Experimental Prediction of Failure Progression of Lithium-ion battery under Lateral and Longitudinal Compression

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Abstract

The crash safety of lithium-ion batteries (LIBs) has recently become a hot topic because of the growing applications of LIBs in electric vehicles nowadays. Present work consists of experimental findings covering the failure progression of LIB under mechanical abuse conditions of lateral and longitudinal.. The compressions test were performed on commercial 18650 battery. The load vs. displacement curve was recorded during deformation under lateral and longitudinal compression. The results are compared and governing failure mode was identified. It was found that battery samples are failed at 53.04kN and at 5kN under lateral and longitudinal compression respectively. This demonstrates the significance of type of loadings considered to predict the failure behavior of LIB during mechanical abuse conditions.

Keywords. Lithium Ion battery, Electric vehicle, Mechanical abuse, Battery Safety.

1. Introduction

Batteries are commonly used in devices such as laptops, trimmers, electric cars, drones, power banks etc. and its market is growing with its wider applications. With the increasing use, there is an increasing safety concerns associated to its use in electric transports (public/private). The safety of lithium-ion batteries in crash events of transports have became a frequently discussed issue. There are various aspects of battery safety such as electrical, thermal and mechanical etc. The latter is the subject of this study, which is to understand the mechanical integrity of the batteries and consequently the electric vehicles against electric short circuit as a result of mechanical failure during vehicle crash. The events of catastrophic failure of batteries due to small intrusion in the battery pack during crash necessitate the requirements of increase research activities in the area of battery safety [1]. There are various chemical reactions, involving conversion of energies apart from the energy involved during lithiation and de-lithiation process, that are responsible for considerable amount of heat released. In case of extreme load or internal short circuits caused by manufacturing defects, these reactions are triggered and may cause thermal runaway and even explosion. Xu et. al [2] have done study on two widely commercialized separators

Celgard 2400 and Celgard 2340 with single layer and three-layer structures respectively. It was found that the failure strain decreases while failure stress increases with the strain rate for materials in all three directions. The studies by Wang et al. [3], covering quasi-static mechanical tests on cylindrical Lithium-ion battery, revealed the essential mechanical properties of the jellyroll. Utilizing the plastic flow rule, it was found that the homogenized mechanical properties of the jellyroll are similar to the clay (clay-like). In the research done by Sahraeia et al. [4] a simple, yet accurate model of a single cell, needed for safety assessment of batteries under mechanical abuse conditions, was developed. Extensive testing was performed on a 18650 lithium ion battery, including indentation by a hemispherical punch, lateral indentation by a cylindrical rod, compression between two flat plates, and three-point bending. A hybrid experimental/analytical approach was developed by Wierzbicki et al [5] for extracting the average mechanical properties of cylindrical Li-ion cells. It was found that the mechanical resistance of the cell comes primarily from the jellyroll. Additional analytical calculations showed that the shell casing and the end-caps provide little contribution to the overall crash resistance of the cell in the loading cases studied in this paper. Gor et al. [6] have tested the mechanical stability of inactive polymeric components (e.g. separator and binder) as they play an important role in the long term performance of lithium-ion batteries. Here they investigated the effects of electrolyte solvents on the mechanical properties of a polypropylene battery separator through experimental measurements of thickness and elastic modulus of separator samples immersed in different solvent environments. They find that certain electrolyte solvents such as dimethyl carbonate, diethyl carbonate, and ethyl acetate cause noticeable softening of the separator. In the study by Zhu et al. [7], a series of indentation tests were conducted on lithium-ion battery with different capacities up to the occurrence of ISC. The external response and internal configuration of these batteries were investigated. It was observed that batterys with different capacities and state of charges exhibited different behaviors. In the paper by Wang et al. [8], the safety performance model of cylindrical lithium-ion batteries, which is based on a second-order oscillation feature that is subjected to mechanical abuse is proposed via a discrete Fourier transformation of experimental data. Combined with the safety performance model and Crushable-Foam material model, the simulation results show that the average predictive error of the force-displacement and failure displacement is less than 8.8% and 4.0%, respectively. Ma et al. [9] have characterized the evolution of the battery's internal structure in nail penetration test by combining multi-methods including computed tomography, mechanics analysis and simulation. Furthermore, through dismantling analysis, the evolution of battery materials during nail penetration is also explored. Liao et al. [10] presented a reviewed the vaiour work done int the field of battery abuse and shown a comparative study on the sensitivity of various monitoring and detection methods of battery abuse. Potential future research directions are also discussed in detail to further enhance the safety and robustness of lithium-ion battery systems [9]. The failure of batteries, as stated earlier is governed by thermal, electrical, mechanical or cascading effect due to one of these reasons. In this regard, thermal abuse conditions due to inappropriate thermal behavior of LIB are also a widely researched area. Ahmad et al [11], discussed efficient cooling by comparing the effectiveness of "both-tab" and "radial cooling" cooling approach to prevent the possibility of thermal runaway. These results shows, the significance of cooling strategy that should be adopted for different battery chemistries. Failure of a battery may lead to failure of whole battery pack and may subsequently results into the failure of the vehicle using it. Such failures of batteries with different battery chemistries [12,13] are detrimental to occupant safety and environment both.

It is to be noted here, that most of the work discussed the different abuse conditions for different battery chemistries. In the present work, comparison of failure progression of LIB, having lithium-cobalt oxide (ICR 18650) cathode, is done considering, lateral and longitudinal compression. The distinct failure behaviour of considered LIB at various failure stages depicts the changing rate of failure progression.

2. MATERIAL AND METHOD

Commercially available 18650 lithium-ion battery (3.2 V/2200 mAh, 65 mm* 18 mm* 18 mm) with lithium-cobalt oxide chemistry are used in this study as they are widely used in laptops, drones etc. The considered batteries at 2.5 V with states of charge (SOC) 0%. The SOC of the battery is 0% to avoid severe thermal runaway or fire at the start of internal short circuit during deformation. The present work does not include the temperature and voltage measurements. A Universal Test Machine (MTS 100 T) is used to perform the compression test as per the loading direction shown in figure 1. The cylindrical battery was compressed between two flat plates in lateral and longitudinal directions at a quasi-static rate of 5 mm/min. The applied load and plate displacement were measured during the experiments. The test was repeated at least three times to ensure the accuracy of the measured data.

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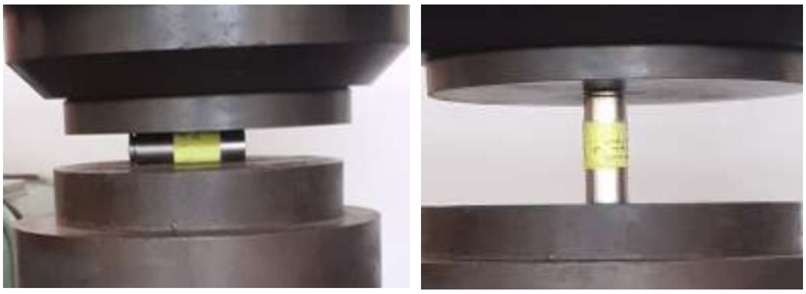

Figure 1. Experimental setup for (a) lateral compression, and (b) longitudinal compression of 18650 lithium-ion batteries.

3. Results and discussion

The, loading at specified rate of feed is provided once the initial contact of the crosshead with the considered LIB as shown in figure 1. (a) and (b). The measured load-displacement curve corresponding to the loadings are shown in figure 2.

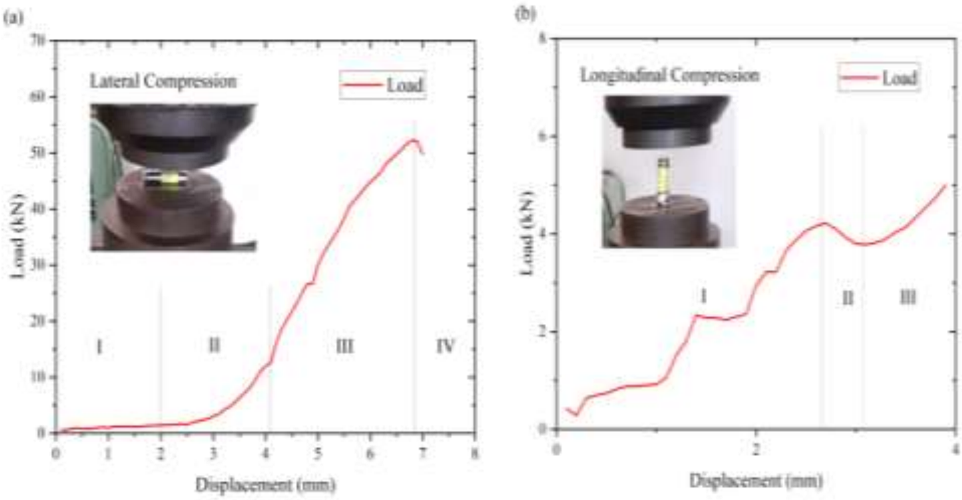

Figure 2. Load vs. displacement behavior and stages of failure progression of LIB (ICR 18650) under (a) lateral compression, and (b) longitudinal compression.

During lateral compression, the load increases linearly for Stage I showing compression of the casing of cell. The load then enters a platform stage referred to as Stage II (onset of jellyroll compression after casing), that is followed by the compaction stage as Stage III (space between the layers of jellyroll is compressed), and finally drops in Stage IV illustrating complete rupture (figure 2a). The peak load is approximately 53.04kN, and the corresponding displacement is 7 mm.

For longitudinal compression, figure 2b shows that the load increases almost linearly in Stage I until reaching the peak force showing compression of end-cap and space between end-cap and jellyroll. The force then fluctuates around 440 N because the casing buckles layer-by-layer in Stage II and finally increases for the multiple ring formation of the casing in Stage IV due to repetitive buckling of casing. Buckle rings form mainly in Stage II, and Stage III, evidenced after loading in the figure 2 b. The peak load in this case is approximately 5kN, and the corresponding displacement is 3.9 mm.

4. CONCLUSION

A set of tests were performed on commercially available 18650 cylindrical cells. The cells were tested with 0% State of charge (SOC). Lateral compression, and longitudinal compression tests between two rigid flat plates were performed to analyze quantitatively the failure of LIB. The results of the tests describe the different stages of the failure depicting the onset of failure and complete failure. The formation of ring in longitudinal compression test revealed the criticality of such loading configuration in comparison to the lateral loading. It was concluded that the local failure of cell in the test can be detected by local peak in the force-displacement curve.

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Biographies

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