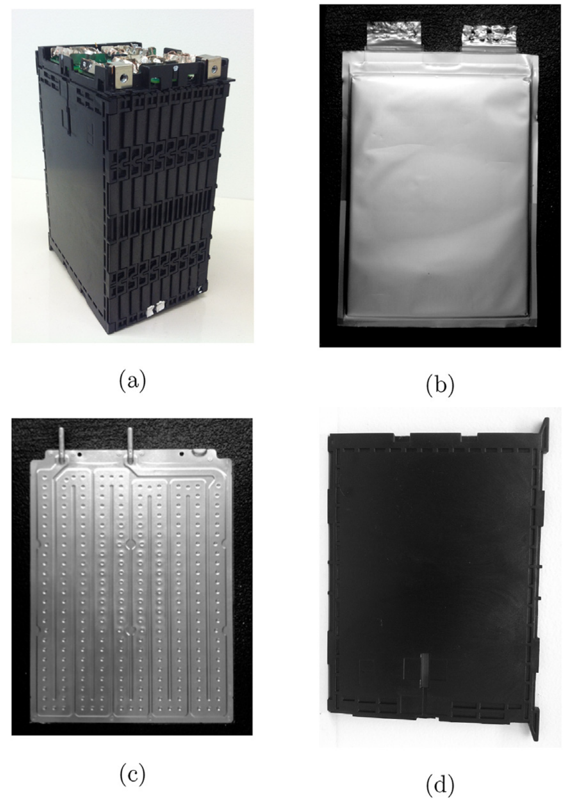

Fig. 1. Battery module and its components used in the current investigation. (a) Battery module; (b) Single pouch cell; (c) Cooling plate; (d) Plastic plate - module enclosure.

is largely lacking [33]. In the current investigation we report on the development of the experimental procedure for controlled deformation of battery pouch cells subjected to boundary conditions corresponding to those of a module. Such setup allows for large tensile and shear strains to develop in the cells, due to compliance of the module as opposed to testing against rigid surface. We investigate the specifics of internal failure in cells using X-Ray computed tomography (CT). In addition we demonstrate that aluminum cooling plates utilized in battery module construction reduce lateral indentation forces, most likely due to collapse of cooling channels and due to yielding in aluminum. This, initially unexpected result, indicates a certain degree of impact energy absorbing capability of such battery modules.

2. Experiments

Li-ion pouch cells for the experiments were harvested from the Ford Focus EV battery pack. The battery was obtained in a completely discharged state which followed the intent of performing experiments without fire events that usually destroy the cells and make post-test analysis of battery structure impossible. The sub-unit of the battery pack, i.e. battery module containing 20 cells is shown in Fig. 1a. The cells (Fig. 1b) are 5.5 mm thick pouch cells arranged such that a cooling plate (Fig. 1c) is placed every second cell. With this arrangement, each pouch cell has one surface in contact with the aluminum cooling plate. The cells and cooling plates stacked in the sequence are enclosed by the plastic frame which has two face plates (Fig. 1d) as well as 10 frames sandwiched in between these plates. The cells are 227 × 165 mm and the cooling plates are 218 × 162 mm in area. The cooling plates (Fig. 1c) have channels for the flow of coolant and the maximum thickness of the plate is 1.3 mm while the minimum thickness (measured at the grooves) is 0.55 mm. The plastic face plates (Fig. 1d) are 240 × 175 mm and are 2.3 mm thick. It should be mentioned that the