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(54) SENSOR AND METHOD FOR INDICATING ADVERSE THERMAL EVENT IN A CELL OF A BATTERY SYSTEM

(71) Applicant: **Caterpillar Inc.**, Peoria, IL (US)

(72) Inventors: **Siddartha Saikia**, Chennai (IN); **Luvkush Kumar**, Mathura (IN)

(73) Assignee: **Caterpillar Inc.**, Peoria, IL (US)

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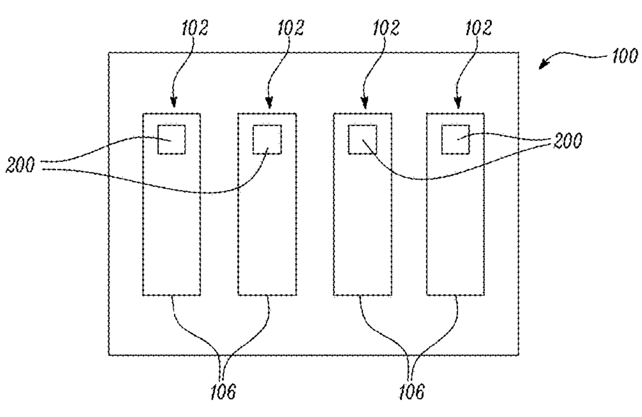
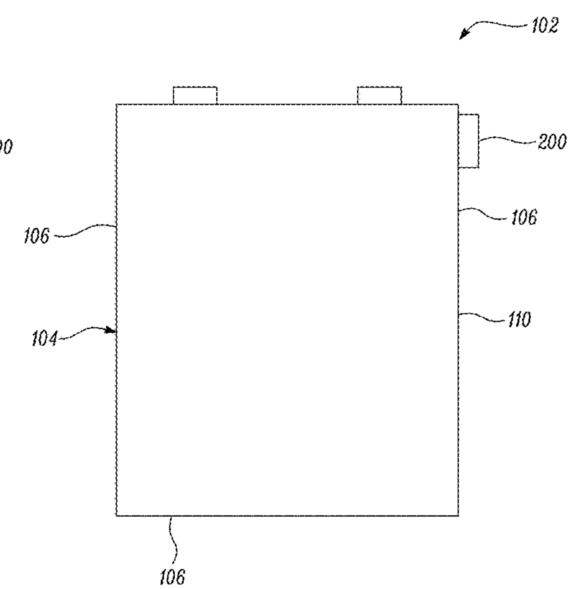
(57) **ABSTRACT**

A battery system includes a cell. The cell includes a including a housing. The housing includes a plurality of walls that define an outer surface of the housing. The housing also includes a sensor coupled to the outer surface of the housing and configured to indicate an adverse thermal event in the 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 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 from the pre-stressed shape to the memorized shape is indicative of the adverse thermal event in the cell.





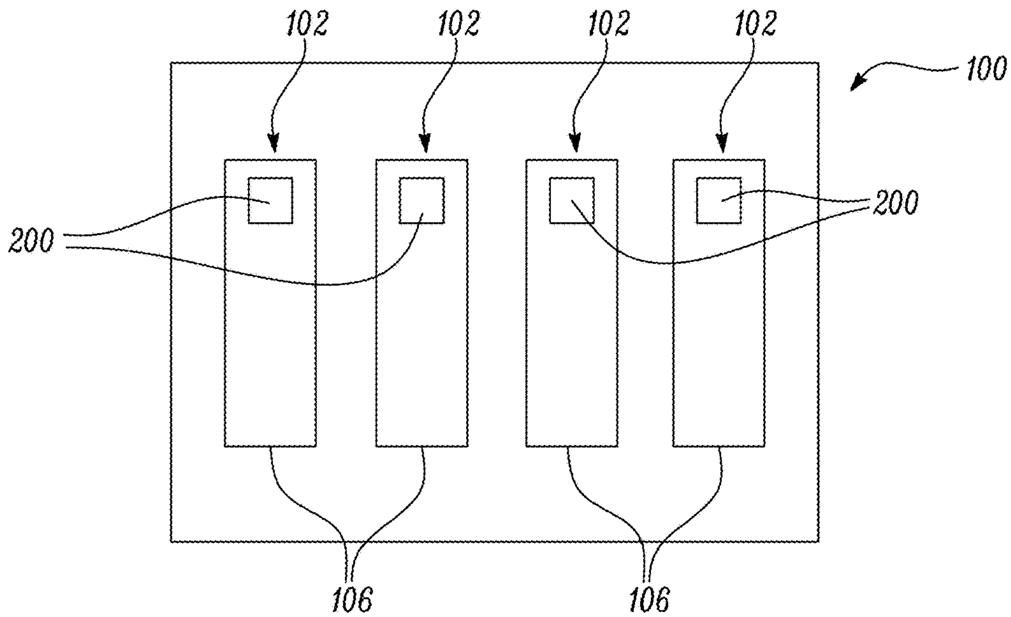


FIG. 1A

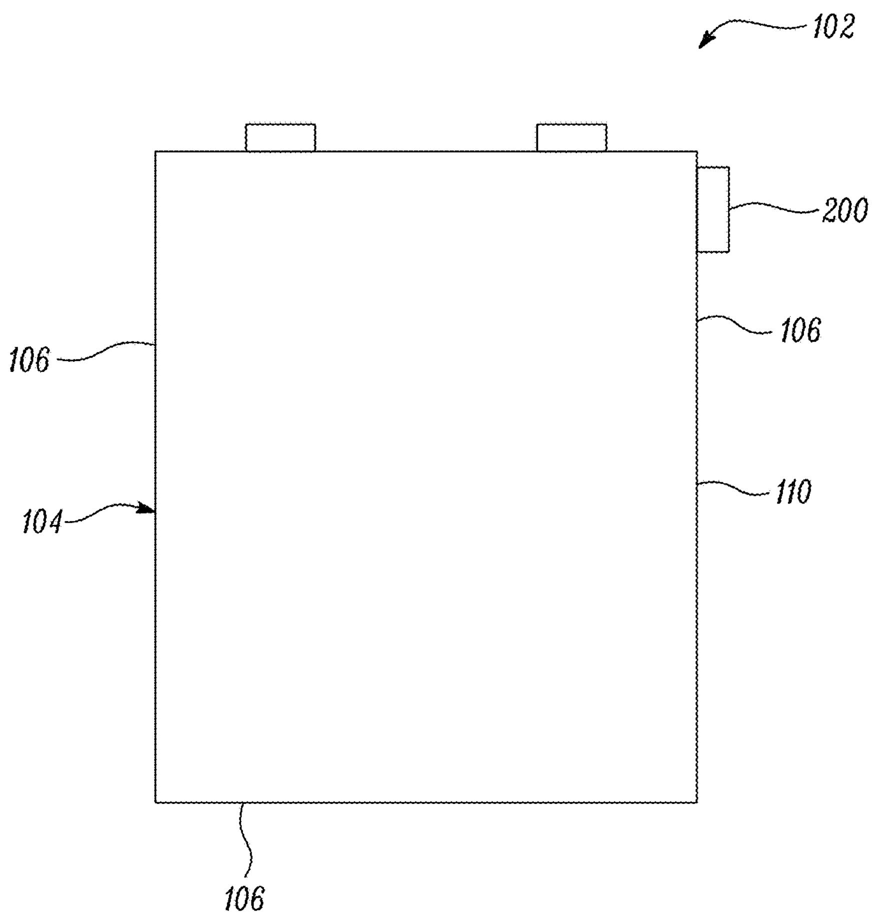


FIG. 1B

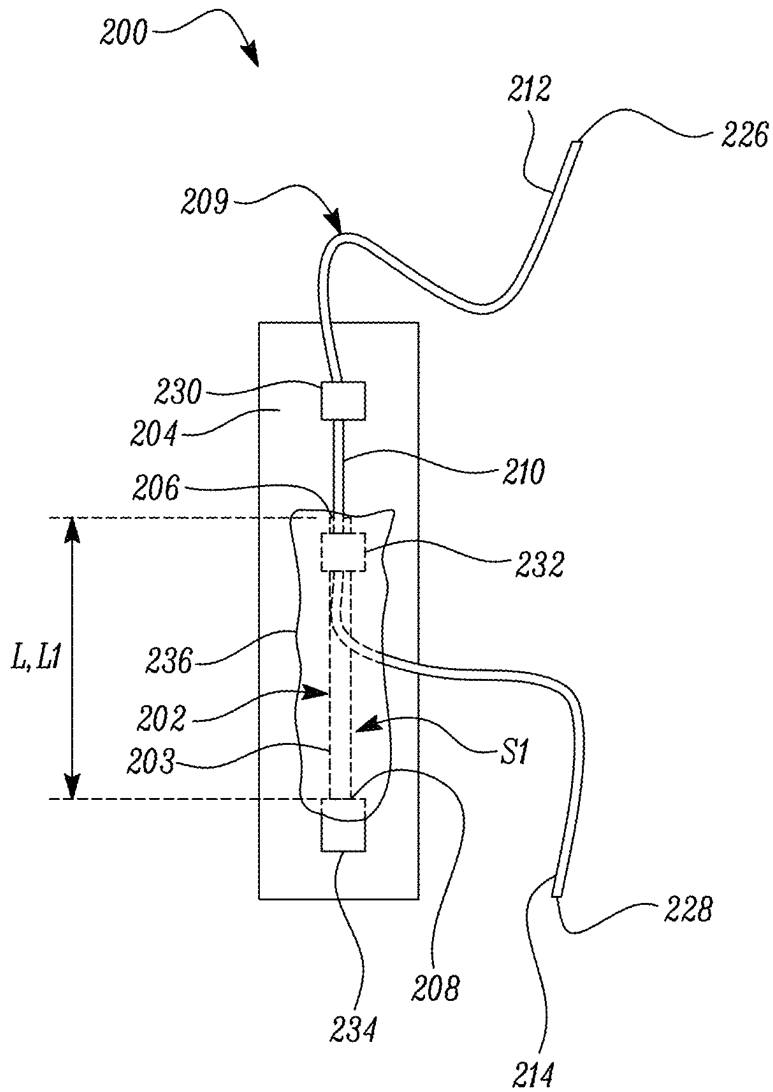

200
212
226
209
230
204
210
206
232
L, L1
236
202
S1
203
228
208
234
214

FIG. 2

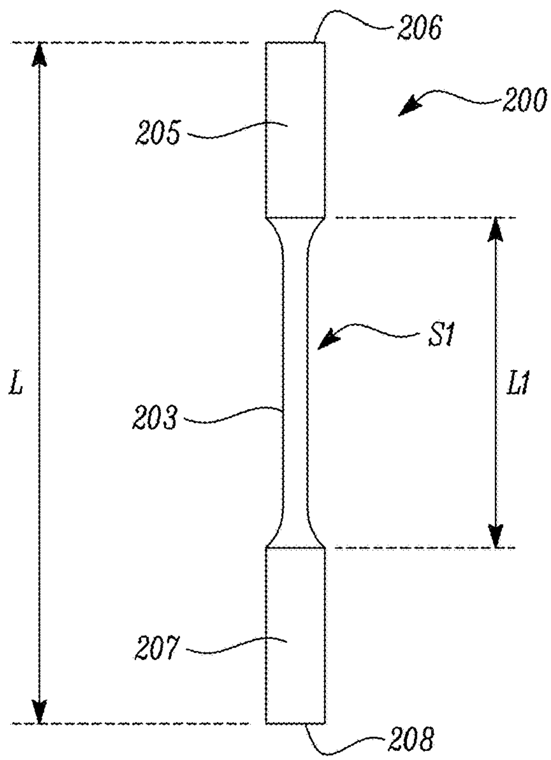


FIG. 3A

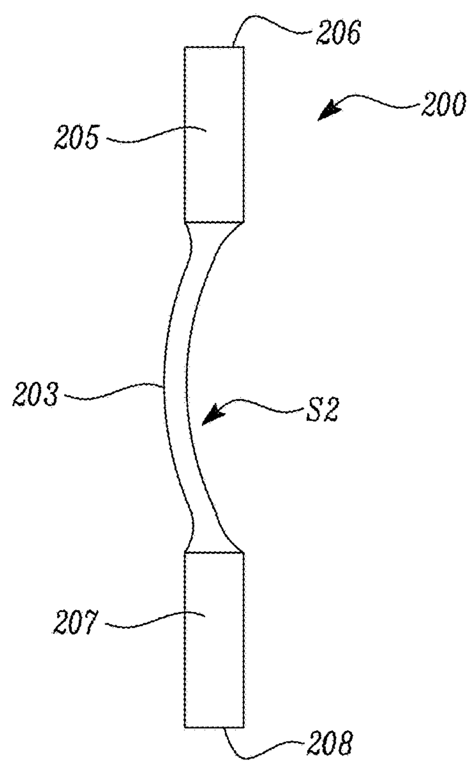


FIG. 3B

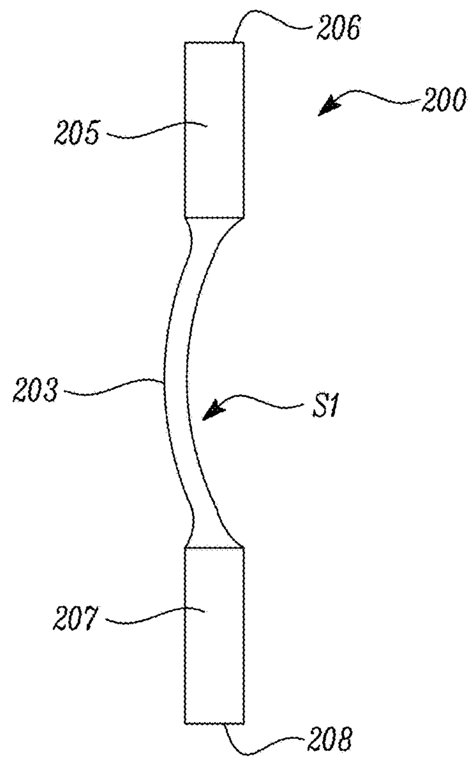


FIG. 3C

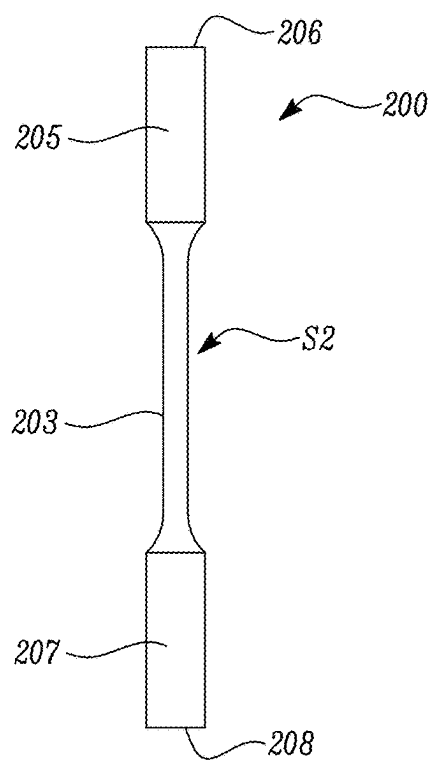


FIG. 3D

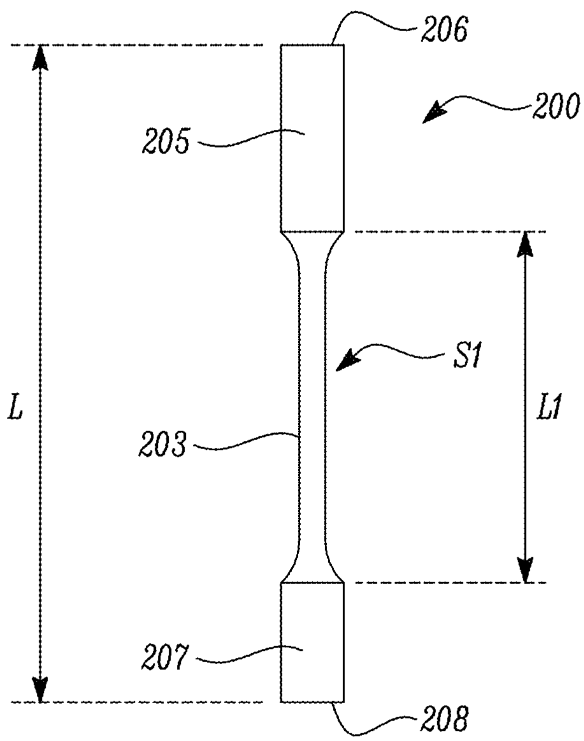


FIG. 3E

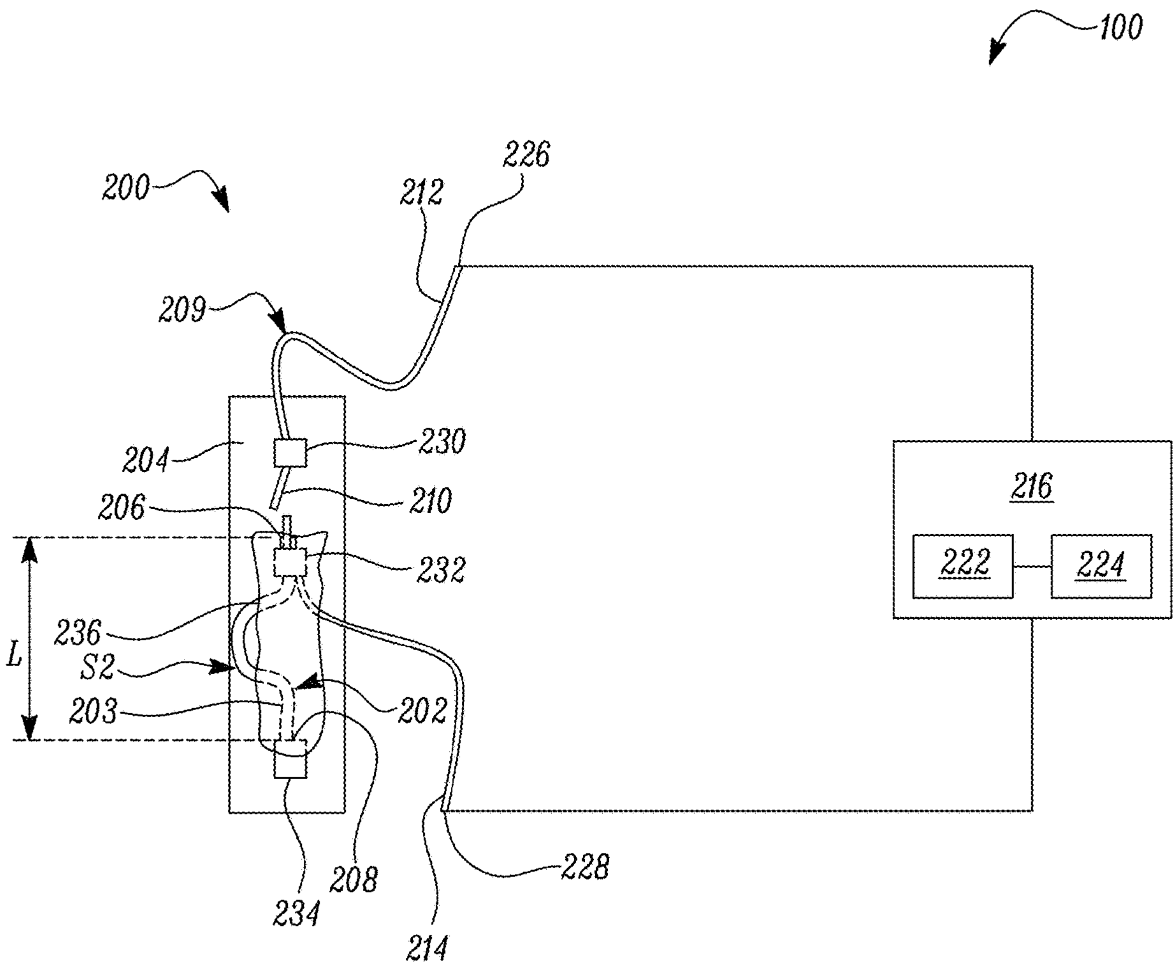

100
200
226
212
209
204
230
206
210
232
236
L
S2
203
202
234
208
214
228
216
222
224

FIG. 4

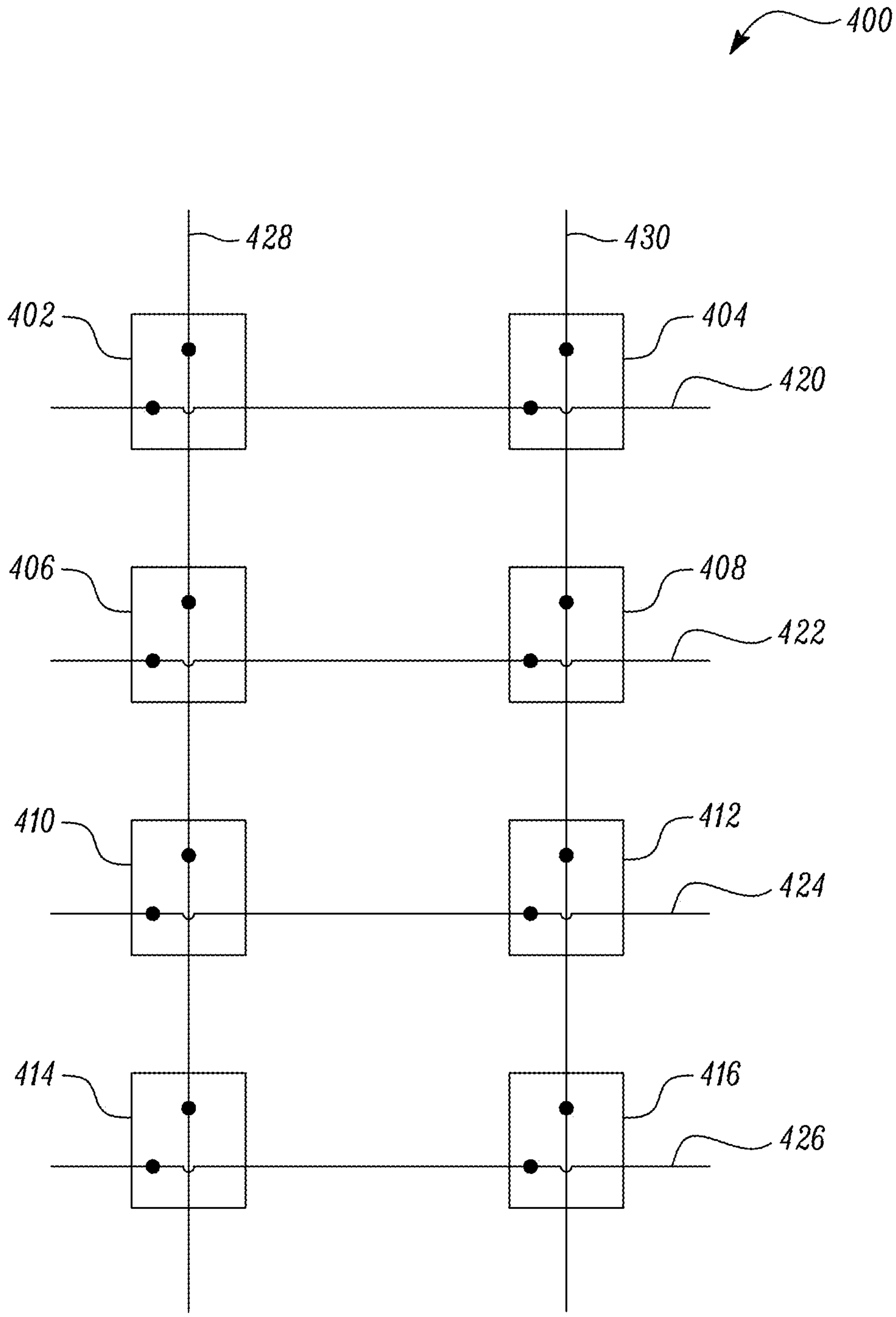


FIG. 5

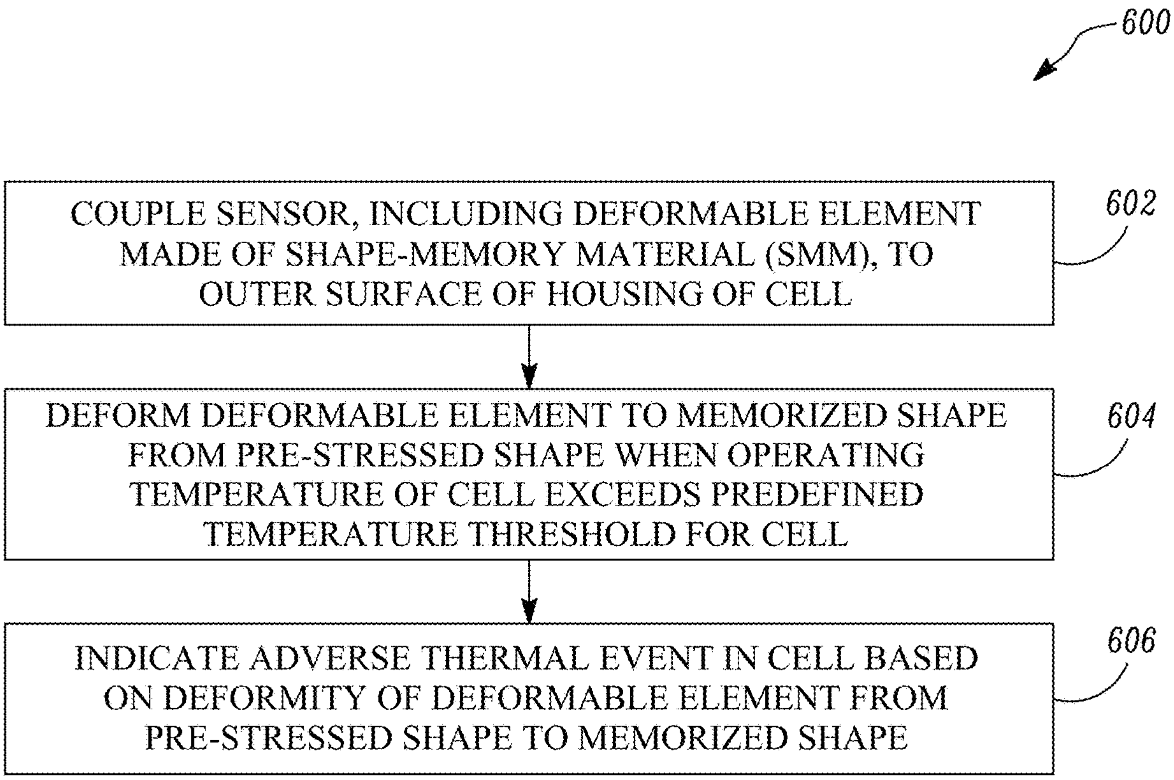

600
COUPLE SENSOR, INCLUDING DEFORMABLE ELEMENT MADE OF SHAPE-MEMORY MATERIAL (SMM), TO OUTER SURFACE OF HOUSING OF CELL
602
DEFORM DEFORMABLE ELEMENT TO MEMORIZED SHAPE FROM PRE-STRESSED SHAPE WHEN OPERATING TEMPERATURE OF CELL EXCEEDS PREDEFINED TEMPERATURE THRESHOLD FOR CELL
604
INDICATE ADVERSE THERMAL EVENT IN CELL BASED ON DEFORMITY OF DEFORMABLE ELEMENT FROM PRE-STRESSED SHAPE TO MEMORIZED SHAPE
606

FIG. 6

SENSOR AND METHOD FOR INDICATING ADVERSE THERMAL EVENT IN A CELL OF A BATTERY SYSTEM

CROSS-REFERENCE TO PRIOR APPLICATIONS

[0001] This application is a Continuation in part of U.S. Ser. No. 18/442,140, filed Feb. 15, 2024, the contents of which are incorporated by reference.

TECHNICAL FIELD

[0002] The present disclosure relates to a battery system including a cell, a sensor for indicating an adverse thermal event in the cell, and a method for indicating the adverse thermal event in the cell.

BACKGROUND

[0003] 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 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 an overheating event, a fire originating from one or more cells, and/or a thermal runaway event.

[0004] 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 including 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.

[0005] It is also known to identify disabled 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.

[0006] 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.

[0007] 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 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 cells.

[0008] 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 to prevent thermal propagation between cells. Thus, the shape memory element is used to contain or mitigate thermal propagation in cells. The shape memory element described in the ’089 reference directly mitigates risk associated with continued operation of the cell but, however, does so without providing an indication as to the occurrence of the adverse thermal event itself. Further, typically 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.

SUMMARY

[0009] In an aspect of the present disclosure, a battery system is disclosed. The disclosed battery system includes a cell. The cell includes a housing. The housing includes a plurality of walls that define an outer surface of the housing. The housing also includes a sensor coupled to the outer surface of the housing and configured to indicate an adverse thermal event in the 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 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 from the pre-stressed shape to the memorized shape is indicative of the adverse thermal event in the cell.

[0010] In another aspect of the present disclosure, a sensor for indicating an adverse thermal event in a cell is disclosed. The disclosed sensor includes a deformable element made of a shape-memory material (SMM) and has a pre- stressed shape. The deformable element is formed as a wire. 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 from the pre-stressed shape to the memorized shape is indicative of the adverse thermal event in the cell.

[0011] In yet another aspect of the present disclosure, a method for indicating an adverse thermal event in a cell is

disclosed. The disclosed 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 cell. At least a segment of the deformable element is formed as a wire. 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 cell exceeds 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. The method further includes indicating the adverse thermal event in the cell based on a deformity of the deformable element from the pre-stressed shape to the memorized shape.

[0012] Other features and aspects of this disclosure will be apparent from the following description and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1**A is a schematic view of a battery system, according to an embodiment of the present disclosure;

[0014] FIG. **1**B is a schematic view of a cell including a sensor, according to an embodiment of the present disclosure;

[0015] FIG. **2** is a schematic view of the sensor for the battery system of FIG. **1**B, wherein a deformable element of the sensor is in a pre-stressed shape;

[0016] FIG. **3**A is a schematic view of an exemplary deformable element in a pre-stressed shape, according to an embodiment of the present disclosure;

[0017] FIG. **3**B is a schematic view of the deformable element of FIG. **3**A in a memorized shape;

[0018] FIG. **3**C is a schematic view of an exemplary deformable element in a pre-stressed shape, according to another embodiment of the present disclosure;

[0019] FIG. **3**D is a schematic view of the deformable element of FIG. **3**C in a memorized shape;

[0020] FIG. **3**E is a schematic view of another exemplary deformable element, according to yet another embodiment of the present disclosure;

[0021] FIG. **4** is a schematic view of the deformable element of the sensor of FIG. **2** in a memorized shape;

[0022] FIG. **5** is a schematic view of an array of sensors to indicate adverse thermal events in corresponding cells of a battery system, according to an embodiment of the present disclosure; and

[0023] FIG. **6** is a flowchart of a method for indicating an adverse thermal event in the cell, according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0024] Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

[0025] Referring to FIG. **1**A, a schematic view 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.

[0026] The battery system **100** includes a number of cells **102**. The number of cells **102** may be arranged in series, in parallel, or in a combination of parallel and series, without limiting the scope of the present disclosure. Four cells **102** are shown in FIG. **1** as an example. In the illustrated embodiment of FIG. **1**A, the cells **102** are embodied as a lithium-ion cell. Alternatively, the cell **102** may include any other type of cell such as a lead-acid cell, a nickel metal hydride cell, or other types of cells known in the art. The cell **102** includes a housing **104**. Each cell **102** includes a respective housing **104** that mechanically separates the individual cells **102** from one another.

[0027] Referring now to FIG. **1**B, a schematic view of a single cell **102** is illustrated. 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.

[0028] In some examples, the cell **102** may, during operation, 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 the type, construction, and composition details of the cell **102** as mentioned herein are exemplary in nature, and the cell **102** may be of any known type and include any other construction and cell composition known to persons skilled in the art.

[0029] 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.

[0030] The sensor **200** is configured to indicate an adverse thermal event, if any, in the cell **102**. Stated differently, if the cell **102** of the battery system **100** experiences any adverse event, especially, a thermally adverse event e.g., overheating beyond a specific threshold, then the sensor **200** is configured to detect such event and provide indication, visually or through other means, of the event. The adverse thermal event in the cell **102** may include an overheating event, a fire originating from one or more cells **102** or a thermal runaway event without any limitations. The thermal runaway event is a phenomenon in which a particular cell enters a self-heating mode.

[0031] In one example, the cell **102** may be designed to operate in a temperature range of 60° C. (C) to 75° C. However, an adverse thermal event such as the thermal runaway event may occur in the cell **102** when the cell **102** operates in a temperature range of 80° C. to 110° C. which exceeds the recommended design and standard operating conditions of 60° C. to 75° C. It is to be noted that the operating temperature values of 60-75° C. for the cell **102** disclosed herein is merely exemplary in nature. The specific operating temperatures of each cell **102** may vary from one application to another based on various factors including, but not limited to, battery composition and cell chemistry.

[0032] 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 pre-stressed shape S**1** is a natural resting shape of the deformable element **202** that is retained by the deformable element **202** at ambient temperature and pressure conditions. In some examples, the pre-stressed shape S**1** is retained when the cell **102** (see FIG. **1**B) is operating within a predefined temperature threshold for the cell **102**. The term "shape" as used herein relates to a form, a posture, or an orientation of an element defined along a length of the corresponding element. Further, the term "shape" does not include a cross-section of the corresponding element. The term "predefined temperature threshold" as used herein may refer to a temperature above which the cell **102** may be susceptible to one or more adverse thermal events. In embodiments herein, it is envisioned that the predefined temperature threshold is greater than ambient temperature conditions and may lie in a range of 80° C. to 110° C. The ambient temperature conditions include conditions in which the cell **102** is likely to be stored or operated during a charge and/or discharge event/cycle.

[0033] In an example, the predefined temperature threshold may lie in a range of 85° C. to 90° C., 90° C. to 95° C., or 95° C. to 100° C. The range of the predefined temperature threshold may vary from one application to another depending on a type of the cell **102** and, for example, based on a maximum state of charge of the cell **102** or cell capacity.

[0034] 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, for example, thermoplastic or thermoset (covalently cross-linked) polymers. It should be noted that the present disclosure is not limited by a type of alloy used to make the SMM. Rather, the present disclosure is applicable regardless of the type or nature of the alloys that are currently known in the art as well as those that may be developed in the future and used in producing/manufacturing the SMM for use, in part, as the sensor **200** of the present disclosure.

[0035] The deformable element **202** defines a first end **206** and a second end **208**. The deformable element **202** defines a length L between the first and second ends **206**, **208**. The second end **208** is defined opposite the first end **206**. At least a segment of the deformable element **202** is formed as a wire **203**. In the illustrated embodiment of FIG. **2**, the deformable element **202** is formed as the wire **203**. In other words, the wire **203** extends from the first end **206** to the second end **208**. It should be noted that the wire **203** of the deformable element **202** transforms from the pre-stressed shape S**1** to a memorized shape S**2** (shown in FIG. **4**). Further, the wire **203** defines a length L**1**. In the illustrated embodiment of FIG. **2**, the length L is equal to the length L**1**, as the entire deformable element **202** is formed as the wire **203**.

[0036] Further, in the illustrated embodiment of FIG. **2**, the pre-stressed shape S**1** of the deformable element **202** is linear. Alternatively, the deformable element **202** may have any other shape e.g., curved, angled, or curvilinear, based on specific requirements of an application. It should be noted that, in the present disclosure, the term "the pre-stressed shape S**1** of the deformable element **202**" relates to the pre-stressed shape S**1** of the wire **203** which is made of the SMM. Further, the term "the memorized shape S**2** of the deformable element **202**" relates to the memorized shape S**2** of the wire **203** which is made of the SMM. The wire **203** consists of or is composed of a single strand or multiple strands. Further, the wire **203** may have an elliptical cross-section, a circular cross-section, a square cross-section, a rectangular cross-section, or any other cross section known to persons skilled in the art. It should be noted that the present disclosure is not limited to a type of the wire **203**, dimensions of the wire **203**, or a cross-section of the wire **203**.

[0037] Referring again to FIG. **2**, 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 the predefined temperature threshold for the cell **102**. The term "transition temperature" as used herein is a temperature at which the deformable element **202** transitions from the pre-stressed shape S**1** to the memorized shape S**2**. Further, the length L of the deformable element **202**, the cross-section of the deformable element **202**, and/or other parameters of the wire **203** or the deformable element **202** may be selected to achieve the deformation of the deformable element **202** at the transition temperature. In some cases, a material of the SMM may be chosen based on the predefined temperature threshold for the cell **102**. In some examples, the transition temperature for the SMM may lie between 85° C. to 90° C., 90° C. to 95° C., or 95° C. to 100° C., without limiting the scope of the present disclosure.

[0038] In some examples, as shown in FIG. **3**A, the wire **203** is disposed midway along the length L of the deformable element **202**. The length LI of the wire **203** is less than the length L of the deformable element **202**. In such examples, the deformable element **202** includes the wire **203**, a remaining portion **205**, and a remaining portion **207**. Further, the remaining portion **205** is equal to the remaining portion **207** as the wire **203** is disposed midway along the length L. In one example, the wire **203** and the remaining portions **205**, **207** may be made of the same material. In another example, the wire **203** and the remaining portions **205**, **207** may be made of different materials. Furthermore, when the deformable element **202** is in the pre- stressed shape S**1**, the wire **203** is co-axial or in alignment with a remaining portion **205**, **207** of the deformable element **202**. In other embodiment, as shown in FIG. **3**C, when in the pre-stressed shape S**1**, the wire **203** may be bent away from the remaining portion **205**, **207** of the deformable element **202**. Further, as shown in FIG. **3**D, upon reaching the predefined temperature threshold, the wire **203** may bend towards and become co-axial with the remaining portions **205**, **207** of the deformable element **202**.

[0039] In another example, as shown in FIG. 3E, the wire **203** may be disposed partway along the length L of the deformable element **202**. In such examples, the remaining portion **205** and the remaining portion **207** are different in lengths as the wire **203** is disposed partway along the length L. The length L1 of the wire **203** is less than the length L of the deformable element **202**.

[0040] As shown in FIG. **4**, the sensor **200** also includes a substrate **204** to mechanically couple the sensor **200** to the outer surface **110** (see FIG. **1**B) of the housing **104** (see FIG. **1**B). The deformable element **202** is in contact with the substrate **204**. The substrate **204** is made from a thermally conductive material. In one example, the substrate **204** may be made of a metal. In another example, the substrate **204** may be made of an alloy. However, it is to be noted that a type of material used to form the substrate **204** may depend on specific requirement of an application.

[0041] In the illustrated embodiment of FIG. **2**, the substrate **204** is rectangular in shape. However, in other embodiments, the substrate **204** may have any other shape known to persons skilled in the art. Materials and form factor of the substrate **204** may be selected and the substrate **204** itself may be designed such that it would be configured to support various components of the sensor **200** including the deformable element **202** thereon. In one example, the remaining portions **205**, **207** (see FIGS. **3**A and **3**B) of the deformable element **202** may be provided with an adhesive layer e.g., adhesive tapes, adhesive coatings, or other adhesion means to adhere with the outer surface **110** of the housing **104** of the corresponding cell **102**.

[0042] The sensor **200** further includes a conductive wire **209** that contacts the deformable element **202**. In an example, the conductive wire **209** may be a thin, enameled wire. Further, the conductive wire **209** may be made of, for example, tin, lead, silver, copper, zinc, or aluminum. The conductive wire **209** may be made of an alloy including one or more of, for example, copper, zinc, lead, tin, silver, and aluminum.

[0043] When in use, a current path is established along the conductive wire **209**. The conductive wire **209** defines a fuse segment **210**, a first electrode **212**, and a second electrode **214**. The first electrode **212** is defined at one end **226** of the conductive wire **209**. The second electrode **214** is defined at an opposing end **228** of the conductive wire **209**. The first and second electrodes **212**, **214** help facilitate connection of the conductive wire **209** to a device, a circuit, or a controller for measuring an electrical resistance across the sensor **200**.

[0044] The sensor **200** further includes a first coupling element **230** to couple the conductive wire **209** with the substrate **204**. The first coupling element **230** may include a fastener. In some examples, the first coupling element **230** may include a stud formed from a thermoplastic material or a metal. Moreover, the sensor **200** includes a second coupling element **232** to couple the deformable element **202** with the conductive wire **209** at the first end **206** of the deformable element **202**. The second coupling element **232** may include a clamp. In some examples, the second coupling element **232** may include a clamp formed from a thermoplastic material or a metal. It should be noted that the second coupling element **232** is not coupled or anchored to the substrate **204**. The fuse segment **210** is defined between the first coupling element **230** and the second coupling element **232**. The fuse segment **210** is held taut between the first and second coupling elements **230**, **232**.

[0045] The sensor **200** further includes a third coupling element **234** to couple the deformable element **202** with the substrate **204** at the second end **208** of the deformable element **202**. The third coupling element **234** may include a fastener. In some examples, the third coupling element **234** may include a stud formed from a thermoplastic material or a metal.

[0046] The sensor **200** further includes a thermally conductive agent **236** disposed around the deformable element **202** to retain the deformable element **202** in contact with the substrate **204**. The thermally conductive agent **236** keeps the deformable element **202** close to the housing **104** (see FIG. **1**B). Moreover, the thermally conductive agent **236** allows heat, from the housing **104**, to reach the deformable element **202**. The thermally conductive agent **236** may completely enclose the deformable element **202** so that the deformable element **202** is in contact with the substrate **204**. In some examples, the thermally conductive agent **236** may also enclose the second coupling element **232**. Moreover, the thermally conductive agent **236** may also partially enclose the third coupling element **234**. The thermally conductive agent **236** includes a glue or paste that retains the deformable element **202** in contact with the substrate **204**. The thermally conductive agent **236** may include, for example, epoxy compounds.

[0047] Referring now to FIG. **4**, the deformable element **202** deforms to the memorized shape S2 from the pre-stressed shape S1 (see FIG. **2**) in response to the operating temperature of the cell **102** exceeding the predefined temperature threshold for the cell **102**. The memorized shape S2 of the deformable element **202** is different from the pre-stressed shape SI of the deformable element **202**. The memorized shape S2 may be a curvilinear shape, a hook shape, or a U-shape or any other shape known to persons skilled in the art. In the illustrated embodiment of FIG. **4**, the memorized shape S2 is the hook shape. Alternatively, the memorized shape S2 disclosed herein may include any other shape, for example, spiral or helical to suit specific requirements of an application. In some examples, as shown in FIGS. **3**A and **3**B, upon deforming to the memorized shape S2, the wire **203** may be misaligned relative to the remaining portion **205**, **207** of the deformable element **202**.

[0048] Referring again to FIG. **4**, as the conductive wire **209** and the wire **203** are held in tension, the conductive wire **209** breaks under any additional strain that is exerted by the wire **203** of the deformable element **202**, which causes the fuse segment **210** to break. Thus, the deformable element **202** breaks the fuse segment **210** based on a deformity of the deformable element **202** from the pre-stressed shape S1 to the memorized shape S2. In other words, the deformable element **202** may curl to the memorized shape S2 when the operating temperature of the cell **102** exceeds the predefined temperature threshold for the cell **102**, thereby snapping the conductive wire **209**.

[0049] The deformity of the deformable element **202** from the pre-stressed shape S1 to the memorized shape S2 is indicative of the adverse thermal event in the cell **102**. The adverse thermal event in the cell **102** is indicated based on a visual inspection of the deformity of the deformable element **202** i.e., when the deformable element **202** has deformed from the pre-stressed shape S1 and currently exhibits the memorized shape S2. As disclosed earlier herein, the deformation of the deformable element **202** to the memorized shape S2 is triggered as a response when 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**. Therefore, if the service technicians observe that the deformable element **202** has changed to the memorized shape S2, the personnel may conclude that the cell **102** has experienced at least one of the many types of adverse thermal events known to persons skilled in the art for at least potentially causing one or more types of current, or future, failures e.g., mechanical, such as, structural, chemical, electrical or all in respective ones of the cell(s) **102** or the overall battery system **400**.

[0050] The battery system **100** further includes a controller **216**. In an example, the controller **216** may indicate occurrence of the adverse thermal event in the cell **102** based on breaking of the conductive wire **209** of the sensor **200**. The first and second electrodes **212**, **214** are in communication with the controller **216**. The controller **216** measures an electrical resistance across the conductive wire **209** of the sensor **200** to indicate the adverse thermal event in the cell **102**.

[0051] 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 known to persons skilled in the art.

[0052] 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**.

[0053] Below the predefined temperature threshold, the electrical resistance across the conductive wire **209** 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 conductive wire **209** of the sensor **200** changes. The electrical resistance across the conductive wire **209** changes when the conductive wire **209** breaks due to a transition of the deformable element **202** to the memorized shape S2. Further, if the electrical resistance measured across the conductive wire **209** is above the predetermined threshold resistance, the controller **216** indicates that the adverse thermal event has occurred in the cell **102**.

[0054] Referring now to FIG. **5**, 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 cells **102**, each of which is same as the cell **102** shown and explained in relation to FIG. **1**B. Further, each sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416**, **418** is similar in terms of construction, components, and functionality to the sensor **200** illustrated in FIGS. **1** to **3**.

[0055] FIG. **5** 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.

[0056] 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**.

[0057] 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**.

[0058] 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.

[0059] The example illustrated in FIG. **5** 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. **5**. 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.

[0060] Below the predefined temperature threshold, the electrical resistance across a fuse segment (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 segment of the corresponding sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** changes. Further, the controller **216** (see FIG. **4**) 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 segment of one or more sensors **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** is above the predetermined threshold resistance, the controller **216** indicates that an adverse thermal event has occurred in the cell **102** of the corresponding sensor **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416**.

[0061] A technician or service personnel may physically conduct a visual inspection to identify the cells **102** in the battery system **100** that have experienced adverse thermal events. Alternatively, a notification may be provided. In an example wherein the controller **216** indicates that the adverse thermal event has occurred in one or more of the cells **102**, the 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.

[0062] It may be noted 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 as defined in the appended claims.

INDUSTRIAL APPLICABILITY

[0063] The present disclosure describes the battery system **100**, **400** including the sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** to indicate 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**. The deformable element **202** is formed as the wire **203** herein. Owing to a construction of the deformable element **202** as the wire **203**, as opposed to other forms, the wire **203** may be cost-effective and may reduce an overall cost of the sensor **200**. Further, as shape memory alloys are readily available in the form of wires, the SMM wire **203** can be manufactured easily from shape memory alloys. Moreover, Owing to the construction of the deformable element **202** as the wire **203**, as opposed to other forms, the sensor **200** described herein uses lesser quantity of the SMM wire **203**, which may further reduce the cost of the sensor **200**. The sensor **200** incorporating the SMM wire **203** as described herein is simple in construction and easy to manufacture.

[0064] The sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may allow service technicians to identify and locate 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 indicate whether one or more 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 indicate whether the cell **102** has exceeded the predefined temperature threshold at which issues, such as, thermal runaway is known to arise. This may allow timely replacement of the cell **102**.

[0065] In an example, the sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may be visually inspected to indicate 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 indicate 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 indicate adverse thermal events, especially in battery systems that include multiple cells arranged in a parallel configuration.

[0066] The sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may be retrofitted in existing battery systems. The sensor **200**, **402**, **404**, **406**, **408**, **410**, **412**, **414**, **416** may embody a compact sticker that can be easily affixed to the housing **104** of the cell **102**.

[0067] 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 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 cells **102**.

[0068] Referring to FIG. **6**, a method **600** for indicating the adverse thermal event in the cell **102** is illustrated. With reference to FIGS. **1** to **3** and FIG. **6**, at step **602**, 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**. At least the segment of the deformable element **202** is formed as the wire **203**. The deformable element **202** has the pre-stressed shape S**1**.

[0069] At step **604**, 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 **606**, the adverse thermal event in the cell **102** is indicated based on the deformity of the deformable element **202** from the pre- stressed shape S**1** to the memorized shape S**2**.

[0070] The method **600** further includes a step (not shown) of coupling the sensor **200** to the outer surface **110** of the housing **104** using the substrate **204** of the sensor **200**. The deformable element **202** is coupled to the substrate **204**.

[0071] The sensor **200** includes the conductive wire **209** that contacts the deformable element **202**. The conductive wire **209** defines the fuse segment **210**, the first electrode **212**, and the second electrode **214**. The method **600** further includes a step (not shown) of breaking, by the deformable element **202**, the fuse segment **210** based on the deformity of the deformable element **202** from the pre-stressed shape S**1** to the memorized shape S**2**.

[0072] The method **600** further includes a step (not shown) of indicating 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** or measuring, by the controller **216**, the electrical resistance across the fuse segment **210** to indicate the adverse thermal event in the cell **102**.

[0073] 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.

What is claimed is:

1. A battery system comprising:
a 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 indicate an adverse thermal event in the 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 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, and
a deformity of the deformable element from the pre-stressed shape to the memorized shape is indicative of the adverse thermal event in the cell.

2. The battery system of claim **1**, wherein at least a segment of the deformable element is formed as a wire.

3. The battery system of claim **2**, wherein the wire consists of or is composed of: a single strand or multiple strands.

4. The battery system of claim **2**, wherein the wire has one of an elliptical cross-section, a circular cross-section, a square cross-section, and a rectangular cross-section.

5. The battery system of claim **2**, wherein the wire is disposed midway along a length of the deformable element.

6. The battery system of claim **2**, wherein the wire is disposed partway along a length of the deformable element.

7. The battery system of claim **2**, wherein, upon deforming to the memorized shape, the wire is misaligned relative to a remaining portion of the deformable element.

8. The battery system of claim **1**, wherein the pre-stressed shape is a natural resting shape of the deformable element that is retained by the deformable element at ambient temperature and pressure conditions.

9. The battery system of claim **1**, wherein the predefined temperature threshold is greater than ambient temperature conditions and lies in a range of **80**° C. (C) to **110**° C.

10. The battery system of claim **9**, wherein the predefined temperature threshold lies in a range of 80° C. to 85° C., 85° C. to 90° C., 90° C. to 95° C., or 95° C. to 100° C.

11. A sensor for indicating an adverse thermal event in a 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 formed as a wire,
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, and
a deformity of the deformable element from the pre-stressed shape to the memorized shape is indicative of the adverse thermal event in the cell.

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

13. The sensor of claim **11**, wherein the memorized shape is a curvilinear shape, a hook shape, or a U-shape.

14. The sensor of claim **11**, wherein the sensor includes:
a substrate to mechanically couple the sensor to an outer surface of a housing of the cell, wherein the deformable element is in contact with the substrate;
a conductive wire that contacts the deformable element, wherein the conductive wire defines a fuse segment, a first electrode, and a second electrode, and wherein the deformable element is adapted to break the fuse segment based on the deformity of the deformable element to the memorized shape;
a first coupling element to couple the conductive wire with the substrate;
a second coupling element to couple the deformable element with the conductive wire at a first end of the deformable element, wherein the fuse segment is defined between the first coupling element and the second coupling element;
a third coupling element to couple the deformable element with the substrate at a second end of the deformable element, wherein the second end is defined opposite the first end; and
a thermally conductive agent disposed around the deformable element to retain the deformable element in contact with the substrate.

15. The sensor of claim **14** further comprising a controller, wherein the first electrode and the second electrode are in communication with the controller, and wherein the controller is configured to measure an electrical resistance across the fuse segment to indicate the adverse thermal event in the cell.

16. The sensor of claim **11**, wherein the SMM of the deformable element is a shape-memory alloy (SMA).

17. A method for indicating an adverse thermal event in a 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 cell, wherein at least a segment of the deformable element is formed as a wire, and 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 tem-

perature of the cell exceeds a predefined temperature threshold for the 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 cell based on a deformity of the deformable element from the pre-stressed shape to the memorized shape.

18. The method of claim **17** further comprising:

coupling the sensor to the outer surface of the housing using a substrate of the sensor, wherein the deformable element is coupled to the substrate.

19. The method of claim **17**, wherein the sensor includes a conductive wire that contacts the deformable element, and wherein the conductive wire defines a fuse segment, a first electrode, and a second electrode, the method further comprising:

breaking, by the deformable element, a fuse segment based on the deformity of the deformable element from the pre-stressed shape S**1** to the memorized shape.

20. The method of claim **18** further comprising:

indicating the adverse thermal event in the cell based on at least one of a visual inspection of the deformity of the deformable element to the memorized shape and measuring, by a controller, an electrical resistance across the fuse segment to indicate the adverse thermal event in the cell.

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