Comparative study of Li-ion 21700 cylindrical cell under mechanical deformation

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Abstract. Lithium-ion batteries (LIBs) are an important component of the automotive industry in terms of electrification. Regarding their safety, the researchers perform different scenarios in which they follow closely and carefully their behavior under the action of induced requests. The most common mechanical abuse tests are three-point bending, simple bending, deformation with hemispherical punch head and nail penetration. In this article, the behavior of the 21700 lithium-ion cell is debated and the results are compared. First, experimental tests are performed and the results are validated with FEM model, to check the veracity of the experiment. Also, the interpreted results can be used in future researches regarding safety of batteries.

1. Introduction

During the use of an electric vehicle, the energy source may be deformed by an outer impact which may lead to mechanical damage of the housing and its components. To design and make a safest lithium-ion energy source, several international organizations and committees have enacted testing standards and specifications. They asses the safety limits of energy sources, such as overload, mechanical deformation, thermal and electrical abuse [1, 2].

Xu et al. [3] developed and analyzed a finite element model using ABAQUS interface. The representative model consisted of the top cover, the housing, the plastic sleeve and the core of the cell. Jellyroll was configured according to the mathematical model adapted to the dynamic Johnson-Cook stress regime.

The model validation was performed after the experimental tests of mechanical deformations by various methods of compression and thermal runaway induced by nail penetration [4]. Two ways of penetrations were done on the 21700 lithium-ion cell, axial direction and radial direction. The constant velocity of the nail was 70 mm/s, the displacement for radial tests was 10.5 mm and 15 mm for the axial test. The whole process was monitored, the maximum temperature reached by the deformed cell being 653.6^{o}C. FEM models were used to validate the experiment and, according to the researcher, the model is common and can be customized according to a specific cell type or simulations.

Recent papers [5, 6] have made a synthesis regarding the processes of mechanical deformation, thermal runaway, internal short circuit and explosions on different cells.

In this paper, deformation with hemispherical punch head is performed on the 21700 lithium-ion cylindrical cell, with SOC = 100%. For validating the experiment, the finite cell element model is developed in Altair software. The paper

2. Experimental

Many experiments have been carried out to simulate various mechanical abuse and to induce internal short circuit. The most common mechanical tests mentioned in the literature are three-point bending, simple bending, deformation of the cell with hemispherical punch and nail penetrations. The experimental stand was developed in order to achieve the objectives related to the necessary experimental research; its components are presented in table 1.

In this research, the commercially available 21700 lithium-ion cell was subjected to mechanical deformation, using the hemispherical punch head.

Table 1. Experimental setup parts.

Cell type	INR21700-40T	3.2 V
Used punch	Pinch indentation	-
Experimental stand	Hydraulic press	10 T
	Hydraulic unit working pressure	50-600 bar
	Tap, hose	-
	Testing surface	-
	Lights	-
Measuring instruments	Multitester	0-600 V
	Caliper	0.01 mm
	Load cell range	0-20 kN
	Multitester with temperature sensor	0-1300 °C

The measured parameters during the experemint are displacement, load, temperature and voltage. CAD model of stand configuration and its components were shown in figure 1.

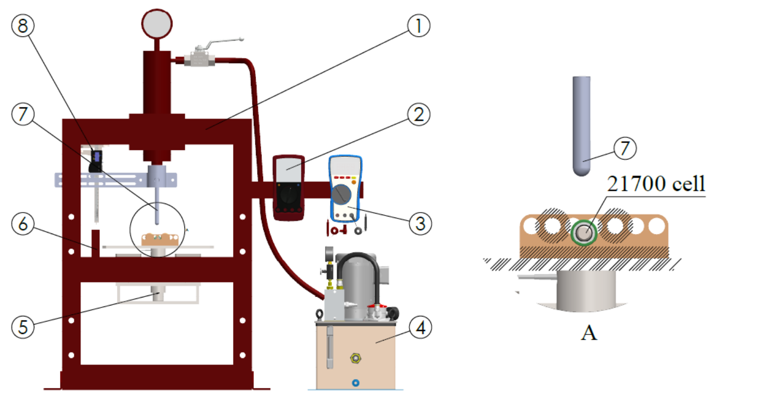

Figure 1. Experiment workbench. 1 -Press structure; 2 – Measuring instrument; 3 – Measuring instrument with temperature sensor; 4 – Central unit; 5 – Flat testing surface; 6 - Lights; 7 - Indenter; 8 – Deformation measuring device.

The experimental workbench of the 21700 cylindrical lithium-ion cells with the hemispherical punch is shown in figure 2, as can be seen the cell was placed between the fixing rollers support to maintain its position during the experiment. The CAD model of the hemispherical head indenter and its dimensions and drawing are represented in figure 3.
Variation of the force from figure 4, shown as the force reaches a maximum value of 11 kN, with a constant increasing displacement. After approximately 3 mm deformation (80 seconds), according to the curve which is presented in figure 5, the internal short circuit occurs and, implicitly, the thermal runaway phenomena appear. This irreversible process is confirmed by the increasing temperature variation and by the voltage, which drops to 0 V after another 50 seconds.

Figure 2. Side view of 21700 lithium-ion cell experiment.

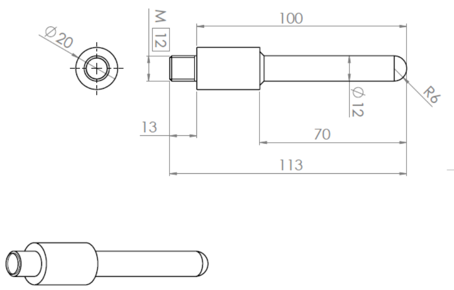

Figure 3. Hemispherical indenter dimension.

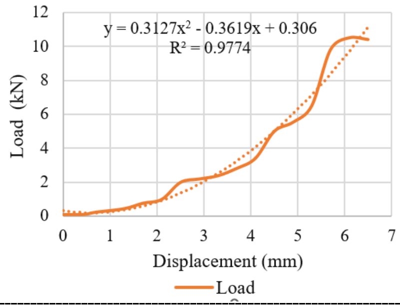

Figure 4. Variation of load.

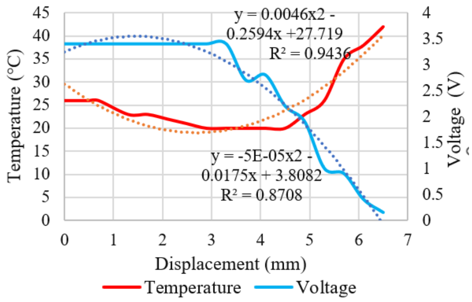

Figure 5. Variation of temperature and voltage.

The validation of the experimental results is determined by comparing the results of the FEM simulation.

3. FEM simulation

To perform a deformation simulation three main steps must be followed: preprocessing, processing, and post-processing. Preprocessing of the simulation includes the design of the CAD model in a design software environment, the cleanup geometry procedure, the material properties assign and the load case creation. The model of the 21700 lithium-ion cells with layers is modelled according to the real dimensions, as it is shown in figure 6. In this study the CAD model are done by using SolidWorks software environment and all simulation process are performed using the Altair Hyperworks trial version for preprocessing and trial version of Radioss solver to second step of the simulation process. The geometry model is meshed in 320,420 trias shell elements. In the last step of the simulation process the results are analyzed by using the post-process viewer, HyperView.

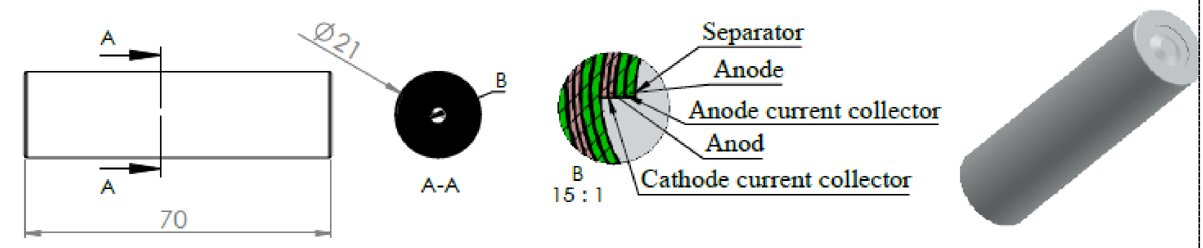

Figure 6. CAD model of 21700 lithium-ion cell with layers.

The simulation scenario and the meshed model of the battery cells are in figure 7. Throughout this process TYPE 7 is used as universal contact. The RBE 2 element, which is rigid, was used to interconnect the elements of the cell layers. Mechanical properties of the materials used in this simulation are summarized in table 3. The material type assigned to cell case, layers and to the other parts is M2_PLAS_JOHNS_ZERIL. Material like M36_PLAS_TAB was designated as an isotropic elastic-plastic material for the separator of the cell [7]. Hemispherical punch head has an imposed velocity at 5mm/s. The load case is prepared to perform a typical quasi-static mechanical loading condition.

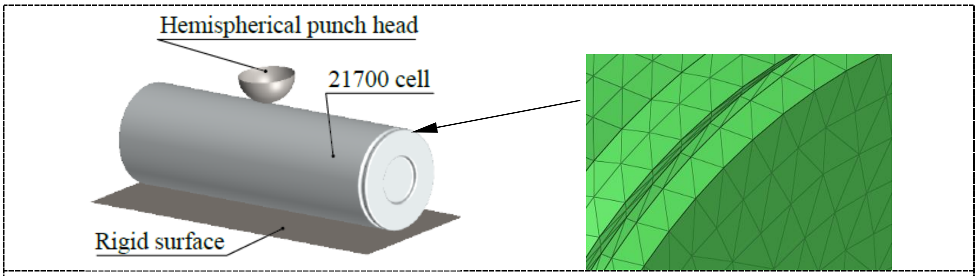

Figure 7. FEM setup for analysis.

Table 2. Mechanical properties of materials [8].

Component	Material	Density (*kg/m³*)	Young modulus (*GPa*)	Poisson ratio	Thickness (*μm*)
Cathode	LCO	-	100	0.35	90
Anode	Graphite	2300	110	0.23	130
Cathode current collector	Aluminum	2700	180	0.35	20
Anode current collector	Copper	7980	210	0.34	10
Separator	PE	1500	20	0.3	10
Case	Steel	7850	210	0.3	460

After computational process the visualization of the results can be done in HyperView. The distribution of von Mises stress is presented in figure 8, where can be observed that the maximal value is at the location where the indenter deformed the cell model. The variation of the load-displacement resulted from FEM simulation, figure 9.

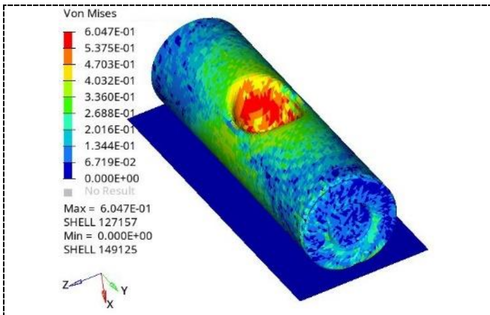

Figure 8. Distribution of von Mises stress.

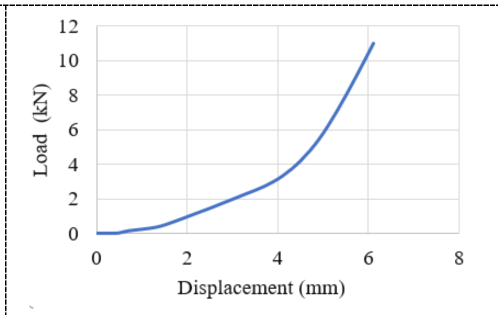

Figure 9. Variation of the load and deformation as FEM result.

4. Discussions

The experimental and simulation curves are overlapped and shown in figure 10. According to the graph, the experiment is validated up to the point where the displacement is 4.5 mm. At the displacement of 2.9 mm, the difference between the lines is of 22% for a displacement section of 1.5 mm. After this correction, the curves overlap. Towards the end of the experiments, there is another intersection of the curves, but the errors is less than 5%. The broad issue related to the temperature increase after the penetration of the 21700 cell can be determined following an experiment-simulation comparison with a developed coupled mechanical-thermal-electric FEA model.

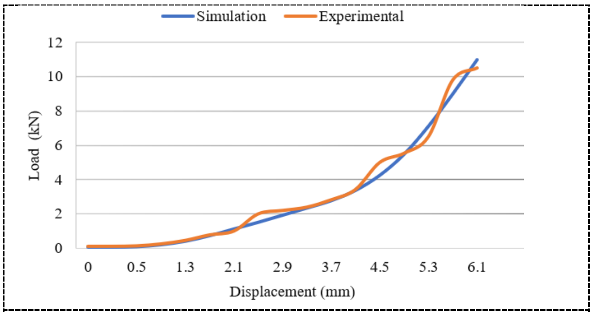

Figure 10. Model validation based on experimental-simulation results

5. Conclusions

The paper follows a primary analysis and comparison, however the validated model can also be used in the evaluation of battery packs of electric vehicles in case of crash.

Lithium-ion batteries became the most popular power sources in many fields, including electrified vehicles. This paper is clarifying the cell behavior under mechanical abuse and deformation of the cell with hemispherical punch head. At the experimental stage, four parameters were measured for better understanding the behavior of the cells in case of accident.

The main conclusion for the present paper was that the models are valid for the specific 21700 lithium-ion cell battery. This approach combines only experimental and FEM analysis, which can clarify and validate one another due to the overlapped curves.

The FE model is the easiest way to predict displacement and load. Internal short circuit and thermal runaway can be predicted from a coupled model.

Acknowledgments:

"This paper was financially supported by the Project "Entrepreneurial competences and excellence research in doctoral and postdoctoral programs - ANTREDOC", project co-funded by the European Social Fund financing agreement no. 56437/24.07.2019."

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