Inferring Battery Current Interrupt Device Activation in a 18650 Cell under High C Discharge using a Foil Strain Gauge

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ABSTRACT

In certain emergency situations, lithium-ion batteries are placed in rapid discharge scenarios that require high current draw. This includes applications where high current loads are required and the loss of power from a battery is unacceptable. Under a significant load, electrolyte vaporization causes gas to accumulate in batteries degrading capacity and potentially leading to current disconnect. This work examines using foil strain gauges to monitor internal pressure accumulation of the batteries. This study focuses on the monitoring of a single cell experiencing a 16 C discharge. This research observes the response of a nickel manganese cobalt 18650 cell monitored using a thermocouple and a strain gauge mounted annularly in the middle of the cell. For a 40 A constant current discharge, activation of the current interrupt device was inferred by observing both instantaneous voltage and current cutoff after 2 minutes of discharge. Experimental results show that a rapid increase in measured strain is observed in the 30 seconds before the activation of the current interrupt device. Since the current interrupt device impeded the discharge, a significant portion of the capacity became unusable. During testing, less than 1400 mAh was discharged, which is below the manufacturer's rated capacity of 2500 mAh. The results suggest that strain-based monitoring could aid in identifying current interruptions, potentially leading to applications including the development of battery management systems that monitor gas formulation inside the cell during high-C discharge events. Additionally, strain diverged from proportionality to temperature early in the discharge, yielding an opportunity to explore BMS control for strain monitoring. Examining a larger sample size in future studies would make any findings more broadly applicable and statistically significant compared to that of a single cell. This study is limited in that capacity degradation cannot be measured once the current interrupt device is activated, so the true capacity lost cannot be quantified; however, future research could be oriented toward assessing the capacity loss related to gas production. Furthermore, this work does not consider the affects of lithium plating on the capacity of the battery that could result from high rate discharge.

Keywords: Lithium-ion Battery, Strain Gauge, Battery Management System, Current Interrupt Device

1. INTRODUCTION

Emergency situations pose a unique challenge for lithium-ion battery technology in that it may necessitates the rapid discharge of energy at high currents. An electric ship micro-grid relies on multiple energy sources; if the main power generation unit goes down, battery will be relied on to compensate. This critical demand underscores the importance of accurately inferring the activation of a battery's current interrupt devices under such extreme conditions; as the activation of a single current interrupt devices will inactivate a whole series of cells. In regards to lithium-ion batteries, the most important job of a battery management systems (BMS) is to prevent thermal runaway. However, caused by electrolyte boiling, the gas production within the cell occurs long before thermal runaway.[1] Thus, the internal pressure from gas generation can deform or strain the battery walls.

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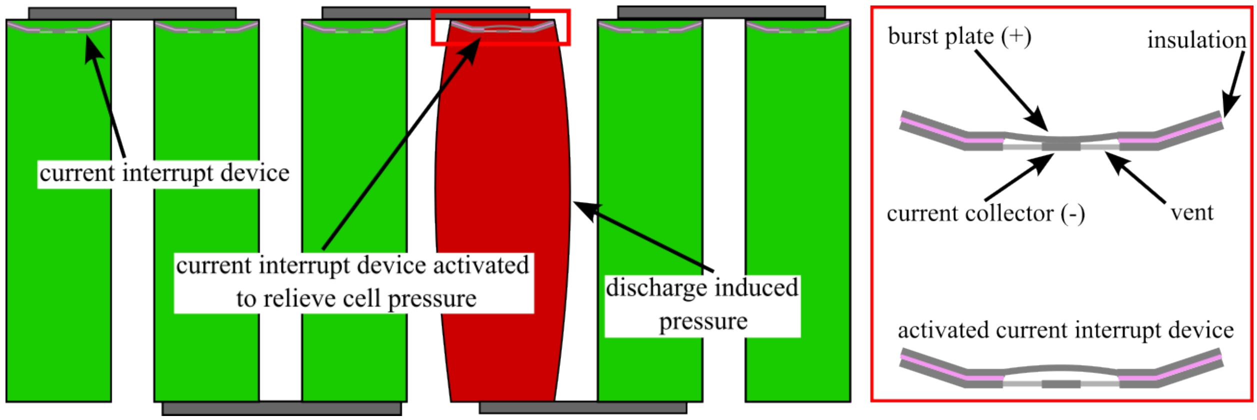

Figure 1. Diagram of 18650 cylindrical cells connected in series, in which one has high internal pressure, as well as a simplified view of the current interrupt device response.

Most commercial BMS regulate voltage and current, while some also include pack level temperature measurement; however, this does not always represent the state of each cell in a pack. Shown in figure 1, a single cell with high internal pressure in a pack that appears to have otherwise normal operation. This would have little impact on the measurements made by the BMS, yet could cause a significant operational disruption. To prevent thermal runaway, battery manufacturers developed a current interrupt device within each cylindrical cell that disconnects the battery circuit should internal pressure reach precarious levels.[2] Power is lost from a battery that has undergone current interrupt device activation, subsequently, any cells in series cannot be drawn on either. Not only is this inefficient, but in safety-critical situations, complete power loss could prove dangerous. To alert the operator of current interrupt device activation as soon as possible, this paper explores the use of strain gauges to monitor the operation of cylindrical 18650 lithium-ion cells. A BMS incorporating strain monitoring could not only alert the operator of power loss in a cell, but possibly make the necessary adjustments to avoid it in the first place. For example, a battery pack under a high current load could contain a cell with high pressure. In this scenario, the electrical data, inlet, and outlet temperatures measured by the BMS would indicate that no fault is apparent. If nothing is done, the current interrupt device would activate, and the entire pack could become ineffective. If the BMS were to incorporate strain gauge data, the load could be adjusted to accommodate that cell, until pressure decreases and the battery could be put under high current again.

This work observes the response from a nickel manganese cobalt 18650 cell monitored using an annularly mounted foil strain gauge to measure cell deformation and a thermocouple for temperature. Experimental results show that a rapid increase in measured strain is observed in the 30 seconds before the activation of the current interrupt device. The contribution of this work is in the development of an experimental methodology for inferring gas formulation using strain data.

2. METHODOLOGY

This work seeks to monitor strain on a single cell using the experimental setup displayed in figure 2. A BE120-5AA 120 Ω quarter bridge strain gauge manufactured by DAOKI is applied horizontally near the middle of a cylindrical 18650 cell, with a thermocouple placed on the cell opposite from the strain gauge. Data is collected using NI-9235 strain gauge and NI-9210 thermocouple signal conditioners, both manufactured by National Instruments, at 10 S/s and 0.5 S/s; respectively. Voltage and current measurements are taken directly from the NHR-9200 battery tester, by National Instruments, at a sampling speed of 10 S/s.

A Samsung 25R at 100% state of health and state of charge was used in this work. The battery is discharged at a 40 A current load and the strain response was observed. During discharging, the batteries heat up causing apparent strain to be measured due to thermal expansion changing resistance in the strain gauge.[3] The expression for total strain is

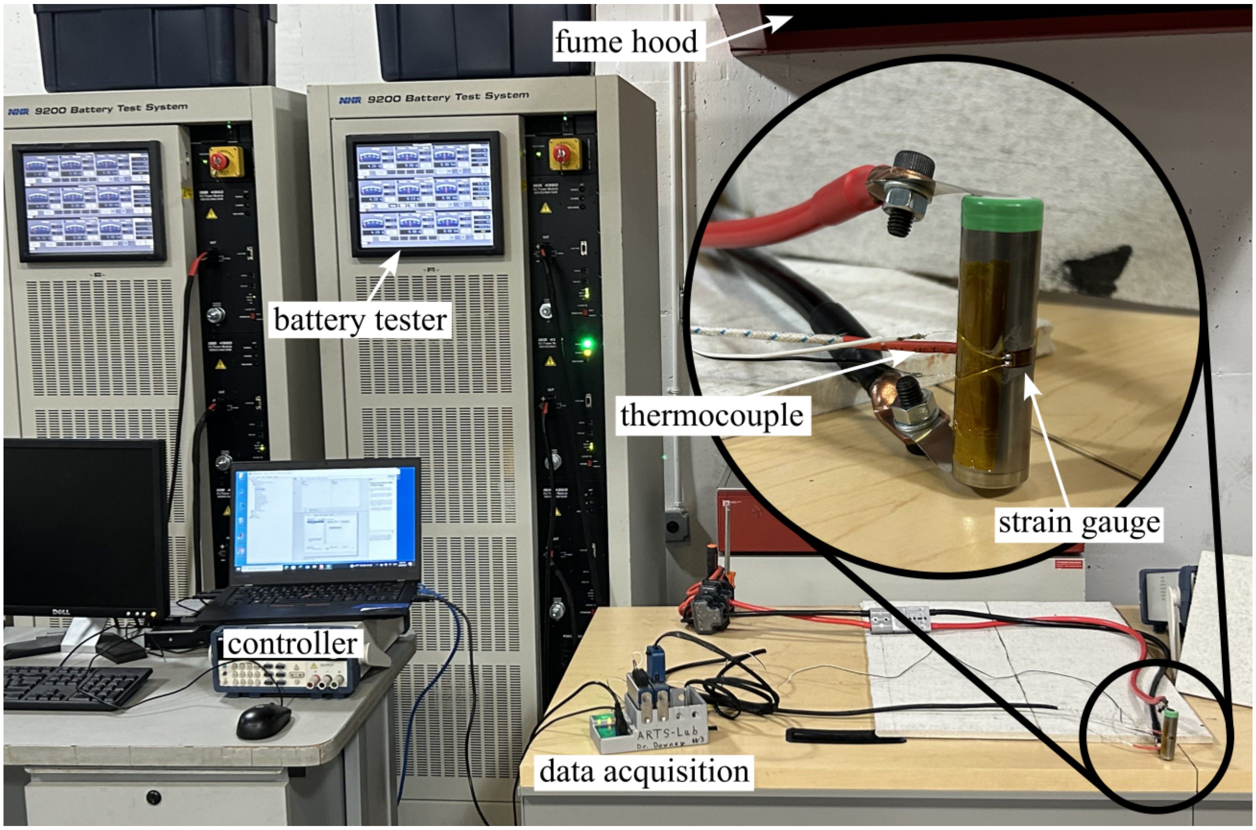

Figure 2. Picture of the experimental setup used, including a zoomed view of the sensor application on the battery.

$$\varepsilon_{\mathrm{tot}} = \varepsilon_{\mathrm{m}} + \left(\frac{\alpha_{\mathrm{r}}}{GF} + \alpha_{\mathrm{b}} + \alpha_{\mathrm{m}}\right) \cdot \Delta T \tag{1}$$

where $\varepsilon_{\mathrm{tot}}$ is the total apparent strain measured, and ε_{m} is the mechanical strain from building internal pressure. Furthermore, the change in temperature, ΔT is directly proportional to the total observed strain. Concerning a BMS, only the mechanical strain is relevant, which can be observed when the total strain is no longer proportional to the change in temperature. Thus, a BMS would interpret the measurement of mechanical strain as the onset internal pressure and decrease the current draw from the battery.

3. RESULTS

After a constant current discharge at 40 A, it was found that instances of internal pressure accumulation could be estimated via strain gauge measurement. As shown in figure 3, the current and voltage drop to zero at 2 minutes, inferring that the current interrupt device was activated. Due to internal pressure mounting, as demonstrated by the rapid increase in strain, it is assumed that the burst disk detached from the current collector. Because the positive and negative electrode were disconnected, there was no path for the current to follow, leaving the battery tester unable to read a signal, explaining the immediate drop in current and voltage. As can be seen during discharge, the temperature continues to increase steadily while the apparent strain rapidly rises, signifying mechanical strain as predicted by Equation (1), identifying gas production in the battery caused by decomposition of the electrolyte. Based on the electrical readings, a BMS monitoring strain in this situation has the capacity to identify activation of the current interrupt device, improving situational understanding for an operator.

As a result of the current interrupt device activation, a significant portion of the batteries capacity is rendered useless. As figure 3 indicates, the current is cut off just after 2 minutes have passed. With a constant discharge of

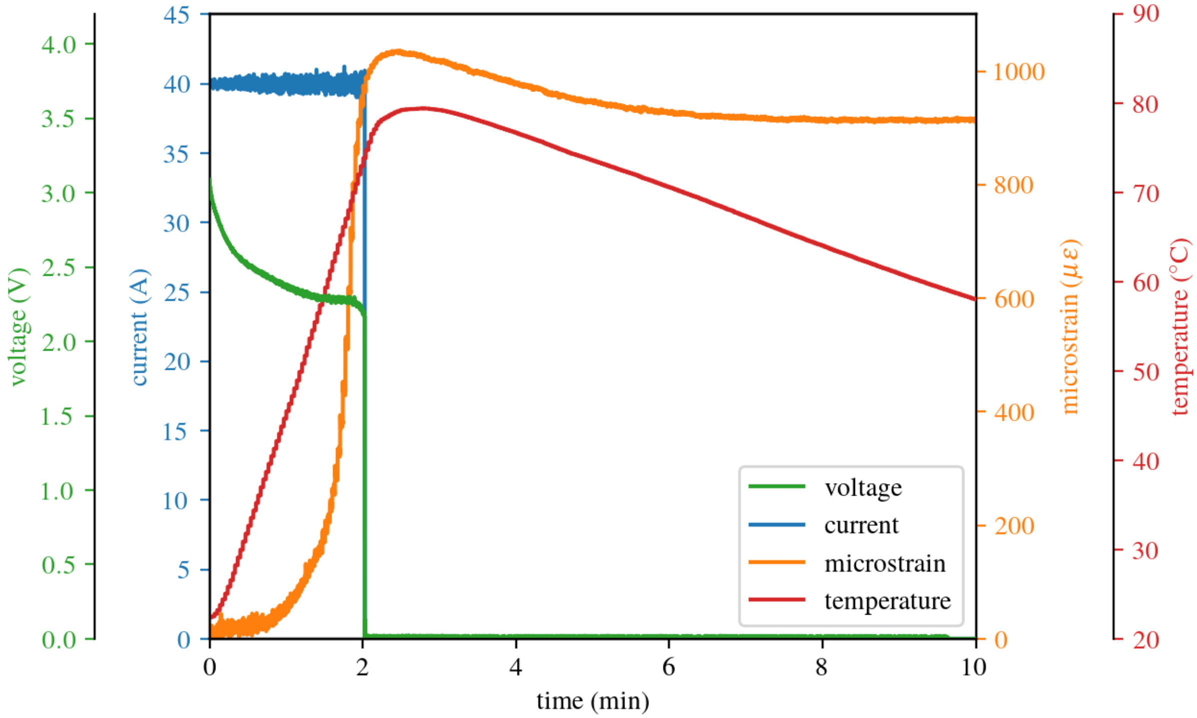

Figure 3. The results of a constant current discharge at 40 A, and the strain, temperature, and voltage response.

40 A, the battery fell well short of the 2500 mAh rated capacity for the Samsung 25R, at just less than 1400 mAh. Because this does not account for lithium plating or electrolyte vaporization, this method is limited in that the loss of the 1100 mAh rated capacity remaining cannot be entirely contributed to the current interrupt device.

4. CONCLUSION

This research presents an approach to identifying activation of a current interrupt device within a cylindrical lithium-ion battery as a means to optimize performance. The results showed potential that strain could be measured as a metric for monitoring internal battery pressure, a precursor to current interrupt device activation. By finding the instance when measured strain increase was not proportional to the temperature, escalation in mechanical stress was identified. This study showed the 40 A discharge resulted in current interrupt device activation, which means total power loss for it and any other cells in series. While a single cell was examined, increasing the sample size in future works would make any findings more generalizable and statistically significant.

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REFERENCES

[1] Rowden, B. and Garcia-Araez, N., "A review of gas evolution in lithium ion batteries," *Energy Reports* **6**, 10–18 (May 2020).

[2] Li, W., Crompton, K., Hacker, C., and Ostanek, J. K., "Comparison of current interrupt device and vent design for 18650 format lithium-ion battery caps," *Journal of Energy Storage* **32**, 101890 (Dec. 2020).

[3] Cazzani, A., Menichino, A., Inverno, M., and Belardo, M., "Strain gauge thermal compensation: approaches and new improvements," in [*2023 IEEE 10th International Workshop on Metrology for AeroSpace (MetroAeroSpace)*], IEEE (June 2023).