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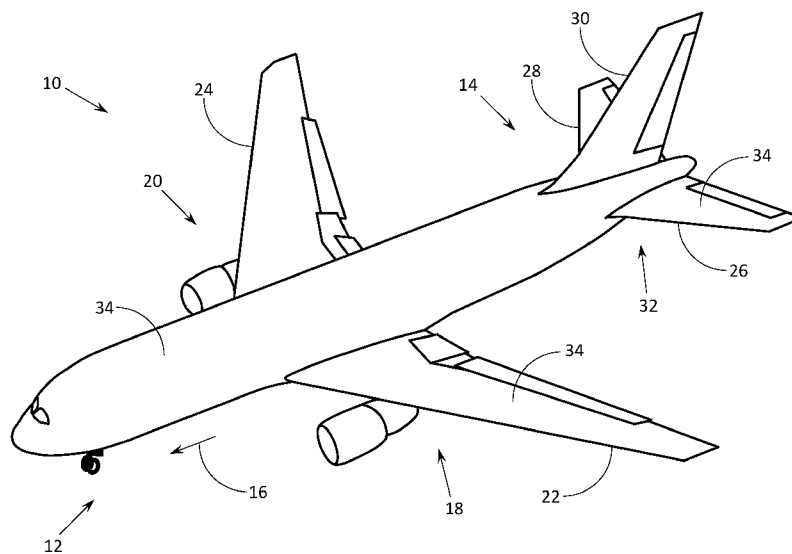


FIG. 1

(57) Abstract: A redundant heating system comprising a redundant CNT heat blanket, comprising at least one heating element located in a first layer and at least one heating element located in a second layer, the heating element located in the second layer registered at least in part with the heating element located in the first layer, each of the heating elements comprising a CNT structured layer defining an electrically conductive pathway having a first end and a second end and a first electrical termination electrically coupled to the first end and a second electrical termination electrically coupled to the second end; an elastomeric insulator located between and electrically isolating the heating element located in the first layer and the heating element located in the second layer; and an elastomeric outer covering encasing both the heating element located in the first layer and the heating element located in the second layer.



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REDUNDANT HEATING SYSTEMS

TECHNICAL FIELD

[0001] The present disclosure is related to tools for manufacturing, assembling, and repairing composite parts.

BACKGROUND

[0002] Structural design includes buildings, towers, bridges, ships, land vehicles, and, aircraft, all of which are subsets thereof. All of the structures in these subsets must be designed with care because human life often depends on their performance. The structures are subject to both one-way and oscillating stresses, the latter giving rise to fatigue and, in some instances, failure. Under certain conditions, the structures can also be subject to corrosion, and some kinds of corrosion are accelerated in the presence of stress.

[0003] Historically, aircraft structural design has moved from the use of wood and fabric with attachment by screws, bolts, gluing and stitching; to metal parts mechanically joined by welding and/or riveting; and, more recently, to composite material parts that are bonded together using various techniques that involve the use of heat and pressure, along with dedicated fixtures.

[0004] Today, many aircraft parts and/or structures are made of carbon fiber composites. Carbon fiber composites are most often used because they are extremely strong, comparatively light, and fatigue resistant. However, carbon fiber composites are not without disadvantages including: material cost, fixture costs, manual processing, and rework and repair issues; to name but a few. For instance, according to one estimate, carbon fiber composites used in aircraft can cost from \$60 to \$400 per pound, compared to \$0.33 for steel and \$100 for aluminum, the main cost element being the fiber. Another cost is the molds, tools or fixtures. These are usually made of Invar or another material with a coefficient of thermal expansion matched to that of the carbon fiber composite materials in order that the curing process does not introduce size or shape variations. Layup, by which is meant placing uncured composite materials onto the mold, tools or fixtures, is another concern. This can be done by machines if the part is flat or nearly flat, such as a wing skin, but is mainly done manually due to the variety of different shapes that are involved. Yet another concern is rework and repair. Composite parts are made in layers, and a major potential failure mode is delamination, or interior separation of layers due to such causes as gas

bubbles or insufficient bonding. Ultrasonic inspection is used to find such flaws, and increasingly they can be repaired even in thermosets. The process is still very costly, however, and the prospect of generating a flawed large assembly that becomes expensive scrap is a deterrent.

[0005] For example, many large airplane parts use what is referred to as “close out box” construction. This type of construction involves building a structural framework, covering a portion of the framework with an outer covering or skin, and, finally, attaching the last portion of the outer covering or skin, in effect, “closing out the box.”

[0006] Since many of these parts have either become too large, inconvenient, impractical, and/or costly for use with an autoclave, or it is simply not possible to achieve a good bond joining various pieces together, heat blankets are often used. Rather than placing the part into the heat, the heat is placed onto the part.

[0007] Conventional heat blankets are constructed using a filament wire that is precision placed in a serpentine arrangement, extending or traversing back and forth across a plane defined by the blanket. As such, conventional heat blankets are difficult to build and costly, and are heavy, rigid and/or stiff, fragile, and, notoriously, unreliable. Unfortunately, with repeated use, i.e., energizing the filament over and over again, the wire becomes brittle and, when flexed thereafter, breaks. This makes a filamentary blanket with any size increasingly difficult to realize. Moreover, any handling or use that results in physical damage to the blanket and that severs or breaks the filament wire results in a blanket without utility.

[0008] Further, any heating blanket that uses two electrically independent filaments in overlapping layers, i.e., a redundant filamentary heat blanket, becomes even more complex, difficult to build and costly, while being even thicker, heavier, more rigid and stiff. Moreover, when one of the filament wires breaks or burns-out in a first layer, it typically burns through, shorts to, and/or damages the filament in the other overlapped layer, rendering also the redundant layer and the blanket totally useless.

[0009] Considering the costs of the parts involved and the potential for scrap, all conventional heating blankets generally suffer from difficulty to some degree as described hereinabove in heating for curing and bonding in producing parts. Accordingly, those skilled in the art continue with research and development efforts in the field of tools for manufacturing, assembling, and repairing composite parts.

SUMMARY

[0010] The present invention provides a redundant heating system, comprising: (A) a redundant carbon nanotube (CNT) heat blanket, comprising at least one heating element located in a first layer and at least one heating element located in a second layer, the at least one heating element located in the second layer registered at least in part with the at least one heating element located in the first layer, each of the at least one heating elements comprising (a) a carbon nanotube (CNT) structured layer defining an electrically conductive pathway having a first end and a second end and (b) a first electrical termination electrically coupled to the first end and a second electrical termination electrically coupled to the second end, (B) an elastomeric insulator located between and electrically isolating the at least one heating element located in the first layer and the at least one heating element located in the second layer, and (C) an elastomeric outer covering encasing both the at least one heating element located in the first layer and the at least one heating element located in the second layer.

[0011] In some embodiments, the at least one heating element located in the second layer is coextensive with the at least one heating element located in the first layer.

[0012] In some embodiments, the CNT structured layer comprises a carbon nanotube (CNT)-polymer film structure including single wall carbon nanotubes (SWCNTs) dispersed within a silicone layer, wherein the mass percentage of the SWCNTs within the CNT-polymer film structure can be selected from any value between and inclusive of at least about 0.25 to about 5 percent by weight, about 5 to about 10 percent by weight, about 10 to about 15 percent by weight, 15 to about 20 percent by weight, and about 20 to about 25 percent by weight.

[0013] In some other embodiments, the mass of the SWCNTs within the CNT-polymer film structure can be selected from the group consisting of at least about 0.25 percent by weight of the CNT-polymer film structure, at least about 0.5 percent by weight of the CNT-polymer film structure, about 1 percent by weight, about 2 percent by weight, about 3 percent by weight, about 4 percent by weight, about 5 percent by weight, about 12 percent by weight, about 13 percent by weight, and about 25 percent by weight of the CNT-polymer film structure.

[0014] In some other embodiments, the CNT-polymer film structure comprises a constant uniform dispersion of the CNTs in the polymer comprising silicone is between about 0.06

millimeters (mm) and about 0.3 millimeters (mm) and the CNT weight percentage is about 3 percent to about 12 percent, resulting in a sheet resistance of about $70 \Omega/\square$ to about $5 \Omega/\square$, respectively.

[0015] In some other embodiments, the thickness of the CNT-polymer film structure is at least about 0.1 millimeters (mm), and less than about 0.2 millimeters (mm).

[0016] In some other embodiments, the thickness of the redundant CNT heat blanket is less than about 0.180 inches (4.572 millimeters) or less than about 0.09 inches (2.286 millimeters).

[0017] In some embodiments and in use, the redundant CNT heating blanket can be folded over and/or doubled over on itself, the mean or average radius of the fold approaching the thickness of the redundant CNT heat blanket, without failure of the heating elements.

[0018] In some other embodiments, the amount of heat produced by the redundant CNT heat blanket is varied by varying resistance by at least one of the thickness of the CNT structured layer, the percentage of CNTs in the CNT-polymer film structure, the length of the CNTs in the CNT-polymer film structure, and the type of the carbon nanotubes (CNTs) in the CNT-polymer film structure, at a fixed voltage.

[0019] In some other embodiments, the resistivity of the CNT-polymer film structure comprising SWCNTs cast from a 1 millimeter (mm) thick layer of CNT/toluene/silicone slurry is about $5 \Omega/\square$, about $6 \Omega/\square$, about $7 \Omega/\square$, about $14 \Omega/\square$, about $36 \Omega/\square$, about $43 \Omega/\square$, about $46 \Omega/\square$, about $47 \Omega/\square$, about $58 \Omega/\square$, about $288 \Omega/\square$, about $450 \Omega/\square$, about $750 \Omega/\square$, and about $1,620 \Omega/\square$; the resistivity of the CNT-polymer film structure comprising SWCNTs cast from a 1.5 millimeter (mm) thick layer of CNT/toluene/silicone slurry is about $3 \Omega/\square$, about $4 \Omega/\square$, about $5 \Omega/\square$, about $9 \Omega/\square$, about $24 \Omega/\square$, about $28 \Omega/\square$, about $31 \Omega/\square$, about $39 \Omega/\square$, about $192 \Omega/\square$, about $300 \Omega/\square$, about $500 \Omega/\square$, and about $1,080 \Omega/\square$; and the resistivity of the CNT-polymer film structure comprising SWCNTs cast from a 1.75 millimeter (mm) thick layer of CNT/toluene/silicone slurry is about $3 \Omega/\square$, about $4 \Omega/\square$, about $8 \Omega/\square$, about $21 \Omega/\square$, about $25 \Omega/\square$, about $27 \Omega/\square$, about $31 \Omega/\square$, about $165 \Omega/\square$, about $257 \Omega/\square$, about $429 \Omega/\square$, and about $926 \Omega/\square$.

[0020] In some other embodiments, the resistivity of the CNT-polymer film structure comprising SWCNTs is at least about $3 \Omega/\square$, at least about $5 \Omega/\square$, at least about $10 \Omega/\square$, at least about $20 \Omega/\square$, at least about $30 \Omega/\square$, at least about $40 \Omega/\square$, at least about $50 \Omega/\square$, at least about $60 \Omega/\square$, at least about $70 \Omega/\square$, at least about $80 \Omega/\square$, at least about $90 \Omega/\square$, at least about $100 \Omega/\square$, at least about $200 \Omega/\square$, at least about $300 \Omega/\square$, at least about $400 \Omega/\square$, at least about $500 \Omega/\square$, at least

about 600 $\Omega/\square$, at least about 700 $\Omega/\square$, at least about 800 $\Omega/\square$, at least about 900 $\Omega/\square$, at least about 1,000 $\Omega/\square$, at least about 1,100 $\Omega/\square$, at least about 1,200 $\Omega/\square$, at least about 1,300 $\Omega/\square$, at least about 1,400 $\Omega/\square$, at least about 1,500 $\Omega/\square$, or at least about 1,600 $\Omega/\square$.

[0021] In some other embodiments, the CNT structured layer further comprises a CNT sheet formed over a porous carrier material.

[0022] In some other embodiments, the CNT structured layer has an upper surface and a lower surface and the at least one pair of heating elements further comprises a thermoplastic film disposed against at least one of the upper surface and the lower surface of the CNT structured layer.

[0023] In some other embodiments, a flexural strength of the CNT structured layer is equal to or greater than a flexural strength of the thermoplastic film.

[0024] In some other embodiments, the thickness of the redundant CNT heat blanket is less than about 0.110 inches (2.794 millimeters) or less than about 0.260 inches (6.572 millimeters).

[0025] In some other embodiments, the elastomeric outer covering and the elastomeric insulating layer are selected individually from the group consisting of a fluoroelastomer (FKM), silicone, a fluorosilicones, a perfluoroelastomers, an ethylene propylene diene rubber (EPDM), a thermoplastic elastomer, and a thermoplastic polyurethane (TPU), butyl rubber, and a combination thereof.

[0026] In some other embodiments, either or both the elastomeric outer covering and the elastomeric insulating layer is selected from the group consisting of an elastomeric silicone rubber and a fiberglass reinforced silicone rubber, and in a thickness selected from the group consisting of 0.015, 0.030 and 0.060 inches (0.381, 0.762, and 1.524 millimeters (mm)).

[0027] In some other embodiments, the redundant CNT heat blanket further comprises a plurality of pairs of heating elements, each pair defining a heat zone.

[0028] In some other embodiments, the first and the second electrical terminals comprise an expanded foil electrode in electrical contact with the CNT structured layer, along the first and the second end of the CNT structured layer, respectively.

[0029] In some other embodiments, the first and the second electrical terminals further comprise a conductive adhesive to interface the expanded foil electrode to the CNT structured layer.

[0030] In some other embodiments, the first and the second electrical terminals further comprise die crimp connectors in electrical contact with the expanded foil electrodes along the first and the second ends of the CNT structured layer.

[0031] In some other embodiments, solder is used to attach wires to the expanded foil electrodes.

[0032] In some other embodiments, the redundant heating system further comprises a power supply electrically coupled to the redundant CNT heat blanket.

[0033] In some other embodiments, the redundant heating system further comprises one or more “hot bonders” electrically coupled to the redundant CNT heat blanket and configured to energize the redundant CNT heat blanket.

[0034] In yet some other embodiments, the redundant heating system further comprises one or more thermocouples electrically coupled to the one or more “hot bonders” and configured for sensing a temperature of a surface of a part, wherein the one or more “hot bonders” energize the redundant CNT heat blanket in response to a temperature sensed by the one or more thermocouples.

[0035] In one embodiment, a method of mechanically coupling composite parts, comprises the steps of: electrically coupling corresponding primary heating and secondary heating elements of a redundant CNT heat blanket to a source of electrical energy; electrically coupling a temperature sensor to a controller; inputting a desired temperature into the controller; placing a first composite part having an outer surface on a second composite part; positioning the temperature sensor on the outer surface of the first composite part; placing the redundant CNT heat blanket over the temperature sensor and on the outer surface of the first composite part; using the controller to monitor the temperature sensed by the temperature sensor, compare the temperature sensed by the temperature sensor to the desired temperature, and control the flow of electrical energy to the primary heating element in response to the comparison to bond the first composite part and the second composite part together; and in the event that the temperature sensed by the temperature sensor deviates from the desired temperature, using the controller control the flow of electrical energy to the redundant heating element to continue bonding the first composite part and the second part together.

[0036] In some embodiments, the first composite part and the second composite part each have a bonding surface, the method further including cleaning the bonding surfaces of both composite parts.

[0037] In some other embodiments, the method further includes placing a bonding tape between the bonding surfaces of the first composite part and the second composite part.

[0038] In some other embodiments, the method further includes timestamping and reporting out the energizing of the primary heating element and the redundant heating element.

[0039] In some other embodiments, the desired temperature comprises a temperature range.

[0040] In yet some other embodiments, the controller is one or more “hot bonders.”

BRIEF DESCRIPTION OF THE DRAWINGS

[0041] Various embodiments of a redundant heating system are understood with regards to the following description, appended claims and accompanying drawings wherein:

[0042] FIG. 1 is a perspective view of an airplane, one or more portions of which were constructed using the redundant heating system of the present invention.

[0043] FIG. 2 is a perspective view of the main torque box of the port side wing of the airplane shown in FIG. 1, the upper wing skin partially cut away.

[0044] FIG. 3 is a perspective view of the port side wing of the airplane shown in FIG. 1 with a redundant heating system configured therefore and located thereon.

[0045] FIG. 4 is a partial exploded view of the redundant carbon nanotube (CNT) heat blanket shown in FIG. 3.

[0046] FIG. 5 is cross sectional view showing the heating elements in a heat zone of the redundant CNT heat blanket shown in FIG. 3, and taken along line 5-5.

[0047] FIG. 6 is a graph showing the sheet resistance versus carbon nanotube (CNT) weight to total weight for a carbon nanotube (CNT) structured layer at various casting coat thicknesses (1 millimeter (mm), 1.5 mm, and 1.75 mm) of a CNT/toluene/silicone slurry.

[0048] FIG. 7 is cross sectional view showing an alternative embodiment of heating elements in a heat zone of the redundant CNT heat blanket shown in FIG. 3, and taken along line 5-5.

[0049] FIG. 8 is a flow chart showing a process for heating or bonding a part using a redundant carbon nanotube (CNT) heat blanket.

DETAILED DESCRIPTION OF THE INVENTION

[0050] The present disclosure includes a redundant heating system including a redundant carbon nanotube (CNT) heating blanket useful for manufacturing, assembling, and repairing composite parts and a method for using the same. The redundant heating systems and methods described herein have several advantages over conventional filamentary heat blankets that can also be used for manufacturing, assembling, and repairing composite parts. Other present tools and methods either lack durability, flexibility, cast-ability, and a robust nature or use another type of heating element to form, bond, or disassembly composite parts. In contrast, the present invention utilizes a carbon nanotube structured layer as a joule-heating or resistive-heating element as will be taught hereinafter.

Definitions

[0051] The term “filamentary heat blanket,” as used herein refers to a heat blanket that is constructed using a filament wire spaced in a plane or an etched metallic foil that functions as an Ohmic or resistive heating element and that is used for Joule heating.

[0052] The term “redundant filamentary heat blanket,” as used herein refers to a heat blanket that is constructed using at least two filament wires, each spaced in a different plane, each of which functions independently as an Ohmic or resistive heating element and that can be used for Joule heating, the heating elements located one overlapping the other, and together defining a heat zone.

[0053] The term “carbon nanotube (CNT) heat blanket,” as used herein refers to a heating blanket that is constructed using a carbon nanotube (CNT) structured layer that functions as an Ohmic or resistive heating element and that is used for Joule heating.

[0054] The term “redundant carbon nanotube (CNT) heat blanket,” as used herein refers to a heating blanket that is constructed using a pair of carbon nanotube (CNT) structured layers, each of which functions independently as an Ohmic or resistive heating element and that can be used for Joule heating, the heating elements located one overlapping the other, and together defining a heat zone.

[0055] Referring now to Figure 1, a perspective view of an aerospace vehicle or airplane 10 is shown, one or more portions of which were constructed using the present invention. For example, the airplane 10 can be a large commercial aircraft configured for hauling freight, as shown.

Alternatively, the airplane 10 can be configured for hauling passengers or passenger service and can include many windows for the passengers to look out of. The present invention can also be used for the construction of a portion of another aerospace vehicle or another airplane, or for some other application as well, as will be appreciated by a person of ordinary skill in the art.

[0056] Like many airplanes currently being manufactured today, substantial portions of the airplane 10 are constructed using composite materials, and more particularly, carbon fiber composite materials. Carbon fiber composite materials are used for both the inner structural framework or airframe and the outer surface or skin 34, covering much of the fuselage, wings, and stabilizers, as specific examples.

[0057] For purpose of orientation and further reference, the airplane 10 has forward and reward portions 12, 14, referred to hereinafter as “fore” and “aft,” respectively. When facing forward, as indicated by an arrow found at reference numeral 16, the airplane 10 also has a left or “port” side 18 and a right or “starboard” side 20. Continuing, the airplane 10 comprises port and starboard wings 22, 24, and port and starboard horizontal stabilizers 26, 28, and a vertical stabilizer 30, located on a tail 32 located at the aft 14 of the aircraft, all of which are largely constructed of parts made using carbon fiber composite materials and that can be assembled using embodiments of the present invention, a non-limiting example for the port side wing 22 now being described.

[0058] Referring also to Figure 2, the main portion of the airframe 100 contained within the port side wing 22 is shown. The airframe 100 of the port side wing 22 comprises a main torque box 102, a beam structure that supports the structural loads on the wing. The main torque box 102 comprises a front or forward spar 104 located along a leading edge 106 and a rear or aft spar 108 located along a trailing edge 110, both of which extend longitudinally from inboard 128 to outboard 130. The main torque box 102 further comprises an interior or inboard rib proximate the fuselage, referred to as a plus chord 112, and an outer most rib 114, both of which extend fore and aft. The fore and aft spars 104, 108 are spaced apart by the plus chord 112 and the outer most rib 114, all of which define a periphery 116 of the main torque box 102. The plus chord 112 is a splice element that is used to attach a wing to an aircraft fuselage.

[0059] The airframe 100 of the port wing 22 further comprises a number of intermediate ribs 118, also extending fore and aft, spaced apart in between the plus chord 112 and the outer most rib 114, and mechanically coupled to the forward spar 104 and the aft spar 108, and a number of

longitudinal skin stiffeners called stringers 120 that extend from the plus chord 112 to the outer most rib 114, and that are mechanically coupled to the plus chord 112, the intermediate ribs 118, and the outer most rib 114. Together, the forward spar 104, the aft spar 108, the plus chord 112, the outer rib 114, the intermediate ribs 118, and the stringers 120 serve as attachment points for a portion of the outer surface or skin 34 of the airplane 10. The portion of the skin 34 of the airplane 10 that is attached to the airframe 100 of the port wing 22 comprises a lower wing skin 122, as indicated from the inside of the wing, and an upper wing skin 124, a portion of which is shown broken away in Figure 2 for purposes of illustrating the airframe 100.

[0060] The skin 34 of the airplane 10 serves two primary functions. First, the skin 34 carries the aerodynamic loads on the airplane 10, directing air over and around the airplane 10, allowing the airplane 10 to move through the air in a desired, controlled, and efficient manner. Second, and less obvious, the skin 34 structurally ties the various components of the airframe 100 together, increasing both the aerodynamic and the structural load carrying capability of the airplane 10 in the process.

[0061] For example, the lower wing skin 122 and the upper wing skin 124 are mechanically coupled to the forward spar 104, the aft spar 108, the plus chord 112, and the outer rib 114 of the main torque box 102 further structurally tying or mechanically coupling them together. The lower wing skin 122 and the upper wing skin 124 are also structurally tied or mechanically coupled to the intermediate ribs 118, further structurally tying or mechanically coupling them to the main torque box 102. Further, the stringers 120 spanning from the plus chord 112 to the outer rib 114 are also structurally tied and mechanically coupled to the intermediate ribs 118 and are further structurally tied or mechanically coupled together by the lower wing skin 122 and/or the upper wing skin 124. Tying together and/or mechanically coupling the various component parts of the port wing 22 works to direct all tension and compression loads from the port wing 22 into the main torque box 102, and from there, into a center box located inside the fuselage of the airplane 10. Again, this tying together and/or mechanical coupling of the various component parts of the airframe 100 through the skin 34 works to increasing both the aerodynamic and the structural load carrying capability of the airplane 10 as will be understood by a person of ordinary skill in the art.

[0062] The main torque box 102 in combination with the lower and upper wing skins 122, 124 are often referred to as a form of “closeout box construction,” or simply a “closeout box,” or in the

case of a wing, a “wing closeout box,” for example. The terminology comes from the notion that the forward and aft spars 104, 108, and the inner and outer ribs, i.e., the plus chord 112 and the outer rib 114, are first assembled, resembling the sides and ends of a box, respectively. The lower wing skin 122 is then attached to the torque box 102, resembling the bottom of the box. Finally, the upper wing skin 124 is attached to the torque box 102, “putting a lid on” or “closing the box,” preventing access to the interior of the box, i.e., “closing out the box” or, more generally, “close out box construction.”

[0063] This type of construction or assembly is of particular significance because many parts of the airplane 10 can be constructed in like manner. For example, referring once again to Figure 1, the wings 22, 24, and the horizontal and the vertical stabilizers 24, 26, 28 are constructed using “close out box construction.” This type of construction or “close out box construction” limits or prevents access to the “inside of the box” when attaching a final portion of the skin 34 or a panel that “closes out the box.”

[0064] In airplanes constructed using metal, aluminum being the preferred metal due to its comparative light weight, the various components of the airframe, as well as the various portions of the skin, are attached or mechanically coupled together using rivets. Riveting is typically used for a couple of reasons. First, were welding to be used, the metal surrounding a weld is typically weakened due to the heat generated in the process of welding, the metal surrounding the weld being more subject to stress and strain, and failure. This is particularly true with aluminum, as aluminum has a lower heat tolerance before a reduction in strength occurs, leading to failure. Second, rivets allow two structural members that are attached together with the rivets to move ever so slightly with respect to one another. This movement results in friction between the two structural members, and that friction generates heat, and that friction is useful in dampening vibrations induced into the members through flight, in the case of an airplane, for example. Moreover, riveting is not particularly problematic when attaching a final wing skin or panel that “closes out the box,” as riveting can be performing from “outside the box,” or from the exterior of the part, e.g., the wings or the horizontal and the vertical stabilizers. Thus, riveting is the preferred method of joining two aluminum components of an airframe, as well as attaching an aluminum skin to an aluminum airframe.

[0065] However, the method of attaching or mechanically coupling changes when the airframe and the skin are made from composite materials, such as, for example, carbon fiber composite materials. Composite materials are engineered materials that comprises two or more constituent materials, each with significantly different physical and/or chemical properties, which remain separate and distinct within a finished product or part, but which cooperate to form a material with enhanced physical properties. For example, a composite material is a term used to refer to a fiber fabric, for example, a woven or non-woven carbon fiber fabric, that has been pre-impregnated with a resin, for example, an epoxy, i.e., a pre-impregnated carbon fiber fabric sheet. As used herein, a resin includes a curing agent or hardener.

[0066] Parts that are made from carbon fiber composites are typically constructed using pre-impregnated carbon fiber fabric sheets that are stacked together, i.e., laid-up, in a mold, and cured under heat and pressure. Once cured, the parts are attached or mechanically coupled together by gluing or bonding using a resin or, for example, an epoxy. Welding is not possible. Riveting is also not typically used because drilling holes for the rivets is time consuming and exposes the fibers contained in the composite material to the environment, allowing for the ingress of moisture which deteriorates the fibers with time. Moreover, rivets are typically made of metal, e.g., steel or aluminum, which is typically harder than the fibers and the resin used in the composite material, and that can, with certain alloys, galvanically interact with the carbon fibers. This allows holes drilled in the composite parts for the rivets to enlarge due to wear or “wallow-out” when the two parts move relative to one another or to corrode over time, the attachment of the two parts loosening, and failing. Additionally, carbon fiber is quite abrasive in nature and when movement between two carbon fiber composite parts occurs, the carbon fiber can quickly wear away the parts and/or rivets, again, leading to failure of the attachment, albeit in a shorter amount of time. Therefore, carbon fiber composite parts are typically bonded together.

[0067] The terms “bond,” “bonding,” and “bonded” as used herein, refer to the act of mechanically coupling or attaching two composite parts together. A technical definition of mechanical bonding is bonding that involves a mechanical constraint preventing two molecules from separating, rather than a chemical linkage based on transfer or sharing of electrons between two molecules. A practical definition of mechanical bonding is a bond formed by keying or interlocking into mechanical features on a surface that bind in an adhesive manner such that it is physically resistant to adhesive failure.

[0068] Applying this to a first instance of composite bonding, “secondary bonding” is defined as the joining together, by the process of adhesive bonding, two or more pre-cured composite parts, during which the only chemical or thermal reaction occurring is the curing of the adhesive itself. Secondary bonding requires careful preparation of each previously cured part at the bonding surfaces, can require the use of clean facilities or a cleanroom, and usually requires well designed fixturing to align and clamp parts during the process. A person of ordinary skill in the art will appreciate that reheating previously cured parts can be risky, leading to a potential failure.

[0069] Further, and with two additional instances and definitions: “co-bonding” is the curing of two or more parts, of which at least one is fully cured and at least one is uncured, while “co-curing” is the act of curing a composite laminate and simultaneously bonding it to some other uncured part or material, or a core material, such as a honeycomb or foam core, wherein all resins and adhesives are cured during the same process. The former also requires careful surface preparation of the previously-cured substrate, and an additional adhesive can be required at the bond line interface.

[0070] A person of ordinary skill in the art will appreciate that the examples used herein in the explanation of the present invention use secondary bonding; that is, adhesively bonding (i) two or more pre-cured composite parts together. However, the present invention is in no way limited to adhesively bonding two or more pre-cured composite parts together; but rather, the present invention can be equally applied to situations where either (ii) at least one part is fully cured and at least one part is uncured, i.e., co-bonding, or (iii) a first part is cured while simultaneously bonding it to some other uncured part, i.e., co-curing. Thus, and as will be appreciated by a person of ordinary skill in the art, the present invention is equally applicable all bonding situations, enumerated hereinabove as (i), (ii), and (iii).

[0071] A person of ordinary skill in the art will also appreciate that two carbon fiber parts that are bonded together will not dampen in the same manner two aluminum parts that are riveted together will dampen and therefore, the bond must be able to withstand any stress due to vibration in addition to any structural and aerodynamic loads, unlike a riveted assembly that dissipates vibration. Therefore, not only are the bonds critical in terms of load carrying, they must also be able to withstand fatigue associated with vibration. The present invention is particularly suited to

bond line optimization and production, achieving a good bond between composite parts as will now be described.

[0072] Referring also to Figure 3, the wing box 210 is shown mostly assembled, the remaining assembly step being the bonding of the upper wing skin 124 to the main torque box 102 along with any intermediate ribs 118 and stringers 120. A non-limiting example of a redundant heating system 200 is also shown. The redundant heating system 200 comprises a redundant carbon nanotube (CNT) heat blanket 202 and a power supply 204. The redundant CNT heat blanket 202 is electrically coupled to the power supply 204 through two or more cables 206a, 206b and is configured for closing out the wing box 210, the structure of which was described in considerable detail in conjunction with Figure 2.

[0073] Of particular note is that the redundant CNT heat blanket 202 only covers a portion 212 of the outer surface 126 of the upper wing skin 124 corresponding to portions of the forward spar 104 and the aft spar 108, the plus cord 112, and the intermediate ribs 118. The non-limiting example is contrived in this manner for a number of reasons as will now be described.

[0074] First, the non-limiting example recognizes that a wing skin of a large aircraft can be comprised of multiple panels that are combined to form a wing skin, rather than one large unitary wing skin, and it is the last of these panels that actually “closes out the wing box.” In some embodiments, the portion 212 represents a last panel. The present invention applies to unitary wing skins and wing skins made from discrete panels alike, as well as to individual panels of an airplane skin 34, as will appreciated by those of ordinary skill in the art.

[0075] Second, the non-limiting example allows the present disclosure to explain that the present invention teaches, *inter alia*, the usage of one or more additional redundant heating systems to perform a particular bonding or heating task, for example, for the remaining portion 214 of the upper wing skin 124 covering the balance of the forward and aft spars 104, any remaining intermediate ribs and/or stringers, and the outer rib 114, or, in other words, “combinations of redundant heating systems.” Persons of ordinary skill in the art will also appreciate that any necessary and additional redundant heating system(s) can be built in like matter to that described for the redundant heating system 200 using the teachings contained herein.

[0076] Third, the non-limiting example affords an opportunity for explaining that a redundant heating system can include various combinations of one or more redundant CNT heat blankets and

one or more power supplies, as contemplated by the present invention. For example, and in some embodiments, a redundant heating system comprises a single redundant CNT heat blanket powered by multiple power supplies. In some other embodiments, a redundant heating system comprises multiple redundant CNT heat blankets that are positioned on a part in combination, and that are powered by a single power supply. Embodiments that lie between these two extremes also exist and will be readily appreciated by those of ordinary skill in the art.

[0077] The reason for some embodiments having to use an additional system or various combinations to perform a particular bonding or heating task is entirely one of desire, using what power supplies might be available at hand, or pragmatics, relating to the difficulty in building a particular redundant CNT heat blanket, as will be described in more detail hereinafter. Those of ordinary skill the art will appreciate how to manage and make these decisions, and adapt the present invention accordingly.

[0078] Continuing with Figure 3, and for example, the port wing 22 is complex, the various parts, i.e., the forward spar 104, the aft spar 108, the plus chord 112, the intermediate ribs 118, and the outer rib 114, and the stringers 120, each requiring differing amounts of power and/or heat based on their relative size and thickness, and their associated ability to sink or absorb heat in the process of bonding. The upper wing skin 124 can also vary in thickness requiring different amounts of heat. This makes a single large redundant heat blanket that accounts for all of the different component parts of the wing and that covers the entire upper wing skin 124 more difficult to build.

[0079] The port wing 22 is also physically large being the wing of a large commercial airplane 10 and requires considerable heat and/or power for bonding the upper wing skin 124 to the main torque box 102 along with any intermediate ribs 118 and stringers 120. This requires power supply with the ability to deliver a substantial amount of power and that may not be readily available or at hand, although such a supply could be constructed in some embodiments.

[0080] Thus, in accordance with principles of the present invention, the task of bonding the upper wing skin 124 to the main torque box 102 along with any intermediate ribs 118 and stringers 120 is broken-up or shared between multiple redundant heating systems to ease the construction of the redundant heat blanket(s) and facilitate the use of readily available power supplies. To this end, the redundant heating system 200 includes a redundant CNT heat blanket 202 that only covers

a portion 212 of the upper wings skin 124, the redundant CNT heat blanket 202 comprising multiple pairs of heating elements, each pair defining a heat zone, the heat produced by the pair of heating elements within each heat zone corresponding to the portions 212 of the forward spar 104 and the aft spar 108, the plus cord 112, and the intermediate ribs 118, and as will be shown in Figure 4, for example.

[0081] Again, the wing box 210 is mostly assembled, the remaining assembly step being the bonding of the upper wing skin 124 to the main torque box 102 along with any intermediate ribs 118 and stringers 120. To do so, the upper wing skin 124 is positioned on the forward spar 104, the aft spar 108, the plus chord 112, the intermediate ribs 118, and the outer rib 114, and the closeout grid blanket 202 is placed on the upper wing skin 124 as generally shown. More specifically, the redundant blanket 202 extends fore and aft on an outer surface 126 of the upper wing skin 124 over the forward spar 104 located below the upper wing skin 124 on the leading edge 106 of the main torque box 102 and over the aft spar 108 located below the upper wing skin 124 on the trailing edge 110 of the main torque box 102, see Figure 2. The closeout grid blanket 202 also extends over the plus chord 112 located below the upper wing skin 124 at the inboard 128 most portion of the main torque box 102 and over the intermediate ribs 118, both of which are also shown in Figure 2. The redundant CNT heat blanket 202 comprises a plurality of pairs of heating elements encased within an elastomeric outer covering 208. The pairs of heating elements are positioned over and correspond to the forward spar 104, the aft spar 108, the plus chord 112, and the intermediate ribs 118, and are energized by the power supply 204 to bond the upper wing skin 124 to the forward spar 104, the aft spar 108, the plus chord 112, and the intermediate ribs 118, tying the various parts of the airframe 100 together through the wing skin 126, thereby “closing out” the wing box 210.

[0082] In a method including the remaining assembly step of bonding the upper wing skin 124 to the main torque box 102 and any intermediate ribs 118 and stringers 120, the upper most surfaces or bonding surfaces of the forward spar 104, the aft spar 108, the plus chord 112, the intermediate ribs 118 and the outer rib 114 are cleaned, preparing them for bonding, as is the inner surface of the upper wing skin 124. Next, a resin, e.g., epoxy, bonding tape is applied to the bonding surfaces of the forward spar 104, the aft spar 108, the plus chord 112, the intermediate ribs 118, and the outer rib 114. The upper wing skin 124 is then placed on the port wing 22, contacting the bonding tape that has been applied to the bonding surfaces of the forward spar 104, the aft spar 108, the

plus chord 112, the intermediate ribs 118, and the outer rib 114. The redundant CNT heat blanket 202 is then positioned on the upper surface 126 of the upper wing skin 124 as shown in Figure 3, and the redundant CNT heat blanket 202 is energized by the power supply 204. Once energized, the plurality of pairs of heating elements encased within the elastomeric outer coating 208 of the closeout grid blanket 202 produce heat that accelerates the curing of or cures the bonding tape, bonding, e.g., secondary bonding, the upper wing skin 124 to the forward spar 104, the aft spar 108, the plus chord 112, and the intermediate ribs 118, “closing out” the wing box 210.

[0083] Typically, the port wing 22 will be located within a fixture and/or “bagged” during this bonding process. As will be understood by a person of ordinary skill in the art, a fixture is used to hold the parts in their respective positions during bonding, while “bagging” generally refers to applying an impermeable layer of film over a part and sealing the edges so that a vacuum can be drawn, i.e., air can be evacuated from the “bag,” so that atmospheric pressure pushes the parts together during curing and/or bonding.

[0084] Once the wing box 210 is “closed,” it is virtually impossible to “open” it again — reheating previously cured parts can lead to a failure. In other words, there is but one chance to “get it right” when “closing out a box;” otherwise, the part becomes scrap and all the time, effort, and expense in building the part up to that point is lost. Recall, “closing out the box” is typically the last step in assembly.

[0085] For example, if the upper wing skin 124 is not completely bonded to the main torque 102, the intermediate ribs 118, and any stringers 120, the various parts of the port wing 22 will not be tied together properly and the port wing 22 will lack its intended strength or load carrying capacity. Further, if the bonds between the upper wing skin 124 and other various parts of the port wing 22 are not complete or sufficient, the parts can vibrate and even oscillate in flight, fatigue, and fail. Not only are bonds critical in terms of load carrying, they must also be able to withstand fatigue associated with vibration. Further, if the upper wing skin 124 is not aligned or positioned properly on the main torque box 102, the port wing 22 will not meet the dimensional tolerances required for assembly, and the port wing 22 is, once again, scrap.

[0086] To meet the heating requirements for bonding the portion 212 of the upper wing skin 124 to the port wing 22, a number of different power sources and/or supplies can be used. In some embodiments, a redundant heat blanket in accordance with principles of the present invention can

be configured for use with the mains electric power referred to by several names including, but not necessarily limited to, “household power,” “household electricity,” “house current,” “powerline,” “domestic power,” “wall power,” “line power,” or “AC power.” All of these terms refer to mains power systems that are primarily characterized by voltage, frequency, and/or Earthing or grounding systems. For example, in the United States of America (USA), the common domestic standards are 120 and 240 volts alternating current (VAC), expressed as root-mean-square (RMS) voltages, single phase (1Ø), 60 hertz (Hz) with appropriate tolerances or variation specified therefore in accordance with the National Electric Code (NEC). Service connections are typically limited to 10-20 amperes (A) for 120 VAC and 20-200 A, or more, for 240 VAC. In some embodiments, requiring lesser amounts of power, these domestic standards can be used. Non-limiting examples include, blankets used with smaller parts or portions of larger parts, or blankets used in composite repair. For higher power applications, a blanket can be configured for use with industrial power distribution standards. Industrial standards include, but are not necessarily limited to, 240 and 480 VAC, single phase (1Ø) and three phase (3Ø). Services in accordance with these standards are typically available in industrial settings, such as factories or facilities where airplanes and airplane parts are built, for example. There are other standards in use elsewhere in the World. A person of ordinary skill in the art can modify or adapt the present invention as required using the teachings contained herein for use with any standard in any location.

[0087] In some other embodiments, the power supply 204 can be any preexisting or purpose built, fixed or adjustable, alternating current (AC) or direct current (DC) power supply configured or select-ably set for any desired or necessary voltage, current, and/or frequency. Further, these power supplies can be programmatically controlled using personal computers, such as through a general-purpose input/output (GPIO) bus or general-purpose interface bus (GPIB), e.g., The Institute of Electrical and Electronics Engineers Standard, i.e., IEEE-488. These types of power supplies are well known to those of ordinary skill in the art.

[0088] In still other embodiments, the power supply 204 can be one or more hot bonders as required by the task at hand. Hot bonders are available from BriskHeat® of Columbus, Ohio; HEATCON® Composite Systems of Seattle, Washington; Applied Heat Composite Repair Systems, Inc. of Chandler, Arizona; and WichiTech Industries, Inc. of Randallstown, Maryland, to name but a few manufacturers and suppliers. In some embodiments, the hot bonder can be

newly purchased, while in others it can be pre-owned and previously used with a filamentary heat blanket, the present invention constituting a new use for a hot bonder with a redundant CNT heat blanket as described and taught herein. In some embodiments, it is believed that configuring a redundant CNT heat blanket for use with a hot bonder will lead to faster and more widespread acceptance of the present invention by those in industry as they will not have to purchase a hot bonder, instead making use of one that they already own, and that was previously used with a filamentary heat blanket.

[0089] Hot bonders are typically electrically connected in one of two ways; namely, AC or DC. In an AC connection, a hot bonder is electrically coupled to the mains electric power or AC power, and acts as an intermediary between the powerline and one or more heating elements, controlling and/or regulating the application of power available from the powerline to the one or more heating elements. For example, and in an AC connection, a hot bonder can include input and output power ports, the input power port electrically connected to the powerline and the output power port electrically connected to one or more heating elements. The hot bonder functions to control the flow of power from the input port to the output port, or from the powerline to the heating elements. In a DC configuration, a hot bonder makes use of one or more internal DC power supplies in powering the one or more heating elements. The present invention applies equally to both AC and DC connections of a hot bonder.

[0090] A hot bonder can be used to provide multiple functions. For example, to apply a vacuum and to heat up an area or surface while constantly monitoring and regulating the temperature of the surface in accordance with a program and/or heat profile, as will be appreciated by a person of ordinary skill in the art. A hot bonder can include a variety of connections and features related to applying a vacuum and heating that are grouped together into what are referred to as “zones,” and that a programmatically controlled through a user interface. In a non-limiting example, and as shown in Figure 3, the power supply 204 can be a dual-zone hot bonder including two zones 216a, 216b for applying a vacuum and heating, and a user interface 218 configured for programmatic control of the zones 216a, 218b. A user interface 218 can include a display or touchscreen 226 and a keypad 228. A hot bonder can further include a universal serial bus (USB) port and an Ethernet port for use in collecting data and creating and transferring programmed heat profiles — the programs and/or heat profiles can be created, entered, and/or managed through the user interface 218 or remoted through the Ethernet port.

[0091] Each zone 216a, 216b comprises vacuum ports for 220a, 220b for use in bagging parts, i.e., applying a vacuum to a sealed-off air volume containing a part or, a part contained within an impermeable or airtight bag, input/output power ports 216a, 216b for supplying power to one or more heating elements, and a plurality of jacks 224a, 224b for connecting thermocouples that can be used in temperature control for and selectively energizing the heating elements. In some embodiments, an infrared (IR) sensor can be used in the alternative.

[0092] As shown in Figure 3, the redundant heating system 200 further comprises thermocouples 230a, 230b electrically connected to the plurality of jacks 224a, 224b through cables 232a, 232b, respectively. In some embodiments, the thermocouples 230a, 230b can be sourced from the aforementioned manufacturers and/or suppliers of the hot bonder, configured for used therewith, and available in a number of different temperature ranges. Those of ordinary skill in the art are able to select the appropriate temperature range thermocouple based on the heating requirements or application. In some other embodiments, the thermocouples 230a, 230b can be integrated into the redundant blanket 202 and contained within the elastomeric outer covering 208.

[0093] Referring now to Figure 4, an exploded view of the redundant CNT heat blanket 202 shown in Figure 3 is illustrated. As mentioned hereinabove, the redundant CNT heat blanket 202 comprises a plurality of pairs of heating elements 300 encased within an elastomeric outer covering 208a-c. More specifically, the pairs of heating elements are arranged in a first or primary layer 301 and a second or redundant layer 302, the pairs of heating elements within each layer corresponding to the forward spar 104, the aft spar 108, the plus chord 112, and the intermediate ribs 118 and to each other as will now be described.

[0094] In the first or primary layer 301, heating element 304_P corresponds to the forward spar 104, heating element 308_P corresponds to the aft spar 108, heating element 312_P corresponds to the plus chord 112, and heating elements 318_P correspond to the intermediate ribs 118, subscript “P” denoting the first or primary layer. Similarly, in the second or redundant layer 302, heating element 304_R corresponds to the forward spar 104, heating element 308_R corresponds to the aft spar 108, heating element 312_R corresponds to the plus chord 112, and heating elements 318_R correspond to the intermediate ribs 118, subscript “R” denoting the second or redundant layer.

[0095] For additional clarity, and when the redundant CNT heat blanket 202 is assembled, heating element 304_R is registered and coextensive with heating element 304_P, heating element

308_R is registered and coextensive with heating element 308_P, heating element 312_R is registered and coextensive with heating element 312_P, and heating elements 318_R are registered and coextensive with heating elements 318_P, an insulating layer 208b located therebetween, see also Figure 5. In some embodiments, the insulating layer 208b can be an elastomer material similar to or like that used for the elastomeric out covering 208a, 208c. In some other embodiments, the insulating layer 208b can be a polyimide film, e.g., a Kapton tape.

[0096] For example, and in the redundant CNT heat blanket 202 shown in Figures 3 and 4, each pair of heating elements 300, one in the primary layer 301 and one in the redundant layer 302, extend over the same area of the outer surface 126 of the upper wing skin 124, corresponding exactly or substantially to the same extent, i.e., coextensive, and are completely redundant. However, the heating elements need not necessarily be coextensive and completely redundant in every embodiment of the present invention. The present invention also contemplates those embodiments where the heating elements are registered with one another, but not coextensive, i.e., partially redundant as will now be described. For example, a heating element in either the first or primary layer 301 or the second or redundant layer 302 can be larger or smaller than the heating element in the other layer, the heating elements being registered with one another, e.g., overlapped to some extent, but not coextensive. Further, the heating element in the first layer 301 and the heating element in the second layer 302 also need not have the same size and shape, rather the heating elements can be sized and/or shaped differently, only a portion of one overlapping the other, the overlapped portion defining the redundancy. Additionally, heating elements that are registered with one another, e.g., positioned “one on top of the other,” in the second layer 302 and the first layer 301 can correspond to each other and be “paired” to define a heat zone, the overlapped portions also defining the heat zone.

[0097] In the embodiment shown in Figures 3 and 4, a primary heating element, denoted “P,” and a redundant heating element, denoted “R,” together define a heat zone. For instance, heating element 304_R overlaps heating element 304_P defining a heat zone for the forward spar 104, heating element 308_R overlaps heating element 308_P defining a heat zone for the aft spar 108, heating element 312_R overlaps heating element 312_P defining a heat zone for the plus chord 112, and heating elements 318_R overlaps heating elements 318_P defining heat zones for the intermediate ribs 118, the forward spar 104, the aft spar 108, the plus chord 112, and the intermediate ribs 118 all

having different heating requirements based on the differences in their sizes and shapes, although both intermediate ribs 118 have the same heat requirement in this embodiment.

[0098] Note a numbering convention is as follows: a 3XX_P numbered heating element and a 3XX_R numbered heating element correspond to each other and combine to form a heat zone corresponding to a 1XX numbered part of the port wing 22. Moreover, a primary heating element, e.g., 3XX_P, and a redundant heating element, e.g., 3XX_R, may also be said to be physically “coextensive” with one another or in correct alignment or in the proper relative position such that when energized either of the paired heating elements are both able to heat a corresponding part, e.g., a 1XX numbered part of the port wing 22, for purposes of bonding or curing.

[0099] Further, and as will be described in more detail hereinafter, the present invention teaches that in the event of a failure of a primary heating element, a redundant heating element is energized in response thereto. This ability allows for continued use of a blanket in producing a part, and ensures that the part is assembled properly, e.g., bonded properly, preventing the part from having to be reworked or becoming scrap due to improper, insufficient, or incomplete bonding.

[0100] In one embodiment, the elastomeric outer covering 208a, 208c and the insulating layer 208b is selected for use in a cleanroom or in a clean facility. In other embodiments of the present invention, the elastomeric outer covering 208a, 208c and the insulating layer 208b can be formed from fluoroelastomers (FKM), silicones, fluorosilicones, perfluoroelastomers, ethylene propylene diene rubber (EPDM), butyl rubber, and thermoplastic elastomers, such as, for example, thermoplastic polyurethanes (TPU) or polytetrafluoroethylene (PTFE). One of ordinary skill in the art will appreciate that the elastomeric outer covering 208a, 208c and the insulating layer 208b can be selected from a variety of materials, natural and synthetic, as desired, depending on the use environment of the redundant CNT heat blanket 202, without departing from the spirit of the present invention.

[0101] For example, and in still other embodiments, the elastomeric outer covering 208a, 208c and the insulating layer 208b is as silicone-based material that offers high reversion resistance and strength, and that can be used in composite laminating and bonding systems using vacuum, e.g., bagging or hydraulic pressure during curing or bonding. One silicone-based material is Airtech 4140 silicone rubber available from Airtech International, Inc. of Huntington Beach, California. Another silicone-based material is Airtech 5553 fiberglass reinforced silicone rubber also available

from Airtech International, Inc. It was found that in some applications, a redundant CNT heat blanket constructed using Airtech 4140 would undesirably wear over time and in repeated use, the outer cover stretching or deforming. The fiberglass reinforcement found in Airtech 5553 combats this problem. Both these silicone-based materials are available in thicknesses of 0.030 and 0.060 inches (0.762 and 1.524 millimeters (mm)), the selection of which thickness depends on how flexible the blanket need be, and as will be discussed in further detail hereinafter. Those of ordinary skill in the art can select an appropriate covering material and thickness for a particular application with the benefit of the teachings contained herein.

[0102] As shown in Figure 4, the insulating layer 208b and the elastomer outer covering 208a, 208b follow the outline of the arrangement of the heating elements 300 in the first and second layers 301, 302 — this can be beneficial in locating the redundant CNT heat blanket 202 relative to the port wing 22. However, this need not necessarily be the case. In some embodiments, the insulating layer 208b and the elastomer outer covering 208a, 208c can be continuous sheets. Further, these sheets can include some demarcation that can be used in locating a redundant CNT heat blanket on a part. Persons of ordinary skill in the art will appreciate that variations in the trimming of the outer covering do not constitute a departure from the spirit of the present invention.

[0103] Referring also to Figure 5, a cross section taken through the portion of the redundant CNT heat blanket 202 configured for the aft spar 108 is shown, heating element 308_P and heating element 308_R are “paired” and located one on top of the other, electrically isolated by insulating layer 208b located therebetween, and encased within the elastomeric outer covering 208a, 208c, formed by placing three elastomeric materials 208a-c together, see also Figure 4, and curing them on a hot plate or in an autoclave.

[0104] The heating elements 308_P, 308_R are the same, both physically and electrically, and are constructed in like manner. Thus, only the heating element 308_P in the first or primary layer 301 will be described in more detail, the heating element 308_R in the second or redundant layer 301 being the same or “redundant.”

[0105] In accordance with principles of the present invention, what allows a heating element to act in a “redundant manner” or to be “redundant” is twofold. First, the heating elements are very thin, allowing for heat produced by a heating element in the redundant layer to pass through a corresponding heating element in the primary layer, the redundant heating element completing a

heating task that the heating element in the primary layer was unable to finish due to some sort of failure associated with the first heating element, e.g., a broken connection, broken or disconnected wire, etc.

[0106] For example, heat produced by the heating element 308_R in the redundant layer 302 passes through the heating element 308_P in the primary layer 301 to heat the upper wing skin 124 and the aft spar 108, and a bonding tape 402 located therebetween, and accelerate the cure of or cure the bonding tape 402 bonding the upper wing skin 124 to the aft spar 108, should the heating element 308_P cease heating, for whatever reason.

[0107] Second, the heating elements 300 are very flexible, allowing two heating elements that are electrically isolated and held together by the elastomeric insulator 208b, and encased within the elastomeric covering 208a, 208c to remain flexible. This allows a redundant heating blanket in accordance with principles of the present invention to flow the contours of curved or irregularly shaped parts. Often times, even when multiple layers of various materials are flexible in and of themselves, once they are joined together they naturally become more rigid. That is not the case with the present invention. The redundant heating blanket 202 is flexible and able to follow contours.

[0108] Each heating element 300 within the redundant CNT heat blanket 202 comprises a carbon nanotube (CNT) structured layer 404 defining an electrically conductive pathway having a first end 406 and a second end 408, and a first electrical termination 410 electrically coupled to the first end 406 and second electrical termination 412 electrically coupled to the second end 408.

[0109] As shown in Figure 5 and in a first process, the CNT structured layer 404 can be made in accordance with International PCT Application PCT/US2017/045422 filed on August 4, 2017, which claims the benefit of US Provisional Application 62/370,712 filed on August 4, 2016, both of which are incorporated herein by reference.

[0110] In the first process for manufacturing the CNT structured layer 404 carbon nanotubes (CNTs), a polymer, and a solvent are mixed using sonication and, in some embodiments, shear mixing to form a CNT-polymer suspension of CNTs in a uniform dispersion within the polymer and the solvent liquid. In some embodiments, the polymer comprises fluoroelastomers (FKM), silicones, fluorosilicones, perfluoroelastomers, ethylene propylene diene rubber (EPDM), butyl rubber, and thermoplastic elastomers, such as, for example, thermoplastic polyurethanes (TPU).

The CNT-polymer suspension is then applied onto a flexible carrier using a solvent cast coating process, a dip coating process, or a spray coating process. Heat is then applied to the applied CNT-polymer suspension and flexible carrier to heat the suspension and evaporate most, substantially all, or all of the solvent from the suspension, leaving the CNTs and polymer film to form a CNT-polymer film structure comprising a dispersion of the CNTs in the polymer structure upon the flexible carrier. The CNT-polymer film structure can then be removed from the flexible carrier, cut to size, and used as shown in Figure 5 for the CNT structured layer 404.

[0111] As person of ordinary skill in the art will appreciate that the purpose of mixing the CNT-polymer suspension is to evenly distribute the CNTs within the suspension so that when the solvent is driven off and the suspension is dried, the resulting CNT-polymer film structure has substantially uniform resistivity throughout the entire film structure in the plane.

[0112] In some embodiments, the thickness of the dried CNT-polymer film structure is at least about 0.06 millimeters (mm), less than about 0.3 mm, or between about 0.1 mm and about 0.2 mm to facilitate an automated manufacturing continuous cast coating process and to aid in or facilitate timely drying therein. The thicker the CNT-polymer film structure, the more drying time is required.

[0113] In a non-limiting example, the CNTs can be SWCNTs, the polymer can be a silicone, the solvent can be toluene, and the flexible carrier can be a polyester (PET) film. Using the forgoing, a number of CNT-polymer film structures were made using a manual solvent cast coating process on a PET film with a thickness of 125 micrometers (μm). For the CNT-polymer film structures made, Figure 6 shows the sheet resistances ($\Omega/\square$) as a function of the weight percentage (%) of SWCNTs within a CNT-polymer comprising silicone using three different casting coat thicknesses of 1.0, 1.5, and 1.75 millimeters (mm). As used herein the term silicone refers to polysiloxanes, the terms used interchangeably. Polysiloxanes are polymers that include any inert, synthetic compound made up of repeating units of siloxane, which is a chain of alternating silicon atoms and oxygen atoms, combined with carbon, hydrogen, and sometimes other elements. As shown, the sheet resistance can be increased by using different types of carbon nanotubes, for example, multiwall carbon nanotubes (MWCNTs) versus single wall carbon nanotubes (SWCNTs) or high aspect ratio versus low aspect ratio carbon nanotubes (CNTs), other factors being equal, e.g., thickness, weight, etc. Conversely, the sheet resistance can also be

decreased by using longer, pristine, SWCNTs, again, other factors being equal, e.g., thickness, weight, etc.

[0114] The sheet resistance can be at least about 3 $\Omega/\square$, at least about 5 $\Omega/\square$, at least about 10 $\Omega/\square$, at least about 20 $\Omega/\square$, at least about 30 $\Omega/\square$, at least about 40 $\Omega/\square$, at least about 50 $\Omega/\square$, at least about 60 $\Omega/\square$, at least about 70 $\Omega/\square$, at least about 80 $\Omega/\square$, at least about 90 $\Omega/\square$, at least about 100 $\Omega/\square$, at least about 200 $\Omega/\square$, at least about 300 $\Omega/\square$, at least about 400 $\Omega/\square$, at least about 500 $\Omega/\square$, at least about 600 $\Omega/\square$, at least about 700 $\Omega/\square$, at least about 800 $\Omega/\square$, at least about 900 $\Omega/\square$, at least about 1,000 $\Omega/\square$, at least about 1,100 $\Omega/\square$, at least about 1,200 $\Omega/\square$, at least about 1,300 $\Omega/\square$, at least about 1,400 $\Omega/\square$, at least about 1,500 $\Omega/\square$, or at least about 1,600 $\Omega/\square$. A useful sheet resistance can be selected from any value between and inclusive of about 3 to about 1,600 $\Omega/\square$. Non-limiting examples of sheet resistances using SWCNTs at a casting thickness of 1.0 millimeters (mm) can include about 5 $\Omega/\square$, about 6 $\Omega/\square$, about 7 $\Omega/\square$, about 14 $\Omega/\square$, about 36 $\Omega/\square$, about 43 $\Omega/\square$, about 46 $\Omega/\square$, about 47 $\Omega/\square$, about 58 $\Omega/\square$, about 288 $\Omega/\square$, about 450 $\Omega/\square$, about 750 $\Omega/\square$, and about 1,620 $\Omega/\square$. Non-limiting examples of sheet resistances using SWCNTs at a casting thickness of 1.5 millimeters (mm) can include about 3 $\Omega/\square$, about 4 $\Omega/\square$, about 5 $\Omega/\square$, about 9 $\Omega/\square$, about 24 $\Omega/\square$, about 28 $\Omega/\square$, about 31 $\Omega/\square$, about 39 $\Omega/\square$, about 192 $\Omega/\square$, about 300 $\Omega/\square$, about 500 $\Omega/\square$, and about 1,080 $\Omega/\square$. Non-limiting examples of sheet resistances using SWCNTs at a casting thickness of 1.75 millimeters (mm) can include about 3 $\Omega/\square$, about 4 $\Omega/\square$, about 8 $\Omega/\square$, about 21 $\Omega/\square$, about 25 $\Omega/\square$, about 27 $\Omega/\square$, about 31 $\Omega/\square$, about 165 $\Omega/\square$, about 257 $\Omega/\square$, about 429 $\Omega/\square$, and about 926 $\Omega/\square$. The useful weight percentage of SWCNTs by weight of the CNT-polymer film structure can be selected from any value between and inclusive of about 0.25 to about 25 percent. For example, in a CNT structured layer including SWCNTs and a silicone, the mass percentage of the SWCNTs within the layer can be selected from any value between and inclusive of at about 0.25 to about 5 percent by weight, about 5 to about 10 percent by weight, about 10 to about 15 percent by weight, 15 to about 20 percent by weight, and about 20 to about 25 percent by weight. Non-limiting examples of percentages include about 0.25, about 0.5, about 1, about 2, about 3, about 4, about 5, about 12, about 13, and about 25.

[0115] In some embodiments, for a CNT-polymer film structure between about 0.1 mm and about 0.2 mm in thickness comprising a constant uniform dispersion of the CNTs in the polymer comprising silicone, a CNT weight percentage of less than about 15 percent proved workable without crumbling with handling, while a CNT weight percentage of about 20 percent, or more,

was unusable, crumbling with handling. In some other embodiments, a CNT weight percentage of about 3 percent to about 12 percent resulted in a sheet resistance of about $70 \Omega/\square$ to about $5 \Omega/\square$, respectively.

[0116] Referring to Figure 7 and in a second process, the CNT structured layer 604 can be made in accordance with International PCT Publication WO 2016/019143 published on February 4, 2016 and US Patent Publication US 2017/0210627 A1 published on July 27, 2017 or US Patent 9,107,292 B2 granted on August 11, 2015, said publications and patent incorporated herein by reference. In another embodiment, the CNT structured layer 604 can further comprise graphene.

[0117] In the second process for manufacturing the CNT structured layer 604 a continuous conveying belt is moved along a path that traverses a pooling region and a vacuum box, and a continuous porous carrier material is applied to an upper side of the continuous conveying belt. An aqueous suspension of CNTs dispersed in a liquid is applied on the porous carrier material. In an embodiment, the dispersed CNTs have a median length of at least 0.05 mm and an aspect ratio of at least 2,500:1, the aspect ratio referring to the length of the CNTs versus the width or diameter of the CNTs, e.g., length to diameter. A continuous pool of the aqueous suspension of the CNTs is formed over and across the width of the continuous porous carrier material in the pooling region, to a uniform thickness sufficient to prevent puddling upon the continuous porous carrier material. As the porous carrier material and the continuous pool of the aqueous suspension of the CNTs are advanced over the vacuum box, the liquid of the aqueous suspension of the CNTs is drawn by vacuum through the porous carrier material, thereby filtering a uniform dispersion of filtered CNTs over the porous carrier material to form a filtered CNT structure. Optionally any residual liquid from the filtered CNT structure can be dried to form a CNT sheet over the porous carrier material. Optionally the CNT sheet can be removed from the porous carrier material. In another embodiment of a process for manufacturing the CNT structured layer 604, carbon nanostructures that are branched, crosslinked, and that share common walls with one another are dispersed in a solvent until the carbon nanostructure are non-agglomerated. The solution is then passed through a support layer including a plurality of fibers, whereby the carbon nanostructures conform to the fibers and bridge across apertures or gaps between the fibers to form a continuous carbon nanostructure layer. In yet another embodiment of a process for manufacturing the CNT structured layer 604, a solution containing carbon nanostructures, that are branched, crosslinked and that

shared common walls with one another, and chopped fibers are filtered to collect the carbon nanostructures on and between the fibers in a structured layer.

[0118] In one embodiment of the present invention, the maximum quantity of heat, in terms of power per unit area, e.g., watts per square inch (centimeter), produced by the redundant CNT heat blanket 202, at a given voltage, can be adjusted by varying the thickness 422 and therefore the electrical resistance of the CNT structured layer 404, 604. In yet another embodiment of the present invention, the maximum quantity of heat produced by the redundant heat blanket 202 can be adjusted by changing the CNT structure in the CNT structured layer 404, 604 for example by using single wall carbon nanotubes (SWCNTs) or multi-walled carbon nanotubes (MWCNTs).

[0119] The heating element 604 further comprises a thermoplastic film 610 disposed against the upper and lower surface of the CNT structured layer 604. The thermoplastic film 610 adds durability and/or functions to protect the structured CNT layer. A carrier material, e.g., carbon fiber, fiberglass, thermoplastic veils, can also increase the durability and/or function to protect the CNT structured layer. The thermoplastic film 610 can also function to prevent the ingress of the molten or floury elastomer that forms the elastomeric outer covering 208a-c, into the CNT structured layer 604 during application, thereby preventing the elastomeric outer covering 208a-c from raising the resistivity of the CNT structured layer 604. Although the ingress of the molten or floury elastomer into the CNT structured layer 604 raises the resistivity of the CNT structured layer 604, once the outer covering 208a-c cures, the redundant heat blanket 202 is still responsive to a power supply 222a, indicated schematically in Figure 7, and able to produce heat, albeit with higher resistivity.

[0120] The elastomeric outer covering 208a-c can be cured and/or formed so that the redundant CNT heat blanket forms a resilient three-dimensional shape that follows or mimics the shape of part, be it an inner or outer contoured surface of a part. A redundant CNT heat blanket with a predisposed shape or contoured shape rather than a shape that is substantially planar in nature makes the heat blanket easier to work with and particularly suited for placing the heat blanket into tight radiuses or narrow crevices in a part or for more closely following, i.e., staying in contact with, transitions between concave and convex portions of a part. For example, a redundant CNT heat blanket can be formed to follow the shape of a caul tool, placed over the caul tool, and then the caul tool with the redundant CNT heat blanket disposed there over, can be placed or inserted

into a tight radius area or narrow crevice in a part that is being bonded. Further, and as another example, a redundant CNT heat blanket with a predisposed shape or contoured shape makes the redundant CNT heat blanket able to follow transitions between the outer surface of an aircraft, e.g., a wing, and an opening therein, e.g., an air intake or outlet. One of ordinary skill in the art will appreciate that the elastomeric outer covering 208 can be cured or “cast,” e.g., “cast-ability,” in a multitude of ways, as desired, to make the redundant CNT heat blanket easier to work with and use without departing from the spirit of the present invention.

[0121] Electrically coupled to the CNT structured layer 404, 604, respectively, are at least two electrical terminations 410, 412, each representing different electrical nodes 424, 426. In one embodiment of the present invention, the first and the second electrical terminations 410, 412 each comprise expanded foil electrodes 414, 416 and die crimp connectors 418, 420. The expanded foil electrodes 414, 416 extend along each respective end 406, 408 of the CNT structured layer 404, 604 and are attached to the CNT structured layer 404, 604 using a conductive paste and are in electrical contact with the CNT structured layer 404, 604. Expanded foil is preferred to solid foil for the electrodes 414, 416 as the expanded foil provides a pathway for any air trapped during the construction of the blanket to escape, thereby preventing a “hot spot.” The addition of conductive adhesive, such as silver filled silicone, can aid in interfacing between the expanded foil and the CNT structured layer, further improving bond strength.

[0122] The die crimp connectors 418, 420 are located at one end of expanded foil electrodes 414, 416 and are crimped over the expanded foil electrodes 414, 416, the die crimp connectors 418, 420 in electrical contact with the expanded foil electrodes 414, 416 and the ends of the 406, 408 of the CNT structured layer 404, respectively. Those of ordinary skill in the art will appreciate that the die crimp connectors 418, 420 can be located elsewhere along the expanded foil electrodes 414, 416 as desired, for purposes of cable or wire management, and that such positioning does not constitute a departure from the present invention. Moreover, soldering can also be used in place of crimp connectors, preferably in blanket repair scenarios, or when the expanded foil electrode width is too narrow to practically crimp.

[0123] Further, in some other embodiments of the present invention, the electrical terminations 410, 412 can be electrically coupled by alternative means without departing from the spirit of the present invention such as electrically conductive adhesives or pastes, or simply with pressure

fittings, fasteners, or clamps that provide enough force against the CNT structured layer 404, 604 to maintain acceptably low contact resistance.

[0124] The electrical terminations 410, 412 of the heating element 308_P are electrically connected or coupled to the power supply 204, through wires or a cable 206a, forming an electrical circuit 430. The heating element 308_P is responsive to the power supply 204, e.g., power port 222a, thereby generating heat. Further, by varying, adjusting, setting, or selecting, i.e., raising or lowering, the voltage provided by the power supply, the quantity of heat, in terms of power per unit area, e.g., watts per square inch (centimeter), produced by the redundant CNT heat blanket 202 can be raised or lowered. In one embodiment of the present invention, the CNT structured layer 404, 604 and the power supply 204 are selected to produce heat to raise the temperature of the upper wing skin 124, the bonding tape 402 and the aft spar 108 to accelerate the cure of or cure the bonding tape bonding the upper wing skin 124 to the after spar, closing out the wing box 210. The temperature required depends on the resin contained in the bonding tape but can range from less than 100 degrees Fahrenheit (°F) to as much 450°F, or more.

[0125] Still referring to Figures 5 and 7 and in accordance with one aspect of the present invention, the redundant CNT heat blanket 202, 602, respectively, comprised of a heating element 308_P, 608_P comprised of a structured CNT layer 404, 604, respectively, is significantly thinner, and more flexible and drapeable, than a conventional filamentary heat blanket. For example, using the first process for making the CNT structured layer 404, a thickness 432 of the heat blanket 202 is less than about 0.170 inches (4.286 millimeters) or less than about 0.340 inches (8.636 millimeters), see Figure 5, the thickness of less than about 0.170 inches (4.286 millimeters) being based on two CNT polymer structure thicknesses, i.e., thickness 422, of about 0.1 mm (0.004 inches) and three layers of 0.030 inch (0.762 millimeters) elastomeric material that are cured together to form the elastomeric covering 208a-c, and two CNT polymer structure thickness of about 2 mm (0.080 inches) and three layers of 0.060 inch (1.524 mm) elastomeric material that are cured together to form the elastomeric covering 208a-c, respectively. Using the second process for making the CNT structured layer 604, a thickness 606 of the heating elements 608_P, 608_R can be less than 0.004 inches (0.1 millimeter) and, in one embodiment, the thickness 606 of the heating elements 608_P, 608_R can be approximately 0.01 inches (0.25 millimeters), see Figure 7. Further, a corresponding thickness 432 of the heating blanket 602, including the elastomeric outer covering

208a-c, can be less than 0.260 inches (6.572 millimeters) and, in one embodiment, the thickness 432 of the heating blanket can be approximately 0.110 inches (2.794 millimeters).

[0126] In other embodiments, a thickness 422, 606 of the heating elements can range from about 0.010 inches (0.25 millimeters) to about 0.008 inches (0.2 millimeters), or more. Additionally, the thickness of the elastomeric outer covering 208a, 208c, and/or the insulator 208b can range from less than 0.030 inches (0.762 millimeters) to about 0.060 inches (1.524 millimeters), or more. Further, the thicknesses of the elastomeric outer covering 208a, 208c, and/or the insulator 208b, need not necessarily be the same. For example, in some embodiments, the elastomeric outer covering 208a, 208c can be one thickness, while the insulator 208b can be another, perhaps lesser, thickness, for enhanced flexibility. In still other embodiments, the elastomeric material 208a that is proximate a part, e.g., wing skin 124 and aft spar 108, and bonding tape 402, can be one thickness while the outer most elastomeric material 208c that is further away from the part can be another thickness. For example, and in some embodiments, the inner elastomeric outer covering 208a can be one thickness, perhaps lesser thickness for enhanced heat transfer to the part, while the outer elastomeric outer covering 208c can be another, perhaps greater thickness providing enhanced insulating capability. To this end and some embodiments, a thickness of the redundant heat blanket according to the present invention is at least 0.020 inch (0.500 millimeters), and up to about 0.340 inches (8.636 millimeters), which can include a thickness of at least 0.110 inches (2.794 millimeters), or at least 0.170 inches (4.286 millimeters), or at least 0.260 inches (6.572 millimeters), and up to about 0.260 inches (6.572 millimeters), or up to about 0.170 inches (4.286 millimeters), or up to about 0.110 inches (2.794 millimeters). The heat blanket can be thinner, or thicker, than the indicated thickness.

[0127] The redundant CNT heat blanket 202, 602 is also quite flexible in nature. For example, in one embodiment, the redundant CNT heat blanket 202 can be folded over and/or doubled over on itself without “failure,” wherein the mean or average radius of the fold approaching or less than the thickness 432 of the redundant CNT heat blanket 202, e.g., 0.340 inches (8.636 millimeters) or less. In another embodiment, the redundant CNT heat blanket 602 can be folded over and/or doubled over on itself without “failure,” the mean or average radius of the fold approaching or less than the thickness 432 of the redundant CNT heat blanket 602, e.g., 0.260 inches (6.572 millimeters) or less, or 0.110 inches (2.794 millimeters) or less.

[0128] Additionally, the redundant CNT heat blanket 202 is also quite durable. For example, a heating element in accordance with principles of the present invention is able to sustain a puncture, such as that caused by a protrusion of a carbon fiber part, and still continue to operate generating the heat necessary for the task at hand, e.g., bonding or curing. Further, a heating element in accordance with principles of the present invention is also able withstand a cut or slice, such as, for example, that caused by passing the redundant CNT heat blanket over a sharp edge or shard of a carbon fiber part, and still continue to operate, generating the heat necessary for the task at hand. A filamentary heat blanket would not have survived either the puncture or, the slice or cut, the filament wire contained therein being severed, the filament therefore lacking electrical continuity, rendering the filamentary heat blanket useless, unable to generate heat for bonding or curing. Those of ordinary skill in the art will appreciate that the production environments that heat blankets are typically used in and the care that the heat blankets are given in those environments can, in many instances, be detrimental to the functionality of a filamentary heat blanket whereas, and in contrast, a CNT heat blanket or a redundant heat CNT in accordance with principles of the present invention would survive such treatment and continue to operate. This thickness, flexibility, cast-ability, and durability makes the redundant CNT heat blanket generally suited to “follow” or “conform” to the surfaces and shapes found in aerospace component parts and, more particularly suited to, closing out a box 210, as shown in Figure 3.

[0129] In some embodiments, the heat can be applied to a part with the use of temperature or thermal monitoring, in a control or feedback loop, that is, adjusting the power supplied to the heating elements within the redundant CNT heat blanket, in response to a measured temperature. The flow chart in Figure 8 includes a control loop that maintains a desired temperature on the surface part, controlling the power applied to one or more primary heating elements in response thereto, and should the temperature deviate from the desired temperature by some preselected amount or fall outside of a prescribed range, one or more redundant heating elements are then energized to maintain the desired temperature.

[0130] As shown, a process or program 500 used for heating or bonding a part 510 begins with a desired temperature being input to a controller 506. In some embodiments, the controller 506 can be a hot bonder as described in conjunction with Figure 3, the temperature being input through the user interface 218, for example. Moreover, the desired temperature 502 is the temperature that is required to accelerate the cure of or cure the bonding tape 402 located between the upper wing

skin 124 and the aft spar 108, bonding the upper wing skin 124 to the aft spar 108, see Figures 5 and 7.

[0131] The controller 506 through programming, controls the application of electrical energy 504 to the primary heating element(s) 508. In some embodiments, there can be a single heating element in a first or primary layer defining a single heat zone, while in other embodiments, there can be multiple heating elements 304_P, 308_P, 312_P, 318_P in the primary layer 301 defining numerous heat zones, see Figure 4, for example.

[0132] Power is applied to the primary heating element(s) 508 to warm a part 510 (e.g., upper wing skin 124, aft spar 108, and bonding tape 402) to the desired temperature 502 that was input. A sensor 516 (e.g., thermocouple 230a) placed on a surface (e.g., the outer surface 126 of the upper wing skin 124) of the part 510 measures the surface temperature of the part 510, feeding the measured temperature back to the controller 506. The controller 506 continues to adjust the electrical energy 504 applied to the primary heating element(s) in response to a comparison made between the desired temperature 502 (i.e., input temperature) and an actual temperature 512 that was measured by the sensor 516 (i.e., output temperature). If the output temperature 512 is greater than the input temperature 502, the electrical energy or power applied to the primary heating element(s) 508 is reduced or suspended. However, if the output temperature 512 is less than the input temperature 502, the electrical energy or power applied to the primary heating element(s) 508 is increased or continued.

[0133] In some embodiments, separate thermocouples 230a, 230b can be used for both the primary and the redundant layers 301, 302, see Figure 3, thereby facilitating the capture of individualized heating data by the controller 506. In other embodiments, a plurality of thermocouples or sensors can be used, for example, one for each heat zone or one for the primary heating element and one for the redundant heating element in each heat zone, or some combination thereof, depending on the heating data desired for a particular part. The controller 506 can then record, collect, and output the temperatures sensed by the thermocouples or sensor(s) 516, outputting the heating data 518, such as through a user interface, USB port, or network interface like included on a hot bonder. In some embodiments, the controller 506 can also record or timestamp when the primary heating element(s) and redundant heating element(s) 514 were

energized, also reporting out the same as heating data 518, thereby providing some record or assurance that the part 510 was heated and/or bonded correctly.

[0134] In the event that the actual temperature falls below some programmed or preselected amount, or falls outside of a prescribed range that has been programmed into the controller 506, the controller 506 then energizes redundant heating element(s) 514 to continue heating the part 510, and the heating or bonding of the part 510 continues on from there as before, the redundant heating element(s) being substituted for the primary heating element(s) for purposes of heating or bonding. This use of primary and redundant heating elements 508, 514 in applying heat to a part 510 with the use of temperature or thermal monitoring using a control or feedback loop, prevents the part from becoming scrap in the event that primary heating element(s) ceases heating for any reason as described hereinabove.

[0135] While various embodiments of a redundant heating system have been illustrated by the foregoing drawings and have been described in considerable detail, it is not intended to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will become readily apparent to persons of ordinary skill in the art.

What is claimed is:

1. A redundant carbon nanotube (CNT) heat blanket, comprising:
 - a primary heating element comprising:
 - a first carbon nanotube (CNT) structured layer defining a first layer and having first and second opposing ends; and
 - a first expanded metal foil traversing along and electrically coupled to the first end and a second expanded metal foil traversing along and electrically coupled to the second end, the first and second expanded metal foils physically and electrically spaced apart at the first and second opposing ends of the first CNT structured layer;
 - wherein the primary heating element is formed by the first CNT structured layer the between the first and second expanded metals foils;
 - a redundant heating element comprising:
 - a second CNT structured layer defining a second layer and also having first and second opposing ends, respectively corresponding to the first and second opposing ends of the first CNT structured layer; and
 - a first expanded metal foil traversing along and electrically coupled to the first end of the second CNT structured layer and a second expanded metal foil traversing along and electrically coupled to the second end of the second CNT structured layer, the first and second expanded metal foils physically and electrically spaced apart at the first and second opposing ends of the second CNT structured layer;
 - wherein the redundant heating element is formed by the second CNT structured layer the between the first and second expanded metals foils;
 - an elastomeric insulator located between and electrically isolating the primary and redundant heating elements; and
 - an elastomeric outer covering encasing both the primary and redundant heating elements, and the elastomeric insulator;
 - wherein the first and second CNT structured layers each comprises a carbon nanotube (CNT)-polymer film structure including single wall carbon nanotubes (SWCNTs) dispersed within a silicone layer, wherein the mass percentage of the SWCNTs

within the CNT-polymer film structure can be selected from any value between and inclusive of at least about 0.25 to about 25 percent by weight, resulting in a sheet resistance of about 1,500 $\Omega/\square$ to about 5 $\Omega/\square$, respectively.

2. The redundant CNT heat blanket of Claim 1, further comprising a conductive adhesive, the conductive adhesive used to interface the expanded metal foils with the CNT structured layers.
3. The redundant CNT heat blanket of Claim 1 or Claim 2, further comprising wires electrically coupled to the expanded metal foils.
4. The redundant CNT heat blanket of any of Claims 1-3, further comprising a power supply electrically coupled to the wires and configured to energize the primary and redundant heating elements.
5. The redundant CNT heat blanket of any of Claims 1-4, wherein the primary and the redundant heating elements are both equally capable of heating a part.
6. The redundant CNT heat blanket of any of Claims 1-5, wherein the primary heating elements is energized first and in the event of a failure of the primary heating element, the redundant element is energized in response thereto.
7. A redundant heating system, comprising:
 - (A) a redundant carbon nanotube (CNT) heat blanket, comprising:
 - (1) at least one heating element located in a first layer and at least one heating element located in a second layer, the at least one heating element located in the second layer registered at least in part with the at least one heating element located in the first layer, each of the at least one heating elements comprising:
 - (a) a carbon nanotube (CNT) structured layer defining an electrically conductive pathway having a first end and a second end; and
 - (b) a first electrical termination electrically coupled to the first end and a second electrical termination electrically coupled to the second end;

- (B) an elastomeric insulator located between and electrically isolating the at least one heating element located in the first layer and the at least one heating element located in the second layer; and
- (C) an elastomeric outer covering encasing both the at least one heating element located in the first layer and the at least one heating element located in the second layer.

8. The redundant heating system of Claim 7, wherein the at least one heating element located in the second layer is coextensive with the at least one heating element located in the first layer.

9. The redundant heating system of Claim 7, wherein the CNT structured layer comprises a carbon nanotube (CNT)-polymer film structure including single wall carbon nanotubes (SWCNTs) dispersed within a silicone layer, wherein the mass percentage of the SWCNTs within the CNT-polymer film structure can be selected from any value between and inclusive of at least about 0.25 to about 5 percent by weight, about 5 to about 10 percent by weight, about 10 to about 15 percent by weight, 15 to about 20 percent by weight, and about 20 to about 25 percent by weight.

10. The redundant heating system of Claim 9, wherein the mass of the SWCNTs within the CNT-polymer film structure can be selected from the group consisting of at least about 0.25 percent by weight of the CNT-polymer film structure, at least about 0.5 percent by weight of the CNT-polymer film structure, about 1 percent by weight, about 2 percent by weight, about 3 percent by weight, about 4 percent by weight, about 5 percent by weight, about 12 percent by weight, about 13 percent by weight, and about 25 percent by weight of the CNT-polymer film structure.

11. The redundant heating system of Claim 9, wherein the CNT-polymer film structure comprising a constant uniform dispersion of the CNTs in the polymer comprising silicone is between about 0.06 millimeters (mm) and about 0.3 millimeters (mm) and the CNT weight percentage is about 0.5 percent to about 25 percent, resulting in a sheet resistance of about 1,500 $\Omega/\square$ to about 5 $\Omega/\square$, respectively.

12. The redundant heating system of Claim 4, wherein the thickness of the CNT-polymer film structure is at least about 0.1 millimeters (mm), and less than about 0.2 millimeters (mm).

13. The redundant heating system of Claim 10, wherein the thickness of the redundant CNT heat blanket is less than about 0.170 inches (4.286 millimeters) or less than about 0.340 inches (8.572 millimeters).

14. The redundant heating system of Claim 13, wherein in use the redundant CNT heating blanket can be folded over and/or doubled over on itself, the mean or average radius of the fold approaching the thickness of the redundant CNT heat blanket, without failure of the heating elements.

15. The redundant heating system of any of Claims 7-14, wherein the amount of heat produced by the redundant CNT heat blanket at a given voltage is varied by varying at least one of the thickness of the CNT structured layer, the percentage by weight of CNTs in the CNT-polymer film structure, the length of the CNTs in the CNT-polymer film structure, and the type of the carbon nanotubes (CNTs) in the CNT-polymer film structure.

16. The redundant heating system of Claim 15, wherein the resistivity of the CNT-polymer film structure comprising SWCNTs at a casting thickness of 1.0 millimeter (mm) is about 5 $\Omega/\square$, about 6 $\Omega/\square$, about 7 $\Omega/\square$, about 14 $\Omega/\square$, about 36 $\Omega/\square$, about 43 $\Omega/\square$, about 46 $\Omega/\square$, about 47 $\Omega/\square$, about 58 $\Omega/\square$, about 288 $\Omega/\square$, about 450 $\Omega/\square$, about 750 $\Omega/\square$, and about 1,620 $\Omega/\square$; the resistivity of the CNT-polymer film structure comprising SWCNTs at a casting thickness of 1.5 millimeters (mm) is about 3 $\Omega/\square$, about 4 $\Omega/\square$, about 5 $\Omega/\square$, about 9 $\Omega/\square$, about 24 $\Omega/\square$, about 28 $\Omega/\square$, about 31 $\Omega/\square$, about 39 $\Omega/\square$, about 192 $\Omega/\square$, about 300 $\Omega/\square$, about 500 $\Omega/\square$, and about 1,080 $\Omega/\square$; and the resistivity of the CNT-polymer film structure comprising SWCNTs at a casting thickness of 1.75 millimeters is about 3 $\Omega/\square$, about 4 $\Omega/\square$, about 8 $\Omega/\square$, about 21 $\Omega/\square$, about 25 $\Omega/\square$, about 27 $\Omega/\square$, about 31 $\Omega/\square$, about 165 $\Omega/\square$, about 257 $\Omega/\square$, about 429 $\Omega/\square$, and about 926 $\Omega/\square$.

17. The redundant heating system of any of Claims 9-16, wherein the resistivity of the CNT-polymer film structure comprising SWCNTs is at least about 3 $\Omega/\square$, at least about 5 $\Omega/\square$, at least about 10 $\Omega/\square$, at least about 20 $\Omega/\square$, at least about 30 $\Omega/\square$, at least about 40 $\Omega/\square$, at least about 50 $\Omega/\square$, at least about 60 $\Omega/\square$, at least about 70 $\Omega/\square$, at least about 80 $\Omega/\square$, at least about 90 $\Omega/\square$, at

least about 100 $\Omega/\square$, at least about 200 $\Omega/\square$, at least about 300 $\Omega/\square$, at least about 400 $\Omega/\square$, at least about 500 $\Omega/\square$, at least about 600 $\Omega/\square$, at least about 700 $\Omega/\square$, at least about 800 $\Omega/\square$, at least about 900 $\Omega/\square$, at least about 1,000 $\Omega/\square$, at least about 1,100 $\Omega/\square$, at least about 1,200 $\Omega/\square$, at least about 1,300 $\Omega/\square$, at least about 1,400 $\Omega/\square$, at least about 1,500 $\Omega/\square$, or at least about 1,600 $\Omega/\square$.

18. The redundant heating system of Claim 7, wherein the CNT structured layer further comprises a CNT sheet formed over a porous carrier material.

19. The redundant heating system of Claim 18, wherein the CNT structured layer has an upper surface and a lower surface and the at least one pair of heating elements further comprising a thermoplastic film disposed against at least one of the upper surface and the lower surface of the CNT structured layer.

20. The redundant heating system of Claim 19, wherein a flexural strength of the CNT structured layer is equal to or greater than a flexural strength of the thermoplastic film.

21. The redundant heating system of Claim 18-20, wherein the thickness of the redundant CNT heat blanket is less than about 0.110 inches (2.794 millimeters) or less than about 0.260 inches (6.572 millimeters).

22. The redundant heating system of any of Claims 7-21, wherein the elastomeric outer covering and the elastomeric insulating layer is selected individually from the group consisting of a fluoroelastomer (FKM), silicone, a fluorosilicones, a perfluoroelastomers, an ethylene propylene diene rubber (EPDM), butyl rubber, a thermoplastic elastomer, and a thermoplastic polyurethane (TPU) fluoroelastomer, and a combination thereof.

23. The redundant heating system of any of Claims 7-19, wherein either or both the elastomeric outer covering and the elastomeric insulating layer is selected from the group consisting of an elastomeric silicone rubber and a fiberglass reinforced silicone rubber, and in a thickness selected from the group consisting of 0.015, 0.030, and 0.060 inches (0.381, 0.762, and 1.524 millimeters (mm)).

24. The redundant heating system of any of Claims 7-23, wherein the redundant CNT heat blanket further comprising a plurality of pairs of heating elements, each pair defining a heat zone.
25. The redundant heating system of any of Claims 7-24, wherein the first and the second electrical terminals comprise an expanded foil electrode in electrical contact with the CNT structured layer, along the first and the second end of the CNT structured layer, respectively.
26. The redundant heating system of Claim 25, wherein the first and the second electrical terminals further comprise a conductive adhesive to interface the expanded foil electrode to the CNT structured layer.
27. The redundant heating system of Claim 25, wherein the first and the second electrical terminals further comprising die crimp connectors in electrical contact with the expanded foil electrodes along the first and the second ends of the CNT structured layer.
28. The redundant heating system of Claim 25, wherein solder is used to attach wires to the expanded foil electrodes.
29. The redundant heating system of Claim 7, further comprising a power supply electrically coupled to the redundant CNT heat blanket.
30. The redundant heating system of Claim 7, further comprising one or more “hot bonders” electrically coupled to the redundant CNT heat blanket and configured to energize the redundant CNT heat blanket.
31. The redundant heating system of Claim 30, further comprising one or more thermocouples electrically coupled to the one or more “hot bonders” and configured for sensing a temperature of a surface of a part, wherein the one or more “hot bonders” energize the redundant CNT heat blanket in response to a temperature sensed by the one or more thermocouples.
32. A method of mechanically coupling composite parts, comprising the steps of:

electrically coupling corresponding primary heating and secondary heating elements of a redundant CNT heat blanket to a source of electrical energy;

electrically coupling a temperature sensor to a controller;

inputting a desired temperature into the controller;

placing a first composite part having an outer surface on a second composite part;

positioning the temperature sensor on the outer surface of the first composite part;

placing the redundant CNT heat blanket over the temperature sensor and on the outer surface of the first composite part;

using the controller to monitor the temperature sensed by the temperature sensor, compare the temperature sensed by the temperature sensor to the desired temperature, and control the flow of electrical energy to the primary heating element in response to the comparison to bond the first composite part and the second composite part together; and

in the event that the temperature sensed by the temperature sensor deviates from the desired temperature, using the controller to control the flow of electrical energy to the redundant heating element to continue bonding the first composite part and the second composite part together.

33. The method of Claim 32, the first composite part and the second composite part each having a bonding surface, further comprising cleaning the bonding surfaces of both composite parts.

34. The method of either of Claims 32 or 33, further comprising placing a bonding tape between the bonding surfaces of the first composite part and the second composite part.

35. The method of any of Claims 32-34, further comprising timestamping and reporting out the energizing of the primary heating element and the redundant heating element.

36. The method of any of Claims 32-35, wherein the desired temperature comprises a temperature range.

37. The method of any of Claim 32-35, wherein the controller is one or more “hot bonders.”

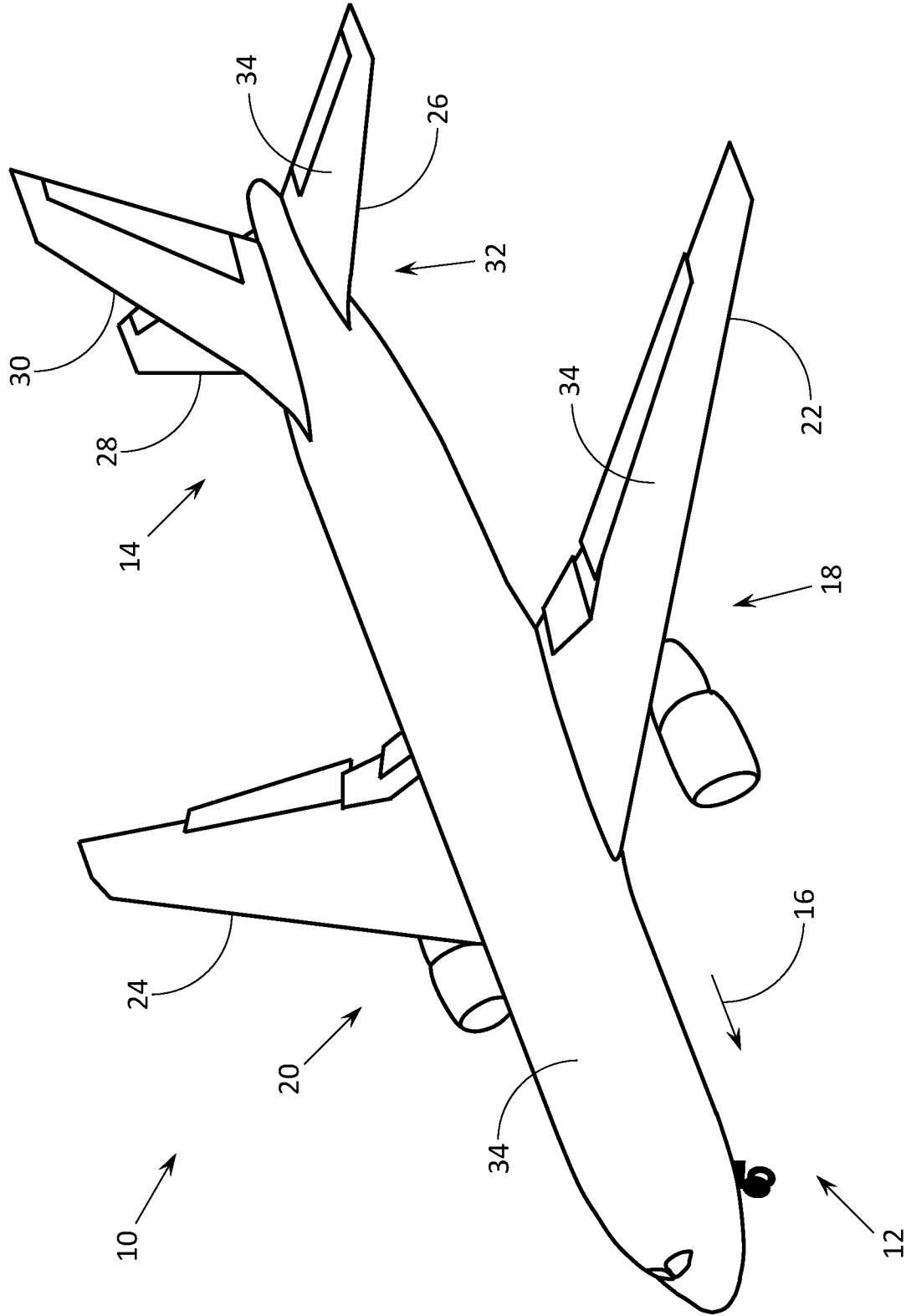


FIG. 1

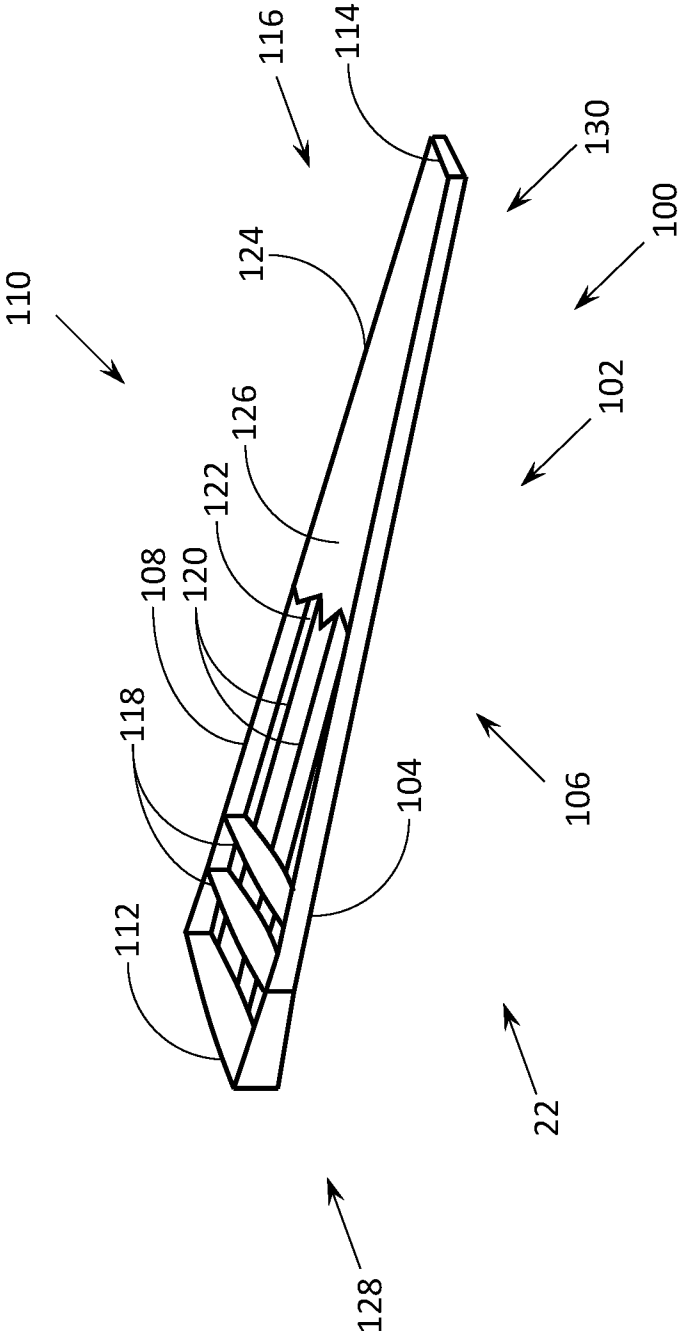


FIG. 2

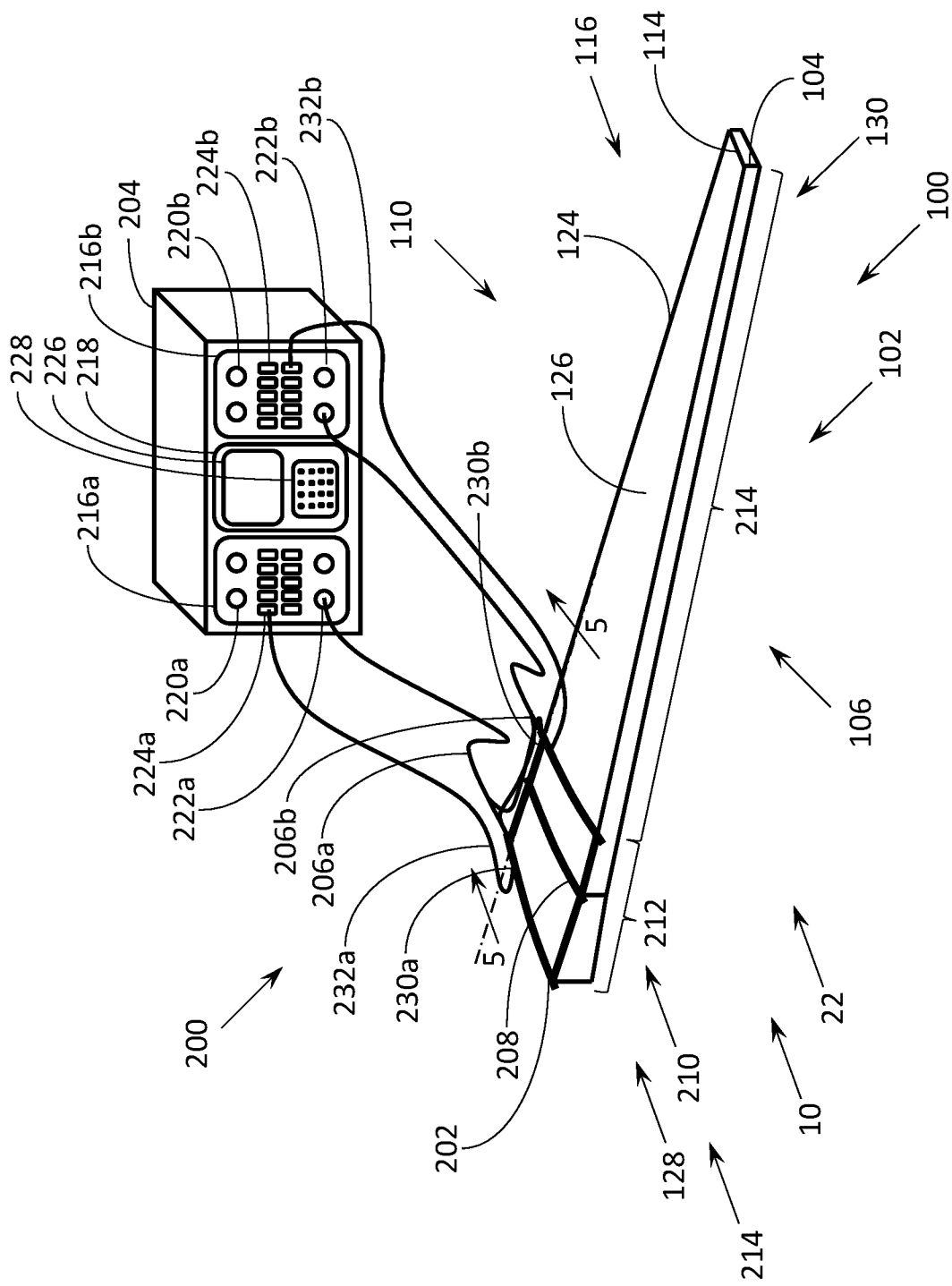


FIG. 3

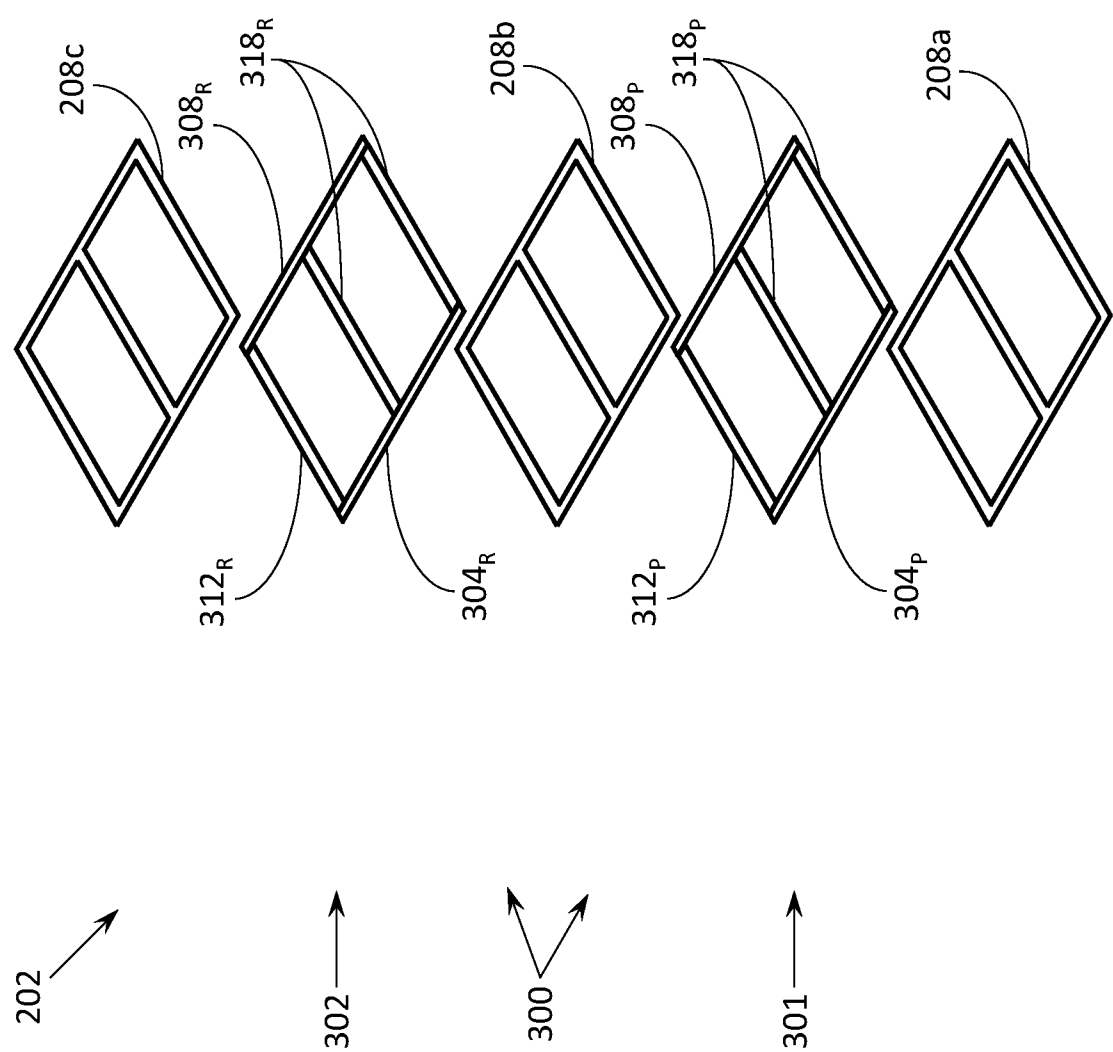


FIG. 4

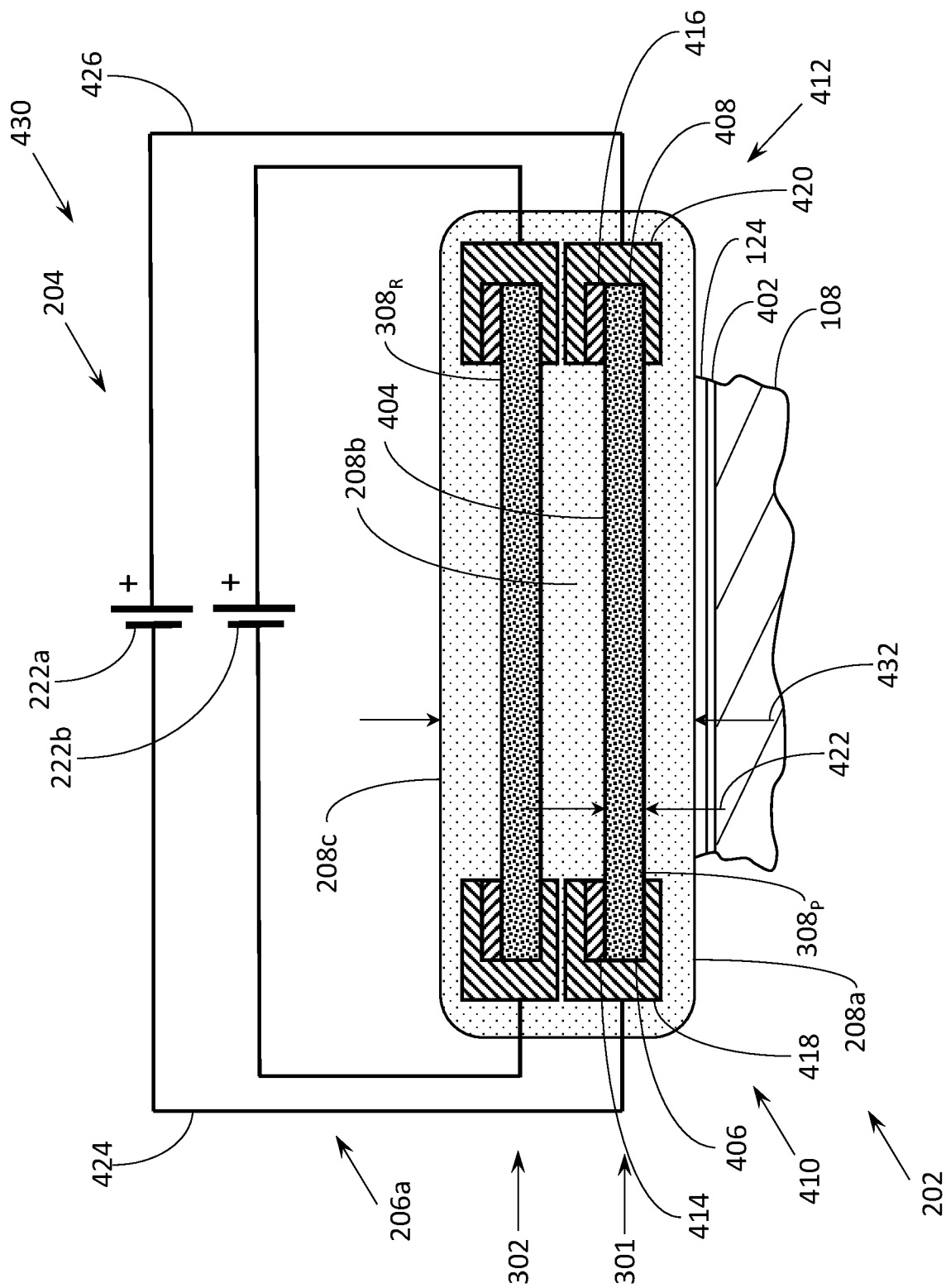


FIG. 5

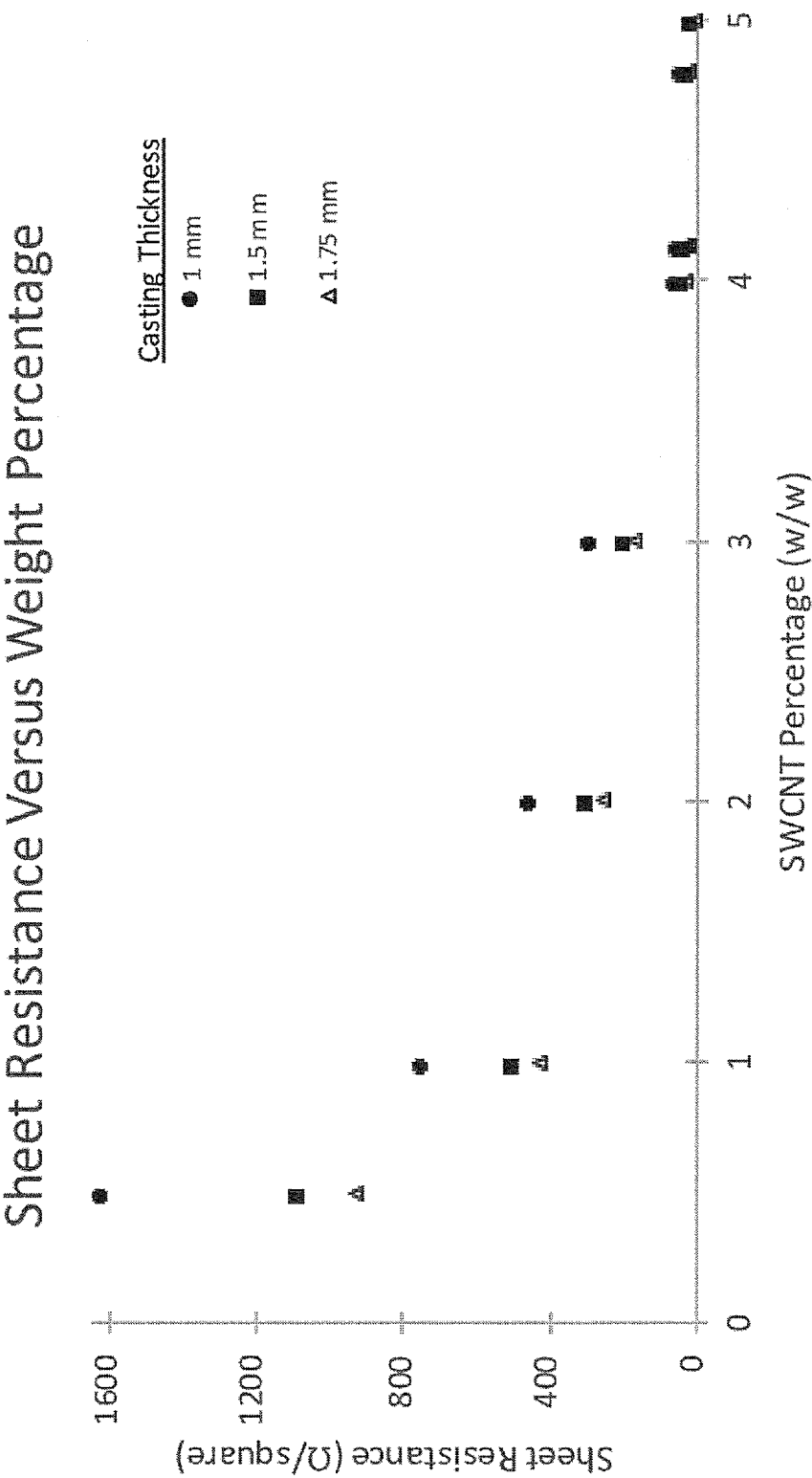


FIG. 6

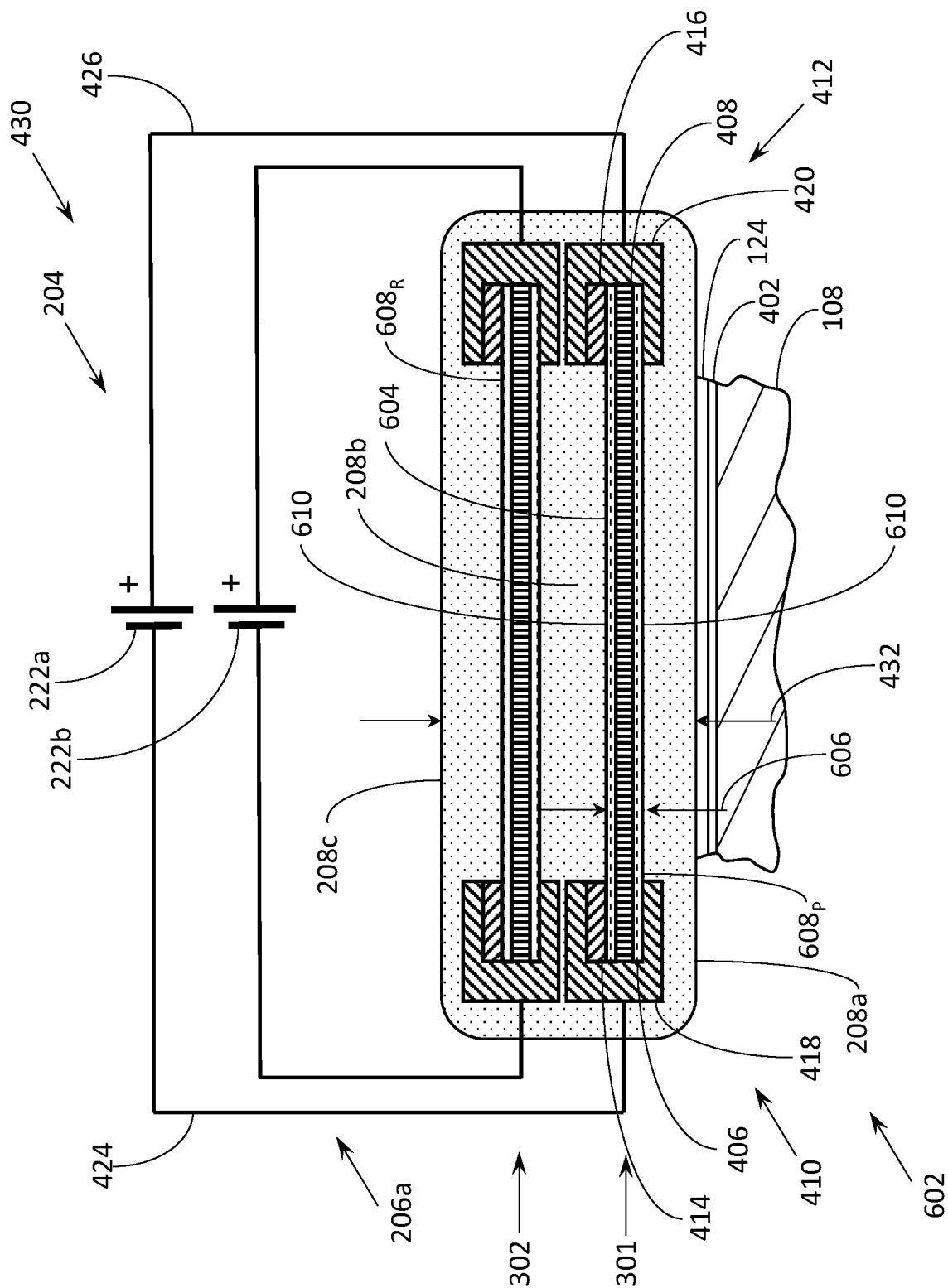


FIG. 7

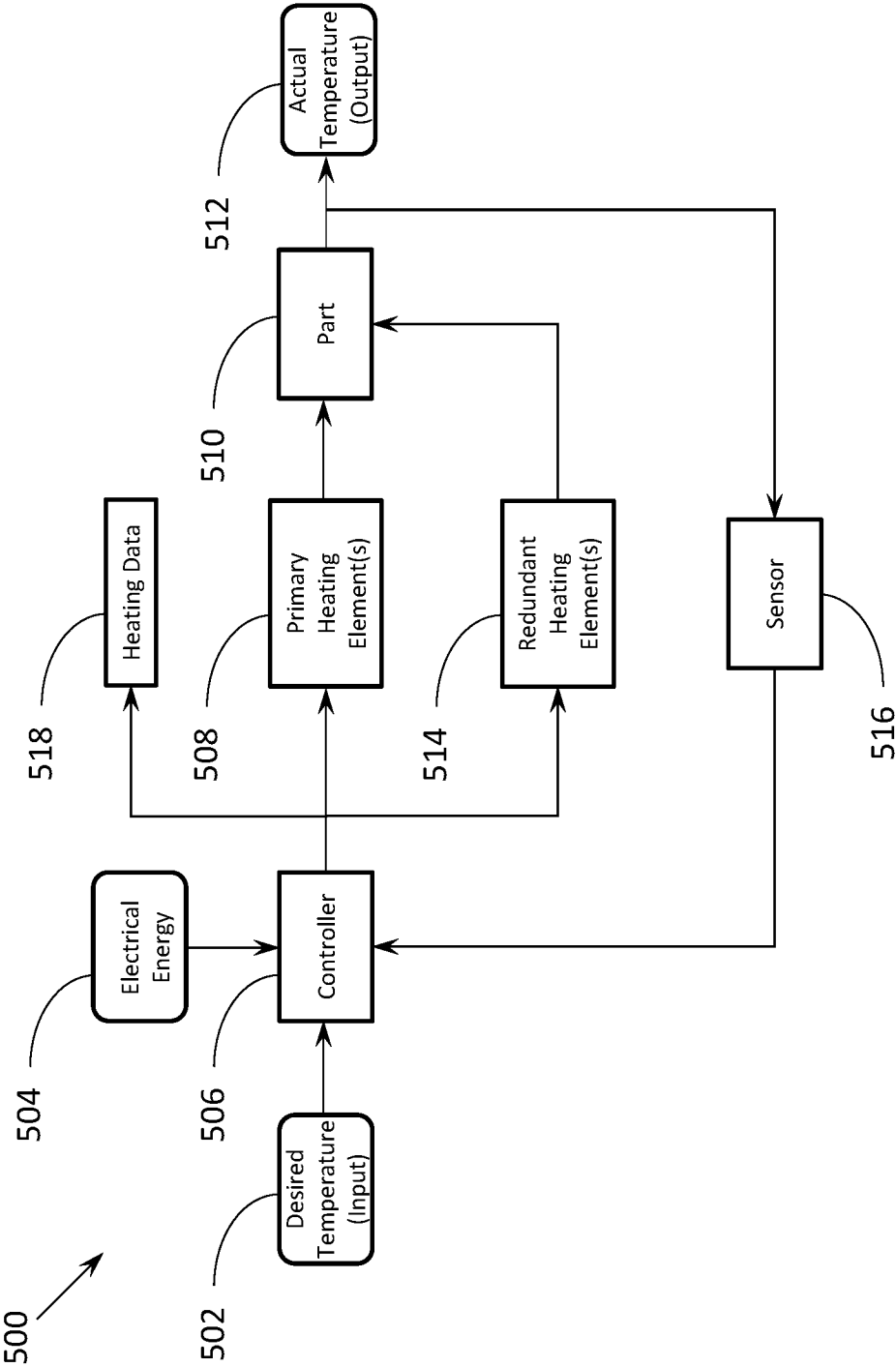


FIG. 8