

Article

Multi-Layered Numerical Model Development of a Standard Cylindrical Lithium-Ion Battery for the Impact Test

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Abstract: For safety issues in lithium-ion batteries (LIBs), international standards and regulations for various abusive environments have been developed, and UL1642 in Underwriters Laboratories (UL) currently covers electrical, mechanical, environmental, and fire exposure tests. An impact test is one of mechanical abuse tests in UL1642, which aims to determine the safe prevention of fire or explosion. As the energy density of a lithium-ion battery is continuously increasing, it is difficult to pass the regulation. Therefore, it is necessary to predict failure mode due to an internal short circuit in developing high-capacity cells. For a sudden and measured mechanical force, we speculate that damage to a separator consisting of LIBs makes the battery experience an exothermic phenomenon due to an internal short circuit because a separator is a key component for preventing the electrical contact between two electrodes. Therefore, if we can find mechanical stresses of each component in LIBs, we can evaluate whether each component is severely damaged or not. In the present study, we propose a finite element model consisting of a multi-layered structure, which will permit us to assess the possible onset location of the short circuit, and to predict the sequence of failure at a cell level. We applied the proposed method to a cylindrical cell, and the accuracy of the model was verified through the comparison of the experiment results. Additionally, simulation results showed that it is possible to track mechanical stress variations of each component progressively. Furthermore, we performed the numerical experiment evaluating the thickness effect of a center-pin. We expect the proposed finite element model to be used in order to devise cell level abuse-tolerant design from a mechanical point of view before conducting mechanical abuse tests as part of the product development process.

Keywords: center-pin; cylindrical cell; frictional contact; impact test; lithium-ion battery



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1. Introduction

A lithium-ion battery is a rechargeable (also known as secondary) battery in which lithium ions can move reversibly through an electrolyte between the negative electrode (the anode) and the positive electrode (the cathode) during charging or discharging. These types of batteries have the advantage of higher energy density and longer cycle life than other secondary batteries. Therefore, these are widely used as a power source and are made in various shapes such as cylindrical cells, prismatic cells, or pouch cells to meet the wide range of product demands [1] and nowadays have been adapted to electric vehicles (EVs). For EVs, each type of battery has its own advantages and disadvantages. Prismatic cells are more resistant to external impact, but they have relatively low energy density. Pouch cells are thin and have high energy density, but they are not as rigid. Cylindrical cells are cheap because of a higher level of production automation and are more resistant to high internal pressure without deforming; however, many are required to power an EV due to lower capacity. As the technology of lithium-ion battery packs using 18,650 batteries develops [2], these disadvantages are overcome, and cylindrical lithium-ion batteries are becoming a

possible choice of power source for EVs. Tesla has shown a higher level of energy density using cylindrical cells [3] and mainly uses them for EVs.

However, the energy density of the batteries in EVs is continuously increasing for long-lasting demands in markets and safety issues have been raised since the battery can be prone to damage caused by accidents in the case of car collisions and other extreme circumstances. The damage makes the battery experience an exothermic phenomenon resulting from its joule heating due to a sudden internal short circuit, which leads to a thermal runaway such as a fire or explosion [4–7]. Therefore, even if the rate of failure in actual use is very low, the overall safety issue is one of the critical challenges in advanced high-capacity batteries.

The safety issues in lithium-ion batteries related to a thermal runaway will occur during mechanical (damage to shell casing, compression, punching, and twisting of cells), electrical (overcharge/discharge and short circuit), and thermal (thermal shock and local heating) abuse situations [8]. The various international standards and regulations for safety testing of lithium-ion batteries in automotive applications are comprehensively reviewed in the paper [9]. To address a range of possible abuses of lithium-ion batteries, a number of standards and testing protocols have been developed by Underwriters Laboratories (UL). UL1642 currently covers electrical, mechanical, environmental, and fire exposure tests [10]. The impact test is one of four mechanical tests such as crush, impact, shock, and vibration required by UL1642 to determine a cell's ability to withstand specified impact applied to a cylindrical steel rod placed across the cell under test, and the test cell may not explode or ignite to pass this regulation. As cell capacity has increased, cell manufacturers are facing difficulties with UL 1642 safety tests [11]. Especially for cylindrical cells, it is challenging since rolled layers of anode/separator/cathode are inserted into a specified hollow cylinder casing. Many researchers have conducted the mechanical abuse tests on cylindrical cells. Kim et al. [12] performed the mechanical behavior analysis through the impact and the heating experiments on a 18,650 lithium-ion cell and observed the damage and temperature change in two types of cylindrical cells, cells with and without a center-pin which is located in the center of the battery. Sahraei et al. [13,14] performed a comprehensive set of mechanical abuse tests on 18,650 cylindrical cells and developed a finite element model using a homogenized and isotropic lump model to predict short circuit detection. For a lump model, it is difficult to find stresses of each layer in a jelly roll. For a sudden and measured mechanical force, we speculate that damage to a separator consisting of LIBs makes the battery experience an internal short circuit because a separator is a key component for preventing electrical contact between two electrodes. Therefore, if we can find accurate mechanical stresses of each component in LIBs, we can evaluate whether each component is severely damaged or not, which makes it possible to capture the onset of short circuit in a jelly roll. In the present paper, we propose a finite element model consisting of the four distinct layered structures, which will permit us to assess the possible onset location of a short circuit, and to predict the sequence of failure due to the internal short circuit. The proposed method will apply to a cylindrical cell to track mechanical stress variations of each component as the test progresses. Since manufacturers should conduct test protocols as part of the product development process, we expect the proposed finite element model to be used efficiently for research and development of cells.

2. Numerical Model for the Impact Test

2.1. Impact Test Results

The UL standard defines the impact test in which a 9.1 kg weight at rest is in free fall from the height of 610 mm to a cylindrical steel rod of 15.8 mm diameter placed across the center of the standard 18,650 lithium-ion cell on a flat surface. Figure 1a shows the localized deformation of the cell resulting from the impact test based on the UL regulation with 50% state of charge (SOC) of the nominal capacity. If the cell is fully charged, it could potentially catch on fire due to an internal short circuit, so we charged 50% SOC enough to identify the onset location of an internal short without the occurrence of thermal runaway.

The cylindrical cell has a shell casing that is made of a steel with inside diameter of 18 mm, wall thickness of 0.15 mm, height of 65 mm, which contains a roll of alternating separator, anode, separator, and cathode. It also shows the severe interior damage of electrodes and a center-pin as shown in Figure 1b,c due to the internal short circuit as well as the external mechanical loading. However, it is not easy to identify the onset location of the damage ignition because the cell has a structure with many layers known as a jelly roll.

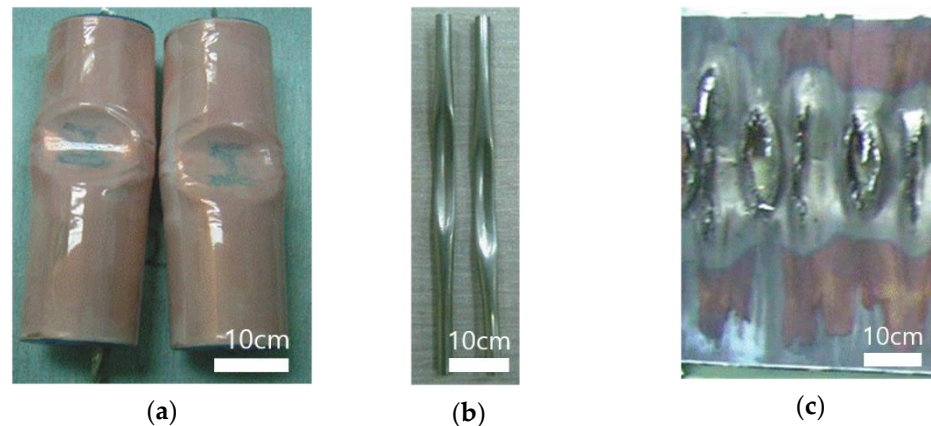


Figure 1. (a) Deformed cells after the impact test. (b) Deformed center-pins. (c) A damaged electrode.

2.2. Numerical Model Development

To track the dynamic response during the impact test and identify the onset location of an internal short inside a cell as shown in the test results, we propose a three-dimensional finite element model consisting of a detailed layered structure of the jelly roll. Figure 2a shows a schematic illustration of the numerical model for the impact test. First, the outer shell casing of a lithium-ion cylindrical cell was modeled with the homogeneous shell elements without considering the endcap for simplification. The shell casing is made from SPCE steel for deep drawing, and the stress–strain data in the literature [12] were used. Second, the surface of the jelly rolls increases as the radius of each layer position increases due to a spiral wound structure. For generating each layer profile of the jelly roll, we obtained the cross-sectional position values from the winding data of four layers (two separators, anode and cathode, respectively). Each separator has a depth of 60 mm, which is located between the anode and cathode to prevent the internal short circuit from occurring while allowing lithium ion to transport through microporous pathways between two electrodes in normal operation. It was modeled as homogeneous shell elements by extruding the sketched position profile. The microporous membrane of the separator is made from mainly polyethylene (PE) or polypropylene (PP), and it shows strong anisotropic properties since the failure strain in the machine direction (at approximately 35% strain) is reached much faster than that in the transverse direction (at more than 400% strain), as shown in [15]. In a failure analysis, the strength in the machine direction is a dominant factor, so the separator is considered to be a homogenous material with a property in the machine direction. Third, the cell is made from lithium cobalt dioxide (LiCoO_2) in the cathode and graphite (C_6) in the anode, respectively. Therefore, the cathode consists of $\text{LiCoO}_2/\text{Al}/\text{LiCoO}_2$ composite membranes and the anode consists of $\text{C}_6/\text{Cu}/\text{C}_6$ composite membranes. Each laminated composite membrane was extruded based on the position profile and was modeled using three superimposed shell elements. The electrodes of both the anode and cathode are made from copper and aluminum membranes, so we used the thin membrane properties of copper and aluminum. The tensile strength of coated materials (known as active material particles) in both the anode (lithium cobalt dioxide, LiCoO_2) and cathode (graphite, C_6) is not clearly specified. Therefore, we approximated the tensile strength of both coated materials to be around 10 MPa used in the literature [14,16], which was assumed to be the tensile cut-off value of the jelly roll as a bulk property. Fourth,

the cylindrical cell also has a center-pin, which prevents deformation of the jelly roll when charging or discharging and releases gas generated in use. The center-pin has a diameter of 2 mm and a thickness of 0.1 mm and it is placed in the center of the jelly roll. It was modeled using the homogenous shell. Last, the cylindrical rod and punch were modeled by solid elements, and the bottom contact surface was modeled as a discrete rigid element. The assembled finite element model of the casing, jelly roll, and center-pin is shown in Figure 2b. The properties of the cell components [12,14–16] are summarized in Table 1.

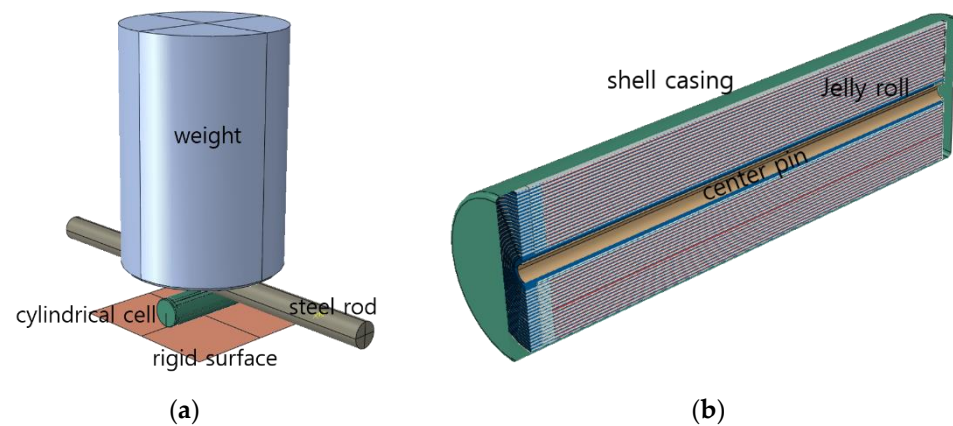


Figure 2. (a) Schematic of the impact test. (b) A cross-section view of a three-dimensional finite element model of a jelly roll, center-pin, and shell casing.

Table 1. Material properties of cell components.

Parts	Elastic Modulus (GPa)	Poisson's Ratio	Density (kg/m ³)	Yield Strength (MPa)
Can (SPCE)	172	0.28	7860.0	256
Cathode (Al foil)	69	0.34	2730.0	165
Anode (Cu foil)	110	0.36	8960.0	333
Separator (PE film)	1.017	0.33	921.0	39.4
Center-pin	193	0.25	7960.0	515

We used the ABAQUS/Explicit module for the impact test simulation in which the homogeneous/composite continuum shell elements (S4R) in three-dimensional analysis are employed, and the continuum shell elements are general-purpose shells that allow finite membrane deformation and large rotations. Thus, these are suitable for nonlinear geometric analysis, and include the effects of transverse shear deformation and thickness change. A general contact algorithm was employed to treat frictional contact interactions between the components. Both weight and steel rod were constrained to move in the vertical direction, and gravity accelerations were applied to all parts. Since the test protocol (UL regulation) defines that the free-falling punch is dropped from the height of 610 mm, it will take a long time to simulate from the beginning of the drop. In order to reduce the computational cost, we predefined the calculated velocity (3.46 m/s) to the 9.1 kg weight, and the simulation started from the impacting moment. The flat surface was fixed to prevent the rigid body motion, and a reference point was set up to measure the reaction force during impact simulation. Several different size of meshes and element types were calibrated in an iterative manner to match the localized deformation amount as shown in Figure 1a, which was obtained from the impact experiment, and the simulation took 12 h for 6 CPUs in the HP Z840 workstation.

3. Results

To evaluate whether the analysis shows an appropriate dynamic response during impact, we plotted the graph of the energy variables with respect to time, as in Figure 3. At the beginning of the simulation, the punch is contacting the rod with a predefined velocity; thus, initial kinetic energy is large. The impact deforms the cell casing and the jelly roll, and the deformation of the cell transfers the kinetic energy to the internal energy; thus, the internal energy increases while the kinetic energy decreases. The internal energy is composed of both elastic and plastically dissipated energies. After reaching the maximum cell deformation at about 2.7 ms, the elastic deformation of the cell recovers until 4 ms, resulting in increasing the kinetic energy. Then, the punch and impacting bar rebound and lose contact with the cell after about 5 ms without a further change in energy variables. The artificial energy which suppresses hourglass is maintained within 15% of the total internal energy and it could be reduced by refining meshes, but the computational cost increases.

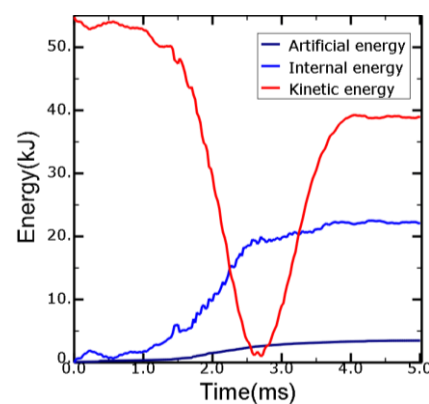


Figure 3. Artificial, internal, and kinetic energy outputs with respect to time.

Figure 4a shows that the localized maximum deflection reaches 7.1 mm at the center of the cell over 2.7 ms of the impact, and Figure 4b shows the calculated force–displacement curve from the simulation. The reaction force is measured from the rigid support, and the displacement is a punch downward movement in vertical direction, respectively. The curve shows two compressive stiffness values as distinct slopes in the linear region. The initial slope shows a gradual increase until compressive force reaches 4 kN, which corresponds to the point where the center-pin collapses (at about 1.5 ms), and then a stiff increase up to 39 kN reaching the maximum localized deformation (at about 2.7 ms).

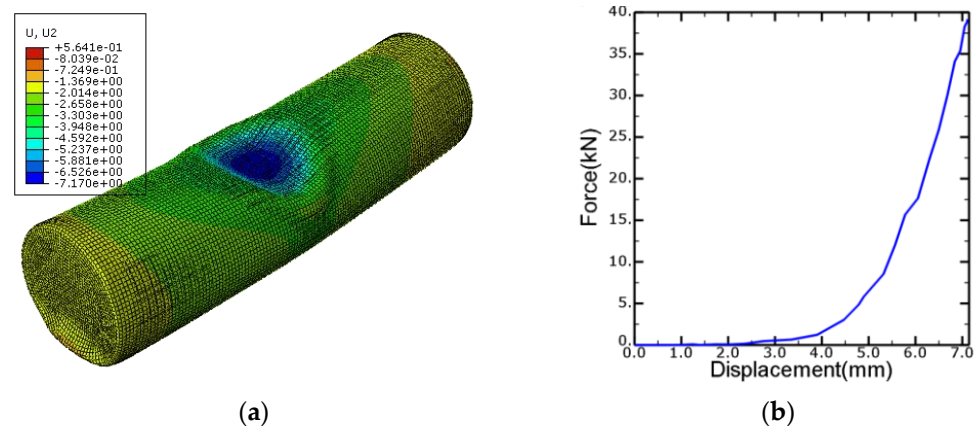


Figure 4. (a) Deformed shape at the maximum deformation. (b) Force vs. displacement curve showing change of compressive stiffness values. Some like $-8.099\text{e-}02$ means -8.099×10^{-2} .

Table 2 shows the von Mises stress of each component at the maximum deformed state (at $t = 2.7$ ms), and it predicts that the can, separator, and center-pin of the cell reach the yield strength. At the maximum deformed state, a set of separators is extracted from the jelly roll to investigate the damage onset location, which could be the advantage of the proposed model compared to a lumped model. Figure 5a shows the stress distribution as well as the deformation, and the maximum plastic deformation occurs around both edges of the inside separators near the collapsed center-pin, as shown in Figure 5b. PEEQ in the figure represents a scalar measure of equivalent plastic strain energy, and failure of the separator occurs at the 0.35 value (a plastic strain energy of 35%) [15]. The simulation shows that the internal damage of the separator could start from edges around the center-pin and, thus, it makes both the anode and cathode of the battery contact each other, resulting in the onset of an internal electric short circuit. It shows severe damage starting from the center of the cell, and its pattern is periodic due to a spiral wound structure. The prediction of the simulation analysis is in good agreement with the test result. The proposed modeling method makes it possible to track the progressive deformation response of each component separately after simulation and to analyze the characteristics of each component depending on changes in material properties or dimensions conveniently.

Table 2. The von Mises stress of each component at $t = 2.7$ ms.

Parts	von Mises Stress (MPa)
Can	416
Cathode	16.4
Anode	10.5
Separator	157
Center-pin	860

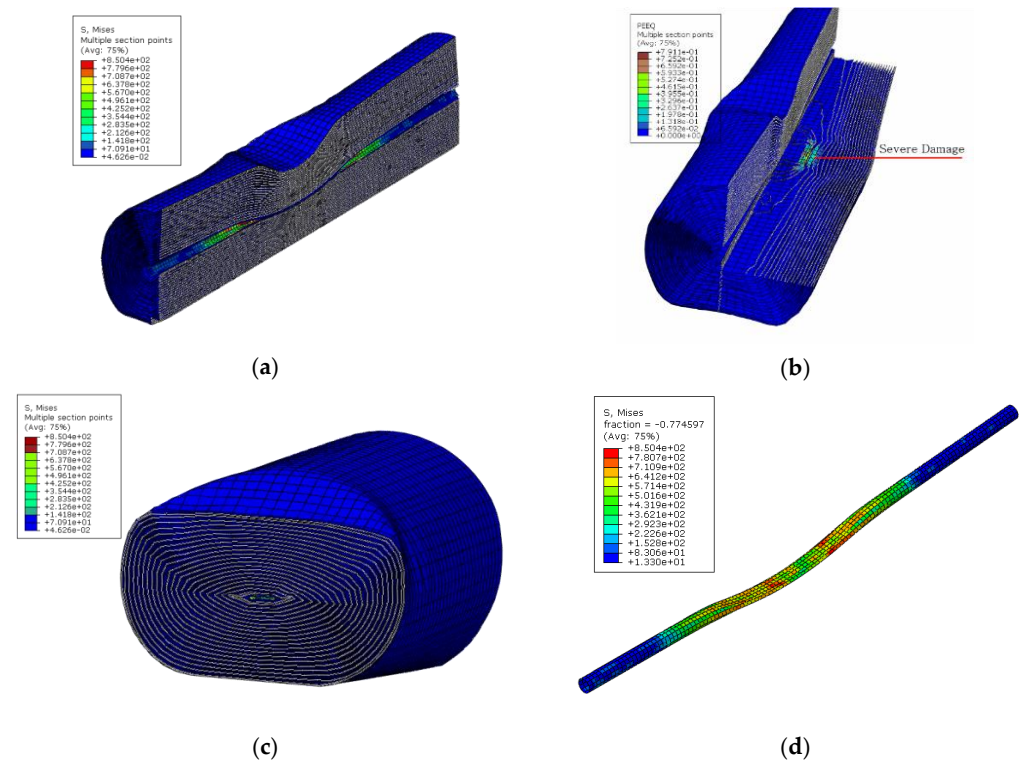


Figure 5. (a) Stress distribution of the deformed jelly roll with a center-pin, (b) damage onset location of a set of separators predicted from the simulation, (c) longitudinal section of the deformed jelly roll, and (d) deformed center-pin. Some like $8.504e+02$ means 8.504×10^2 .

Furthermore, we performed a numerical experiment to examine the internal damage levels depending on a center-pin. In Figure 6, plastic energy dissipations for three cases (without a center-pin, 0.1 and 0.3 mm-thick center-pins) are compared, and curves provide the damage level of each separator which is relevant to an internal short. Over the simulation, the cell without a center-pin dissipates more plastic energy than the other two cases. Therefore, we speculate that the separator for the cell without a center-pin could be damaged severely, and the prediction is in good accordance with the experimental result [12], which showed a thermal runaway due to severe damage of both separators and electrodes.

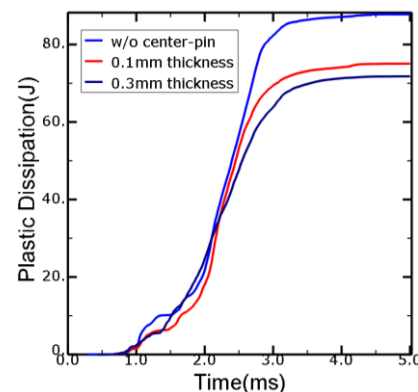


Figure 6. Plastic dissipation comparison plot in a roll of a separator for without, 0.1 and 0.3 mm-thick center-pin cases, respectively.

4. Discussion

For cases with a center-pin, we compared the initial plastic energy dissipation within a few milliseconds, and a cell with a 0.3 mm thickness center-pin dissipates more plastic energy than a cell with a 0.1 mm thickness. Although the difference in plastic energy dissipation is subtle, it is possible that the cell with a 0.1 mm thickness center-pin might suffer from a thermal runaway. At the beginning of an internal short, the battery is still active, and the magnitude of the short area is heuristically considered to be a dominant factor for a thermal runaway. If the short area is large enough to discharge the stored energy within a short period, a thermal runaway will not occur. Otherwise, the battery might lead to a thermal runaway. At present, the criterion to distinguish these two different events is an open question. In order to predict whether the final state is thermally stable or not, correlation between the diameter of the short circuit area and joule heats induced by an internal short should be properly evaluated by experiments. Further, an electro-chemical reaction as well as a mechanical response is considered at the same time to capture accurate abuse reactions. Even if the finite element model could not distinguish the final state of the battery, we could conclude that a center-pin has an important role to protect a cell by absorbing impulsive energy and its thickness influence on the short area.

So far, the developed finite element model shows that it has a capability to track qualitative damage level of an internal cell structure. In cell development, it could also be used to investigate responses when mechanical properties of separators, electrodes, and shell casing change. Furthermore, we could extend this finite element model to predict dynamic response to various abuse behaviors such as crushing [13] or nail penetration [17], as well as impact.

5. Conclusions

The external mechanical loading to a lithium-ion battery is likely to cause localized damage of an internal cell structure leading to an internal short circuit. This failure mode is experimentally devised as an impact test in order to consider battery design safety at a cell level. As energy density increases, a cell is vulnerable to the impact test due to a densely

occupied jelly roll. Therefore, new cell developments require reliable prediction of onset of the internal short circuit and the damage propagation induced by the impact. In this research, we developed a numerical finite element model incorporating the multi-layered structure based on the winding data of the jelly roll to predict the failure mode at a cell level. The accuracy of the model was verified through the comparison of the experiment results. Furthermore, we performed the numerical experiment evaluating the thickness effect of a center-pin. We expect that this model will be an effective tool to support abuse-tolerant and safe cell development.

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References

- George, B. The Development and Future of Lithium Ion Batteries. *J. Electrochem. Soc.* **2017**, *164*, A5019–A5025.
- Zwicker, M.F.R.; Moghadam, M.; Zhang, W.; Nielsen, C.V. Automotive battery pack manufacturing—a review of battery to tab joining. *J. Adv. Join. Process.* **2020**, *1*, 100017. [\[CrossRef\]](#)
- Löbberding, H.; Wessel, S.; Offermanns, C.; Kehler, M.; Rother, J.; Heimes, H.; Kampker, A. From Cell to Battery System in BEVs: Analysis of System Packing Efficiency and cell Types. *World Electr. Veh. J.* **2020**, *11*, 77. [\[CrossRef\]](#)
- Spotnitz, R.; Franklin, J. Abuse behavior of high-power, lithium-ion cells. *J. Power Sources* **2003**, *113*, 81–100. [\[CrossRef\]](#)
- Feng, X.; Ouyang, M.; Liu, L.; Xia, Y.; He, X. Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. *Energy Storage Mater.* **2018**, *10*, 246–267. [\[CrossRef\]](#)
- Zhu, J.; Wierzbicki, T.; Li, W. A review of safety-focused mechanical modeling of commercial lithium-ion batteries. *J. Power Sources* **2018**, *378*, 153–168. [\[CrossRef\]](#)
- Zhang, J.; Zhang, L.; Sun, F.; Wang, Z. An Overview on Thermal Safety Issues of Lithium-ion Batteries for Electric Vehicle Application. *IEEE Access* **2018**, *6*, 23848–23863. [\[CrossRef\]](#)
- Chen, Y.; Kang, Y.; Zhao, Y.; Wang, L.; Liu, J.; Li, Y.; Liang, Z.; He, X.; Li, X.; Tavajohi, N.; et al. A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards. *J. Energy Chem.* **2021**, *59*, 83–99. [\[CrossRef\]](#)
- Ruiz, V.; Pfrang, A.; Kriston, A.; Omar, N.; Van den Bossche, P.; Boon-rett, L. Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. *Renew. Sustain. Energy. Rev.* **2018**, *81*, 1427–1452. [\[CrossRef\]](#)
- Aalund, R.; Pecht, M. The Use of UL 1642 Impact Testing for Li-ion Pouch Cells. *IEEE Access* **2019**, *7*, 176706–176711. [\[CrossRef\]](#)
- UL 1642; UL Standard for Safety Lithium Batteries. 6th ed. Underwriters Laboratories Inc.: Northbrook, IL, USA, 29 September 2020.
- Kim, S.; Lee, Y.S.; Lee, H.S.; Jin, H.L. A Study on the behavior of a cylindrical type Li-ion secondary battery under abnormal conditions. *Mater. Sci. Eng. Technol.* **2010**, *41*, 378–385.
- Sahraei, E.; Campbell, J.; Wierzbicki, T. Modeling and short circuit detection of 18,650 Li-ion cells under mechanical abuse conditions. *J. Power Sources* **2012**, *220*, 360–372. [\[CrossRef\]](#)
- Wierzbicki, T.; Sahraei, E. Homogenized mechanical properties for the jellyroll of cylindrical Lithium-ion cells. *J. Power Sources* **2013**, *241*, 467–476. [\[CrossRef\]](#)
- Avdeev, I.; Martinsen, M.; Francis, A. Rate and temperature dependent material behavior of a multilayer polymer battery separator. *J. Mater. Eng. Perform.* **2014**, *23*, 315–325. [\[CrossRef\]](#)
- Liu, P.; Sherman, E.; Jacobsen, A. Design and fabrication of multifunctional structural batteries. *J. Power Sources* **2009**, *189*, 646–650. [\[CrossRef\]](#)
- Zhao, W.; Luo, G.; Wang, C.Y. Modeling Internal Shorting Process in Large-Format Li-Ion Cells. *J. Electrochem. Soc.* **2015**, *162*, A1352–A1364. [\[CrossRef\]](#)