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SENSOR AND METHOD FOR DETERMINING ADVERSE THERMAL EVENT IN BATTERY CELL

Abstract

A battery system includes a battery cell including a housing. The housing includes a plurality of walls that define an outer surface of the housing. The battery system also includes a sensor coupled to the outer surface to determine an adverse thermal event in the cell. The sensor includes a deformable element made of a shape-memory material (SMM) that has a pre-stressed shape. The deformable element is adapted to deform to a memorized shape from the pre-stressed shape in response to an operating temperature of the cell exceeding a predefined temperature threshold for the cell. The memorized shape of the deformable element is different from the pre-stressed shape of the deformable element. A deformity of the deformable element to the memorized shape is indicative of the adverse thermal event in the cell.

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Background/Summary

TECHNICAL FIELD

[0001] The present disclosure relates to a battery system including a battery cell, a sensor for determining an adverse thermal event in the battery cell, and a method for determining the adverse thermal event in the battery cell.

BACKGROUND

[0002] Battery systems are used in various applications such as in energy storage systems, work machines, or electric vehicles to store and provide operating power. Each of these battery systems have multiple battery cells therein, arranged either in parallel, in series or in combinations thereof. These cells may be sensitive to temperature. It may be preferable to operate these cells below their maximum operating temperature. Above the maximum operating temperature for a particular cell, a performance of the cell may deteriorate or the cell may altogether fail. For example, under heavy load conditions, an increase in current demand from the cells may lead to heating of the cells. If a temperature of the cell exceeds the maximum operating temperature, an adverse thermal event may occur in the cell, that, in turn, may lead to a failure of the cell and consequently, the battery system. These adverse thermal events may include at least one of an overheating event, a fire originating from the battery cell and a thermal runaway event.

[0003] Conventional cells have a separator that is configured to disable the corresponding cell when the temperature of the cell exceeds the maximum operating temperature. The separator may allow exchange of ions between a cathode and an anode of the cell, via the separator at temperatures below the maximum operating temperature and may prevent exchange of ions through the separator at temperatures above the maximum operating temperature, thereby preventing adverse thermal events in most cases. For example, the separator may melt at the maximum operating temperature, permanently disabling the cell. An example of such a separator is a tri-layer cell separator comprising a layer of polyethylene between two layers of polypropylene. In an event that a cell undergoes such a failure, a service technician would be able to identify and replace such disabled cells.

[0004] It is also known to identify disabled battery cells by measuring an impedance of the cells. However, if these cells are disposed in parallel, it may be challenging to measure the impedance of the individual cells. Moreover, although it is possible to measure impedance of individual cells that are connected in series, the process of repeating the measurement process for each cell can be time consuming. Often batteries are packaged in such a way that opening a battery pack for impedance measurements may be a time consuming exercise.

[0005] As an alternative to measuring individual impedances of cells connected in series, it is known to monitor the temperature of the cell to determine whether the maximum operating temperature at which the separator melts has exceeded. This may be achieved by disposing a thermistor in each cell. However, incorporating a thermistor in each cell may be expensive and may increase overall costs associated with manufacturing the battery system.

[0006] PCT Publication 2023/279089, hereinafter referred to as ‘the '089 reference’, describes materials and systems to manage thermal runaway issues in a battery module. In the '089 reference, the battery module includes battery cells separated by spacer elements. To mitigate thermal runaway issues, spacer elements may be extended to the interior surface of the enclosure. A seal is formed between the spacer elements and the interior wall to form a thermal barrier between adjacent battery cells.

[0007] However, the spacer elements described in the '089 reference includes a heat activated material made from a shape memory element that flips upward when triggered by heat thereby blocking heat, fire, and other materials that are released during thermal runaway events in order to prevent thermal propagation between cells. Thus, the shape memory element is used to contain or mitigate thermal propagation in battery cells. However, the shape memory element described in the '089 reference directly mitigates risk associated with continued operation of the battery cell but, however, does so without providing an indication as to the occurrence of the adverse thermal event itself. Further, typically very high levels of current flow through a battery terminal, which makes it necessary for a direct current bus to be laser welded to the battery terminal to prevent arching. It may be challenging for a disclosed in the '089 reference to maintain necessary contact without forming arc in case of high levels of current.

SUMMARY

[0008] In an aspect, a battery system is provided. The battery system includes a battery cell. The battery cell includes a housing. The housing includes a plurality of walls that define an outer surface of the housing. The battery system also includes a sensor coupled to the outer surface of the housing and configured to determine an adverse thermal event in the battery cell. The sensor includes a deformable element made of a shape-memory material (SMM) and has a pre-stressed shape. The deformable element is adapted to deform to a memorized shape from the pre-stressed shape in response to an operating temperature of the battery cell exceeding a predefined temperature threshold for the battery cell. The memorized shape of the deformable element is different from the pre-stressed shape of the deformable element. A deformity of the deformable element to the memorized shape is indicative of the adverse thermal event in the battery cell.

[0009] In another aspect, a sensor for determining an adverse thermal event in a battery cell is provided. The sensor includes a deformable element made of a shape-memory material (SMM) and has a pre-stressed shape. The deformable element is adapted to deform to a memorized shape from the pre-stressed shape in response to an operating temperature of the battery cell exceeding a predefined temperature threshold for the battery cell. The memorized shape of the deformable element is different from the pre-stressed shape of the deformable element. A deformity of the deformable element to the memorized shape is indicative of an adverse thermal event in the battery cell.

[0010] In yet another aspect, a method for determining an adverse thermal event in a battery cell is provided. The method includes coupling a sensor, including a deformable element made of a shape-memory material (SMM), to an outer surface of a housing of the battery cell. The deformable element has a pre-stressed shape. The method also includes deforming the deformable element to a memorized shape from the pre-stressed shape when an operating temperature of the battery cell exceeds a predefined temperature threshold for the battery cell. The memorized shape of the deformable element is different from the pre-stressed shape of the deformable element. The method further includes indicating the adverse thermal event in the battery cell based on a deformity of the deformable element to the memorized shape.

[0011] Other features and aspects of this disclosure will be apparent from the following description and the accompanying drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIG. **1** is a schematic view of a battery system including a battery cell and a sensor, according to an embodiment of the present disclosure;

[0013] FIG. **2** is a schematic view of the battery system of FIG. **1**, wherein a deformable element of the sensor is in a pre-stressed shape;

[0014] FIG. **3** is a schematic view illustrating the deformable element of the sensor of FIG. **2** in a memorized shape;

[0015] FIG. **4** is a schematic view illustrating an array of sensors to identify adverse thermal events in corresponding battery cells in a battery system, according to an embodiment of the present disclosure; and

[0016] FIG. **5** is a flowchart of a method for determining an adverse thermal event in the battery cell, according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0017] Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

[0018] Referring to FIG. **1**, a schematic view of a portion of an exemplary battery system **100** is illustrated. The battery system **100** is typically used to store electrical power and distribute the stored electrical power at a desired power output and a desired voltage output. In an example, the battery system **100** may be used in energy storage systems. In another example, the battery system **100** may supply electrical power to a moving machine or a stationary machine, such as, a work or construction machine.

[0019] The battery system **100** includes a battery cell **102**. In this disclosure, the battery cell **102** will be hereinafter interchangeably referred to as 'cell **102**'. In the illustrated embodiment of FIG. **1**, the cell **102** is embodied as a lithium-ion battery cell. Alternatively, the cell **102** may include any other type of battery cell, such as, a lead-acid battery cell, a nickel metal hydride battery cell, and so on. Further, for illustrative purposes, the battery system **100** is shown to have a single cell **102** in FIG. **1**. However, the battery system **100** may include multiple battery cells, similar to the cell **102**, that may be arranged in series, in parallel, or in a combination of parallel and series, without limiting the scope of the present disclosure.

[0020] The cell **102** includes a housing **104**. The housing **104** includes a number of walls **106** that define an outer surface **110** of the housing **104**. Further, an enclosed space (not shown) is defined within the number of walls **106**. The cell **102** also includes a cell unit (not shown) disposed within the enclosed space of the housing **104**. The cell unit may include an anode, a cathode, and an electrolyte disposed between the anode and the cathode. In some examples, the anode may be made of graphite into which lithium can be incorporated. The cathode may be made of lithium cobalt (III) oxide ($LiCoO_2$), lithium-nickel-manganese-cobalt oxides, and other materials known to a person having ordinary skill in the art. The electrolyte may include a lithium salt dissolved in a specific solvent for example, ethylene carbonate (EC), diethyl carbonate (DEC), dimethyl carbonate (DMC), propylene carbonate (PC), or the like. In an example, during discharging of the cell **102**, lithium may be oxidized at the anode and may be migrated through the electrolyte towards the cathode. Conversely, during charging of the cell **102**, the reverse process may take place.

[0021] In some examples, the cell **102** may be designed to trigger an endothermic reaction in the active material, for example, in the anode, the cathode, or the electrolyte arranged between them, in response to an undesired adverse thermal event. It should be noted that construction and composition details of the cell **102** as mentioned herein are exemplary in nature, and the cell **102** may include any other construction and cell composition.

[0022] The battery system **100** also includes a sensor **200** coupled to the outer surface **110** of the housing **104** of the cell **102**. In use, the sensor **200** may be placed adjacent to a region of the cell **102** that is visible in an event that the battery system **100** is opened. For example, the sensor **200** may be placed adjacent to a top rim of the cell **102**. The sensor **200** may be placed such that it may be easy to access.

[0023] The sensor **200** determines an adverse thermal event in the cell **102**. The adverse thermal event in the cell **102** may include an overheating event, a fire originating from the cell **102**, or a thermal runaway event, without any limitations. The thermal runaway event is a phenomenon in which a particular battery cell enters a self-heating state and can be an issue if a rechargeable battery cell is handled improperly, or if there are defects or faults in the battery cell.

[0024] In some examples, the cell **102** may be designed to operate in a temperature range of 60 to 75° C. As an example, adverse thermal events, such as the thermal runaway event, may occur in the cell **102** operating in a temperature range of 85 to 110° C. However, it is to be noted that values of an operating temperature of the cell **102** as disclosed herein are merely exemplary in nature. The specific operating temperatures of each cell **102** may vary based on various factors including, but not limited to, battery composition and cell chemistry.

[0025] Referring to FIG. **2**, a schematic of the battery system **100** including the sensor **200** is illustrated. The sensor **200** includes a deformable element **202**. The deformable element **202** is a heat sensitive element herein. The deformable element **202** is made of a shape-memory material (SMM) and has a pre-stressed shape S**1**. The SMM of the deformable element **202** is a shape-memory alloy (SMA). The shape-memory alloy may be an alloy made of one or more metallic materials or one or more polymers. In some examples, the SMA may include copper-aluminum-nickel alloy, nickel-titanium (NiTi) alloy, or an alloy based on zinc, copper, gold, and iron. In other examples, the SMM of the deformable element **202** is a shape-memory polymer. The shape-memory polymer may include thermoplastic or thermoset (covalently cross-linked) polymers, for example. It should be noted that the present disclosure is not limited by a type of the SMM.

[0026] In an embodiment, the deformable element **202** may be a thin film made of the SMM. Further, the deformable element **202** may be a strip, a membrane, or a micro machined element made of the SMM. In some examples, the deformable element **202** may include a spring element, such as, a coil spring, a leaf spring, a helical spring, and so on. It should be noted that a transition temperature of the SMM of the deformable element **202** may be selected or tuned based on a value of a predefined temperature threshold for the cell **102** (see FIG. **1**). The term “predefined temperature threshold” as used herein may refer to a temperature beyond which the cell **102** may be susceptible to one or more adverse thermal events. In an example, the predefined temperature threshold may lie in a range of 85 to 110° C. The range of the predefined temperature threshold may vary, for example, based on an electrical capacity of the cell **102**. In some cases, a material of the SMM may be chosen based on the predefined temperature threshold.

[0027] The deformable element **202** defines a first end **206** and a second end **208** distal to the first end **206**. Further, in the illustrated embodiment of FIG. **2**, the pre-stressed shape S**1** of the deformable element **202** is bent partway along a length thereof and defines an included angle A**1**. When the deformable element **202** is in the pre-stressed shape S**1**, the deformable element **202** has a first portion **218** defining the first end **206** and a second portion **220** defining the second end **208**. Thus, when the deformable element **202** is in the pre-stressed shape S**1**, the first portion **218** is angled or bent relative to the second portion **220**, such that the deformable element **202** is substantially V-shaped. Alternatively, the deformable element **202** may be U-shaped or arcuate, for example. It should be noted that the pre-stressed shape S**1** may have any other shape, based on specific requirements of an application. Further, when the deformable element **202** is in the pre-stressed shape S**1**, the first portion **218** has a length that is greater than a length of the second portion **220**.

[0028] The sensor **200** also includes a coupling structure **204** to couple the sensor **200** to the outer surface **110** (see FIG. **1**) of the housing **104** (see FIG. **1**). In some examples, the coupling structure **204** may be made of a polymer or a metal to suit specific requirement of an application. The coupling structure **204** may be in the form of a plastic strip, for example. The first end **206** of the deformable element **202** is coupled to the coupling structure **204**. Specifically, the first portion **218** of the deformable element **202** is coupled to the coupling structure **204**. In an example, the first portion **218** of the deformable element **202** may be welded to the coupling structure **204**. In other examples, the first portion **218** may be soldered, brazed, or coupled with the coupling structure **204** using any other coupling process known in the art.

[0029] In the illustrated embodiment of FIG. **2**, the coupling structure **204** is C-shaped. However, in other embodiments, the coupling structure **204** may be V-shaped, arcuate, or have any other shape depending on specific requirement of an application. In one example, the sensor **200** may include an adhesive layer (not shown herein). The adhesive layer may be disposed on the coupling

structure **204** to couple the sensor **200** to the outer surface **110** of the housing **104**.
[0030] The sensor **200** further includes a metallic fuse element **210** coupled to the coupling structure **204** and the second end **208** of the deformable element **202**. In an example, the fuse element **210** may be welded to the second portion **220** of the deformable element **202**. In other examples, the fuse element **210** may be soldered, brazed, or coupled with the second portion **220** of the deformable element **202** using any other coupling process known in the art. Further, the fuse element **210** may be a thin strip, a thin wire, or a thin filament, made of, for example, tin, lead, silver, copper, zinc, or aluminum. The fuse element **210** may be made of an alloy including one of, for example, copper, zinc, lead, tin, silver, or aluminum.
[0031] The sensor **200** includes a first electrode **212** coupled to one end **226** of the fuse element **210**. The sensor **200** also includes a second electrode **214** coupled to another end **228** of the fuse element **210**. In some cases, each of the first electrode **212** and the second electrode **214** may be made of a metallic material, such as, copper or any other conductive material. In this context, the first and second electrodes **212**, **214** allow connection of the fuse element **210** to a device, a circuit, or a controller for measuring an electrical resistance across the sensor **200**. The first and second electrodes **212**, **214** are connected to the fuse element **210** such that current is able to flow through the fuse element **210** from the first electrode **212** to the second electrode **214**, or from the second electrode **214** to the first electrode **212**. A current path is possible along the first electrode **212** through the fuse element **210** and the second electrode **214**, or vice versa.
[0032] Referring now to FIG. **3**, the deformable element **202** deforms to a memorized shape S**2** from the pre-stressed shape S**1** (see FIG. **2**) in response to the operating temperature of the cell **102** (see FIG. **1**) exceeding the predefined temperature threshold for the cell **102**.
[0033] The memorized shape S**2** of the deformable element **202** is different from the pre-stressed shape S**1** of the deformable element **202**. The memorized shape S**2** may be linear or curvilinear. In the illustrated embodiment of FIG. **3**, the memorized shape S**2** is curvilinear. Alternatively, the memorized shape S**2** may have any other shape, for example, the memorized shape S**2** may be spiral or helical, based on application attributes.
[0034] The deformable element **202** breaks the fuse element **210** of the sensor **200** based on a deformity of the deformable element **202** to the memorized shape S**2**. In other words, the deformable element **202** may curl to the memorized shape S**2** when the operating temperature of the cell **102** exceeds the predefined temperature threshold for the cell **102**, thereby snapping the fuse element **210**. The deformity of the deformable element **202** to the memorized shape S**2** is indicative of the adverse thermal event in the cell **102**. The adverse thermal event in the cell **102** is determined based on a visual inspection of the deformity of the deformable element **202** to the memorized shape S**2**. Specifically, the deformation of the deformable element **202** to the memorized shape S**2** is triggered as a response as soon as the operating temperature of the cell **102** exceeds the predefined temperature threshold, and is therefore visually indicative of, the adverse thermal event. Thus, service technicians may determine if the cell **102** has experienced the adverse thermal event based on the visual inspection of the deformable element **202**. Specifically, if the service technicians observe that the deformable element **202** has changed to the memorized shape S**2**, the personnel may conclude that the cell **102** has experienced at least one of the many types of adverse thermal events.
[0035] The battery system **100** further includes a controller **216**. In an example, the controller **216** may determine occurrence of the adverse thermal event in the cell **102** based on breaking of the fuse element **210** of the sensor **200**. Specifically, the first and second electrodes **212**, **214** are in communication with the controller **216**. The controller **216** measures an electrical resistance across the fuse element **210** of the sensor **200** to determine the adverse thermal event in the cell **102**.
[0036] The controller **216** includes one or more memories **222** to store information pertaining to the predefined temperature threshold of the cell **102**. The memories **222** may include any means of storing information, including a hard disk, an optical disk, a floppy disk, ROM (read only

memory), RAM (random access memory), PROM (programmable ROM), EEPROM (electrically erasable PROM), or other computer-readable memory media.

[0037] The controller **216** also includes one or more processors **224** communicably coupled to the one or more memories **222**. It should be noted that the one or more processors **224** may embody a single microprocessor or multiple microprocessors for receiving various input signals and generating output signals. Numerous commercially available microprocessors may perform the functions of the one or more processors **224**. Each processor **224** may further include a general processor, a central processing unit, an application specific integrated circuit (ASIC), a digital signal processor, a field programmable gate array (FPGA), a digital circuit, an analog circuit, a microcontroller, any other type of processor, or any combination thereof. Each processor **224** may include one or more components that may be operable to execute computer executable instructions or computer code that may be stored and retrieved from the one or more memories **222**.

[0038] Below the predefined temperature threshold, the electrical resistance across the fuse element **210** of the sensor **200** may have a predetermined threshold resistance. The predetermined threshold resistance may be stored in the memories **222** of the controller **216**. In an event that the sensor **200** is heated above the predefined temperature threshold, the electrical resistance across the fuse element **210** of the sensor **200** changes. Specifically, the electrical resistance across the fuse element **210** changes when the fuse element **210** breaks due to a transition of the deformable element **202** to the memorized shape S**2**. Further, if the electrical resistance measured across the fuse element **210** is above the predetermined threshold resistance, the controller **216** determines that the adverse thermal event has occurred in the cell **102**.

[0039] Referring now to FIG. **4**, a schematic view of a battery system **400** is illustrated, according to an embodiment of the present disclosure. The battery system **400** is substantially similar to the battery system **100** illustrated in FIGS. **1** to **3**, with common components being referred to by the same numerals. The battery system **400** has an array of sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** corresponding to a number of battery cells **102**, each of which is same as the cell **102** shown and explained in relation to FIG. **1**. Further, each sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416**, **418** is substantially similar in terms of construction, components, and functionality to the sensor **200** illustrated in FIGS. **1** to **3**.

[0040] FIG. **4** shows the sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** arranged in an array of rows and columns, allowing each sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** to be addressed by row-column.

[0041] A first electrode (not shown herein) of the first (top) row of each sensor **402**, **404** is connected to a first bus **420**. A first electrode (not shown herein) of the second row of each sensor **406**, **408** is connected to a second bus **422**. A first electrode (not shown herein) of the third row of each sensor **410**, **412** is connected to a third bus **424**. A first electrode (not shown herein) of the fourth row of each sensor **414**, **416** is connected to a fourth bus **426**.

[0042] Further, a second electrode (not shown herein) of the first (left hand) column of each sensor **402**, **406**, **410**, **414** is connected to a fifth bus **428**. A second electrode (not shown herein) of the second column of each sensor **404**, **408**, **412**, **416** is connected to a sixth bus **430**. The point at which each sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** is connected to the respective bus **420**, **422 424**, **426**, **428**, **430** is shown by a dot. In this way, each sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** can be addressed individually to measure its electrical resistance. For example, the first bus **420** and the fifth bus **428** may be used to measure the electrical resistance of the sensor **402**, and does not result in current flowing through other sensors **404**, **406**, **408**, **410**, **412**, **414**, **416**.

[0043] The bus **420**, **422 424**, **426**, **428**, **430** may be connected to corresponding sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** such that the electrical resistance measurement is made in the plane of the sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416**, or such that the electrical resistance measurement is made through the sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416**, or in some other configuration.

[0044] The example illustrated in FIG. **4** shows eight sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** and six buses **420**, **422 424**, **426**, **428**, **430**. Alternatively, the battery system **400** may include any number of sensors and buses, based on an electrical capacity of the battery system **400**. Further, the sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** and the buses **420**, **422 424**, **426**, **428**, **430** may be arranged in a different configuration from that shown in FIG. **4**. Any arrangement of the buses **420**, **422 424**, **426**, **428**, **430** that allows the electrical resistance of each sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** to be measured individually is possible.
[0045] Below the predefined temperature threshold, the electrical resistance across a fuse element (not shown) of a corresponding sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may have a predetermined threshold resistance. In an event wherein one or more of the sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** are heated to above the predefined temperature threshold, the electrical resistance across the fuse element of the corresponding sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** changes. Further, the controller **216** (see FIG. **3**) is in communication with each of the buses **420**, **422 424**, **426**, **428**, **430**. In an event that the measured electrical resistance across the fuse element of one or more sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** is above the predetermined threshold resistance, the controller **216** determines that an adverse thermal event has occurred in the cell **102** of the corresponding sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416**.
[0046] In an example wherein the controller **216** determines that the adverse thermal event has occurred in one or more of the battery cells **102**, a notification may be provided to a user of the battery system **400**. The notification may be sent to a user interface (not shown), and may include an electronic message or a wireless message, turning-on of a light or buzzer, or any other notification. The notification may be visual, audible, electronic, wireless, or otherwise.
[0047] It is to be understood that individual features shown or described for one embodiment may be combined with individual features shown or described for another embodiment. The above described implementation does not in any way limit the scope of the present disclosure. Therefore, it is to be understood although some features are shown or described to illustrate the use of the present disclosure in the context of functional segments, such features may be omitted from the scope of the present disclosure without departing from the spirit of the present disclosure as defined in the appended claims.
Industrial Applicability
[0048] The present disclosure describes the battery system **100**, **400** including the sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** to determine the adverse thermal event in the cell **102**. As described above, the sensor **200** includes the deformable element **202** that deforms to the memorized shape S**2** from the pre-stressed shape S**1** in response to the operating temperature of the cell **102** exceeding the predefined temperature threshold for the cell **102**.
[0049] In this manner, it would be possible for service technicians to identify and locate battery cells **102** in which the operating temperature has exceeded the predefined temperature threshold. For example, the sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may be used to determine whether one or more battery cells **102** have exceeded the operating temperature at which a separator is configured to disable the cell **102**, so that any disabled cell **102** may be removed and replaced. In an example, the sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may be used to determine whether the cell **102** has exceeded the predefined temperature threshold at which issues, such as, thermal runaway are known to arise. This may allow timely replacement of the cell **102**.
[0050] In an example, the sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may be visually inspected to determine the adverse thermal event in the cell **102**. In another example, the controller **216** may be used to measure the electrical resistance across the one or more sensors **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** to determine the adverse thermal event in the cell **102**. In some examples, the electrical resistance may be measured by the controller **216** in a sequential manner to identify failed or disabled cells **102**. Incorporation of the sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may improve safety of the cell **102** and may also reduce the time required to determine

adverse thermal events, especially in battery systems that include multiple battery cells arranged in a parallel configuration.

[0051] The sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may be cost-effective and may be retrofitted in existing battery systems. The sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may be simple in construction and may embody a compact sticker that can be easily affixed to the housing **104** of the cell **102**.

[0052] The sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may improve battery management system estimation of the battery system **100**, **400**. For example, the sensor **200** may allow a more accurate estimation of various parameters associated with the cell **102** by analyzing the battery cell-level information such as voltage, temperature and current. Further, the sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may improve reliability and serviceability of the cell **102** by aiding in determining the failure of one or more battery cells **102**.

[0053] Referring to FIG. **5**, a method **500** for determining the adverse thermal event in the cell **102** is illustrated. With reference to FIGS. **1** to **3** and FIG. **5**, at step **502**, the sensor **200** including the deformable element **202** made of the shape-memory material (SMM) is coupled to the outer surface **110** of the housing **104** of the cell **102**. The deformable element **202** has the pre-stressed shape S**1**.

[0054] At step **504**, the deformable element **202** is deformed to the memorized shape S**2** from the pre-stressed shape S**1** when the operating temperature of the cell **102** exceeds the predefined temperature threshold for the cell **102**. The memorized shape S**2** of the deformable element **202** is different from the pre-stressed shape S**1** of the deformable element **202**. At step **506**, the adverse thermal event in the cell **102** is indicated based on the deformity of the deformable element **202** to the memorized shape S**2**.

[0055] The method **500** further includes a step (not shown) of determining the adverse thermal event in the cell **102** based on the visual inspection of the deformity of the deformable element **202** to the memorized shape S**2**.

[0056] The method **500** further includes a step (not shown) of coupling the sensor **200** to the outer surface **110** of the housing **104** using the coupling structure **204** of the sensor **200**. The first end **206** of the deformable element **202** is coupled to the coupling structure **204**.

[0057] The method **500** further includes a step (not shown) of breaking, by the deformable element **202**, a metallic fuse element **210** of the sensor **200** based on the deformity of the deformable element **202** to the memorized shape S**2**. The fuse element **210** is coupled to the coupling structure **204** and the second end **208** of the deformable element **202**.

[0058] The method **500** also includes a step (not shown) of communicably coupling the first and second electrodes **212**, **214** of the sensor **200** with the controller **216**. The first electrode **212** is coupled to one end **226** of the fuse element **210** of the sensor **200** and the second electrode **214** is coupled to another end **228** of the fuse element **210**. The method **500** further includes a step (not shown) of measuring, by the controller **216**, the electrical resistance across the fuse element **210** of the sensor **200** to determine the adverse thermal event in the cell **102**.

[0059] While aspects of the present disclosure have been particularly shown and described with reference to the embodiments above, it will be understood by those skilled in the art that various additional embodiments may be contemplated by the modification of the disclosed work machine, systems and methods without departing from the spirit and scope of the disclosure. Such embodiments should be understood to fall within the scope of the present disclosure as determined based upon the claims and any equivalents thereof.

Claims

1. A battery system comprising: a battery cell including a housing, the housing including a plurality of walls that define an outer surface of the housing; and a sensor coupled to the outer surface of the housing and configured to determine an adverse thermal event in the battery cell, wherein: the sensor includes a deformable element made of a shape-memory material (SMM) and has a pre-stressed shape, the deformable element is adapted to deform to a memorized shape from the pre-stressed shape in response to an operating temperature of the battery cell exceeding a predefined temperature threshold for the battery cell, the memorized shape of the deformable element is different from the pre-stressed shape of the deformable element, and a deformity of the deformable element to the memorized shape is indicative of the adverse thermal event in the battery cell.

2. The battery system of claim 1, wherein the adverse thermal event in the battery cell is determined based on a visual inspection of the deformity of the deformable element to the memorized shape.

3. The battery system of claim 1, wherein the pre-stressed shape of the deformable element is bent partway along a length thereof and defines an included angle.

4. The battery system of claim 1, wherein the memorized shape is linear or curvilinear.

5. The battery system of claim 1, wherein the sensor includes: a coupling structure to couple the sensor to the outer surface of the housing, wherein a first end of the deformable element is coupled to the coupling structure; a metallic fuse element coupled to the coupling structure and a second end of the deformable element; a first electrode coupled to one end of the fuse element; and a second electrode coupled to another end of the fuse element.

6. The battery system of claim 5, wherein the deformable element is adapted to break the fuse element of the sensor based on the deformity of the deformable element to the memorized shape.

7. The battery system of claim 5 further comprising a controller, wherein the first and second electrodes are in communication with the controller, and wherein the controller is configured to measure an electrical resistance across the fuse element of the sensor to determine the adverse thermal event in the battery cell.

8. The battery system of claim 1, wherein the SMM of the deformable element is a shape-memory alloy (SMA).

9. The battery system of claim 1, wherein the adverse thermal event in the battery cell includes one of an overheating event, a fire originating from the battery cell, and a thermal runaway event.

10. A sensor for determining an adverse thermal event in a battery cell, the sensor comprising: a deformable element made of a shape-memory material (SMM) and has a pre-stressed shape, wherein: the deformable element is adapted to deform to a memorized shape from the pre-stressed shape in response to an operating temperature of the battery cell exceeding a predefined temperature threshold for the battery cell, the memorized shape of the deformable element is different from the pre-stressed shape of the deformable element, and a deformity of the deformable element to the memorized shape is indicative of the adverse thermal event in the battery cell.

11. The sensor of claim 10, wherein the adverse thermal event in the battery cell is determined based on a visual inspection of the deformity of the deformable element to the memorized shape.

12. The sensor of claim 10, wherein the pre-stressed shape of the deformable element is bent partway along a length thereof and defines an included angle, and wherein the memorized shape is linear or curvilinear.

13. The sensor of claim 10 further comprising: a coupling structure to couple the sensor to an outer surface of a housing of the battery cell, wherein a first end of the deformable element is coupled to the coupling structure; a metallic fuse element coupled to the coupling structure and a second end of the deformable element; a first electrode coupled to one end of the fuse element; and a second electrode coupled to another end of the fuse element.

14. The sensor of claim 13, wherein the deformable element is adapted to break the fuse element of the sensor based on the deformity of the deformable element to the memorized shape.

15. The sensor of claim 13, wherein the first and second electrodes are in communication with a controller, and wherein the controller is configured to measure an electrical resistance across the fuse element of the sensor to determine the adverse thermal event in the battery cell.

16. A method for determining an adverse thermal event in a battery cell, the method comprising:

coupling a sensor, including a deformable element made of a shape-memory material (SMM), to an outer surface of a housing of the battery cell, wherein the deformable element has a pre-stressed shape; deforming the deformable element to a memorized shape from the pre-stressed shape when an operating temperature of the battery cell exceeds a predefined temperature threshold for the battery cell, wherein the memorized shape of the deformable element is different from the pre-stressed shape of the deformable element; and indicating the adverse thermal event in the battery cell based on a deformity of the deformable element to the memorized shape.

17. The method of claim 16 further comprising determining the adverse thermal event in the battery cell based on a visual inspection of the deformity of the deformable element to the memorized shape.

18. The method of claim 16 further comprising: coupling the sensor to the outer surface of the housing using a coupling structure of the sensor, wherein a first end of the deformable element is coupled to the coupling structure.

19. The method of claim 18 further comprising: breaking, by the deformable element, a metallic fuse element of the sensor based on the deformity of the deformable element to the memorized shape, wherein the fuse element is coupled to the coupling structure and a second end of the deformable element.

20. The method of claim 19 further comprising: communicably coupling, the first and second electrodes of the sensor with a controller, wherein the first electrode is coupled to one end of the fuse element of the sensor and the second electrode is coupled to another end of the fuse element; and measuring, by the controller, an electrical resistance across the fuse element of the sensor to determine the adverse thermal event in the battery cell.
