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Short communication

Internal resistance matching for parallel-connected lithium-ion cells and impacts on battery pack cycle life

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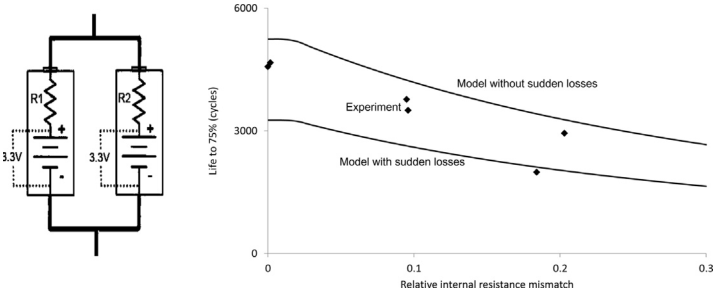
HIGHLIGHTS

- We demonstrate the importance of resistance matching in battery packs.
- At 4.5C charge and discharge, 20% resistance mismatch reduces lifetime by 40%.
- We quantitatively explain experimental results using a model of SEI formation.
- Resistance mismatch causes uneven current sharing.
- Uneven current results in high operating temperatures, decreasing lifetime.

GRAPHICAL ABSTRACT



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ABSTRACT

When assembling lithium-ion cells into functional battery packs, it is common to connect multiple cells in parallel. Here we present experimental and modeling results demonstrating that, when lithium ion cells are connected in parallel and cycled at high rate, matching of internal resistance is important in ensuring long cycle life of the battery pack. Specifically, a 20% difference in cell internal resistance between two cells cycled in parallel can lead to approximately 40% reduction in cycle life when compared to two cells parallel-connected with very similar internal resistance. We show that an internal resistance mismatch leads to high current into each cell during part of the charging cycle. Since capacity fading is strongly dependent on temperature, and hence on charging rate when this rate is sufficiently high, the high current leads to substantially accelerated capacity fade in both cells. A model, based on the formation of a solid-electrolyte interphase, is able to explain the dependence of lifetime on resistance mismatch, and also identifies the importance of random sudden capacity losses.

1. Introduction

In this paper, we present experimental results showing the impact of internal resistance mismatch on cycle life, and outline a model to explain this effect.

Internal resistance mismatch becomes an important problem for applications where the battery pack is subjected to high C rates, and required to have a long cycle life (many hundreds to tens of thousands of cycles). Example applications include hybrid vehicle and power tool battery packs.

The detrimental effect of internal resistance mismatch between parallel-connected cells arises because differences in internal resistance lead to uneven current distribution within the cells; the

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List of symbols

A	surface area on which solid-electrolyte interphase (SEI) can form, m^2
c	concentration of S at the graphite surface, M
D	diffusivity of S through SEI, m^2 s^{-1}
D_0	diffusivity of S through SEI when charging current is negligible, m^2 s^{-1}
E	activation energy for the diffusion of S through SEI, J
I	maximum charging C rate to which a cell is subjected in a particular cycle
k	rate constant of the reaction forming SEI, s^{-1} m^{-2} M^{-1}
m	molecular mass of SEI, kg
Q	capacity of a cell, Ah
Q_0	capacity of a cell when uncycled, Ah
Q_1	capacity of the more resistive cell in a cell group, Ah
Q_2	capacity of the less resistive cell in a cell group, Ah
Q_x	excess capacity of the more resistive cell in a cell group, Ah
R_1	resistance of the more resistive cell in a cell group, Ω
R_2	resistance of the less resistive cell in a cell group, Ω
S	the species that reacts with Li to form SEI
s	thickness of the SEI, m
T	temperature, K
t	time, s
α	parameter quantifying the dependence of D on current
Δ	internal resistance mismatch
ρ	density of SEI, kg m^{-3}

resulting unexpectedly high currents decrease battery pack life. Current distribution within parallel-connected cells is typically not monitored in commercial battery packs in order to reduce battery management system complexity and cost. This means that the effect of internal resistance mismatch must be quantified in order to assess the importance of this consideration in battery pack assembly.

In this paper we quantify the relationship between internal resistance mismatch and battery degradation, combining experimental data with a simple model of capacity fade. This model assumes that the growth of a solid electrolyte interphase is the primary cause of capacity fade [1,2], though the conclusions regarding the importance of internal resistance mismatch do not rely on the details of the fade mechanism.

2. Experimental setup

2.1. Cell characterization

The cells used in this study were commercially available 2.2 Ah cylindrical $LiFePO_4$ cathode, graphite anode cells, designed for use in high-C-rate applications.

The internal resistance of 72 cells was tested. Internal resistance was measured at 50% state of charge (SOC) with a 15 s DC pulse of 40 A (17C). While there is no commonly accepted standard for measuring the internal resistance of lithium-ion batteries, we chose this current and time profile because it is relevant to the duty cycle seen by these cells in hybrid vehicles and power tools. A comparison of several methods for the internal resistance of lithium-ion cells is provided by Schweiger et al. [3]. The 15 s current pulse allows the effects of the mass-transfer limited reaction to show. Longer delay times can lead to significant self-heating of the cell which affects the measured internal resistance. This 17C discharge rate is within the specified rating for this high-power cell, of 32C continuous discharge and 55C for 10-s peaks. The characterization tests were done on bare cells in a background room temperature of 25 °C.

The resistance difference between the most and least resistive cells was 24.7%. The maximum difference in capacity in this same batch of cells (one full discharge cycle at 17C continuous discharge current) was 3.6%. For the purposes of this experiment, the differences in initial capacity were considered to be negligible compared to the differences in internal resistance (Fig. 1).

2.2. Lifetime cycling setup

Six battery packs (each containing two cells connected in parallel, as depicted in Fig. 5) were tested using the method described below. For further reference within this paper, two parallel-connected cells are called a “cell group”. The current to each cell and the temperature of each cell were recorded. A photo of the experimental cell groups is seen in Fig. 2. The cell group assembly was designed to thermally decouple the two cells: each cell had its own 8 cm wire lead and the cells were physically separated with plastic spacers so that the casings were 8 mm apart.

The cycling tests were carried out with the following parameters:

- Constant current charging of 20A to 3.65 V per cell group (4.5C)
- Constant voltage held at 3.65 V with termination current of 1 A
- 1 min rest period between charge and discharge
- Constant current discharge of 20 A to 2.40 V (4.5C)
- 1 min rest period between discharge and charge.

Cycling tests were done at a loosely controlled background room temperature that varied between 24 °C and 31 °C, and the temperature of each cell’s aluminum casing was monitored continuously. The background temperature profile was the same for all cells. Data collection was done using an Agilent 34980A multifunction switch/measure mainframe with a 34921A multiplexer card. Charging, discharging and current control automation was done using 6 FMA Direct PowerLab 6 bidirectional chargers, running on a regulated 24 V DC bus.

3. Results

Fig. 3 plots cycle life, defined as the number of cycles for the cell group to reach 75% of the initial capacity, vs. internal resistance mismatch, defined by

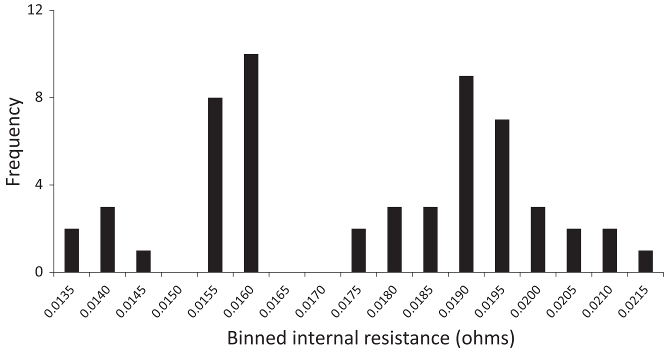

Fig. 1. Internal resistance distribution of cells tested.