Comparative study of Li-ion 18650 cylindrical cell under pinch indentation

I Szabo[1] *, A A Sirca[1], L Scurtu[1], L Kocsis[1], I N Hanches[2], F Mariașiu[1]

[1 -] Technical University of Cluj-Napoca, Automotive Engineering and Transports Department, Bd. Muncii 103-105, Cluj- Napoca, Romania
[2-] Magneti Marelli Automotive Cluj-Napoca

Ioan.Szabo@auto.utcluj.ro

Abstract. Conventional fuels for vehicles, which are non-renewable energy sources, are still currently in use. To reduce noise and CO_2 emissions, electric vehicles dictate a remarkable research and developments in order to reach a viable solution. Electrified vehicles have a dedicated energy store, usually batteries, to improve emissions or replace the conventional energy source with electric power. For almost a decade now, the use of Li-ion batteries as a source of energy for electric vehicles has exploded, but there are also many questions about their safety. This study is dedicated to compare the results obtained by experiment with the result obtained by simulation about mechanical behavior of an 18650 Li-ion cell under pinch indentation.

1. Introduction

Lithium-ion batteries are used to power portable electronics and are also used in electrified vehicles [1], where different vehicle types can be mentioned: EV (electric vehicles), EREV (Range-extended electric vehicle), SHEV (series hybrid electric vehicles), PHEV (parallel hybrid electric vehicles), SPHEV (series-parallel hybrid electric vehicles).

Nowadays, many researchers study and try to predict the behavior of -different types of lithium-ion cells under mechanical abuse. Thermal run-away was tested thru experiments on lithium-ion cells using different trigger methods, while the parameters of the cells were measured with dedicated equipment [2, 3]. The conclusions obtained by researchers highlighted the comparison between mechanical abuse with nail penetration and thermal stress of the cell. In case of mechanical abuse with nail penetration, the heat output (kJ/Ah) is preponderant.

Other researchers have extensive studies regarding the short circuit phenomena of the batteries [4, 5]. Conclusions were mentioned also in the papers, the simulation were validated, load versus deformation results overlapped on the graph.

In their research paper, Spielbauer et al. [6] have highlighted that even a 1 mm deformation on an 18650 electrochemical cell can have fatal consequences. The cell was monitored for 8 weeks, during which time multiple deformations were simulated and load force and cell voltage were monitored simultaneously.

Through this research a primary simulation-experiment comparative analysis is approached, in which the deformation is not analyzed on each layer, but only on the whole electrochemical cell.

In this paper, primary nail penetration test is performed on the 18650 lithium-ion cylindrical cell, with SOC = 85%.

2. Experiment-and results

The following steps were implemented to perform the experiment: experimental stand development, establishing the test parameters, performing experimental tests and centralizing the obtained results.

The experimental stand used has the parts presented in table 1. The equipment related to the experimental stand, in order to measure the established parameters, are presented in table 1. Also, the 18650 lithium-ion cylindrical cell subjected to mechanical stress has a casing with 0.4 mm thickness and overlapped layers of its components. The specific components of the cell are anode current collector, anode, cathode, cathode current collector and separator. The pinch indentation is done on 18650 lithium-ion cell to evaluate the mechanical response of the cell and to determine the onset of the short circuit.

Table 1. Experimental setup parts.

Experimental stand	Hydraulic unit working pressure	50-600 bar
	Hydraulic press	10 T
	Tap, fittings	-
	Flat surface	-
	Led light	-
Measuring instruments	Load cell range	0-20 kN
	Temperature sensor	0-1300 °C
	Voltmeter	0-600 V
	Digital caliper	0.01 mm
Cell type	INR18650-25R	3.2 V
Used punch	Pinch indentation	-

The measured parameters during the experemint are load, intrusion, voltage and temperature , also the sumary of these parameters are presented in table 2.

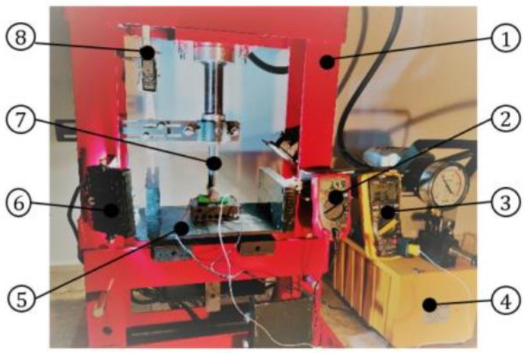

Figure 1. Workbench. 1 - Press; 2 - Voltmeter; 3- Temperature measuring device; 4 –Electric unit; 5 -Testing board; 6 – Led lights; 7- Pinch indentation head; 8 – Digital caliper.

Table 2. Summary of the testing parameters

Testing parameters	Deformation	mm
	Temperature	° C
	Current	V
	Force	kN

The configuration of the cell on the stand load cell mounting plate under nail penetration can be seen in figure 2. On the testing board of the workbench, the 18650 cylindrical cell was fixed and equipped with temperature measuring device. The pinch indenter was used, while the current and temperature multimeters have been connected to the cell. Figure 3 shows the geometric shape of the indenter tool with a sharp top.

The values of the results, obtained by experimental testing, have been centralized, where in figure 4 the deformation and force are shown and in figure 5 the temperature and current measured are shown. According to figure 4 and 5, the short-circuit occurred after the cell was punched, the deformation depth was 1.7 mm, and the current started to drop to 0 V. The temperature started to rise from 25^{o}C to more than 100^{o}C, being more than 3 times the initial value. The maximum load reached in this case was 0.3 kN.

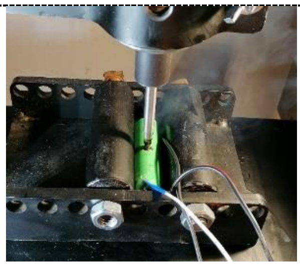

Figure 2. Experiment stand for 18650 cell.

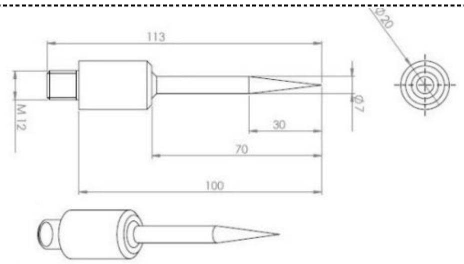

Figure 3. Pinch indenter dimension.

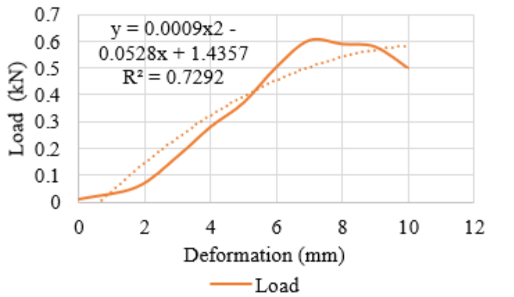

Figure 4. Variation of the load in relation to deformation

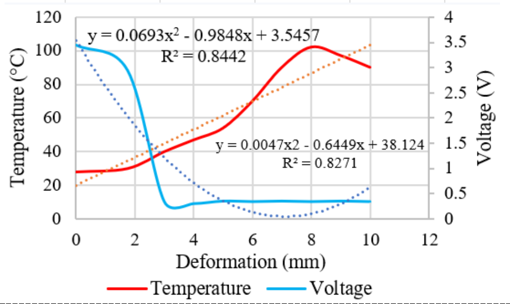

Figure 5. Variation of the temperature and voltage.

3. Finite element simulation and results

The first step of the simulation process in this article is given by the realization of the CAD model of the 18650 cylindrical cells in the computer-aided design software, SolidWorks. All the cell components were design according to the dimensions physically measured in advance.

The second step was the preprocessing part, performed in Altair, HyperMesh software under the Radioss solver environment. Cell geometry is imported in HyperMesh and is meshed in 248,383 shell elements. An optimal quality criterion was chosen to mesh all the cell components. The last step in this setup is defining initial velocity, assignations of the proper materials for each component.

Figure 6 shows the layered CAD model, and figure 7 shows the imported model in HyperMesh. Between components the predefined TYPE 7 interface contacts were used, which ensure permanent contact between the surfaces of the model.

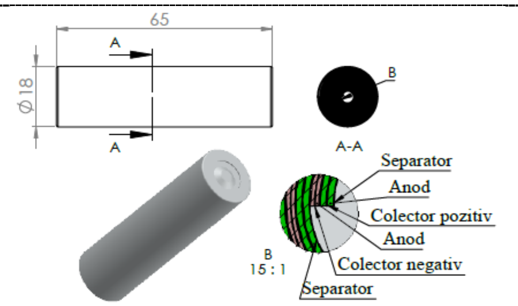

Figure 6. CAD model of 18650 lithium-ion cell with layers.

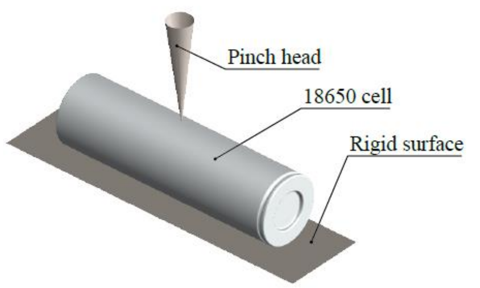

Figure 7. FEM setup for analysis.

The properties of the materials used are summarized in table 3. Type of the materials assigned to the components is M2_PLAS_JOHNS_ZERIL.The specified material has isotropic elastic plastic properties and renders internal stresses depending on deformations and temperature.

Table 3. Mechanical properties of materials [7].

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

Processing part is the third stage of the simulation and the configured model is launched in Radioss solver for analysis. Depending on the complexity of the model, analysis time may extend over a period of time. The last step of the simulation is represented by the post-processing of the obtained data. The obtained results are interpreted through the HyperView and HyperGraph modules from Altair. In HyperView interface the von Mises stress distribution can be observed, as shown in figure 8. HyperGraph offers the possibility to display the curve of the results obtained by simulation of the puncture of the cell with the sharp pinch head, as it shows in figure 9.

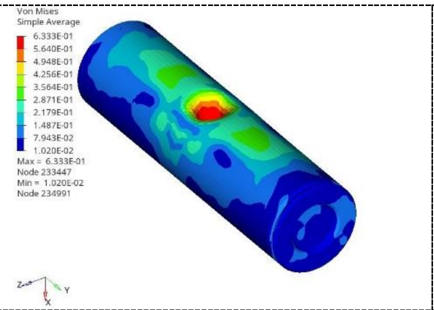

Figure 8. Distribution of von Mises stress.

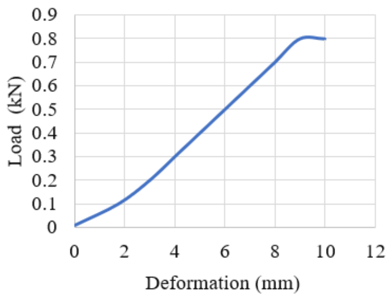

Figure 9. Variation of the load and deformation as FEM result.

4. Discussions

The results obtained in case of penetration of the 18650-lithium-ion cell with the sharp pinch head are shown in figure 10. After the curve observation can be mentioned the differentiation of less than 3 % until to the point where the deformation reaches 7.5 mm. After that point the curves diverge. Based on the mentioned facts the experimental model is validated between 0- and 7.5-mm deformation. Also, as the graph shows, the downward trend of the curves and the differentiation of 30% are due to the input parameters of the simulated model, which require more in-depth study.

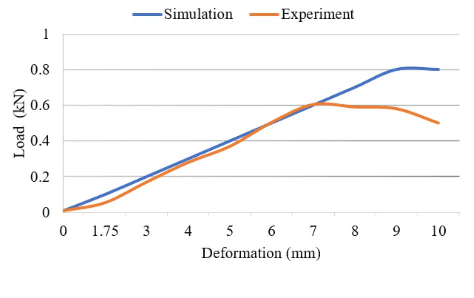

Figure 10. Model validation based on experimental-simulation results

5. Conclusions

Through mechanical abuse such as pinch indentation on the 18650 lithium-ion cell the short circuit is missing when the sharp head touched the cell. By the action of force, the deformation is increasing to a maximum value of 17 mm. After the short circuit debuted, thermal run-away occurs due to the deformation of the cell with pinch head, which is confirmed by multimeter sensor which detected temperature increase on the case exterior surface of the cell. Also, after the structural deformation failure, the cell changes its shape, due the short-circuit the voltage starts to drop, and electrolyte leakage occurs.

The experiment was validated by finite element method, and as the results shown in figure 10, the experimental test is validated where the curves are almost overlapping.

Regarding the validation area, the two curves overlap to the point where the deformation is 7.5 mm.

On the basis of this information, it can be concluded that the model is validated up to a certain point. For the validation of bigger deformations, a coupled electrochemical-thermal-mechanical model needs to be developed.

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.”

References

[1] L. Usai, J. J. Lamb, E. Hertwich, O. S. Burheim and A. H. Strømman, "*Analysis of the Li-ion battery industry in light of the global transition to electric passenger light duty vehicles until 2050*", vol. 2, I. Science, Ed., Environmental Research: Infrastructure and Sustainability, 2022.

[2] M. Sharp, J. J. Darst, P. Hughes, B. Julia, M. Pham, D. Petrushenko, T. M. M. Heenan, R. Jervis, R. Owen, D. Patel, D. Wenjia, H. Michael, A. Rack, O. V. Magdysyuk, T. Connolley, D. J. L. Brett, G. Hinds, M. Keyser, E. Darcy, P. R. Shearing, W. Walker and D. P. Finegan, "*Thermal Runaway of Li-Ion Cells: How Internal Dynamics, Mass Ejection, and Heat Vary with Cell Geometry and Abuse Type*", vol. 169, J. o. T. E. Society, Ed., IOP, 2022.

[3] C. Zhao, J. Sun and Q. Wang, "*Thermal runaway hazards investigation on 18650 lithium-ion battery using extended volume accelerating rate calorimeter*," Journal of Energy Storage, vol. 28, 2020.

[4] I. Szabo, L. Kocsis and F. Mariasiu, "*Research on the behaviour of a LiFePo4 pouch cell under mechanical stress*", vol. 898, I. C. S. M. S. a. Engineering, Ed., IOP Publishing Ltd, 2020.

[5] M. Sheikh, M. Elmarakbi, R. Sheikh and A. Elmarakbi, "*Internal Short Circuit Analysis of Cylindrical Lithium-Ion Cells Due to Structural Failure*", vol. 168, J. o. T. E. Society, Ed., IOP Publishing Limited, 2021.

[6] M. Spielbauer, O. Bohlen and A. Jossen, "*Safety behavior of mechanically damaged 18650 lithium-ion battery cell*s," Advanced Battery Power, 2022.

[7] T. Waldmann, R.-G. Scurtu, K. Richter and M. Wohlfahrt-Meh, "18650 vs. 21700 Li-ion cells – A direct comparison of electrochemical, thermal, and geometrical properties", vol. 472, Elsevier, Ed., Journal of Power Sources, 2020.

[8] X. Duan, W. Jiang, Y. Zou, W. Lei and Z. Ma, "A coupled electrochemical–thermal–mechanical model for spiral-wound Li-ion batteries," *Journal of Materials Science,* vol. 53, 2018.