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Characterization of plasticity and fracture of shell casing of lithium-ion cylindrical battery

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HIGHLIGHTS

- A comprehensive set of mechanical tests on shell casing of 18650 cells was performed.
- Plastic and fracture models of shell casing were provided along with calibration procedure.
- Jellyroll was described by means of a crushable foam model.
- The presence of shell casing significantly improves the cell's resistance to mechanical abuse loading.

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ABSTRACT

Most of the literature on lithium-ion battery cells is concerned with modeling of jellyroll with little attention to properties of shell casing. However, shell casing provides substantial strength and fracture resistance under mechanical loading and therefore must be an important part of modeling of lithium-ion batteries. The paper reports on a comprehensive test program on commercially available empty shell casing of 18650 lithium-ion cylindrical cells. Part of the tests was used to determine plastic and fracture properties from sub-size specimens cut from lateral part of the cans. The other part served to validate plasticity and fracture models under various loading conditions. The associated flow rule was used to simulate plasticity behavior and Modified Mohr-Coulomb (MMC) fracture model was adopted to predict crack initiation and propagation of shell casing. Simulation results confirmed that present plasticity and fracture models could predict global plastic behavior of the cells under different loading conditions. The jellyroll model with volumetric hardening was introduced to compare the performance of empty shell casing, bare jellyroll and complete battery cell. It was shown that in many loading situations, for example, three point bending of the cylindrical cells, the metallic shell casing provides most of mechanical resistance.

1. Introduction

Shell casing of lithium-ion batteries provides the first level of thermal and mechanical protection to the jellyroll. It has to perform well under verity of abuse loading, and it must be light and easy to manufacture. The casings are often made from extruded aluminum tubes with laser welded endcaps. More commonly, a multi-stage deep drawing technology is used for both steel and aluminum thin sheets. The supplier of shell casing provided minimum or no information on the mechanical properties of raw material used or the final product. Such information is critical to assess performance limit of cells in terms of resistance to mechanical loading and fracture during accidental load and/or compliance with safety standards such as SAE J2464 [1].

There are a number of requirements that lithium-ion batteries must satisfy regarding electro-chemical, thermal and mechanical properties. Most of the literature on the modeling of lithium-ion cells is devoted to thermal management [2,3]. Recently, the importance of the laboratory mechanical test and numerical simulation has been recognized by the community. Sufficient evidence has now been accumulated proving that fracture of shell casing is a valid and serious failure mode, exposing the partially damage jellyroll to the environment. Sahraei and Hill [4] performed tests on axially compressed cylindrical cells during which a longitudinal crack was developed from a local bulge. Fracture on the tensile side of shell casing was observed in three-point bending test

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[5,6]. Sahraei et al. [7] described a dynamic test on large format cylindrical cell subjected to axial compression. The cell exploded, tearing the shell casing into small pieces. Recently, Xia et al. [8] performed numerical simulation of the 18650 cell under symmetric and eccentric load by a sharp punch, parallel to the longitudinal direction. The symmetrically loaded shell casing ruptured under 6 mm indentation depth. Fracture of eccentrically loaded cell occurred much earlier, when the punch travelled only 1.6 mm. Considering the existing evidence and potential hazard associated with spreading gases, spill of the electrolyte and possible fire from the bursting cell to the neighboring ones, a proper attention should be given to this problem by the battery safety community.

The objective of the present paper is to determine the contribution of the strength of the shell casing to the overall response of the cells to the mechanical loading. To this end, plastic and fracture properties of the shell casing material were determined by using the most modern technology developed in the Impact and Crashworthiness Lab of MIT [9–16]. This effort consisted of an extensive experimental program, model calibration and component validation. Almost 100 empty shell casings were tested to complete the stated task. Specimens were cut from the actual shell casing, which restricted their size and shape to a certain degree. The shell casing material had undergone relatively large strain during the deep drawing process. These strains were distributed non-uniformly along the length of the cell. The anisotropic properties arising first from the rolling process of the sheets and then deep drawing process are substantial and were to be taken in to account. There is a considerable variation in thickness of the can from 0.253 mm to 0.29 mm at the ends. The endcap on the other hand was not subjected to any strain histories and represents the virgin material. However, the size of the endcap is too small to cut any specimens. All the above features made the testing and calibration procedure much more difficult as compared to previous work in the lab on thin automotive sheets. From this point of view, the present paper is indeed innovative in terms of both test procedures and numerical simulations.

In the last section of the paper, numerical simulations were performed on bare jellyroll, empty shell casing and complete cells. It was conclusively proven that in some loading situation, such as three point bending, the shell casing provided most of the mechanical resistance of the cell. Distinguished feature of the present paper is that not only it provides new information about the important modeling problem, but also shows in some details how the information was obtained.

2. Plasticity modeling for the battery shell casing

2.1. Material

The cylindrical cells are widely used as batteries for laptop and portable power. Such cells are also powering the Tesla Model S. The shell casing is made by deep drawing, which can reduce the cost compared with the extruding one with welded endcap. The present paper is studying the properties of the commercially available deep-drawn shell casing of the 18650 cell made from low carbon steel, which is approximately 18 mm in diameter and 65 mm in length.

Generally, a typical deep drawing process consists of several steps from a flat circular sheet to the final shape. The deep drawing process results in considerable accumulated plastic strain, leading to the deformation induced anisotropic of the casing that can be determined experimentally. Therefore, due to the anisotropic properties of the virgin rolled sheet and deformation induced anisotropy, the thickness of the shell casing varies along both axial direction and hoop direction of the casing, as shown in Fig. 1. The area with maximum thickness is around the open end of the can and minimum thickness is approximately in the middle. Such a distribution of thickness was also reported in the literature for deep drawn shell casing [17]. The average wall thickness is 0.26 mm. The chemical composition is summarized in Table 1. All specimens were extracted from the same package of the battery cell (100 pieces) and can be assumed to have the same mechanical properties.

2.2. Preparation of the specimens and description of the test method

In this section, a rather detailed procedure on the preparation and test method is given so that similar test could be performed around other labs in the world. Two methods were used to prepare tensile specimens for plasticity calibration. In both methods, the endcap was removed. In the first method, the shell casing was cut lengthwise and flattened, as shown in Fig. 2. Dogbone-shaped specimens were cut from three different flattened-sheet orientations (axial or deep drawing direction, hoop direction and diagonal direction) using a milling machine. The specimen geometry (Fig. 3a) is different from that in ASTM-E8M standard (sheet type), due to the limited length and diameter of the shell casing. Since the dimension of the flattened sheet of the shell casing is 65 mm in length and 56 mm in width (hoop direction), the geometry of

Table 1
Chemical composition of the shell casing.

Element	Mn	P	Ni	Cr	Cu	Mo	V	Ti	Co
Percentage	0.16	0.008	1.36	0.056	0.012	0.002	0.003	0.003	0.006

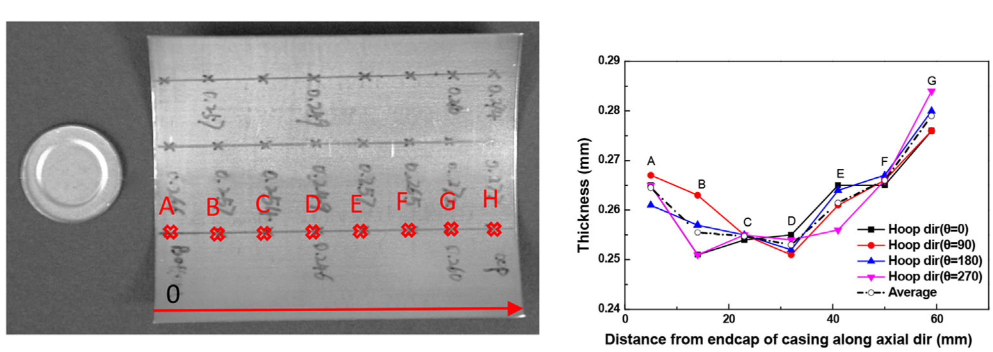

Fig. 1. Non-uniform thickness distribution of the shell casing.