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Hardware Article

Development and evaluation of *in-situ* instrumentation for cylindrical Li-ion cells using fibre optic sensors

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ABSTRACT

This work demonstrates the development and evaluation of FBG optical fibre sensor technology for monitoring the distributed *in-situ* in-operando temperature of cylindrical 18650 lithium-ion cells. The influence of the sensing element on the electrochemical system was evaluated using EIS, CT scanning and cell cycling characterisation and was proven to be negligible. Furthermore, the FBG sensors were proven to be resistant to the strain imposed during the cell instrumentation procedure and the harsh chemical environment inside the Li-ion cells. The sensing methodologies and modification techniques developed in this work can be applied to large scale battery modules and pack systems and integrated within the cell manufacturing process. This work identified a clear and significant difference between the cells can and core temperatures of up to 6 °C at discharge and 3 °C at charge, as well as axial temperature gradient. The findings of this study are of significance to the performance and safety limits of energy storage systems. This article indicates the clear need for reliable sensing systems that enable accurate *in-situ* in-operando monitoring of lithium-ion energy storage systems.

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1. List of files

No	Name	Description	Version	Location
1	A1006 FBG Battery	Assembly procedure for sensor and instrumented cell	1.0	Uploaded with manuscript

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2. Specifications table

Hardware name	An Instrumented Cylindrical Lithium-ion Battery for distributed temperature monitoring of core temperature
Subject area	 Please select the subject area most relevant to the original community for which this hardware was developed Engineering and Material Science Chemistry and Biochemistry General
Hardware type	Measuring physical properties and in-lab sensorsField measurements and sensors
Open Source License	Creative Commons – Attribution – ShareAlike 3.0
Cost of Hardware Source File Repository	Approximate cost of hardware (complete breakdown will be included in the Bill of Materials)

3. Hardware description and context

Lithium-ion cells are a common choice for high power and high energy automotive applications due to several advantages over other cell chemistries, such as high energy density, minimal memory effect and high cell voltage [1]. However, Li-ion chemistries are sensitive to temperature variations which affect performance [2], lead to capacity degradation [3] or even catastrophic failures [4]. Risk of internal overheating is especially increased during cells' performance assessment, when it is especially important to closely monitor thermal responses. As the current applied to the cells increases, so does the heat generation – Joule (resistive) heating coming from the electrolyte, anode and cathode resistances (R_e, R_a and R_c), and exothermic reactions – electrode materials entropy changes, phenomena unavoidable as part of the cells normal operation [5]. In extreme cases, as the cell internal temperature increases so does the rate of electrolyte decomposition, leading to gas formation and eventually cell rupture [6]. Currently, to monitor cells operating parameters and estimate their State of Health (SoH), they are fitted with sensors that monitor voltage, current flow and surface temperatures. However, in most use cases, especially in automotive applications, battery modules contain an array of tightly packed lithium-ion cells to meet specific power and energy requirements, which consequently generate significant amounts of heat during cycling, leading to overheating, performance issues and thermal gradients.

The method of single point sensing and surface measurements cannot reflect the true state of a cell, due to limited spatial resolution and the technological restriction to surface measurements only. Therefore, unobservable events such as thermal hotspots, non-uniform activity or mechanical expansion go undetected, causing irreversible damage to the electrochemical system in question. Additionally, thermal-management strategies used, e.g. air flow cooling [7], can cause external sensors and instrumentation to produce inaccurate data. An in-operando distributed temperature profiling could provide significantly more valuable, stable data, which could offer an insight into the pre-failure events within the cell. This could be used to support the optimisation of thermal management and improve the cell, module and pack cycle-life. Certain diagnosis techniques, e.g. Differential Thermal Voltammetry [8] which couples thermal and electrochemical measurements for electrodes phase-change analysis, greatly benefit from high-precision temperature measurements.

There are a number of challenges associated with introducing sensors into Li-ion cell systems, including: harsh chemical environment – electrolyte can give rise to hydrofluoric acid [9] in the presence of moisture – and the resulting interactions with sensing elements; thermal effects causing expansion of materials and temperature gradients; and electrical and mechanical interference encountered during normal cell usage. Fibre sensors are the solution of choice described in this article, as they can resist the harsh environmental conditions and meet the specific system requirements. Optical fibre sensors have several benefits when compared with electronic/silicon sensors, such as an immunity to electromagnetic interference, distributed sensor topologies, no spark risk due to no current carrying conductors and a low mechanical profile. However, the technology has several limitations, including a cross sensitivity to temperature and strain, meaning differentiating between the two is challenging. Furthermore, fibres in their bare form are extremely brittle and prone to failure if handled incorrectly. Finally, inherent mechanical restrictions of the fibre due to reliance on light propagating through the fibre mean mechanical bending and compression can cause signal loss and inaccurate results if not prevented. These effect have to be kept in mind when designing optical sensing elements and resolved before application.

The proposed method for temperature measurement using optical fibres as the base element is possible by modifying the refractive index at discrete locations, forming Bragg Grating zones. The selected sections achieve a high refractive index at a specific light frequency spectrum, effectively forming a light filter. The modification is implemented by etching a fibre using a laser. A broadband light source is then beamed into the fibre causing the Fibre Bragg Grating (FBG) sensors to reflect the

light spectrum at the Bragg wavelength chosen during etching. A shift in reflected frequency is proportional to the temperature and strain of the selected FBG sensor of interest.

The use of optical fibres is now becoming an area of interest for monitoring lithium-ion cells [1,10–24], where traditional sensing technology could fail [25]. However, currently available literature regarding instrumentation of cylindrical cells using fibres and the effects upon the electrochemical devices are limited. *In-situ* measurement for various li-ion cell form factors are available, including; pouch [1,13,14,16] and coin [12], but none have described embedding optical fibres within cylindrical cells, where significant engineering challenges need to be considered due to internal structure differences, assembly materials and manufacturing methods. However, Instrumentation of cylindrical cells using thermocouples has been explored briefly [2,26–30], mainly for validating a computation model or monitoring temperature evolution during various environmental conditions. Unfortunately, a thermocouple can only measure relative temperature changes, which could make the technology unsuitable, due to a cold junction requirement requiring an extra calibration and added system costs. The sensitivity of the device is also low, requiring additional analogue conditioning circuits. Furthermore, a thermocouple is not capable of multiplexing to a single wire, which means distributed sensing causes signal lines to increase, increasing the sensor thickness and adding further points of failure. Finally, many of the methods proposed for *in-situ* sensors in the currently available literature require the sensor to be bent at a right angle and would therefore not be suitable for an optical fibre solution, due to the mechanical restrictions of the fibre. Therefore, the solution applied must take into account the geometric restrictions of the fibre.

In this work, distributed FBGs were modified to cope with the Li-ion cells' harsh environmental conditions and the instrumentation procedures enabling *in-situ* monitoring of cylindrical lithium-ion cells. The impact of the sensing element upon the electrochemical system was explored and validated versus non-modified devices using Electrochemical Impedance Spectroscopy (EIS), X-ray Computed Tomography (X-CT) and cell cycling behaviour. This work proves that FBG optical sensors can be used to obtain reliable *in-situ* cell temperatures, essential in assessing the performance limits of Li-ion cells, instead of depending on surface temperature measurements alone. As such, it is a valuable tool for the characterisation and optimisation [31] of Li-ion energy storage and development of safe yet highly efficient charging protocols.

4. Bill of materials

Designator	Component	Number	Cost per unit – currency	Total cost – currency	Source of materials	Material type
1	Optical Sensor	1	£93	£93	FBGS (See drawing A1001)	
2	PTFE/FEP Dual Wall Heat Shrink Tubing and Sleeving	1	£13.61 per metre	£13.61	Supplier: Adtech Part Number: FIP19T	*only inner tube of FEP used.
3	Aluminium Tube	1	£2.40	£2.40	Supplier: Albion Alloys Part Number: A6063 Aluminium Tube 0.5 mm o.d. × 0.1 mm wall (0.3 mm i.d.) × 60 mm length	
4	Araldite 2-Part Epoxy Adhesive Tubes Opaque 2 × 1 5 ml	1	£5.25	£5.25	Supplier: screw fix Part Number: 2547H	
5	Ø900 µm ww	1	£0.79 Per Meter	£0.79	Supplier: thorlabs Part Number: FT900Y	
6	Splice protection sleeve	1			Supplier: thorlabs Part Number: SPS40	
7	Cable Tie	1	£0.10	£0.10	Supplier: ANY Part Number: ANY	
8	Kapton Tape	1	£0.10	£0.10	Supplier: ANY Part Number: ANY	

5. Build instructions

5.1. FBG sensor fabrication & validation

The base sensor element is a single-mode SMF-28, $9/125 \,\mu$ m fibre with four 5 mm FBGs evenly spaced (Item 1) and a polyamide recoat. Each FBG element has an approximate sensitivity factor of 11 pm/°C and a -270 °C to +300 °C temperature range. However, due to the sensitive nature of silica fibre and the cell's core environment, further sensor modifications were necessary. The fibre was threaded through a bespoke aluminium tube (Item 3), to provide strain relief. An outer skin of Fluorinated Ethylene Propylene (FEP) (Item 2), was applied over the aluminium tube (Item 3), thus holding the strain relief tubing in place and providing protection from environmental interaction with the electrolyte. The strain relief tubing has the added benefit of protecting the element from mechanical influence during manufacturing, lifetime operating disturbances and thermal expansion from the FEP material. Furthermore, within the cell core is considerable room for manoeuvre, this can be seen in Fig. 1. The optical fibre would deform and therefore off-set the temperature calibration. Additionally, a single point calibration might not be possible in a production facility, where the smart cells would be embedding during a module assembly.

The FEP resistance to the electrolyte was evaluated by immersing a section of FEP tubing in commercial Li-ion electrolyte solution (LP30, *BASF*) for 1 month, which revealed no noticeable degradation of the material. Parylene [32], SBR [1], Kapton [33] and Apiezon [27] have been successfully used by other researchers for coating various *in-situ* sensing elements. However, they were less desirable in this instance due to the requirement of the additional strain relief housing, availability of materials and increased manufacturing costs. Furthermore, any conformal coating upon the fibre would affect the thermal sensitivity of the element and strain effects upon the fibre from thermal expansion of the coating, possibly causing false temperature readings. To overcome the reduced flexibility and high element failure risk, an outer skin of HytrelTM Furcation Tub-ing (Item 5), was applied to the tail end of the fibres. Fig. 2(a) shows the complete instrument design for the FBG sensor and Fig. 2(b) presents the complete instrumented cell setup.

After sensor fabrication and embedding within the cell, any mechanical deformation imposed during the process will affect the response of the element. Therefore, a single point calibration was necessary. This was achieved using a thermal chamber and a high accuracy platinum resistance temperature detector (RTD) PT100 (*Pico*[®]) with a UKCAS accredit test certificate. In the long term, mechanical drift arising from abuse conditions such as vibration and shock could cause the Bragg wavelength to shift from the ambient temperature wavelength. As such, occasional recalibrations are advised for measurement certainty over a long period of time.



Fig. 1. Instrumented 18650 Cell.



Fig. 2. (A) Assembly detail for instrumented cell and (B) Complete system.

5.2. Cell modification procedure

A commercial 18650 Lithium Nickel Cobalt Aluminium cathode and graphite anode cell with a 3Ah rated capacity and nominal voltage of 3.6 V was used for the experiment. The cell was discharged to the minimum voltage of 2.5 V as stated on the manufacturer's specification sheet before being transferred into an argon glove box with atmospheric O_2 and H_2O concentrations of <1 ppm. The optical sensor assembly was prepared in advance and fed through a pre-drilled cell cathode cap for easier assembly. A non-conductive pipe cutter was used to remove the cathode cap, after which the internal cathode current collector was slung over the side of the cell can. The FBG sensor assembly was then carefully fed into the core, the attached cathode cap held in place using Kapton tape around the rim and an external application of a fast-setting epoxy resin, ensuring gas-tightness. The Kapton tape is critically important for isolating the current collector tab from the body of the battery which would create a short circuit, furthermore, the Kapton reinforces sealing the battery. However, resealing would not be required if manufactured from scratch as a custom-made cap could be made. Kapton tape is already present in the cell as it is used in the manufacturing process, e.g. to hold the final separator wrapping in place or insulate the current collector from shorting with the opposite electrode, therefore this addition is not changing the cell composition. Modifying the cell to the degree described here would not be necessary in an industrial application as a custom design could be implemented

6. Validation and characterization

6.1. Experimental procedure

All experiments were conducted in an environmental chamber maintaining a temperature of 25 °C (±0.1 °C). Calibration of all sensing equipment was conducted where possible near the time of the experiment. Additionally, all equipment was warmed up for 4 h before experimentation to reduce the effects of analogue measurement error due to temperature variations. An optical spectrum analyser (AQ6370, *Yokogawa*), broadband laser source and a 3-port optical circulator (*Thor Labs*) were used for interrogating the FBG elements implemented into the cells. A complementary thermal sensor – K-type thermocouple – was placed on the outside of the cell can.

To validate the modification procedure, sensing methodology and the cell's State of Health after modification, the following experiments were conducted; the cells were cycled using the manufacturer's stated rating of 1C charge and 1C discharge for 100 cycles. The results were compared to unmodified cells with several cycles conducted under ambient temperature conditions. EIS was conducted at States of Charge of 0% and 100%, and the results investigated for pre- and postmodification cells. Lastly, an *in-situ* X-ray of the battery was undertaken to see the mechanical effects of the element on the mandrel core and to inspect if any physical damage had occurred to the sensor or cell during the modification procedure.

6.2. Experimental results

The response of the internal and external sensor data during a CC/CV charge and CC discharge cycling is shown in Fig. 3(a). Additionally, one peak charge and discharge period is extracted from the cycling procedure for temperature analysis, shown in Fig. 3(b) and (c) respectively. It can be seen that the recorded optical sensors wavelength shift response is closely related to the charge/discharge phase of the battery. This validates that the elements are responding with no visible lag and providing accurate thermal data. The data presented indicates a clear and significant temperature difference between the core and can of the cell of up to 6 °C during discharge and 3 °C during charge, thus underlining that the surface measurements do not reflect the real temperature of a cell. Temperature spikes observed during the cell cycling are correlated to the constant current/constant voltage charge phase. The high temperature rise can be explained by the internal resistance increasing as the cell reaches maximum charge [34], thus generating more heat under constant load. Finally, previous work [28,29] has not measured axial temperature differences within the cell core, with this work clearly displaying temperature gradients depending on the cell cycling phase.

It was observed that, during charge, the area closer to the positive end of the cylindrical cell presented higher temperatures, while the opposite was observed during discharge – a clear 1 °C temperature gradient was observed. Anode vs. cathode temperature disparity can be caused by differences in heat generation, observation of which is possible due to the anisotropic heat conduction inside the cell and the preferential heat conduction path being the current collector, resulting in local heat zones. Differences in the heat generated during charge/discharge can be correlated to the reactions occurring on the electrodes and the subsequent entropy changes [1], quantifiable by the per-electrode voltage changes, however it is not the topic of this article and is a subject of future work. Furthermore, some 18650 cells have a metal pipe within the centre of the battery called the mandrel core, which forms part of the manufacturing process. If the metal core is left in place it acts as a heat conductor, thus making temperature gradient between the negative and positive ends of the cell is less likely, however this is not the case in this study.

The capacity of a cell before and after modification was evaluated at a rate of 1C. The data recorded shows a complete match between the cell discharge profile before and after modification. This suggests that any loss of electrolyte or cell material damage incurred during cell modification is negligible and has no observable effect on the electrochemical system in the short term. However, due to the cells being constructed by a third party manufacturer, a true understanding of capacity fade and pre-cycling procedures can be difficult to quantify, as the exact cell chemistry, batch tolerance and manufacturing errors are unknown. Therefore, in our future work, cylindrical cells will be built from raw materials in an in-house production line



Fig. 3. (a) Average core temperature, can and drive voltage, (b) thermal discharge characteristics extract from figure (a), (c) thermal charging characteristic extract from plot (a).



Fig. 4. Instrumented cell cyclic aging.

with sensors embedded during production. To have an understanding of the long-term implications of an *in-situ* sensor influence on the cell, long-term cycling data is shown in Fig. 4, It was evaluated over 100 full cycles that the cells can successfully withstand long-term cycling without sustaining any damage that would be indicative of the negative influence of the fibre modification applied. Some capacity fade is be expected as the cell is opened post-production, however the cycling data shows a 11% capacity drop during the first 100 cycles, which is 1% greater when compared with non-modified cells under the same cycling regime. This suggests that, if applied in-line during the cell manufacturing process, the cell functionality would not be dissimilar from the standard cells.

6.3. Impedance behaviour

Loss of electrolyte, cell damage and other parasitic effects encountered during the modification procedure may not appear in time domain analysis conducted in the previous section. Therefore, three cells were evaluated using EIS at 100% and 0% SoC before and after modification and after 100 cycles. For modified cells, the now-exposed current collector had to be connected to the potentiostat using crocodile-clips instead of bulky but more consistent brass or copper blocks. The sensitive nature of EIS measurements means that even minimal electromagnetic interference can cause data to be misleading. Therefore, the series resistance element of the Nyquist plot was zeroed to obtain characteristic features that are present in the data. This enabled us to focus the analysis on the internal cell changes. Experimental data generated is presented in. A clear shift in the diffusion element of the EIS spectrum can be seen for 100% SoC, which is absent from the 0% SoC scan. This phenomenon can be explained by the possible pressure relief enabled during cell modification, as the pressure building up during cell formation cycles is never released in case of cylindrical cells manufacture procedures. This results in less overpressure experienced in fully charged state, slightly improving the cell performance. Such a difference would not be noticed during normal cell usage, but is visible using methods of high precision such as EIS (Fig. 5).

6.4. In-situ sensor and sealing inspection

In order to assess possible failure of the epoxy sealing method and subsequent loss of the electrolyte solution, the 18650 cells were weighed directly after the modification procedure and later after cycling. No difference in mass was recorded over the period of time taken for cell cycling and evaluation. This proves that the epoxy resin applied is an effective solution for sealing the modified cells, preventing exposure to air or electrolyte leaks.

The exact position of the fibre sensor within the cell core and the element's construction was evaluated using X-ray Computed Tomography (X-TEK XTH 320 LC, *Metris*), the results of which are shown in Fig. 6. As can be seen in Fig. 6(C), the optical fibre is in near contact with the jelly roll, providing good thermal contact yet leaving considerable room available within the core. The scans also shows that certain fibre sections are likely to become in contact with the metallic tubing, leading to a strain effect imposed upon the fibre due to the thermal expansion of the surrounding material in case of higher temperature scenarios. However the presence of an air gap between the tubing and the fibre minimises this possibility.



Fig. 5. EIS of Instrumented and virgin cells 100% SoC and 0% SoC.



Fig. 6. CT Scan of a modified cell - (A) instrumented cell assembly (B) CT tomography top view (C) CT tomography side view.

When applied to a number of cylindrical cells or various models, the external sensor tubing may become in contact with and impose pressure on the jelly roll material, due to the variability of the cell core diameters and possible cell manufacturing inconsistencies. This could have a direct impact upon the cell performance, causing local impedances increase where the sensor has a physical connection with the active battery materials. Therefore, cell geometry and space constraints have to be considered before sensor application, and small adjustments might be required depending on the specific cell design. Alternative studies have measured radial [29] and axial [28] temperatures using multiple temperature sensors, adding complexity, potential failure points and considerable modification time, in which extended exposure of the cell active materials may result in cell degradation. The novel solution presented here provides distributed and high-accuracy insight into the thermodynamic properties of cylindrical lithium-ion cells using a single-fibre solution, having a near negligible impact upon the cell performance whilst providing highly relevant and complementary thermal data.

7. Conclusions

This work shows the development of a promising temperature sensor for *in-situ*, *in-operando* monitoring of live Li-ion cells. Utilising modified optical fibre sensors has been proven to be the optimal solution for Li-ion cells instrumentation due to their low profile and high resilience to the internal cell environment. The cell instrumentation method used also allows for easy sensor recovery and subsequent reuse, while being proven to have negligible impact on the cell's performance. A significant temperature difference was identified between the cell's core and can temperatures of up to 6 °C during

discharge and 3 °C during charge phase. Therefore, underlining the necessity of real internal cell temperature measurements for thermal management and safety validation. The observed axial temperature gradient can be a vital source of information about local overheating zones and anode/cathode temperature differences, supporting materials and electrochemical research. The knowledge gained from the instrumentation developed here can be used to significantly improve and support the design and prototyping of cells and battery modules for optimum charging profiles and greater safety and offers highly reliable validation for thermodynamic models and State of Health prediction mechanisms.

8. Data statement

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

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Author information

The authors declare no competing financial interests.

J.F and T.A. performed the experiments with assistance of E.M-T. J.F. and T.A. analysed the data.

R.B. supervised the project and offered advice. All authors wrote the manuscript.

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