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Duty-cycle characterisation of large-format automotive lithium ion pouch cells for high performance vehicle applications

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ABSTRACT

The long-term behaviour of lithium ion batteries in high-performance (HP) electric vehicle (EV) applications is not well understood due to a lack of suitable testing cycles and experimental data. As such a generic HP duty cycle (HP-C), representing driving on a race track is validated, and six NMC graphite cells are characterised with respect to cycle-life. To enable a comparison between the HP-EV environment and conventional road driving, two test groups of cells are subject to an experimental evaluation over 200 duty cycles that includes a representative HP-C and a standard duty cycle from the IEC 62660-1 standard (IECC). After testing, both test groups display increased energy capacity, increased pure Ohmic resistance, lower charge transfer resistance an extended OCV operating window. The changes are more pronounced for cells subject to the HP-C. Based on capacity tests, Electrochemical Impedance Spectroscopy (EIS), pseudo-OCV tests, and Pulse Multisine Characterisation, it is concluded that the changes in cell characteristics are most likely caused by cracking of the electrode material caused by high electrical current pulses. With continued cycling, cells cycled with the HP-C are expected to show degradation at an increased rate due to raised temperatures, and more pronounced electrode cracking.

1. Introduction

In recent years, the development and improvement of lithium ion batteries (LIBs) has underpinned the electrification of the transport sector with new markets, such as the strategically important high-performance (HP) vehicle segment, becoming a target sector for many new start-up organisations and more established original equipment manufacturers (OEMs) [1]. Currently, automotive OEMs are developing innovative electric vehicles (EVs) for this segment, with examples including the Jaguar I-PACE and Aston Martin Rapid-E, both set to launch in 2018 [2], in addition to more established vehicles such as the Tesla Model S. Challenges for the success of these vehicles are often reported to be key battery characteristics such as: Cycle life, energy capacity, power capability, degradation, safety, reliability, and cost. Notwithstanding the system integration requirements, such as packaging and thermal management that are required to realise a complete battery system [3].

Extensive research has been undertaken regarding the operation and degradation of lithium ion battery cells intended for automotive use [4,5]. One limitation of this research is that often, several studies use relatively simplistic constant current charge and discharge tests, often at different current rates and environmental temperatures as a means to estimate cycle life over a broad spectrum of operating conditions [5–7]. These tests are known to be largely unrepresentative of the day to day battery operation within an EV. Research published by Barre et al. [8] has indicated that complex electrical loading profiles result in different ageing characteristics than conventional galvanostatic profiles.

As such, more complex testing profiles are required to more accurately predict the behaviour and cycle ageing progression of cells in HP automotive use cases. A study by Barre et al. [9] investigated battery data, which was collected from a passenger EV following a predetermined driving cycle, to determine the causality between vehicle use and battery ageing. This study identified that capacity fade is

Abbreviations: BEV, battery electric vehicle; BTMS, battery thermal management system; CC-CV, constant current - constant voltage; DOD, depth of discharge; EIS, electrochemical impedance spectroscopy; EV, electric vehicle; G-NMC, graphite – lithium-nickel-manganese-cobalt-oxide; HP, high-performance; HP-C, high-performance-cycle; HP-EV, high-performance electric vehicle; IECC, IEC 62660 – dynamic discharge profile A for BEV cycle test; LIB, lithium ion battery; NMC, lithium-nickel-manganese-cobalt-oxide; OCV, open circuit potential; OEM, original equipment manufacturer; PMC, pulse-multisine characterisation; p-OCV, pseudo-OCV; SEI, solid-electrolyte-interface; SOC, state of charge; WLTP, worldwide harmonised light vehicle Test procedure

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primarily related to temperature and time, and impedance rise is primarily related to the current profile and the maximum current delivered by the battery. Omar et al. [10] used the cycle life tests defined within the International Standard IEC 62660-1 [11] and ISO 12405-2 [12] to determine the cycle life of a cell intended for passenger vehicle use. Further, Dubarry et al. utilised a dynamic stress test, described within [13], in a cycle life evaluation to determine the rate of change and nature of battery degradation within a passenger vehicles [14,15], providing further evidence that battery degradation is a function of usage profiles.

The authors assert that the nature of high-performance electric vehicle (HP-EV) use cases when compared to driving on public roads is fundamentally different. Previously established testing procedures for cell and battery systems are insufficient to evaluate the suitability of LIB cells (in terms of: cycle life, thermal behaviour, and progression of degradation) for use in evaluation battery technology for HP-EVs [16].The authors' previous work [17] demonstrated significant differences between the "Dynamic discharge profile A for BEV cycle test" as described in the IEC 62660-1 standard, and a newly developed duty-cycle representing HP scenarios. Whilst the IEC standard serves to represent a cell profile for BEVs operating on the road, the high-performance duty cycle (HP-C), in contrast, is representative of an HP-EV driving on a race circuit and was derived from a database of race circuit driving simulations. The validity of the HP-C was assessed against one representative example - the Bahrain International Circuit. This assessment was undertaken using comparative measures based on the duty-cycle design criteria and a thermal simulation.

The derived HP-C has facilitated further engineering activities that are key to successful battery system design and integration. Recently, the authors investigated the differences in thermal behaviour of large format pouch cells subject to the HP-C and IEC standard [18]. The results show that HP scenarios result in higher temperatures and temperature gradients across the cell surface, suggesting increased degradation and localised ageing over prolonged use. Worwood et al. [19] demonstrated that due to the aggressiveness of the HP-C, more involved and unconventional cooling strategies are required for the battery thermal management system (BTMS) to ensure the cells remain within acceptable thermal limits (operating temperature between circa 15–35℃ [20] and maximum temperature gradient of 5 ℃ [21]). Specifically, for cylindrical cells [19], internal cooling with an inserted heat pipe system and/or double tab cooling strategies were required to limit the maximum cell temperature gradient to 5℃, where conventional radial surface cooling gave rise to temperature gradients exceeding 15 ℃. Other experimental studies for pouch cells [22] have also demonstrated the need for more advanced cooling materials to avoid the evolution of thermal gradients exceeding 10 ℃ when exposed to the HP-C. Hosseinzadeh et al. [23] developed a 1D electrochemical-thermal model to simulate the heat generation a 53 Ah pouch cell at various ambient temperatures. In their study a cell was subject to the HP-C, and a profile derived from the WLTP (Worldwide Harmonised Light Vehicle Test Procedure) Class 3 to validate the model and predict the increase in cell temperature arising from these vastly different automotive use cases.

Despite these recent publications assessing battery thermal behaviour when a cell is electrically loaded with a cycle derived from a HP test case, experimental data regarding continuous operation under HP has not been reported within the literature. To better understand and quantify the longer-term impact of such HP-Cs, the next step is to undertake a prolonged experimental study to characterise cell performance and expected life for the HP-EV market.

The research presented within this study extends that published in [17] and provides two key contributions to the body of literature within this field. Primarily, an ageing and characterisation study is conducted to investigate the possible effects and consequences of continuous HP cycling on the electrical characteristics of a 53 Ah pouch cell of G-NMC chemistry (Graphite - Lithium-Nickel-Manganese-Cobalt-Oxide). Within the experimental study, two test groups of cells are subject to continuous cycling using the HP-C and IEC standard profiles to identify the rate and nature of changes in cell behaviour, identified through regular characterisation of the cells during electrical cycling. Prior to this, the validity of the HP-C is refined through an experimental assessment, specifically with regard to the instantaneous electrical behaviour and heat generation of a large format pouch cell.

The paper is structured as follows. Section 2 describes the cell selection process, experimental set-up, HP duty-cycle definitions, and testing methodology. A detailed description of the characterisation tests used to quantify cell parameters is provided. Section 3 presents and discusses the results from the initial cell characterisation, duty cycle validation, and short-term duty-cycle degradation study. Section 3.4 further discusses the results of the cycling study and implications for battery system design for HP vehicle applications, and future testing requirements. Further work and conclusions are presented in Section 4 and 5, respectively.

2. Experimental assessment of cell performance and ageing

Experimental work was undertaken to initially refine the validity of the HP-C developed in [17], and subsequently to characterise large format XALT Energy® 53 Ah NMC pouch cells with regards to its thermal performance and cycle-life. In this section, cell selection, experimental rig design and assembly, cycle choice and methodology is discussed.

2.1. Cell selection

The cells selected are large format pouch cells with G-NMC chemistry at a rated C/2 capacity of 53 Ah (196 Wh); key cell parameters are listed in Table 1. The cell format features a larger surface area-to-volume ratio compared to cylindrical cells and as such, the cell is described by the manufacturer as having better heat dissipation. According to the manufacturer, the cells target high energy applications such as energy storage for HEVs and EVs, grid storage, marine vessels, and locomotives. The combination of high power capability, low internal resistance and higher heat dissipation capability compared to cylindrical cells makes this cell a suitable candidate for HP-EV applications.

2.2. Experimental rig

An experimental rig was designed to facilitate this research. Due to the intensity of the employed testing profiles, an active cooling system was required to keep cells within their thermal safety window. As such the requirement for the experimental rig was to provide a suitable housing for a cooling system, and to facilitate a means of connecting individual cells to a battery cycler.

The experimental rig was modelled using the commercially available software Solidworks. A computer drawing of the test rig is

Table 1
Cell characteristics.

Performance Characteristics	Typical Value (2016)
Capacity at C/2	53 Ah
Nominal Voltage	3.7 V
Discharge Energy (C/2)	196 Wh
Weight	1.15 kg
DC Resistance (10 s @ 50% SOC)	1.33 mΩ
Peak Discharge C-Rate (10 s @ 50% SOC)	8.0 C
Upper Voltage Limit	4.2 V
Lower Voltage Limit	2.7 V
Charge Tempertaure Range	0 °C ~ 45 °C
Discharge Temperature Range	−20 °C ~ 60 °C
Cell Dimensions (LxWxT)	225 × 225 × 11.8 mm