

Article

Fiber Bragg Grating Array-Based Synchronous Monitoring of Spatiotemporal Surface Temperature–Strain Fields in a 314 Ah Energy Storage Battery

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Abstract

Lithium-ion batteries undergo coupled thermal and mechanical responses during operation, which are closely related to their safety and reliability. However, simultaneously monitoring the surface temperature and strain fields of large-format prismatic batteries remains challenging. In this study, a fiber Bragg grating (FBG) array-based dual-parameter sensing system was developed to synchronously measure the temperature and strain of a 314 Ah lithium iron phosphate battery during charge–discharge cycling under different power conditions. Continuous surface temperature and strain fields were reconstructed from the measured data to investigate their spatiotemporal evolution. The results reveal significant differences between the temperature and strain distributions as well as asynchronous dynamic responses. Spatially, with increasing power, temperature hotspots shifted toward the central region, whereas strain extrema migrated toward the positive electrode side, revealing distinct spatial heterogeneity in the thermo-mechanical response. Temporally, the strain extrema consistently appeared tens to hundreds of seconds earlier than the temperature peaks. These findings provide direct experimental evidence of the thermo-mechanical coupling behavior of large-capacity lithium-ion batteries, establish baseline temperature–strain distributions under normal operating conditions, and offer valuable guidance for battery state evaluation, thermal management, and early fault diagnosis.

Keywords: energy storage battery; fiber Bragg grating sensors; temperature distribution; spatial and temporal distribution



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1. Introduction

With the continuous expansion of energy storage systems, the operational safety of large-capacity lithium-ion batteries has become an increasing concern. During battery charging, discharging, and aging, temperature changes and structural strain are important physical responses reflecting internal electrochemical reactions, heat generation, and material volume expansion. Existing research has largely focused on small-scale batteries. In contrast, large-capacity energy storage batteries are larger and have more complex internal structures, and their temperature and strain spatial distribution non-uniformity during operation may be more significant. Conducting temperature and strain monitoring of batteries, especially large-capacity batteries, is of great significance for the refined thermal management and condition diagnosis of energy storage systems.

Regarding the temperature and strain detection of batteries, conventional sensing methods face significant limitations in obtaining multidimensional field information. Traditional point-based sensors provide only discrete and localized measurements, making it difficult to capture spatially heterogeneous thermal and mechanical responses over large battery surfaces [1–6]. Although infrared thermography enables non-contact visualization of temperature distributions, it cannot simultaneously measure strain and is susceptible to surface emissivity, ambient light interference, and battery deformation [7–10]. These limitations become particularly important for large-capacity batteries, where substantial temperature variations and volume changes may occur during operation. Therefore, sensing technologies capable of simultaneously resolving temperature and strain with high spatial resolution are highly desirable for characterizing the spatiotemporal evolution of battery thermo-mechanical responses [11].

Compared with the above-mentioned conventional detection methods, fiber Bragg grating (FBG) sensors provide an attractive solution to these sensing limitations owing to their small size, wavelength-division multiplexing capability, high sensitivity, and immunity to electromagnetic interference [12,13]. In recent years, FBG-based optical fiber sensing has been increasingly applied to the in situ monitoring of lithium-ion batteries [14]. For example, Sheng et al. [15] constructed a high-density FBG sensing network on and inside cylindrical batteries to achieve dynamic reconstruction of the temperature field, while Zhang et al. [16] employed distributed optical fibers on pouch batteries to monitor temperature evolution during charging and discharging. More importantly, recent studies have extended optical fiber sensing to large-format single cells. For instance, Zeng et al. [11] constructed an array of FBG sensors to monitor the internal temperature evolution of a commercial 280 Ah LiFePO₄ prismatic battery, demonstrating significant spatial variations in temperature during cycling. The same group further applied FBG-based sensing to a 280 Ah prismatic battery for in situ internal pressure monitoring, demonstrating its capability to capture electrochemically induced pressure variations and provide early warning of thermal runaway under overcharge conditions [17]. These studies indicate that optical fiber sensing is capable of providing valuable thermal and mechanical information for large-capacity lithium-ion batteries. However, existing studies have predominantly focused on internal temperature, pressure, or individual mechanical responses, whereas systematic and spatially resolved characterization of the coupled surface temperature–strain evolution of large-capacity prismatic cells remains limited. In particular, for large-capacity LiFePO₄ energy storage batteries with complex internal stacking structures and rigid metal enclosures, the synchronous spatial distribution and temporal evolution of surface temperature and strain during charge/discharge processes have not yet been sufficiently investigated. Therefore, developing an FBG array capable of simultaneously mapping the surface temperature and strain fields of large-capacity prismatic batteries is of considerable significance for understanding their thermo-mechanical behavior and identifying spatially localized abnormal responses.

To address the aforementioned research gaps, this paper aims to construct a temperature–strain synchronous detection system based on a quasi-distributed FBG array for the 314 Ah large-capacity prismatic lithium iron phosphate (LFP) energy storage battery. A strain isolation strategy based on a specific packaging design, combined with systematic cross-sensitivity calibration, is introduced in this study, effectively overcoming the cross-sensitivity problem of the grating and achieving precise decoupling of the temperature and strain parameters. Based on this, high-spatiotemporal-resolution discrete sensing data are acquired under selected charge–discharge processes, and a continuous surface temperature and strain field is reconstructed using algorithms. This paper focuses on evaluating the non-uniformity and evolution of multi-field distribution under different operating conditions.

This not only provides new experimental evidence for revealing the thermo-mechanical coupling evolution mechanism of large-capacity batteries, but also provides important theoretical support and engineering reference for the subsequent development of refined thermal management and multi-level safety early warning strategies.

2. Experimental Setup

2.1. FBG Array Design

Large-capacity energy storage batteries exhibit typical thermo-mechanical coupling behavior during operation: the endogenous heat generated by electrochemical reactions leads to an increase in casing temperature, while material expansion and electrode deformation cause a simultaneous increase in surface strain. To achieve real-time detection of the co-evolution of temperature and strain during the charging and discharging process of large-capacity energy storage batteries, a high-density FBG matrix array is constructed in this paper. Employing FBG sensors that are sensitive to both temperature and strain, and through a rationally designed spatial arrangement structure, the array can cover the main areas of the battery surface, thereby enabling distributed measurement of multidimensional physical quantities.

As shown in Figure 1, in order to realize the field distribution detection on the battery surface, a 4×4 FBG array with a total of 16 measurement points was constructed on the battery surface.

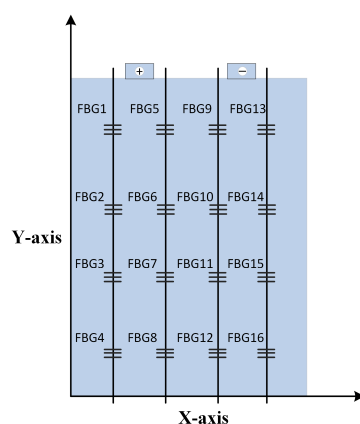


Figure 1. Schematic diagram of fiber optic grating array arrangement on the surface of battery.

To accurately quantify the anisotropic characteristics of the battery surface field, a two-dimensional physical coordinate system is combined in this paper, defining the direction parallel to the bottom of the battery as the X-axis and the direction perpendicular to the height of the tab as the Y-axis.

2.2. Temperature–Strain Decoupling

The fiber Bragg grating is a reflective optical sensor that works based on the principle of Bragg diffraction. Its core consists of a periodic refractive index modulation structure, which can generate narrowband reflection within a specific wavelength range. The center reflection wavelength of the FBG satisfies the Bragg condition [18]

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad (1)$$

where n_{eff} represents the effective refractive index of the fiber core, and Λ represents the grating period.

When a grating is subjected to temperature changes or mechanical strain, the change in refractive index and the change in grating period together cause a shift in the central

reflection wavelength. If the temperature change is ΔT and the strain is $\Delta \varepsilon$, then the wavelength shift can be expressed as

$$\Delta \lambda_B = (\alpha + \xi) \lambda_B \Delta T + (1 - p_e) \lambda_B \Delta \varepsilon \quad (2)$$

where ξ represents the effective elastic optical effect coefficient.

As can be seen, both temperature and strain cause spectral drift, and the temperature sensitivity and strain sensitivity of FBG are both significantly linear. Therefore, the temperature sensitivity K_T and strain sensitivity K_ε can be obtained through calibration, thus simplifying the wavelength drift as follows:

$$\Delta \lambda_B = K_T \Delta T + K_\varepsilon \Delta \varepsilon \quad (3)$$

This quantitative relationship forms the theoretical basis for subsequent temperature–strain dual-parameter decoupling.

The center wavelength drift of the FBG is sensitive to both temperature and strain. In the measurement signal of a single FBG, there is an inevitable cross-sensitivity effect, making it difficult to directly distinguish the independent contributions of temperature and strain changes to the spectrum. Therefore, a reference compensation mechanism needs to be introduced. Existing literature has proposed a variety of dual-parameter decoupling schemes [19]. A temperature–strain decoupling strategy based on a mechanically isolated reference FBG was adopted in this study. Specifically, an additional reference FBG was encapsulated within a ceramic capillary tube and installed on the battery surface as a temperature-compensation element. The additional reference FBG with a grating length of 10 mm was encapsulated in a cylindrical ceramic tube with a length of approximately 30 mm and a diameter of approximately 2 mm. The encapsulation structure was designed to minimize the transfer of mechanical deformation from the aluminum battery shell to the grating region. Consequently, the wavelength response of the reference FBG was primarily attributed to temperature variations, while the residual influence of mechanical strain was minimized. The temperature obtained from the reference FBG was subsequently used to compensate for the temperature-induced wavelength shift in the surface-mounted sensing FBGs, thereby enabling the extraction of the strain response [20]. To monitor the external surface temperature and strain of the battery, the FBG sensor array was fully bonded to the cell surface using an epoxy resin adhesive, ensuring intimate and continuous contact between the sensors and the aluminum shell.

The center wavelength drift $\Delta \lambda_{B1}$ of the reference FBG is driven only by the change in ambient temperature, and its mathematical relationship is as follows,

$$\Delta \lambda_{B1} = k_{T1} \Delta T \quad (4)$$

where k_{T1} represents the temperature sensitivity coefficient obtained by calibration of the reference FBG.

Based on the principle of independent linear response of wavelength shift to temperature and strain, the total spectral response of the surface measurement FBG under the combined effects of temperature change and mechanical strain is as follows,

$$\Delta \lambda_{B2} = k_{T2} \Delta T + k_{\varepsilon 2} \Delta \varepsilon \quad (5)$$

where $k_{\varepsilon 2}$ and k_{T2} respectively represent the strain and temperature sensitivity coefficients determined by the systematic calibration procedure of the measured FBG.

Accordingly, the specific logic of dual-parameter decoupling can be described as follows: first, using Equation (4), the wavelength drift obtained by the reference FBG is

accurately converted into a pure temperature change; then, the temperature variable is substituted into Equation (5) to eliminate the thermo-optic effect and thermal expansion crosstalk in the measured FBG signal, and thereby accurately inverting the true structural strain of the battery surface [21].

The calibration experiments were carried out on the FBG sensor to identify the temperature and strain sensitivity before attaching the sensor to the battery; the setup is shown in Figure 2.

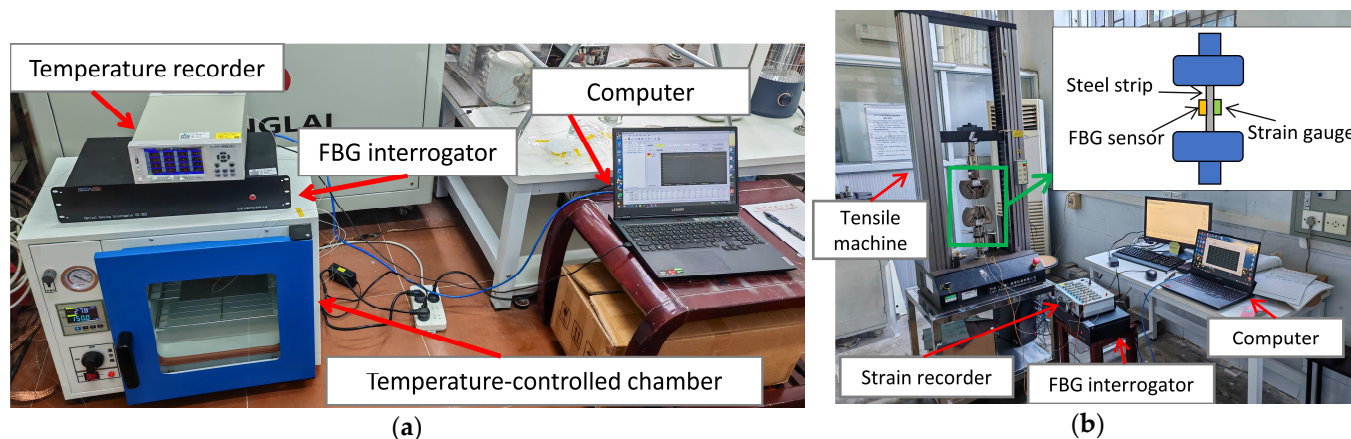


Figure 2. (a) Temperature calibration experiment setup; (b) strain calibration experiment setup.

For temperature calibration, a thermostat is used to heat the optical fiber step by step under no external force, with a temperature range of 25–100 °C; the setup is shown in Figure 2a. The average data for the wavelength shifts and temperature on the plate monitored by the thermocouple are shown in Figure 3a, indicating that there was a good linear fit between the temperature and wavelength shift.

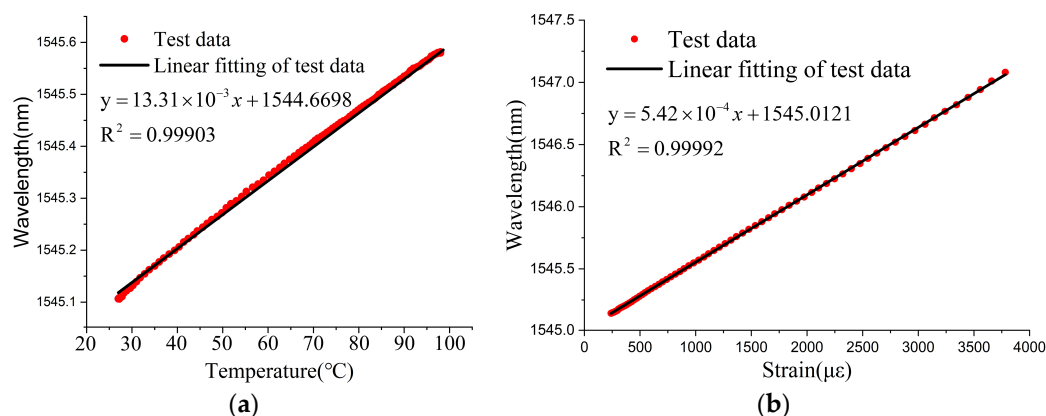


Figure 3. (a) Temperature calibration experiment result; (b) strain calibration experiment result.

For strain calibration, the sensor was installed on a steel strip and an electrical resistance foil gauge was fixed to the strip; the setup is shown in Figure 2b. The plate was stretched with a tensile machine and the deformation of the plate was transferred to the sensor. A FBG interrogator (OS265, Photospeed, Beijing, China) was used to record the shifts in the FBG wavelength. A strain recorder (JMTS–116, Jing Ming Technology, Yangzhou, China) was used to record the data from the foil gauge [22]. The average data for the wavelength shifts and strain on the plate monitored by the foil gauge are shown in Figure 3b, indicating that there was a good linear fit between the strain and wavelength shift with a strain range of 0–4000 $\mu\epsilon$.

Since the FBG array provides temperature and strain information at only 16 discrete locations, a biharmonic spline interpolation method was employed to estimate the corresponding values at unsampled spatial locations. Biharmonic spline interpolation has been applied to spatially distributed data analysis in lithium-ion batteries, demonstrating its applicability to reconstructing continuous spatial fields from discrete measurements [23].

The 16 FBG sensing points were first mapped onto their corresponding physical coordinates on the battery surface, forming a set of discrete spatial temperature and strain measurements. A regular 200×200 computational grid was subsequently established over the sensing domain, with temperature and strain values estimated at each grid node. The biharmonic spline interpolation was independently applied to the temperature and strain measurements to reconstruct the corresponding continuous surface fields. This procedure transformed the discrete spatial measurements obtained from the FBG array into continuous temperature and strain distributions, providing a basis for subsequent hotspot identification, strain concentration analysis, and quantitative evaluation of temperature–strain spatial non-uniformity.

2.3. Test Batteries and Test Platform

The LP71173207SS-314 Ah prismatic LFP battery is selected as the test object in this paper. The basic information of the battery is shown in Table 1.

Table 1. Battery parameters.

Parameter	Specification
Typical capacity	314 Ah
Typical energy	1004.8 Wh
Charging upper limit voltage	3.65 V
Discharge cut-off voltage	2.5 V
Cell weight	5.6 kg
Cell dimensions (width $\times$ height $\times$ thickness)	178.3 $\times$ 207.2 $\times$ 71.5 mm

The test platform mainly consists of a TROPPOWER battery testing system (CTSH-6-600-81S0, ± 600 A/1.5~6 V), a Temperature Test Chamber (TODH-165, TOMILO, Kunshan, China), a computer, a multi-channel temperature recorder (MT500P, Shenhwa Technology Co., Ltd., Shenzhen, China), and a 314 Ah prismatic LFP test battery, as shown in Figure 4. To monitor the external surface temperature of the battery, the FBG sensor array was attached onto the cell surface using an epoxy resin adhesive.

If a traditional constant current control mode is used, large-capacity energy storage batteries need to withstand a large operating current during charging and discharging, which often leads to significant instantaneous power fluctuations and rapid heat accumulation, thereby exacerbating the internal thermal stress and structural load of the battery, which is detrimental to its safe and stable operation. Therefore, constant-power charging and discharging methods are usually adopted when conducting charging and discharging tests on large-capacity energy storage batteries. According to the GB/T 36276-2023 standard (Lithium ion battery for electrical energy storage. China Electricity Council: Beijing, China, 2023), the constant-power control mode is used to conduct complete charging and discharging tests of the battery under different power conditions in this paper. The power levels are normalized based on the battery's rated power and set to 0.5P, 0.75P, and 1P, respectively. The corresponding battery operating parameters under each condition are listed in Table 2. The test procedure is as follows: first, the battery with a SOC of 100% is discharged to 2.5 V under constant power, left to stand for 10 min, and then charged to 3.65 V under constant power.

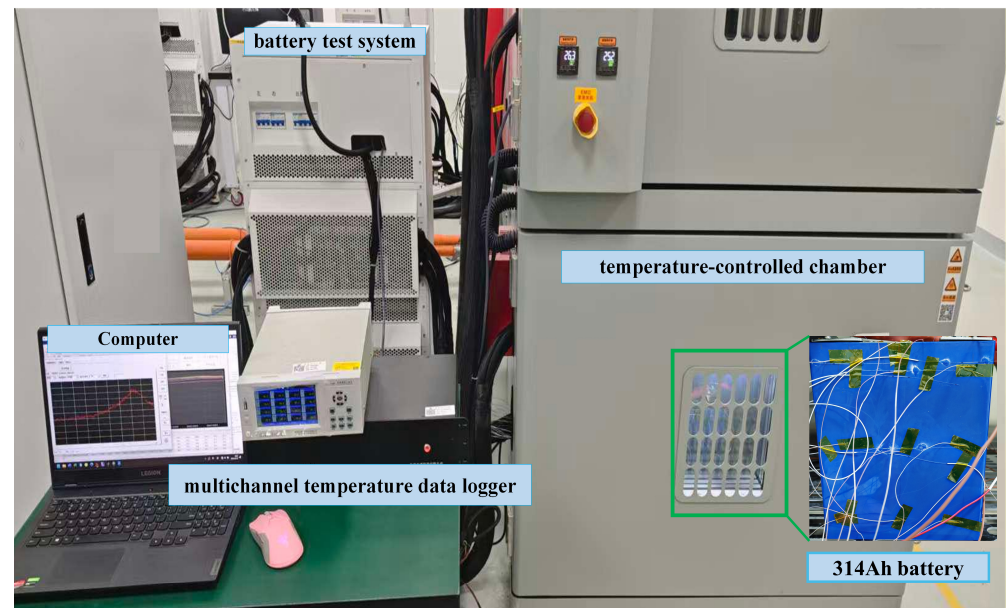


Figure 4. Test platform.

Table 2. Battery operating parameters.

Condition	Power (W)	Cut-Off Voltage (V)	Discharge Current Range (A)	Charge Current Range (A)
0.5P	502.4	2.5/3.65	149.1 → 201.0	169.5 → 137.6
0.75P	753.6	2.5/3.65	226.6 → 301.4	251.4 → 206.5
1P	1004.8	2.5/3.65	304.2 → 401.9	335.0 → 275.3

3. Results

3.1. Spatial and Temporal Distribution of Surface Temperature Field

To systematically reveal the thermal behavior characteristics of large-capacity energy storage batteries under different charge and discharge conditions, the spatial and temporal evolution of battery surface temperature during charge and discharge based on a FBG array arranged on the battery surface is analyzed in this section.

To reveal the temporal pattern of temperature rise, data obtained from the FBG6 measuring point that is continuously located in the surface hotspot region were selected for analysis. Figure 5 shows the temperature change curves of the FBG6 measured over time under conditions of 0.5P, 0.75P, and 1P.

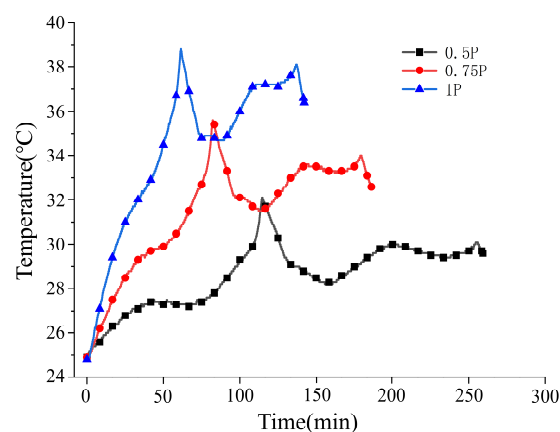


Figure 5. Temperature variation curves during charge and discharge under different power conditions.

As shown in Figure 5, regardless of the 0.5P, 0.75P, and 1P conditions, the battery surface temperature rises rapidly during the initial stage of discharge. The rate of temperature rise then gradually decreases, entering a relatively stable dynamic thermal equilibrium phase. Finally, the temperature rises sharply again until the end of discharge. Unlike the discharge process, during the initial stage of charging, the battery surface temperature rises rapidly, followed by a significant cooling period, before rising sharply again until the end of charging.

These distinct thermal evolution patterns can be attributed to the coupled effects of irreversible heat generation, reversible entropic heat, and heat dissipation. During charge and discharge, the total heat generation of the LFP battery mainly consists of irreversible heat associated with ohmic resistance and electrochemical polarization, together with reversible entropic heat arising from changes in the entropy of the electrochemical reactions. Under the constant-power conditions investigated in this study, the current varies inversely with the terminal voltage. Therefore, toward the end of discharge, the progressive decrease in terminal voltage leads to an increase in current, which further amplifies the ohmic heat generation and heat associated with electrochemical polarization and mass-transport limitations, thereby contributing to the renewed temperature rise observed near the end of discharge. Meanwhile, reversible entropic heat may either absorb or release heat depending on the electrochemical state and can consequently modify the net heat-generation rate during different stages of charging and discharging. During charging, the initial temperature rise is mainly associated with the dominance of irreversible heat generation; however, the subsequent cooling indicates that the instantaneous net heat generation temporarily becomes lower than the heat dissipation rate, potentially due to the combined effects of reversible entropic heat and changes in electrochemical polarization. As charging proceeds, irreversible heat generation gradually becomes dominant again, resulting in a renewed increase in surface temperature [24].

Figure 6 shows the 2D surface temperature contours of the battery under different power conditions, where the red crosses represent the extreme points of the battery surface temperature.

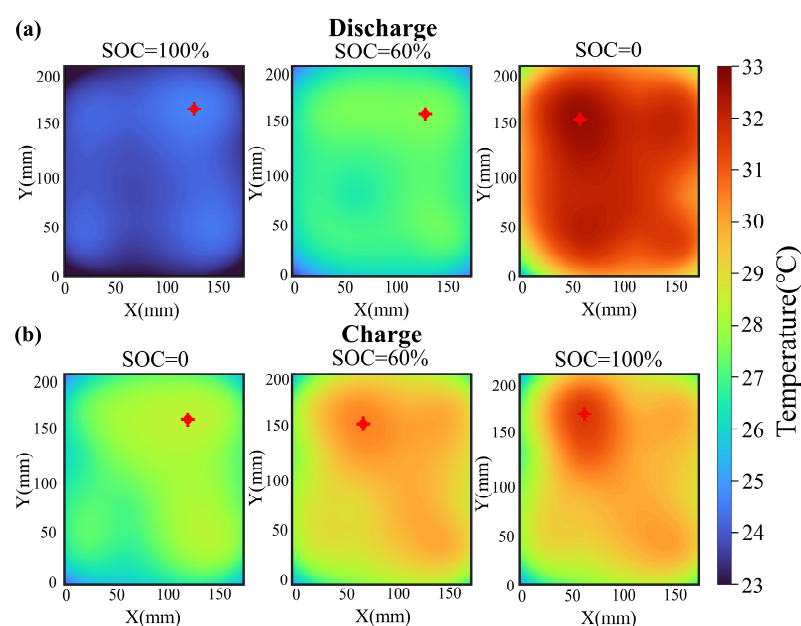


Figure 6. Cont.

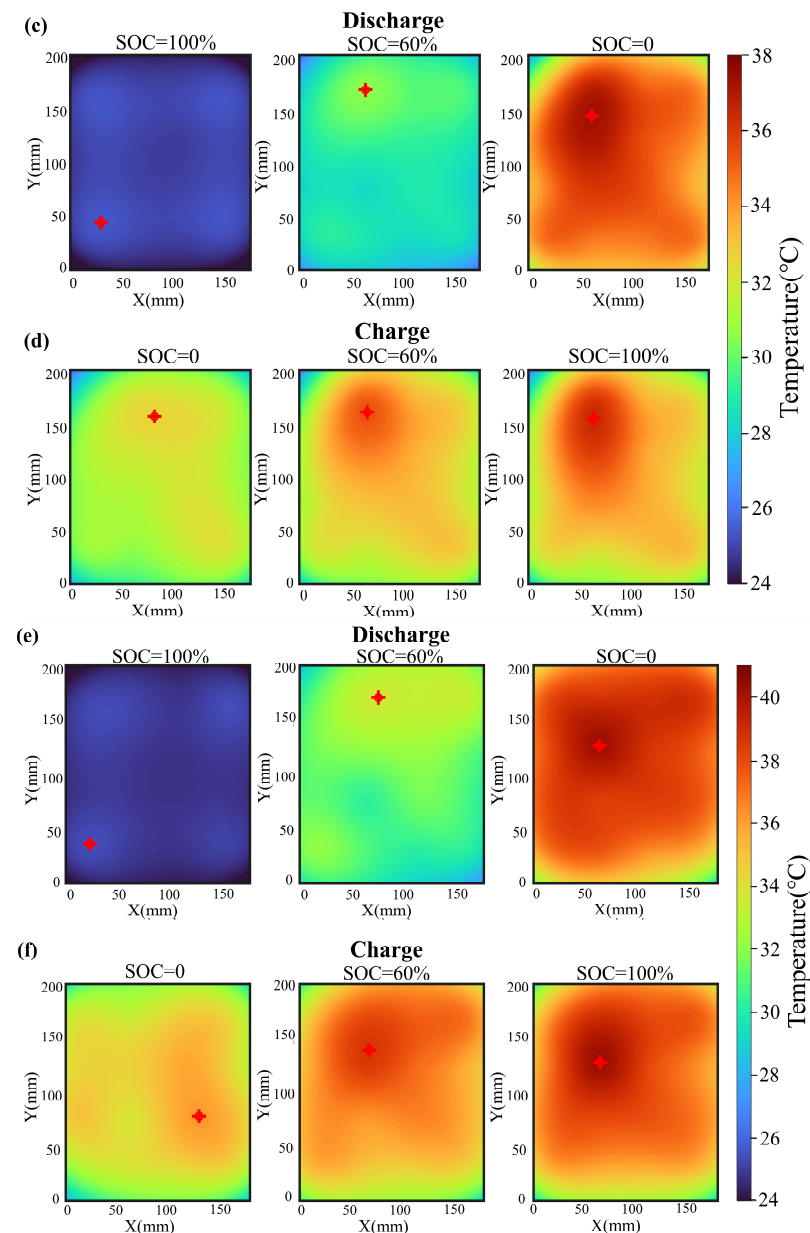


Figure 6. Distribution of battery surface temperature field at specific moments under different power conditions. (a) Discharging at 0.5P; (b) charging at 0.5P; (c) discharging at 0.75P; (d) charging at 0.75P; (e) discharging at 1P; (f) charging at 1P. Red crosses: temperature extrema.

The following observations can be seen from the figure:

1. Under the low-power reference condition of 0.5P, the peak temperatures at the end of discharge and charging reached 32.71 °C and 31.60 °C, respectively. The maximum surface temperature difference during the entire charge and discharge cycle was only 3.12 °C. This indicates that the surface temperature distribution of the large-capacity battery remains relatively uniform at 0.5P.
2. Under the 0.75P condition, the peak temperatures of discharge and charge rise to 37.38 °C and 36.46 °C, respectively, and the maximum surface temperature difference increases to 5.15 °C. When the power is further increased to 1P, the peak temperatures reach 40.28 °C and 40.38 °C, respectively, and the maximum surface temperature difference increases sharply to 9.31 °C. This indicates that as the charging and discharging power increases, the deterioration trend of the temperature gradient becomes more and more obvious.

3. The local aggregation and spatial migration characteristics of hotspots vary significantly under different power conditions. Under the 0.5P condition, the surface temperature extrema are located slightly toward the positive electrode tab region rather than exactly at the geometric center, while the temperature gradient along the vertical direction remains relatively small. As the operating power increases, the temperature extrema gradually shift downward toward the central region of the battery surface. This spatial migration can be attributed to the changing balance between spatially non-uniform heat generation and heat dissipation under different power conditions. At low power, the temperature distribution is more strongly influenced by local thermal boundary conditions, resulting in a relatively higher temperature near the positive-tab region. With increasing power, the overall heat generation and internal thermal gradients become more pronounced, while the central region may exhibit a relatively lower effective heat dissipation capability. Consequently, heat accumulation becomes increasingly prominent in the central region, leading to the observed downward migration of the temperature extrema from the positive-tab side toward the central region.

Figure 7 shows temperature slices along the Y-axis of the battery surface under 0.5P, 0.75P, and 1P conditions. These spatial slice profiles were captured at the end of discharge, at which point the cell accumulated internal heat and exhibited pronounced temperature non-uniformity. As can be seen from the figure, under the 0.5P low-power condition, the surface temperature field exhibits high axial symmetry, with the local highest temperature predominantly distributed in the upper-central region of the battery, while the temperature gradients on the upper and lower end faces are weak and similarly distributed. When the charging and discharging power increases dramatically, the spatial evolution trajectory of the temperature field shifts, and the local temperature rise near the upper electrode region is amplified dramatically, which affects the movement of hotspots on the battery surface.

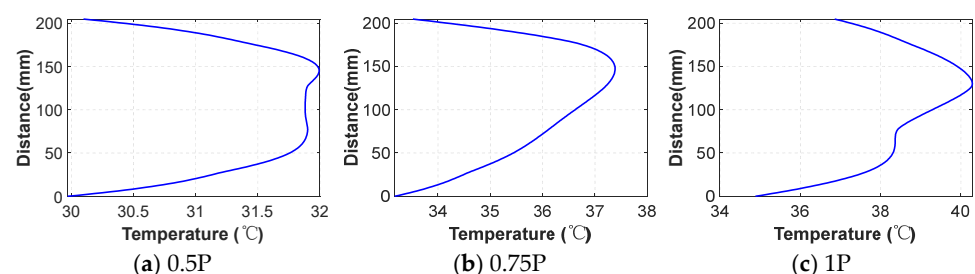


Figure 7. Temperature slices along the Y-axis of battery surface under 0.5P, 0.75P, and 1P power conditions at the end of discharge.

The results above show that the surface temperature field distribution of a large-capacity battery during charging and discharging is correlated with power conditions. The main reasons for this spatial migration are the high heat generation intensity of the positive electrode collecting fluid and the tab region under high current load, as well as the physical differences in electrical and thermal conductivity between the positive and negative electrode materials. These factors lead to a large accumulation of heat on the positive electrode side, which exacerbates the non-uniformity of the temperature field under high power.

In routine testing of small and medium-sized batteries, due to the limited spatial resolution of point sensors and the constraints of battery specifications, the battery is often regarded as having lumped heat capacity in engineering, or the highest temperature is assumed to reside at the geometric center [25–28]. The experimental results in this paper show that due to the drastic scaling effect of the 314 Ah battery, there is an

extreme surface temperature difference of up to 9.31 °C on the battery surface and a shift in hotspots towards the battery tabs. The above phenomena indicate that blindly following the single-point temperature measurement strategy at the center of small and medium-sized batteries may completely miss the early detection capability of local thermal runaway of large-capacity cells.

3.2. Spatial and Temporal Distribution of Surface Strain Field

The spatial and temporal distribution of surface strain field in large-capacity energy storage batteries during charging and discharging is systematically analyzed in this section.

To reveal the temporal law governing strain rise, data measured at the FBG6 measuring point, which is continuously located in the surface strain concentration region, were selected for analysis. Figure 8 shows the curves of battery surface strain versus time under 0.5P, 0.75P, and 1P conditions.

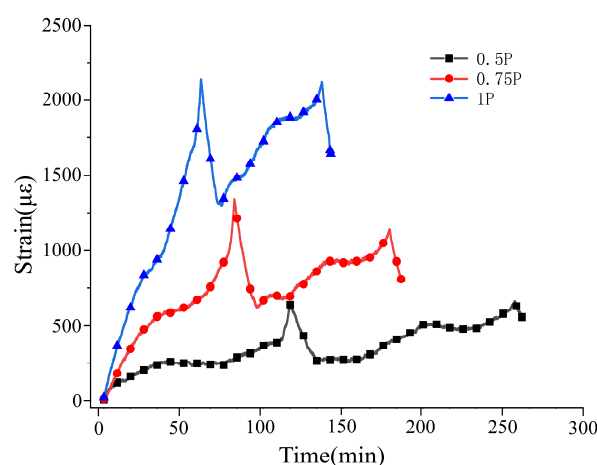


Figure 8. Strain variation curves during charging and discharging under different power conditions.

As shown in Figure 8, regardless of the 0.5P, 0.75P, and 1P conditions, the strain on the battery surface increases rapidly in the initial stage of charging and discharging. Subsequently, the strain increase rate gradually decreases, entering a relatively smooth dynamic equilibrium phase, before finally experiencing another sharp strain rise to end the process.

The observed strain evolution is governed by the coupled effects of electrochemically induced deformation, thermal expansion, and mechanical constraints imposed by the mechanically constrained aluminum casing. During charging and discharging, lithium-ion redistribution between the positive and negative electrodes induces reversible changes in electrode lattice structure and volume, which are mechanically transferred through the electrode stack to the aluminum casing and manifested as position- and state-dependent surface strain responses [29,30]. At the initial stage of charging or discharging, the relatively rapid change in lithium-ion concentration and electrochemical state leads to a pronounced strain response. As the electrochemical redistribution gradually approaches a dynamic balance, the rate of electrochemically induced deformation decreases, while the rigid casing constrains further macroscopic deformation, resulting in a relatively stable strain response. Toward the end of discharge, the decrease in terminal voltage under constant-power operation leads to a rapid increase in the discharge current, thereby enhancing ohmic heating and electrochemical polarization. The resulting temperature rise promotes thermal expansion of the aluminum casing, while the intensified polarization may further increase internal stress accumulation. These thermal and mechanical contributions can offset and eventually exceed the contraction-related deformation induced by electrochemical delithiation, thereby

producing the renewed increase in surface strain observed near the end of discharge. During charging, however, the terminal voltage generally increases under constant-power operation, resulting in a gradual decrease in the charging current; therefore, the renewed strain increase near the end of charging is more likely associated with the evolving electrochemical deformation, polarization, thermal expansion, and mechanical constraint, rather than an increase in current. Overall, the measured surface strain represents a coupled mechanical response to electrochemical volume change, thermal expansion, and enclosure constraints, rather than a direct consequence of temperature variation alone.

Figure 9 shows the 2D surface strain contour maps of the battery under different power conditions, where the extreme points of surface strain are denoted by the red crosses.

The following observations can be seen from the figure:

1. Under low-power conditions of 0.5P, the maximum strain of the battery occurs at the end of charging, with a maximum value of 675.08 $\mu\epsilon$. When the power is increased to 0.75P and 1P, the strain peaks occur at the end of discharging, with maximum values of 1359.74 $\mu\epsilon$ and 2180.28 $\mu\epsilon$, respectively. Under different constant-power conditions, the timing and magnitude of the maximum strain on the battery surface show a clear correlation with the charging and discharging power.
2. Spatially, the strain concentration zone throughout the charge–discharge process is predominantly located in the central-to-upper region of the battery surface. With increasing operating power, the localized strain concentration area exhibits a distinct spatial migration toward the positive electrode side. This evolution can be attributed to the coupled effects of enhanced electrochemical polarization, spatially non-uniform heat generation, and heterogeneous mechanical constraints associated with the large-format prismatic cell. The positive electrode tab region may experience stronger electrochemical and thermal effects under high-power operation, while its local structural stiffness can constrain and redistribute the surrounding deformation, thereby promoting the observed shift in the strain concentration area toward the positive electrode side.

The observed strain characteristics can be understood from the coupled effects of electrochemical deformation, thermal expansion, and mechanical constraints. During charge and discharge, lithium-ion insertion and deinsertion induce reversible changes in the lattice structure and volume of the electrode materials, generating deformation that is transferred through the electrode stack to the aluminum casing [30]. As the operating power increases, the higher current intensifies electrochemical polarization and internal heat generation, thereby increasing both the electrochemically induced deformation and the thermally induced strain. Under constant-power discharge, the decrease in terminal voltage toward the end of discharge further increases the discharge current, which enhances ohmic heating and polarization and can consequently amplify the late-stage deformation response. Meanwhile, the spatial redistribution of strain is strongly affected by the heterogeneous mechanical constraints of the large-format prismatic cell. The central region is more susceptible to deformation because the expansion and contraction of the large electrode stack are constrained by the perimeter boundaries of the aluminum enclosure, whereas the positive electrode tab and its adjacent structure introduce additional local stiffness and thermal–mechanical coupling. With increasing power, the stronger local thermal and electrochemical effects near the positive electrode region can therefore alter the stress distribution and promote the observed migration of the strain concentration area toward the positive electrode. Thus, the measured surface strain reflects the combined response of electrochemical volume change, thermal expansion, and non-uniform mechanical boundary constraints rather than temperature variation alone.

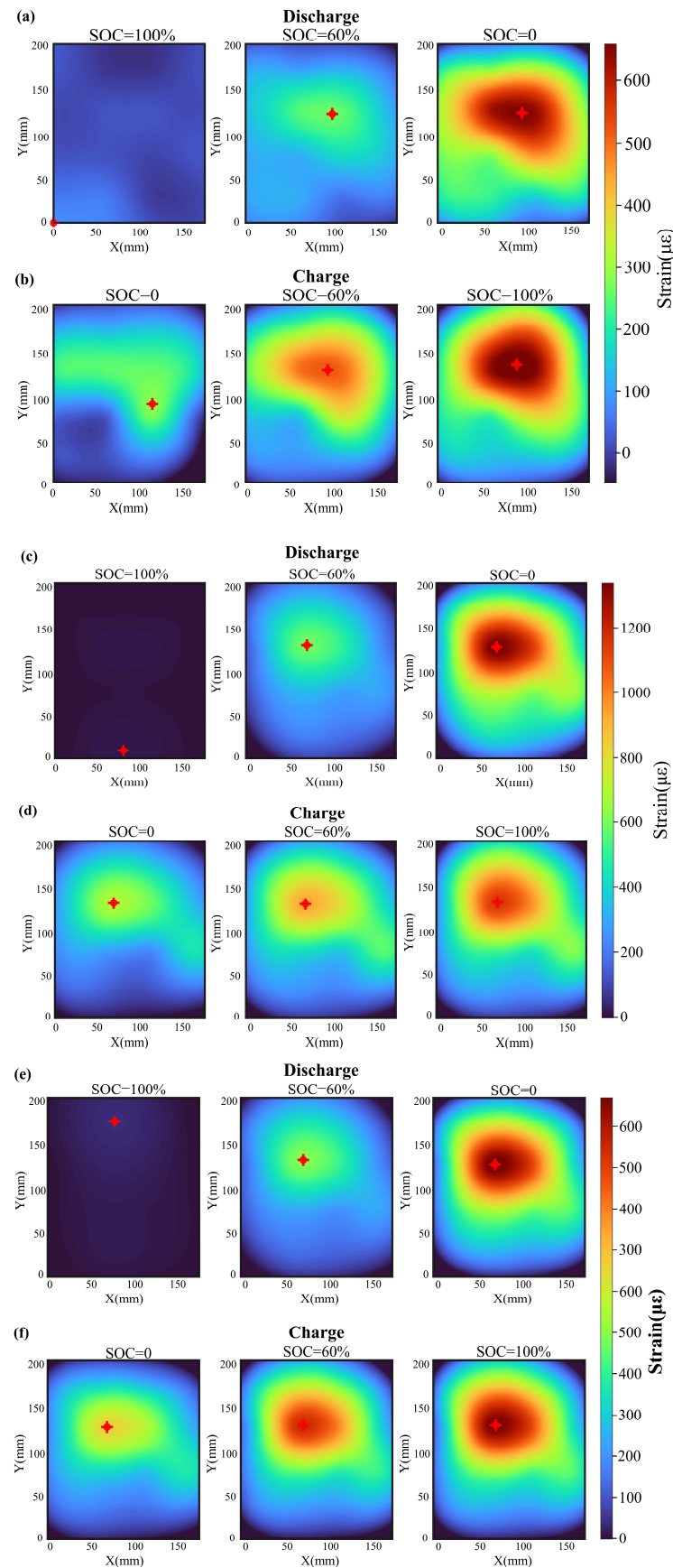


Figure 9. Distribution of battery surface strain field at specific moments under different power conditions. (a) Discharging at 0.5P; (b) charging at 0.5P; (c) discharging at 0.75P; (d) charging at 0.75P; (e) discharging at 1P; (f) charging at 1P. Red crosses: strain extrema.

Figure 10 shows cross-sections of the battery surface strain field under different power conditions. (a), (b) and (c) are cross-sections along the X-axis under conditions of 0.5P, 0.75P, and 1P, respectively, while (d), (e) and (f) are cross-sections along the Y-axis under conditions of 0.5P, 0.75P, and 1P, respectively. As can be seen from the figure, the overall deformation distribution along the X-axis is relatively gentle, but the strain concentration area tends to shift towards the positive electrode as the power increases. The strain along the Y-axis exhibits a significantly non-uniform distribution characteristic with a gradient decay from the center to the edge in space.

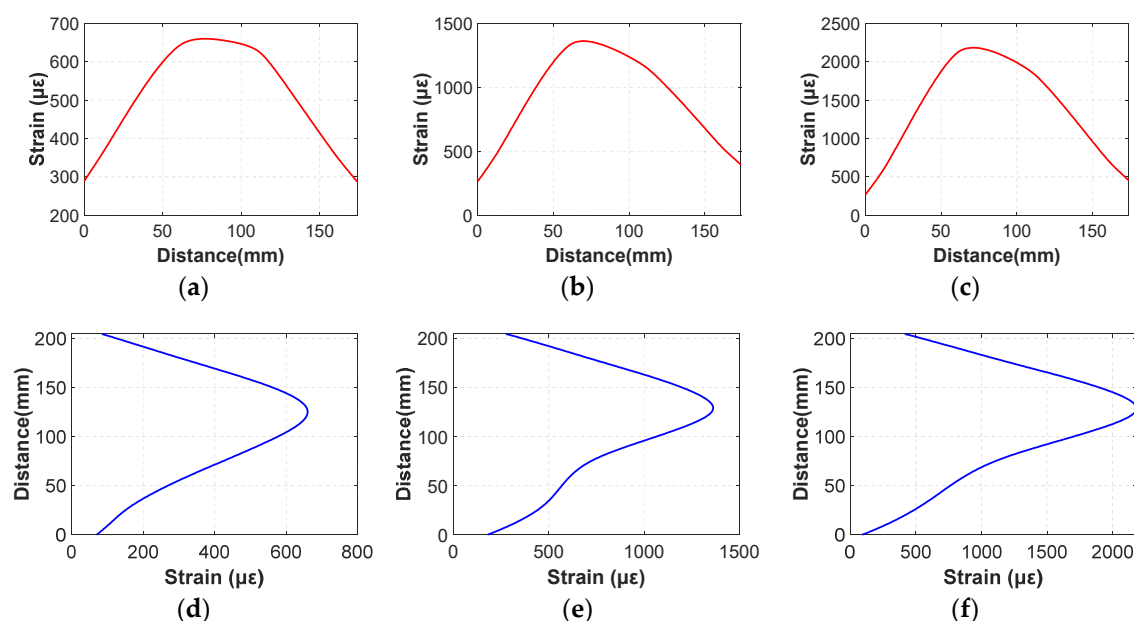


Figure 10. Strain field slices of batteries at the end of discharge: (a–c) longitudinal profiles along the X-axis under different power conditions. (a) 0.5P, (b) 0.75P, (c) 1P; (d–f) transverse profiles along the Y-axis under different power conditions. (d) 0.5P, (e) 0.75P, (f) 1P.

In order to quantitatively characterize the spatial non-uniformity of the battery surface field, the coefficient of variation (CV) is introduced as the core evaluation index in this paper [31]. The coefficient of variation is the ratio of the standard deviation to the average value. It can effectively eliminate the influence of dimensions and scale caused by the difference in absolute deformation amplitude under different working conditions, thus objectively reflecting the relative dispersion of the physical field. Its calculation formula is as follows,

$$CV = \frac{\sigma}{\mu} \times 100\% \quad (6)$$

where σ represents the spatial standard deviation of surface strain data in a specific direction, and μ represents the average strain value of the corresponding region. The larger the CV value, the steeper the spatial gradient of the strain field and the more uneven its distribution.

Under different power conditions, the CVs for strain in the X-axis direction were 23.5%, 35.25%, and 41.46%, respectively, while the CVs for strain in the Y-axis direction were as high as 49.04%, 44.23%, and 52.41%. Comparison of the CV data under different power conditions reveals that the strain field on the battery surface exhibits extremely strong anisotropy. The CVs in the X-axis direction monotonically jump from 23.5% to 41.46%, showing extremely strong sensitivity to power. This is because the high current load exacerbates the local differences in in-plane polarization and heat generation in the lateral direction. Although the CV in the Y-axis direction is accompanied by slight oscillations,

it exhibits a highly stable and steep spatial deformation gradient. This is because a huge mechanical stiffness barrier is formed between the top and bottom shells of the battery and the unsupported center of the large surface area. This constrained boundary prevents the enormous volumetric expansion stress generated by the internal electrodes from being uniformly dissipated throughout the entire area.

Unlike the uniform in-plane expansion of small pouch batteries and the axisymmetric radial deformation of cylindrical batteries [32,33], the significant anisotropy of large-capacity prismatic batteries mainly stems from the differences in mechanical boundary constraints of the internal structure of the battery. At the same time, compared with medium-capacity power batteries, due to the difference in the geometric dimensions of their individual cells, the spatial anisotropy of their surface strain field is nonlinearly amplified. The experimental results in this paper prove that blindly following the homogenization mechanical assumption based on small and medium-sized batteries may lead to severe structural overload and sensory misalignment.

3.3. Spatial and Temporal Distribution of Surface Temperature–Strain Field

After constructing the spatiotemporal evolution diagrams of the surface temperature and strain fields of a large-capacity energy storage battery, the distribution characteristics and coupling relationships of the temperature and strain fields at different operating powers and stages will be systematically analyzed in this section.

Figure 11 shows the temperature and strain curves of the battery surface measured by the FBG6 over time during charging and discharging at different power levels. As shown in Figure 11, at 0.5P power, the extreme temperature and strain values during discharging occur at 7550 s and 7500 s, respectively, while during charging, they occur at 16,000 s and 15,940 s, respectively. At 0.75P power, the extreme temperature and strain values during discharging occur at 4970 s and 4900 s, respectively, while during charging, they occur at 10,784 s and 10,725 s, respectively. At 1P power, the extreme temperature and strain values during discharging occur at 4440 s and 4400 s, respectively, while during charging, they occur at 9020 s and 8910 s, respectively. These results consistently show that the strain extrema precede the corresponding temperature extrema under all tested power conditions, with temporal offsets ranging from approximately 40 to 110 s. This consistent lead of the strain response provides the quantitative basis for further discussing the different dynamic response pathways of electrochemical deformation and heat transfer.

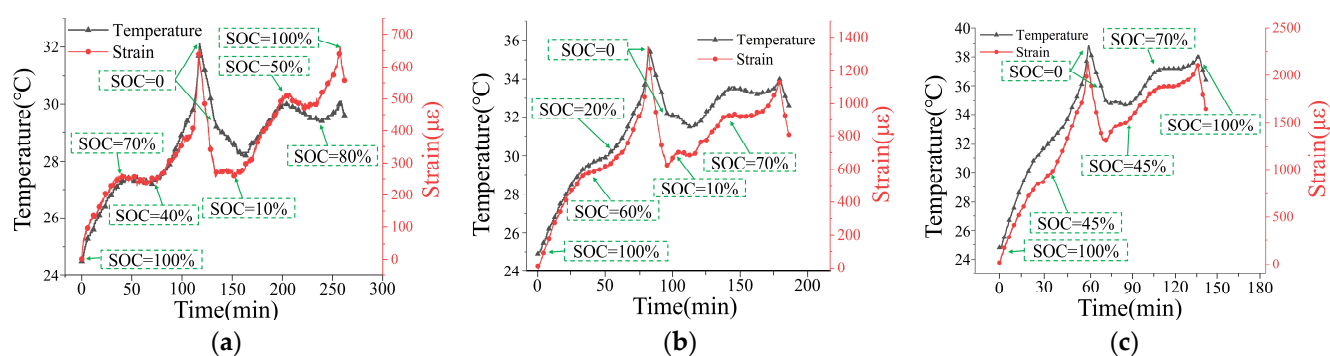


Figure 11. Surface temperature and strain changes in the 314 Ah cell during charging and discharging under different power conditions. (a) 0.5P, (b) 0.75P, (c) 1P.

The results above show that although the overall temporal evolution of the surface temperature and strain responses remains highly consistent during charging and discharging, a distinct difference is observed in the timing of their extrema. A relatively stable temporal offset of tens to hundreds of seconds is observed between the strain and temperature

extrema. This offset reflects the different dynamic response pathways of electrochemical deformation and heat transfer rather than a simple thermal diffusion delay. During charge/discharge, Li ion insertion and deinsertion induce reversible changes in electrode volume, generating mechanical deformation that is transferred through the electrode stack and constrained by the aluminum casing. As a result, the surface strain can respond relatively rapidly to changes in the electrochemical state. In contrast, heat generated inside the cell must be transferred through the electrode stack and casing before producing a measurable response at the external surface, giving rise to a finite thermal response time. Meanwhile, thermal expansion and the mechanical constraints of the casing also contribute to the measured surface strain. Therefore, the observed temporal offset represents the combined effects of electrochemical volume change, mechanical constraint and load transfer, thermal expansion, and heat-transfer dynamics in the large-format battery.

Figure 12 shows the coupled temperature–strain field distribution of the battery surface under 0.5P, 0.75P, and 1P conditions. The temperature field is depicted by the background color map, while the strain contours are illustrated by the overlaid solid lines. Extreme temperature and strain points are denoted by red crosses and white triangles, respectively.

As shown in the figure, under low-power conditions, both the high-temperature hotspots and localized high-strain regions on the battery surface are mainly concentrated near the central region, although the strain extrema exhibit a slight intrinsic spatial offset. With increasing charge/discharge power, the temperature extrema gradually shift from the positive electrode tab side toward the central region of the battery surface, whereas the strain extrema remain mainly within the central-to-upper region, with a moderate shift toward the positive electrode side.

This spatial decoupling can be attributed to the different physical origins of the two parameters. The temperature field is primarily governed by the spatial distribution of heat generation and heat transfer, whereas the surface strain reflects the combined effects of electrochemical volume change, thermal expansion, and mechanical constraints imposed by the prismatic aluminum casing. Therefore, even when the local temperature reaches its maximum near the positive electrode region, the corresponding strain maximum does not necessarily occur at the same location. The heterogeneous structural constraints and stiffness distribution around the electrode and tab regions can redistribute the deformation, resulting in a spatial offset between the thermal and mechanical extrema.

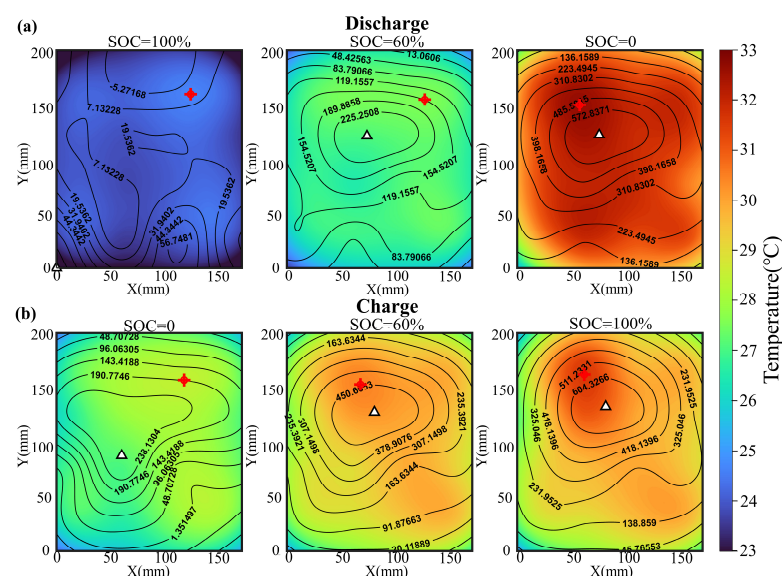


Figure 12. Cont.

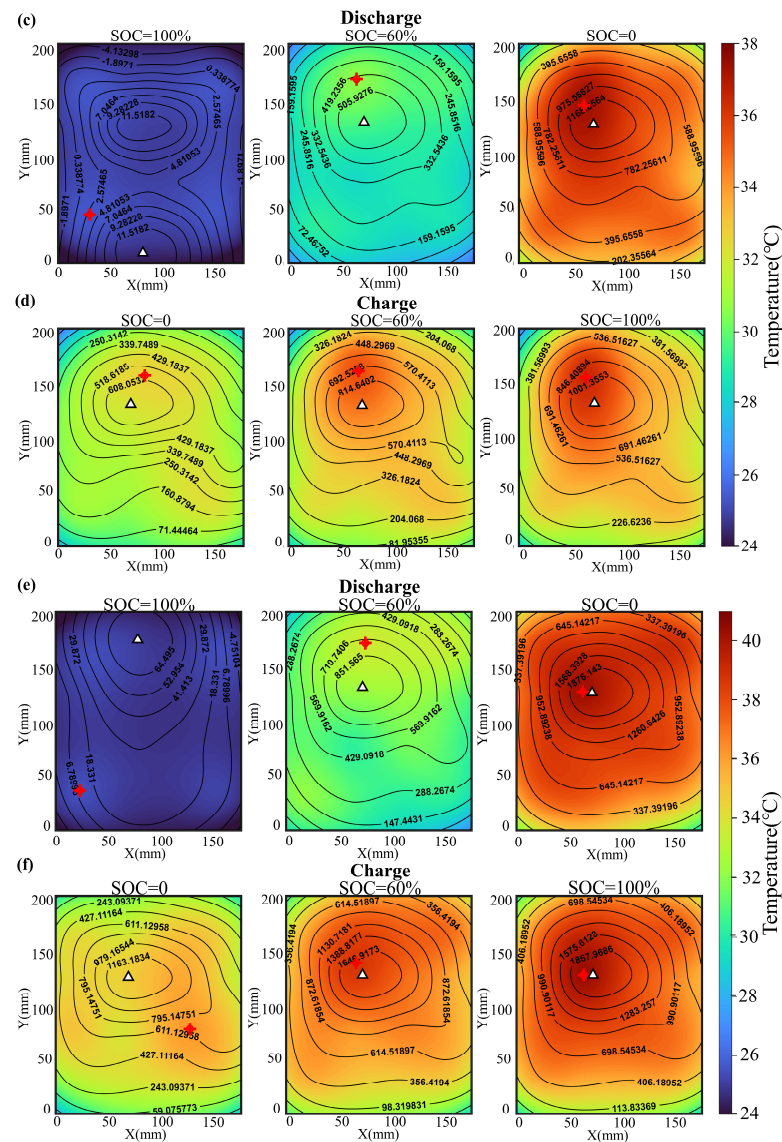


Figure 12. Temperature–strain field coupling distribution on battery surface under different power conditions. (a) discharging at 0.5P; (b) charging at 0.5P; (c) discharging at 0.75P; (d) charging at 0.75P; (e) discharging at 1P; (f) charging at 1P. Background color: temperature; solid contours: strain; red crosses: temperature extrema; white triangles: strain extrema.

The observed spatial offset between the temperature and strain extrema demonstrates that these two parameters provide complementary information on the thermo-mechanical state of large-capacity prismatic batteries. Compared with single-point surface temperature monitoring, simultaneous spatial measurement of temperature and strain can provide additional information on the distributions of thermal and mechanical responses, thereby improving the characterization of spatially heterogeneous battery behavior under different operating conditions.

4. Conclusions

To address the lack of data on the surface temperature and strain evolution of large-capacity prismatic energy storage batteries, a high-resolution detection method and a temperature–strain field distribution estimation method for LFP batteries using the FBG array are proposed in this paper. The main conclusions are as follows:

1. During charging and discharging, the surface temperature distribution exhibits a strong dependence on the applied operating power. Under the 1P condition, the temperature extrema gradually shift from a region slightly toward the positive electrode tab at low power toward the central region as the operating power increases, and the maximum surface temperature difference increases to 9.31 °C. These results demonstrate pronounced spatial thermal non-uniformity in the large-capacity prismatic battery and indicate that a spatially lumped or uniform-temperature assumption may not adequately describe its surface thermal behavior under high-power operation.
2. The strain concentration region is mainly located in the central area of the battery surface during charge and discharge. With increasing operating power, the strain concentration region tends to shift toward the positive electrode side. The coefficient of variation further demonstrates pronounced spatial heterogeneity in the surface strain field. Under operating powers from 0.5P to 1P, the coefficient of variation along the Y-axis reaches 52.41%, while that along the X-axis increases from 23.50% to 41.46%. These results indicate that the surface deformation of the large-capacity prismatic battery is strongly influenced by its mechanical boundary constraints and operating power.
3. The spatial distributions of temperature and strain exhibit distinct evolution characteristics under different power conditions. The temperature extrema shift from the positive-tab side toward the central region as the operating power increases, whereas the strain concentration zone remains mainly in the central-to-upper region and gradually shifts toward the positive electrode side. The non-coincident spatial evolution of the two parameters demonstrates that temperature and strain respond differently to heat generation, electrochemical deformation, and mechanical constraints, highlighting their complementary roles in characterizing the spatially heterogeneous thermo-mechanical behavior of large-capacity prismatic batteries. The combined temperature–strain field therefore provides complementary information for characterizing the thermo-mechanical behavior of large-capacity prismatic batteries.
4. The temporal evolution of the two parameters further reveals a distinct phase relationship between the surface strain and temperature responses. Across the investigated operating power range from 0.5P to 1P, the strain extreme consistently occurs earlier than the surface temperature peak, with a temporal offset of tens to hundreds of seconds. This temporal difference is attributed to the different dynamic response pathways of electrochemical-induced deformation and thermal evolution: electrochemical-induced volume changes can be transmitted through the electrode stack and battery casing, whereas the heat generated inside the cell requires finite time to propagate to the external surface. The observed temporal offset demonstrates the complementary temporal characteristics of strain and temperature during normal charge/discharge operation.

From a practical perspective, the proposed FBG-array-based sensing system could serve as a complementary spatial sensing layer for battery management systems (BMSs). In practical implementation, the FBG interrogator constitutes a major component of the overall system cost, while multiplexing multiple FBG sensing points through a shared interrogator can improve cost efficiency at the sensing-point level [34]. Meanwhile, the limited number of sensing points and the relatively simple field reconstruction process impose modest computational requirements, making real-time processing feasible in principle. Key spatial features, including the maximum temperature, temperature/strain gradients, strain concentration, and the temporal offset between temperature and strain extrema, could provide additional inputs for thermal monitoring, power derating, and abnormal-state diagnosis [35]. However, quantitative decision thresholds and closed-loop safety protection

strategies will require further investigation through systematic experiments under battery aging and representative fault conditions in future studies.

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