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Zhu, Juner; Koch, Marco Miguel; Lian, Junhe; Li, Wei; Wierzbicki, Tomasz Mechanical Deformation of Lithium-Ion Pouch Cells under In-Plane Loads-Part I

Published in: Journal of the Electrochemical Society

DOI: 10.1149/1945-7111/ab8e83

Published: 07/01/2020

Document Version Publisher's PDF, also known as Version of record

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Please cite the original version:

Zhu, J., Koch, M. M., Lian, J., Li, W., & Wierzbicki, T. (2020). Mechanical Deformation of Lithium-Ion Pouch Cells under In-Plane Loads-Part I: Experimental Investigation. *Journal of the Electrochemical Society*, *167*(9), Article 090533. https://doi.org/10.1149/1945-7111/ab8e83

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To cite this article: Juner Zhu et al 2020 J. Electrochem. Soc. 167 090533

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# Mechanical Deformation of Lithium-Ion Pouch Cells under In-Plane Loads—Part I: Experimental Investigation

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During an accident of an electric vehicle, the battery pack can be damaged by the intrusion of an external object, causing large mechanical deformation of its lithium-ion battery cells, which may result in an electrical short circuit and subsequently the possible thermal runaway, fire, and even explosion. In reality, the external objects can come in different directions, for example, an out-of-plane indentation that perpendicularly punches the large surface of the pouch cell and an in-plane loading that compresses the thin edge of the cell. In this study, the mechanical deformation of a large-format lithium-ion pouch cell under in-plane loads is investigated via three different types of tests — in-plane compression of fully constrained cells, in-plane compression of cells sandwiched by foams, and in-plane indentation by a round punch. A special apparatus is designed to apply different boundary conditions on the cell, and the deformation history, especially the formation of the buckles of the cells, are monitored by two digital cameras. Post-testing structural analysis is carried out by a cross-sectional cutting and polishing procedure, which gives clear evidence of buckling of all the component layers.

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Manuscript submitted March 23, 2020; revised manuscript received April 27, 2020. Published May 7, 2020. This paper is part of the JES Focus Issue on Battery Safety, Reliability and Mitigation.

The commercialization of lithium-ion battery cells has paved a way for technical innovations in how we power everything from smartphones to electric vehicles (EV). To meet the ever-increasing demands of high-performance batteries from these two industries, great efforts have been made to improve the battery technologies in six important areas: lifespan, cost, performance, specific energy, specific power, and safety.<sup>1</sup> Compared with the first five aspects that have enjoyed extensive research, safety has not been studied to the extent it deserves. This situation is not only disappointing but also dangerous because it is the only aspect that can directly expose the end-users of batteries to fatal risks such as a fire accident or an explosion of an EV.<sup>2–5</sup>

Safety issues of lithium-ion cells can be generally classified into two groups with respect to their origins: i) charging-discharginginduced and ii) mechanical-deformation-induced.<sup>6,7</sup> The safetyfocused studies of lithium-ion batteries in the open literature have been mainly concerned with the first group, which happens during the normal service life of battery cells and oftentimes starts from the microscopic material level. One of the most-studied examples in this group is perhaps the formation of lithium dendrites that can penetrate the porous separator, leading to an internal short circuit. Various experimental investigations<sup>8–10</sup> and theoretical characterizations<sup>11–14</sup> have been carried out to understand and address this particular safety issue.

At the same time, the second group, the mechanical-deformationinduced safety issues, has not been extensively studied, although, in reality, it is as prevalent as, if not more than, the first group. This group of safety issues usually happen at the structural level, involving the damage and failure of lithium-ion cells<sup>3,15,16</sup> when subjected to external mechanical loads, for example, an intrusion from another vehicle during a car collision or impact of road debris. In such cases, battery cells could undergo a large irreversible deformation, resulting in the fracture of battery components (the electrodes and especially the separator) followed by the direct contact of the positive and negative electrodes.<sup>17,18</sup> The resultant internal short circuit of the cells,<sup>19</sup> can lead to possible thermal runaway of the whole pack<sup>20–22</sup> and even fire accident of the car.

The biggest challenge of investigating mechanical-deformationinduced safety issues is the high dimensionality of the accident prismatic), designs, materials, and chemistries. What is oftentimes overlooked is the numerous loading and boundary conditions of the cells. Existing experimental and numerical studies on battery safety in the open literature have been trying to identify the most representative loading and boundary conditions of the real-world accident scenarios, and six types of conditions have been extensively studied,<sup>6</sup> namely out-of-plane compression,<sup>15,16,18,23-27</sup> in-plane compression,<sup>28–36</sup> indentation,<sup>3,15,17,19,23,36,40</sup> pinching,<sup>37–39</sup> three-point hemispherical indentation,<sup>3,15,17,19,23,36,40</sup> three-point bending,<sup>24,36,41–44</sup> and plane-strain cylindrical indentation.<sup>17,18,45</sup> Among these six types of conditions, the in-plane compression is perhaps the least studied with only several publications available in the open literature. Pan et al.<sup>29–33</sup> carried out a series of in-plane constrained compression tests on prismatic battery cells and modules and developed numerical RVE (representative volume element) models for characterization. Zhu et al.<sup>28</sup> performed tests and simulations for the axial compression of 18650 battery cells, during which the jellyroll of the cell was subjected to an in-plane compression load and showed local bulking patterns. Mason<sup>34</sup> and Sahraei et al.<sup>36</sup> studied the in-plane compression behavior of a small-size pouch battery cell and attempted to derive the theoretical solutions for the deformation pattern. In a recent publication, Kermani and Sahraei<sup>35</sup> investigated into the inplane compression behavior of an elliptical battery cell with the help of numerical simulations of the battery cell. To sum up, these existing studies on the in-plane compression are limited in two aspects: 1) there is still no investigation on the large-format EV pouch batteries that is the prevailing type of batteries in the current EV market, and 2) still no numerical model has been reported that can capture both the force-displacement response and the buckling pattern at the same time.

scenarios. This is easy to understand considering the large number of

battery types represented by the form factors (cylindrical, pouch, and

The purpose of our present study is to fill the above gaps by diving deeply into the in-plane deformation of a large-format pouch battery cell. In the present investigation, both experimental tests and numerical simulations will be reported in two publications. The present Part I will describe the details of the experimental investigations, which will be further used by Part II<sup>46</sup> for developing a numerical model for characterization.

## Material and Experimental Setup

Battery cells.—The lithium-ion battery investigated in this study 26.3 large-format pouch is Ah cell with а LiMn<sub>2</sub>O<sub>4</sub>(LMO)/LiNi<sub>1/3</sub>Co<sub>1/3</sub>Mn<sub>1/3</sub>O<sub>2</sub>(NCM111)-graphite chemistry and carbonate-based liquid electrolyte (manufactured by LG Chem). The cells used for testing were disassembled from a battery module purchased from the open market. As illustrated in Fig. 1, the overall dimensions of the cell are 225 mm (length)  $\times$  165 mm (width)  $\times$  7.5 mm (thickness), and the dimensions of the core component of the cell, the stack of electrodes and separator, are 195 mm  $\times$  150 mm  $\times$  7.5 mm. The architecture of the stack consists of alternating layers of 20 anodes, 19 cathodes and separator layers in between. The 171- $\mu$ m-thick cathode is a 20- $\mu$ m-thick aluminum foil double-side coated with LMO/NMC111 powders, and the 143- $\mu$ m-thick anode is a 10- $\mu$ m-thick copper foil double-side coated with graphite and carbon black powders. The separator (27  $\mu$ m) is dryprocessed poly- propylene (PP) with ceramic coatings on both sides. The exterior of the cell is an aluminum laminated film (pouch) with 150  $\mu$ m thickness. All the cells are tested at a low state-of-charge (around 10%) for safety considerations. Mechanical characterizations are often performed independently from the electrochemical state of the cells and components due to the fact that mechanical abuse events often happen in a much smaller timeframe than the electrochemical loads. A study on the state-of-charge dependence of different types of cells could be found in a previous publication of the authors' team.<sup>4</sup>

*Experimental setup.*—In this work, a 200 kN displacementcontrolled MTS loading frame was used. To ensure a maximumaccuracy displacement measurement, a digital camera (Imaging Retiga 1300i) was used to take every second an image of the crosshead. The images were further processed with the digital image correlation (DIC) method (platform: VIC-2D) to calculate the displacement at the loaded edge of the specimens. The cell voltage was monitored during the tests to identify an internal short circuit where an obvious voltage drop was observed.

The main difficulty of the in-plane compression tests lies in applying proper boundary conditions on the battery cell. In several previous studies by the Pan research group, <sup>32,33</sup> a screw-tightening device was designed for clamping the cell in the out-of-plane direction and applying the compressive loading in the in-plane

direction. To mimic the boundary condition of the cells in reality, foams and thick aluminum plates were placed between the cells during the tests. The clear disadvantage of Pan's design is that the lateral pressure on the cell cannot be precisely imposed. As a result, only two types of boundary conditions can be investigated-fullyconfined and confined by a foam. To overcome this shortcoming, a new type of apparatus was designed by Mason and Zhang following the idea of an "anti-buckling" device for the in-plane compression of sheet metals.<sup>48–50</sup> This apparatus applies a uniform pressure through 12 springs on each side of the battery cell and uses a load sensor to measure this pressure. In this way, the lateral pressure can be well controlled before the in-plane compression is applied. But its disadvantage is also clear-the stiffness of the system relies on the property and the number of the springs and, therefore, cannot reach a sufficiently high value unless a large number of stiff springs are used, which nevertheless makes the apparatus very hard to assemble and use. This disadvantage becomes even more significant when the battery cell for investigation is a large-format EV cell.

For this reason, this present study develops an improved device, which allows on the one hand fully confined tests and on the other hand, can mimic a battery module-like environment in a repeatable way. Figure 2 shows the explosion view of the device and how it is assembled and used for the in-plane compression of pouch cells. The battery cell is placed between two steel holders (side walls), and the in-plane compressive loading is applied in the width direction via a thick steel punch blade with a long groove on its edge to avoid any slip of the battery edge during compression. Each of the steel holders has a thickness of 15.875 mm so that all occurring forces during testing can be withstood with negligible elastic deformation. The bottom parts are 25.4 mm high and connected from below to the holders to ensure the best possible stability of the device. The two holders are connected by four M16 screws with a pitch of 2 mm. In the middle of one holder, there is a small window installed where an acrylic glass is inserted. During the test, two digital cameras were used to monitor the deformation pattern of the cell, one from the front through this window, and the other from the side through the gap between the two holders.

# **Test Results**

The following three types of compression tests were performed.



Figure 1. Photographs and dimensions of the battery module and pouch cell.



Figure 2. Experimental setups of the in-plane compression test.

- In-plane compression without foams padding (fully confined),
- In-plane compression with foams padding, and
- In-plane indentation with a round punch (fully confined).

The first and the second types of tests adopted the aforementioned punch blade with a long groove, while in the third test, another punch blade with a round punch nose (radius: 24 mm) in the center was used to trigger local indentation. The results of these three types of tests will be described in the following three subsections.

In-plane compression without foams .--- In the first type of tests, no foam was placed between the sides of the battery cell and the steel holders. Since the holders were designed to allow for no lateral deformation, the battery cell was supposed to be in an ideal fullyconfined in-plane compression status if there is no gap between the cell and the holder. However, it was found that the friction between these two surfaces could be too large for the cell to deform if no gap was allowed even though a thin Teflon sheet is placed for lubrication. Therefore, a small gap of 0.8 mm on each side was pre-set for each of the tests. It is worth noting that such a loading condition is seldom seen in reality when the battery pack is damaged during car accidents. However, it is a very important test for a comprehensive characterization of the mechanical property of a porous medium. It not only provides a stress-strain hardening curve that is necessary for many material models such as the Deshpande-Fleck<sup>51</sup> and Drucker-Prager/cap<sup>17</sup> but also helps to probe the shape of the yield surface.

The nominal stress-strain curves of three repeats are depicted in Fig. 3. The plots show relatively good repeatability except for a small degree of shift in the nominal strain axis. Three stages can be observed from the stress-strain curves: 1) a short steep increasing stage, followed by 2) a plateau with several oscillations and 3) an exponentially increasing final stage. An intuitive mechanical interpretation of the second stage is a progressive local buckling of the battery cell under in-plane compression. In fact, the buckling phenomenon is indeed observed from the post-testing examination of the tested battery cells (see Fig. 4). It is also worth noting that no electrical short circuit was observed during all of the three times of tests, and the voltage was kept at its original value throughout the whole testing procedure.



Figure 3. Nominal stress-strain response of the pouch battery cell during the in-plane compression without foams (three repeats).

Two cameras on both sides of the battery cell record the process of the formation of the buckles. Figure 5 shows the side view of the battery edge (width) from the gap between the two steel holders. As shown by the first picture, there is a pre-buckling compression until a 2% deformation (displacement divided by the original width, 150 mm). With 5% compression, the upper part of the battery started to buckle. With a further compression of 6%–12%, the buckles became clearer and more extensive, and waves were fully developed at the compression of 18%. From there on until 27%, the battery undergoes large densification.

Because of the almost plane-strain compression, the interior of the cell should follow a similar deformation pattern as the side view. A more clear sequence of the progressive folding is provided by the frontal view through the small window (see Fig. 6). It is seen that after one buckle had formed at 7% compression, this pattern continues up to 12% compression, during which new buckles were formed from the upper end of the battery, one at a time. At 13% compression, another buckle slowly developed from the lower end of the battery whilst many buckles had already formed from the upper end. At 19% compression, the buckles finally met at the lower end of the battery and the densification stage began.

The observed deformation is analogous to the process of progressive folding on prismatic columns, studied extensively in



Figure 4. Battery cell (#2) after in-plane compression showing clear buckling phenomenon.



Nominal strain (mm/mm)

Figure 5. Deformation patterns (side view) of the pouch battery cell during the in-plane compression without foams.

the literature over the past three decades.<sup>52–56</sup> The crushing force oscillates around the mean crush force, in a much similar way as in Stage 2) of the test. The mechanism of the progressive folding was explained in the papers of one of the present authors.<sup>52–54</sup> A photograph of a partially crushed column and the corresponding load-displacement curve are shown in Fig. 7.

So far only the deformation pattern could be observed from the outside of the battery, but the most interesting part is to see the internal deformation. The present large-format pouch battery cells are too big to fit in the chamber of most micro-computed tomography ( $\mu$ CT) devices. Therefore, the pouch of the tested batteries was cut open and the cells were left to dry in a fume hood for a week so that most of the electrolyte could evaporate. The opened battery cell was fixed by an epoxy followed by a cutting-and-polishing procedure to obtain the cross-sectional views. Figures 8a

and 8b respectively show the cross-sections of two different cells after 15% and 30% compression. At 15%, the global buckles had already formed, and as a result, the cell stack inside the pouch developed two important features—kinks and shear bands. Both features are very common in multi-layered structures with granular materials.<sup>17,57,58</sup> As the compressive strain increased, more kinks and shear bands formed across the length of the battery. With 30% compression as shown in Fig. 8b, the kinks and shear bands were fully developed, and the shear-band regions can be seen very clearly, especially in a zoomed view. As already known from the stress-strain curves, from 15% to 30% compression, the cell is entering the stage of densification. Therefore, it is understood that the densification process consists of the compaction of the granular materials of the coatings.



Nominal strain (mm/mm)

Figure 6. Deformation patterns (frontal view) of the pouch battery cell during the in-plane compression without foams.



Figure 7. A photograph of a partially crushed column (a) and the typical experimental and analytical load-displacement curves (b).

Figure 8 also provides a detailed view of the mesoscale structure of the cell stack. Even though the battery just has 0.8 mm space on each side for the development of buckles, the component layers of the cell are compressible due to the large porosity of the graphite, LMO/NMC, and the separators. The cross-sectional view confirms a rather smooth bending deformation of layers with relatively large bending radius *R* compared to the thickness of individual layers *t*. From the bending theory of beams, the strain (tensile or compressive) is  $\epsilon = t/2R$ , which is very small. Consequently, no crack or fracture is observed even under the large 30% deformation. This finding well agrees with the previous experimental observation that no short circuit happened during the uniform in-plane compression process. With 30% compression, the battery is close to the fully compacted stage. At this point eleven half-waves of buckles have been formed with a half wavelength of 7–8 mm, which is approximately identical to the cell thickness.

**In-plane compression with foams.**—In a realistic module, one individual battery cell is stacked with a number of other cells in parallel and sandwiched by thin aluminum plates for cooling. To mimic this boundary condition, one aluminum plate and one foam layer were placed on each side of the battery cell for testing. For this purpose, we tested 13 different types of foams and the one with a stiffness closest to that of a battery cell was chosen. A precompression pressure of 5 MPa, a magnitude oftentimes studied for pouch cells, <sup>59,60</sup> was applied on both sides of the cell.

Figure 9 shows the nominal stress-strain curve of the battery cell with foams and cooling plates on its sides. The measured force



Figure 8. Cross-sectional views of the pouch battery after 15% (a) and 30% (b) compression without foams.



Figure 9. Stress-strain response of the pouch battery cell during the in-plane compression with foams.

increases generally with the punch displacement. Compared with the response under in-plane compression without foams, there is not a stage showing a plateau. Force oscillations are still visible meaning that progressive folding occurs under the increasing force.

The post-testing examination of the tested battery cell reveals much less regular buckling patterns, where there are several zigzag folds, as shown in Fig. 10. like under the in-plane compression with the fully-confined condition (without foams), the folding seems to start from the upper edge of the battery cell, but it was not progressively formed. The observed pattern is a combination of a global Euler-type buckling and a local buckling.

Cross-sectional cutting and polishing shown in Fig. 11 was also performed, confirming that the battery cell underwent both global and local buckling. This response is explained by the presence of gaps and elastic foundation on both sides of the deforming cell. The global buckling has a large wavelength of 40–50 mm, and the local buckles has a small wavelength of less than 5 mm, less than the cell thickness. The local buckling forms a number of kinks in the external enclosure. As before, no electrical short circuit was observed in this type of test although the battery cell underwent a large deformation.

*In-plane indentation with a round punch.*—The uniform inplane compression is still a relatively idealized loading condition even with foams on the two sides of the cell. In real accidents, local cell indentation is caused by objects with irregular geometries such as a road debris or a stone,<sup>3</sup> or else a sharp edge of the impacting vehicle. Therefore, it is important to perform in-plane indentation tests on the battery cell with an object smaller than the width of the cell. In this test program, the battery cell was fully confined, as it was in the case of the in-plane compression test without foams. The two steel holders were tied with the four bolts, and a small space of 0.8 mm was left on both sides of the cell. The radius of the indenter is 24 mm. The force-displacement response of the battery cell is shown in Fig. 12. like the other two types of tests, there are several



Figure 10. (a) Front, (b) rear and (c) side view of the pouch battery cell after the in-plane compression with layers of foams on its two sides and a precompression pressure of 5 MPa.



Figure 11. Cross-sectional views of the pouch battery after 30% in-plane compression with layers of foams on its two sides and a pre-compression pressure of 5 MPa.

large-amplitude oscillations. What is different is that an electrical short circuit happened in this test almost at the same time as the

force drop. It was seen that the short circuit was initiated near the punch head causing a local fire and smoke at the upper part of the cell. Because of the low state-of-charge, the reaction was limited, posing no danger to the environment.

The test was stopped at the force drop (52 mm) and crosssectional cutting and polishing of the cell were performed after the test. Figure 13 shows the cross-sectional view of the cell. Some local fractures were observed in the battery component layers, which triggered multiple short circuits. The upper part of the battery cell was burnt. On the structural side, buckles, kinks, and shear bands also exist in the battery cell under this type of loading, as an explanation of the oscillations in the force-displacement curve. It is also worth noting that the bottom part of the cell showed signs of gas generation and expansion.

## **Discussions and Conclusions**

The mechanical behavior of a large-format lithium-ion pouch cell under in-plane compression was studied experimentally. Three types of tests were performed—uniform in-plane compression without foams (fully confined), in-plane compression with foams padding on the two sides of the cell to mimic the real boundary condition, and local in-plane indentation with a round punch. A special apparatus was designed, with adjustable displacement-controlled boundary conditions and simultaneous measurements of the deformation with two digital cameras. Force-displacement or averaged stressstrain responses were measured during the tests. Post-testing examinations were carried out on the tested battery cells, particularly including a cross-sectional cutting and polishing procedure. Based on the experimental observations, the following points are summarized for further investigations and discussions.

**Buckling.**—Buckling of the battery cells exists in all the three inplane loads. This is mainly a result of the large width/thickness ratio and the low bending stiffness of the cell. However, it should also be pointed out that the compressibility of the cell components also plays



Figure 12. Force-displacement response of the pouch battery under in-plane indentation with a round punch.



Figure 13. Cross-sectional views of the pouch battery after 52 mm displacement in-plane indentation with the 24 mm round punch without foams on the sides.

an important role—buckles were observed even though the battery cell was fully confined (with a very small gap in real tests). This is seldom seen for other incompressible materials like metals. While it is true that all the three tests showed evidence of buckling and subsequent folding, the deformation patterns in each test are different. Under in-plane confined compression, the buckles were progressive, similar to the compression of thin-walled prismatic columns. The wavelength of the local buckles is close to the thickness of the cell. Under in-plane compression with foams on its two sides, the cell developed a combined global and local buckling procedure, which is triggered similarly with the Euler buckling of a beam resting on the foundation. Under in-plane indentation with a round punch, buckles occurred in an irregular geometry mainly because the stress and strain were localized.

*Safety.*—Generally, in-plane loads appear to be safer than the transverse out-of-plane loads. Many existing studies on out-of-plane loads have reported a small displacement at the onset of an electrical

short circuit.<sup>15,16,18,37</sup> However, in the two types of uniform in-plane compression tests performed in the present study, no electrical short circuit was seen. In the more real-world local indentation test, localized three-dimensional deformation developed, followed by the fracture of individual components of the cell. In a recent publication, Xia et al.<sup>61</sup> performed dynamic punch tests on a battery module in three different directions. It was found that when the loading comes from the in-plane direction of the cells by a large diameter punch, there was almost no short circuit on each cell, while out-of-plane punch can cause short circuits, leading to severe fire accidents of the whole module. This finding agrees very well with our present study. The only short circuit observed in our in-plane tests happened in the local indentation. In terms of the displacement to structural failure, this type of tests is still not more susceptible to short circuits than the out-of-plane loads. To improve the safety of cells under such loading conditions, the present study suggests that the ductility of the separator should be sufficiently large to avoid the possible contact between the positive and negative electrodes due to mismatching.

Modeling .- In the present research (Part I), only the experimental program is presented, while most of the modeling work will be described in Part II. One way of modeling the in-plane mechanical behavior of an individual cell is to develop a so-called "detailed model" in which every component of the cell could be considered. However, it is usually very computationally expensive. What is more popular in the EV industry is a "homogenized" battery cell model, in which all the five different materials in the cell stack are smeared into one homogenized medium. Theoretically, such a homogenized model is unable to simulate the realistic buckling patterns even if the initial imperfections or modal patterns could be introduced, because the real battery structure is anisotropic and has a large in-plane stretching stiffness but a small bending stiffness. The possibility of developing a high-efficiency computational model to predict both the stress-strain response and the deformation pattern will be extensively investigated in the second part of the research.

*Applications.*—The present paper provides much-needed data to develop the failure envelope of pouch cells. The concept of the failure envelope was first introduced by Prasad in her master thesis<sup>62</sup> and was further extended in the recent paper by Li et al.<sup>63</sup> We know that the severity of the response depends on the ratio of the radius of a punch to the linear dimension of the cell. For the same type of external objects, a short circuit develops at about 20%–30% of the deformation in either of the three dimensions. More research is needed to get better understandings of several other battery and loading parameters. Part II paper describes new computational tools for constructing a safety envelope and designing safer cells modules and battery packs.

#### Acknowledgments

The authors are grateful to the MIT Battery Modeling Consortium (Altair, AVL, Boston-Power, Daimler, Jaguar-Land Rover, LG Chem, Murata, and PSA Groupe) and Ford-MIT Alliance for financial support.

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