Thermal and Electrical failure analysis of lithium-ion battery after crash

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Abstract: Due to the growing electric vehicle market and new trends to reduce fuel consumption for a healthy environment, safe and reliable vehicles are desirable for reasons beyond EV and new technology. Although certain safety standards and legislations are in place and continuously improving but number of concerns including battery safety, battery performance, vehicle structure and battery design to be considered as these affect overall reliability of Electric vehicles (EV). With this paper on the thermal and electrical failure analysis of 18650 lithium-ion battery when involve in crash/collision for Electric vehicle safety, a stone wants added to the nascent building sustainable alternatives to an energy model in disgrace. This brief addresses the uses of lithium-ion batteries as energy storage function to the convergence needs of electric transport. The term "electric transport" means both the transmission on the network and the mobility of people in electric vehicle. In the beginning of this paper, after exposure of the contextual framework and study of the research fields, scanning the subject allow to identify the main lines of research to exploit and develop.

Keywords: Lithium-ion battery, thermal runaway, crash/impact

I. INTRODUCTION

Lithium-ion battery technology is considered good solution to power electric vehicles but potential overheating due to stressful conditions such as mechanical abuse, overcharge, over-discharge, short circuit and excessive heat from outside gives rise to safety issues and occurrence of one or more than one of these can lead to thermal runaway [1]. If the cell has not reacted immediately after an incident, thermal runaway could be slow to develop. The process of electrochemical reaction and the release of dangerous gases could occur over a period of hours, which lead to catastrophic events (fire, injury or death) [2-3]. As part of this research battery failures are identified and causes of failures with respect to severity are explained. Thermal models incorporating the effects of charge, discharge and internal temperature for aging and capacity fading due to temperature change are analysed. Results from experimental work and simulation are used to develop heat generation model which form effective thermal model to predict thermal runaway after crash/collision using finite element model (FEM).

Among different types of batteries used in the automotive industry Lithium-ion batteries are growing popular due to their high energy density, high galvanic potential, low self-discharge, low weight and the fact that they have almost no memory effect [4], also lithium-ion batteries have high power and higher open circuit voltage[5] [6] [7].

Lithium-ion batteries are common power source for many portable devices and latest Battery Electric Vehicles (BEV's) such as Nissan Leaf, Tesla Roadster and extended range electric vehicle (E-REV) such as Chevy Volt [8] [9].

Research on Electric vehicle safety was conducted [6], [10-13] and discussed several of the risks to Electric Vehicles, namely electricity damage, battery pressure, combustion and explosion, electrolyte splash and heat damage [10]. Due to the chemical properties of lithium-ion, the batteries can adapt higher temperatures quickly and these higher temperatures can trigger exothermic chemical decomposition of lithium-ion battery component material [11,12] that lead to further temperature rise and possible catastrophic failure of the lithium-ion battery system which is known as thermal runaway[6]. Temperatures of lithium-ion batteries depend on the operating conditions. Under normal operating conditions temperatures of these batteries can be easily controlled to remain in the range of 20-55°C; however stressful conditions such as high power draw at high cell/ambient temperatures as well as defects in individual cell may steeply increase local heat generation [13].

Studies [9], [14-20] has suggested that lithium-ion batteries with high capacity raise safety, durability, uniformity and cost concerns which imposes limitations on the wide applications of lithium-ion batteries in the vehicle [14][15][9]. Failure scenarios of lithium-ion batteries are also discussed by many researchers and suggested the unsafe high trigger temperatures may be reached due to a variety of failure scenarios including overcharge of an individual cell or the entire lithium-ion battery system, an internal short circuit (ISC) of cells resulting from a latent defect due to an internal foreign object, separator wear out, dendrite growth, crushing or penetration of a cell, an external short circuit of cells module or pack, and/or exposure to abnormal high temperature due to fire or failure of neighboring components [16-20].

Although all the above mentioned failure scenarios effect the performance of Lithium-ion batteries and cause temporary or permanent damages but some of the abusive conditions also play important role in battery failures. Many researchers worked on it and mentioned electrical integrity, thermal integrity and mechanical integrity are interrelated aspects of battery safety [21, 22]. In most of the cases electric short circuit is a necessary but not sufficient condition for the occurrence of thermal runaway after mechanical abuse. Chemistry of the cell, resistance of separator to heat, size of the fractured part and rate of heat transfer all play a role in processes leading to a thermal runaway, if the cell has not gone to thermal runaway right away it can still go into a slow process of electrochemical reaction, releasing gases that eventually could lead to a catastrophic event [23].

The collision of electric vehicle may cause the movement, pressing, short-circuit, cracking, leakage, thermal shock, explosion and burning of the power battery [24].

Safety analysis of Electric vehicle batteries enclose many challenges and complete understanding of battery chemistry, material properties, thermal modelling of batteries, battery performance under normal to extreme conditions, battery abusive conditions, battery behavior after a temporary or permanent damages. Studies in these subjects are critically reviewed to set grounds for research and gain useful knowledge. In the next sections of this literature review results from the studies are discussed to show the effectiveness of the proposed concepts in thermal runaway detection after a collision.

II. THERMAL RUNAWAY

Three interrelated aspects of battery safety are electrical integrity, thermal integrity and mechanical integrity. Mechanical or electrical abuses individually or together can lead to thermal runaway. Figure below shows variety of causes, processes and effects which can happen in lithium ion cell, these can be related or can trigger each other.

III. MODELLING OF LITHIUM-ION BATTERIES

To ensure safety and enhance performance of Lithium-ion batteries basic equivalent circuit model to advance finite element models are investigated by researchers. Based on the dynamic characteristics and working principles of the battery, the equivalent circuit model was developed by using resistors, capacitors and voltage sources to form a circuit network [25].

Thermal management of Li-ion batteries is critical for high-power applications; it is vital to safety and to enhance battery performance and extend cycle life. The operating temperature controls the electrochemical performance of the Li-ion battery. One of the side effects of exposure to high temperature is premature aging and accelerated capacity-fade. Governing the thermal environment is critical in Li-ion technology. Therefore, efficient thermal management that continuously regulates battery operating temperature is essential to safety and optimal performance in high temperature and high discharge Li-ion applications. Resolving the thermal management issues with Li-ion batteries will benefit it heir use in electric and hybrid electric vehicles [26].

Researcher [27] suggested that the state of charge dependent entropy is a significant heat source and is therefore essential to correctly predict the thermal behavior of Li-ion batteries under a wide variety of operating conditions, and introduced an adaptive model to obtain these entropy values. To obtain these values heat generation equations are considered where chemical heat, joule heating and polarization heat is main source of battery heat generation and divided into reversible and irreversible heat generation of lithium ion battery. To predict heat generation in rechargeable batteries for high power applications such as electric vehicles an accurate thermal model is an essential tool [27].

A. Test techniques

To characterize lithium ion battery different testing techniques were used by researchers [16-20]. Some of the methods employ advance equipment and tools including universal battery testers, advanced power supplies, Accelerating rate calorimeter (ARC), thermal chambers, temperature chambers, IR thermography, high resolution cameras etc. some of these techniques are combination of basic lab based techniques, including characterization at different charging and discharging rates, variation of applied current and voltages, capacity estimation at different operating temperatures and cell temperature estimation using thermocouples. Literature is studied to analyses these techniques and their implementation for characterization and cell thermal behaviors.

In [28] researchers conducted numerical simulation to predict thermal behavior of lithium ion battery during charge and discharge using cylindrical 18650 battery. Author used two different models. To obtain lithium content inside particles porous electrode model is used to predict temperature distribution inside the cell thermo-electric model is used. The charge capacity was predicted at rates of 0.5C, 1C and 2C. Author predicted that the capacity increases at low charge rates and decreases at high charge rates. The ratio of the capacity variation to a 1C charge is 108.1% and 89.2% at 0.5C and 2C respectively. Author mentioned solid phase diffusion limitation plays a significant role at high charge rates. Similar to charge capacity discharge capacity is predicted at rates of 0.5C, 1C and 2C. Results shows capacity decreases at high discharge rates but increases at low discharge rates. The ratio was estimated for capacity variation to 1C discharge is 100.7% and 96.3% at 0.5C and 2C respectively.

Results from above experimental work suggest that the increase in temperature during discharge is higher than that during charge also temperature difference between charge and discharge is decreased with increasing C-rates. Author also mentioned at a rate of 1C, the discharge temperature increases with a waving region at the beginning, whereas the charge temperature increases until certain point and then decreases.

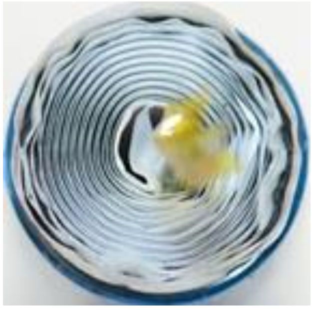
To form better thermal model both electrical and thermal properties are important as mentioned above results from different researches shows C-rates, SOC, DoD and operating temperature influence battery performance as thermal behavior is closely related to the change in entropy and applied current [28]

B. Cell formation

Cells used in this work are Samsung 2200mAh lithium-ion cell from Samsung, Korea. Cell has dimensions of 18mm diameter and 65mm height. Low capacity cells were chosen to avoid severe conditions during cell conditioning and actual tests. Figure 2 shows 18650 Samsung 2200mAh cell.

These cells has steel shell casing of thickness 0.3mm and spiral wound layers of anode, cathode, separator, anode current collector and cathode current collector as shown in figure 1.

a)



b)

Figure 1: a) 18650 Lithium ion cylindrical cell b) Spiral wound layers of cell

Cell temperatures were not fixed so the temperature variations are results of natural heat up and cool down phenomena. According to [28], accurate measurement of cell temperatures is difficult as in situ measurement is not possible in all applications so they proposed temperature measurement at cell terminals where negative electrode has high thermal conductivity compare to positive electrode and this method gives better accuracy of temperatures compare to measuring on surface. Experimental setup is shown in figure 2.

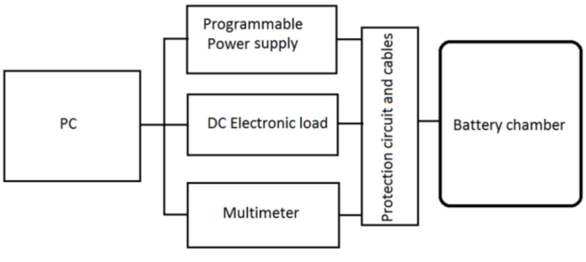


Figure 2: Experimental setup

Experimental setup consist of battery chamber, Chroma DC electronic load, Chroma power supply, thermocouples, Datum data logger to log voltage, temperature and applied force. FLIR infrared thermal camera was also used to capture and record thermal data where reference point was set with the software operated tool.

Results from experiment are listed in following sections were temperature variations and hot spot are shown.

IV. RESULTS AND DISCUSSION

A. Results

Set of experiments were conducted where 4 crash scenarios (Rod indentation test, 3-point bending test. Flat plate deformation test and Circular punch test) are used to study electrical and thermal integrity of lithium-ion batteries in case of mechanical abuse. In this study formation and shapes of crash scenarios are not discussed in detail but thermal and electrical analysis results are shown and discussed later. Results from thermal analysis are shown from figures 3-5.

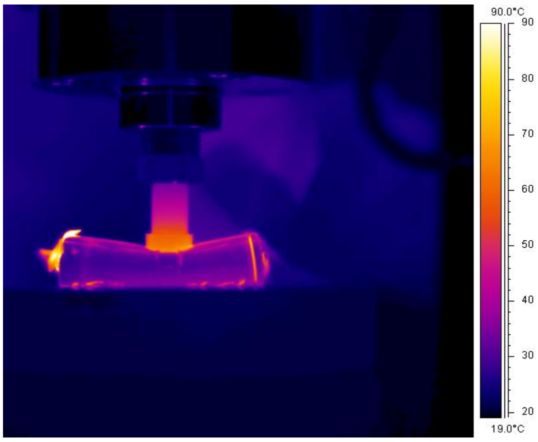


Fig. 3 Thermal hotspot of Rod indentation test

As shown in figure 3, circular punch did not give instant battery failure but slow build up of temperature across terminals show failure of components inside the battery which results in increased temperatures.

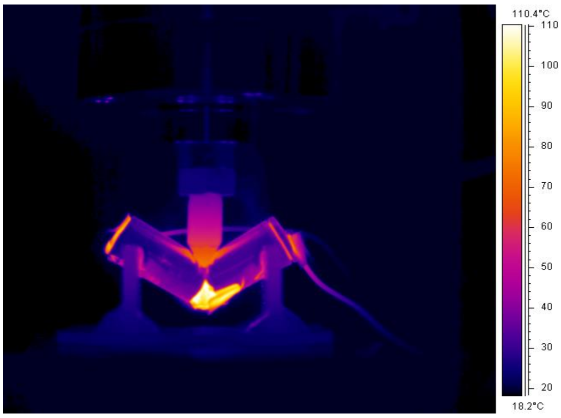


Fig. 4 Thermal hotspot of 3-point bending test

Unlike circular punch in three point bending with sharp edge sort circuit initiated at mid surface but temperature rise underneath mid surface suddenly shoot up to 110°C. which gives sudden voltage drop and temperature rise.

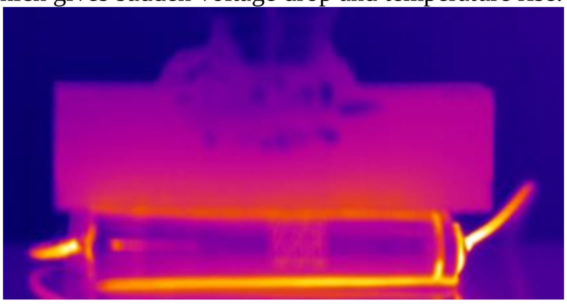


Fig. 5 Thermal hotspot of Flat plate deformation test

Flat plate deformation requires high initial force to compress battery casing and layer which gives slow build up of temperature inside the battery and heat transfer phenomena occurs.

Above figures show high temperatures at some locations after crash/impact where temperature increase instantly. Graphs showing electrical and thermal response in case of crash are shown in figures 5-7.

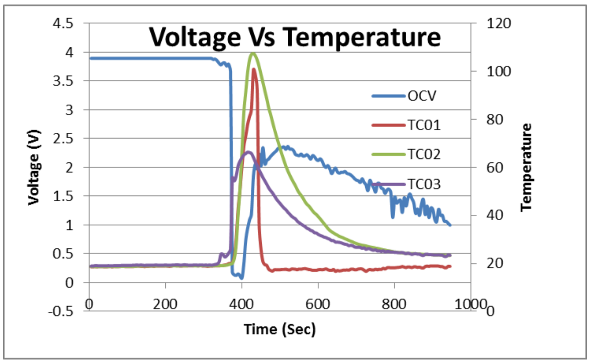


Fig. 6 Voltage and temperature relationship due to Rod indentation test

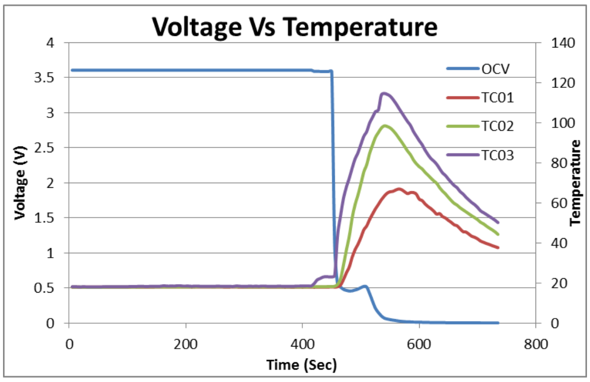


Fig. 7 Voltage and temperature relationship due to 3-point bending test

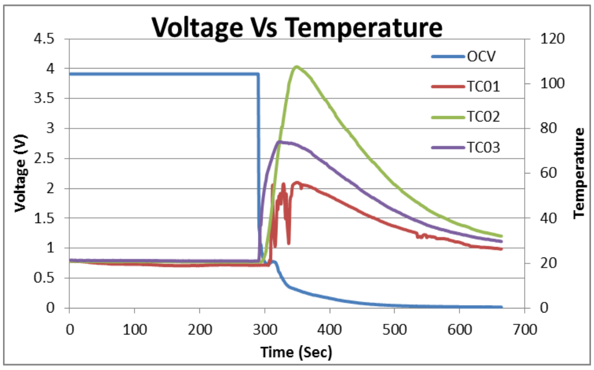


Fig. 8 Voltage and temperature relationship due to Flat plate deformation test

Figure 6-8 shows voltage drop as temperature rise after short circuit occurs where short circuit initiation time depends on the indenter type.

B. Discussion

Thorough experimental work is conducted to understand battery characteristics at different operating conditions and some of the relevant results are presented in this section to show taken approaches and limitation of work due to safety and reliability issues. Some of those approaches show good approximation of battery parameters and cover cell electro-chemistry for single cell and battery pack although shortcomings and gaps are found, those gaps are addressed in above sections. To generalize crash testing, 18650 li-ion battery cells were used to achieve maximum accuracy using extensive abuse testing where maximum parameters with different values are used. Reason to choose 18650 cells is to minimize risk of danger and also achieve high computational efficiency for simulation.

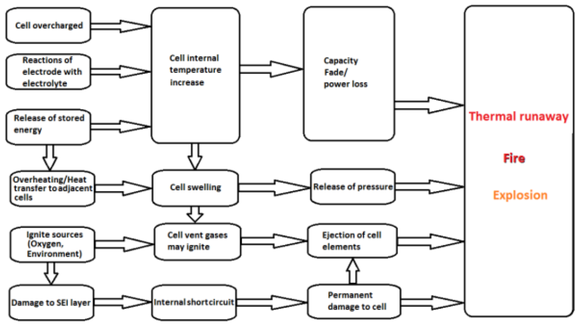


Fig. 9 Triggers of thermal runaway

Triggers of thermal runaway are shown in figure 8. If cell doesn't undergo thermal runaway then there are chances that cell might experience thermal runaway after short time or vice versa.

Some of the factors that influence the effect of failures in Lithium-ion cells are cell chemistry, Electrical abuse, Thermal abuse, Mechanical abuse, degradation of electrode, external short circuit, heat generation inside cell, penetration, Degradation of separators, Over-charge, Crush, Chemical leakage, Over-discharge, high ambient temperatures, self-heating rate, aging and state of charge.

Key results from this research are as follows

- ➢ Sudden voltage drop and instantaneous rise in temperature due to impact
- ➢ Instantaneous voltage drop and temperature rise depend on size of affected area due to crash/impact
- ➢ State of charge (SoC) play major role for temperature variations due to crash/impact
- ➢ Battery formation is also critical for battery abuse testing
- ➢ Initiation of short-circuits due to structural fracture and post short thermal and electrical responses are key to detect signs of thermal runaway.

V. CONCLUSION

Research is conducted to find crash induced electrical and thermal performance of lithium-ion 18650 battery and found that key performance indicators of 18650 lithium ion battery are voltage and temperature variations. Battery testing is conducted to observe battery maximum performance capability and to detect early signs of thermal runaway which depends on gradual temperature increase cause by mechanical abuse and chemical reaction inside batteries. Short circuit is observed with crash location and type of crash which lead to sequential failure of battery.

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