Journal of Power Sources 214 (2012) 377–385

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Mechanical testing and macro-mechanical finite element simulation of the deformation, fracture, and short circuit initiation of cylindrical Lithium ion battery cells

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HIGHLIGHTS

► Mechanical cell testing with in-situ short circuit location identification.
► Macroscopic jelly roll fracture initiates the internal short circuits.
► Stress-based fracture and short circuit criterion developed.
► Finite element crash simulation of the cell tests.

ARTICLE INFO

Article history:
Received 7 March 2012
Received in revised form
20 April 2012
Accepted 22 April 2012
Available online 28 April 2012

Keywords:
Mechanical
Abuse
Short circuit
Simulation
Fracture

ABSTRACT

A quasi-static mechanical abuse test program on cylindrical Lithium ion battery cells has been performed at a state of charge (SoC) of 0%. The investigated load cases involved radial crushing, local lateral indentation and global three-point bending of the cell. During the tests, the punch load, the punch displacement, the cell voltage and the temperature development of the cell have been monitored using an infrared camera and temperature sensors. After the test, the cells have been analysed using computer tomography.

It is indicated that macroscopic jelly roll fracture on a global scale initiates the internal short circuits, revealed by a sudden decrease of the global mechanical load due to the rupture, followed by a drop of the measured voltage and immediate increase in cell temperature.

A macro-mechanical finite element crash simulation model has been established for the cell housing and the jelly roll. The classical stress-based criterion after Mohr and Coulomb (MC) has been applied to predict fracture and the initiation of an internal short circuit of the jelly roll. The MC criterion correctly represents the punch displacement to fracture, where the predicted fracture locations correspond to the observed locations of the internal short circuits of the cells.

1. Introduction

Plug-in hybrid electronic vehicles (PHEV), range extender battery electronic vehicles (RE BEV) and pure battery electric vehicles (BEV) are likely to play an important role in future road traffic, depending on the predicted future regulation scenarios [1]. Currently, the Lithium ion battery technology is of primary interest to the automotive industry, since it provides one of the best energy densities available today, e.g. ([2,3]).

The active material of standard Lithium ion battery cells is represented by stacked or wrapped layers of the cathode and anode material sheets, which are physically separated by a porous but mechanically robust separator foil, in order to help prevent an internal short circuit of the cell. Battery systems in electric vehicles are protected against deformation by massive structural measures in order to fulfil federal crash laws, consumer crash tests and other requirements. Despite these achievements, the knowledge of the limiting deformability of Lithium ion cells prior to short circuit

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doi:10.1016/j.jpowsour.2012.04.055

initiation can potentially provide valuable additional information for the design of future battery cells.

On the experimental side, extensive research focused on the investigation of the different cell components, where special emphasis is put on the development and characterisation of separators for improved cell performance ([4–6]).

Simulation-based research included stress and damage analysis due to thermal expansion mismatch of the different electrode components during charging/discharging. Xiao et al. [7] modelled the stress and deformation in electrode particles and separators using a meso-scale representative volume element (RVE) coupled to a 1D macroscopic battery model. Zhang et al. [8] simulated the intercalation-induced 3D stress in Lithium ion battery electrode particles of different size and shape. They concluded that smaller sized particles with large aspect ratios lead to reduced intercalation-induced stresses and damage.

Extensive research also went into the analysis and simulation of abuse tests (oven, short circuit, overcharge, nail, crush), with emphasis on the cell behaviour after short circuit initiation. A summary paper is provided by Spotnitz and Franklin [9]. Maleki and Howard [10] investigated the internal short circuit behaviour of prismatic cells, subject to small nail penetration, small indentation and cell pinching, experimentally and numerically. They concluded that the risk of a critical thermal runaway of the cell is mainly controlled by the local heat conduction of the cell structure around the shorted region. In the worst case of the investigated load cases, namely cell pinching, the heat cannot be transferred to the cell-can, but is transferred back into the jelly roll. Spotnitz et al. [11] simulated the thermal abuse resistance of 18 650-size cells. Analogous to Maleki and Howard [10], the authors identified heat transfer as the governing factor for thermal runaway, where thermal runaway of a single cell of a battery pack is more likely to cause thermal runaway of the whole battery pack when the initiating cell is in good contact with other cells and is close to the pack wall.

Safety issues related to Lithium ion battery cells are discussed controversially in the literature. Generally, there are two different strategies.

1. Improving the safety by avoiding abuse and protecting the cells appropriately.
2. Improving the safety of the cells by understanding the mechanisms causing internal short circuits under mechanical loading, and by improving the cells or cell components accordingly.

Farrington [12] suggested that “effective regulations should promote and maximize safe transportation of lithium batteries through […] the elimination of unsafe circumstances”. Sahraei et al. [13] believe that “advanced constitutive models are needed for strength/weight optimization and safety assessments of Li-ion batteries”. The authors performed a comprehensive structural testing program on prismatic pouch cells with the aim to set up a finite element model for representing the deformation behaviour of the interacting cell components on a macro-mechanical homogenized scale, and also on a refined meso-mechanical scale, where individual layers of the electrodes are modelled distinctively. In another paper [14], the same authors investigated cylindrical cells subject to axial crushing, radial crushing (without end caps) and radial indentation, and used numerical finite element simulations and analytical solutions for describing the deformation response of the cells.

The two papers by Sahraei et al. ([13,14]) were the only publications in the open literature found by the present authors in which the deformation behaviour of battery cells during mechanical abuse loading was investigated and modelled. No publications could be identified for predicting the onset of short circuits of battery cells under mechanically loading, using finite element modelling.

In the present study, cylindrical Lithium ion cells are subjected to various mechanical abuse tests, in order to create a crash simulation model of the cell. The developed simulation model allows representation of the cell deformation, and also features a stress-based fracture criterion for predicting the load state and location for internal short circuit onset during deformation.

2. Mechanical cell abuse testing program

2.1. Test preparation

Cylindrical Nickel Cobalt Oxide (NCA) Lithium ion cells (GAIA, HP 602030 NCA-45 Ah/162 Wh) are used in this study. The main cell dimensions are provided in Fig. 1a, and the interested reader is referred to the online data sheet of the cell [15] for further information about the physical and mechanical characteristics, the electro-chemical characteristics, and the operating conditions of the cell.

The cells are discharged at a state of charge (SoC) of slightly greater than 0%, or to the recommended voltage limit for discharge, approximately 3 V, respectively.

A zero SoC is expected to enable assessment of the heat location and propagation at internal short circuit initiation, but at the same time allows avoiding severe cell reaction like smoke and fire development. Three temperature sensors are applied on the cell mandrel, Fig. 1a, and the cell voltage is also recorded during the test.

For safety reasons, the cells are located in a windowed cave featuring a gas exhaust device, Fig. 1b.

The cave is mounted on a hydraulic tension/compression testing device allowing the application of compressive loading using different types of punches and bearings, Fig. 1c. The tests are performed under quasi-static loading at 0.1 mm s^{-1}. During

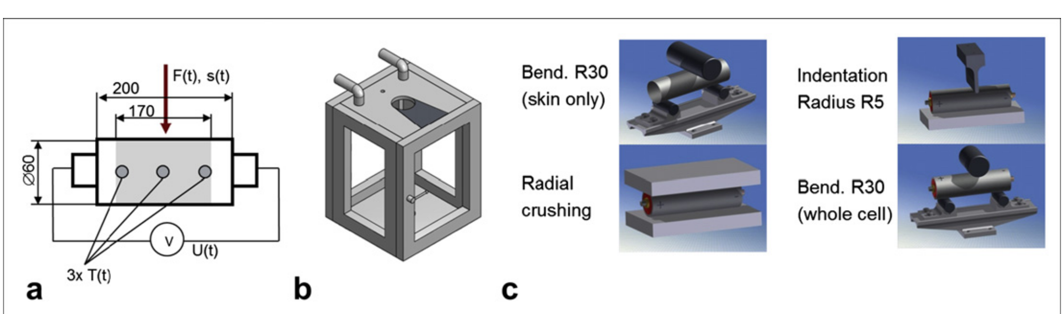

Fig. 1. a) Main cell dimensions (in mm) and cell instrumentation; b) test chamber set up; c) investigated load cases.