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(54) Title: METHOD AND APPARATUS FOR DETECTING A CRACK OR DEFECT IN A CONDUCTIVE OR SEMICONDUCTIVE MATERIAL

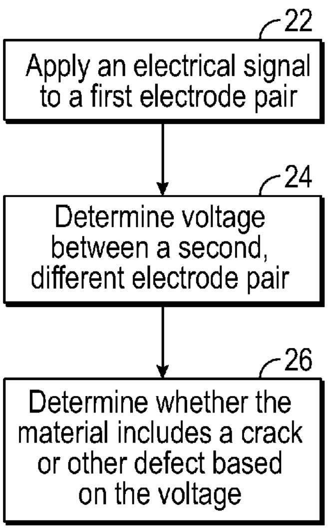

FIG. 2

(57) Abstract: The disclosure describes techniques for detecting a crack or defect in a material. The technique may include applying an electrical signal to a first electrode pair electrically coupled to the material. The method also may include, while applying the electrical signal to the first electrode pair, determining a voltage between a second, different electrode pair, where at least one electrode of the second, different electrode pair is electrically coupled to the material. The method further may include determining whether a crack or other defect is present in the material based on the voltage.

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METHOD AND APPARATUS FOR DETECTING A CRACK OR DEFECT IN A CONDUCTIVE OR SEMICONDUCTIVE MATERIAL

TECHNICAL FIELD

The disclosure relates to techniques for verifying structural integrity of conductive or semiconductive materials.

BACKGROUND

Many materials are useful when their mechanical properties remain intact, but less useful when damaged, such as when cracked. Thus, detection whether these materials are damaged is important. As one example, ceramic body plating is used to protect soldiers, police officers, and other security personnel from projectiles. Ceramic body plating may be useful when undamaged, but may be replaced after being damaged, e.g., after cracking.

X-ray scanning, including X-ray radiography and X-ray computed tomography (CT scanning) may be used to detect cracks or other defects in materials. However, such techniques may utilize large and heavy scanners, which may not be easily portable. Further, X-ray scanning and X-ray CT scanning may be relatively expensive, relatively slow, or both.

SUMMARY

In general, this disclosure describes systems and techniques for verifying structural integrity of a material. The techniques may utilize a four-point voltage measurement to determine whether the material includes a crack or other defect. In the four-point voltage measurement, a power source may apply an electrical signal to the material via a pair of drive electrodes and the resulting voltage may be determined (e.g., measured or determined from another measured electrical parameter) via a pair of measurement electrodes. One or both electrodes of the pair of measurement electrodes is electrically coupled to the material. In examples in which both electrodes of the pair of measurement electrodes are electrically coupled to the material, the determined voltage is the voltage difference between the first and second measurement electrodes electrically coupled to the material. In examples in which one electrode of the pair of measurement electrodes is electrically coupled to the material, the other electrode of the pair of measurement electrodes may be at a reference voltage, such as ground. In such examples, the determined voltage is the voltage difference between the first measurement electrode electrically coupled to the material and the second measurement electrode at the reference voltage. By comparing the resulting voltage to a control voltage corresponding to the same measurement electrode pair when the material or a similar material or set of materials is known to be intact (undamaged) or a predetermined threshold voltage, the four-point voltage measurement may be used to determine whether the material is damaged or intact.

In some examples, the disclosure describes a method for detecting a crack or defect in a material. The method may include applying an electrical signal to a first electrode pair electrically coupled to the material. The method also may include, while applying the electrical signal to the first electrode pair,

determining voltage between a second, different electrode pair, wherein at least one electrode of the second, different electrode pair is electrically coupled to the material. The method further may include determining whether the material includes a crack or other defect based on the voltage.

In some examples, the disclosure describes a method for detecting a crack or defect in a material. The method may include, for each respective pair of drive electrodes of a plurality of respective pairs of drive electrodes electrically coupled to the material, applying an electrical signal to the respective pair of drive electrodes. The method also may include, for each respective pair of drive electrodes, determining a respective voltage between each respective pair of measurement electrodes of a plurality of pairs of measurement electrodes while applying the electrical signal to the respective pair of drive electrodes, wherein at least one electrode of each respective pair of measurement electrodes is electrically coupled to the material. The method further may include determining whether the material includes a crack or other defect based on the respective voltages.

In some examples, the disclosure describes system including a set of N electrodes electrically coupled to a material; an electrical signal source; and a computing device. The computing device may be configured to cause the electrical signal source to apply an electrical signal to a first pair of drive electrodes. The first pair of drive electrodes are from the set of N electrodes. The computing device also may be configured to determine a voltage between a first pair of measurement electrodes. At least one electrode from the first pair of measurement electrodes is from the set of N electrodes and both electrodes of the first pair of measurement electrodes are different than the first pair of drive electrodes. The computing device additionally may be configured to determine whether the material includes a crack or other defect based on the voltage.

The techniques described herein may provide one or more advantages. For example, a four-point voltage measurement may offer improved accuracy and sensitivity for detecting cracks or other defects in a material compared to a two-point voltage measurement. As another example, a four-point voltage measurement system may offer improved portability and cost compared to an X-ray radiography or X-ray computed tomography system, while offering sufficient accuracy and detail to enable detection of cracks or other defects in a material being used in the field.

The details of one or more examples are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a conceptual and schematic diagram block illustrating an example system for determining whether a material includes a crack or other defect using a four-point voltage measurement.

FIG. 2 is a flow diagram illustrating an example technique for determining whether a material includes a crack or other defect using a four-point voltage measurement.

FIG. 3 is a conceptual and schematic block diagram illustrating an example system for determining whether a material includes a crack or other defect using a four-point voltage measurement.

FIG. 4 is a flow diagram illustrating an example technique for determining whether a material includes a crack or other defect using a four-point voltage measurement.

FIG. 5 is a diagram illustrating an example finite element model of a material that includes a simulated crack or other defect.

FIG. 6 is a diagram illustrating an example false color model output overlaid on an example finite element model of a material that includes a simulated crack or other defect.

FIG. 7 is a diagram illustrating an example false color output of a finite element model of a material that includes a simulated crack or other defect.

FIG. 8 is a drawing illustrating an example ceramic sample including a sixteen element electrical contact array and a flex circuit.

FIG. 9 is a drawing illustrating the example ceramic sample of FIG. 8 attached to a flex circuit, a breakout board, and a set of leads.

FIG. 10 is a drawing illustrating the example ceramic sample of FIG. 8 including an electrode array and a location of a crack.

FIG. 11 is a diagram illustrating an example false color output of the EIDORS algorithm for the example ceramic sample of FIG. 10.

DETAILED DESCRIPTION

The disclosure describes systems and techniques for verifying structural integrity of a material. The techniques may utilize a four-point voltage measurement to determine whether the material includes a crack or other defect. In the four-point voltage measurement, a power source may apply an electrical signal to the material via a pair of drive electrodes and the resulting voltage may be determined (e.g., measured or determined based on another measured electrical parameter) via a pair of measurement electrodes. One or both electrodes of the pair of measurement electrodes is electrically coupled to the material. In examples in which both electrodes of the pair of measurement electrodes are electrically coupled to the material, the determined voltage is the voltage difference between the first and second measurement electrodes electrically coupled to the material. In examples in which one electrode of the pair of measurement electrodes is electrically coupled to the material, the other electrode of the pair of measurement electrodes may be at a reference voltage, such as ground. In such examples, the determined voltage is the voltage difference between the first measurement electrode electrically coupled to the material and the second measurement electrode at the reference voltage.

By comparing the resulting voltage to a control voltage or a predetermined threshold voltage, the four-point voltage measurement may be used to determine whether the material is damaged or intact. In some examples, the control voltage may be determined for the same material via the same pair of measurement electrodes when the material is known to be intact (undamaged), the control voltage may be determined using a model of the material in an intact (undamaged) state, or the control voltage may be determined as an average (e.g., mean) of a plurality of similar materials (e.g., in geometry and composition) that are known to be intact (undamaged). In some examples, the predetermined threshold voltage may be selected so that a voltage below the threshold voltage value is indicative of a crack or other defect and a voltage above the threshold voltage value is not indicative of a crack or other defect.

A four-point voltage measurement for verifying structural integrity may provide advantages compared to two-point voltage measurements and other techniques for verifying structural integrity. A two-point voltage measurement may be affected not only by electrical property variations in the material under test, but also in any electrical connections between the measurement apparatus and the material, such as within electrical leads, in electrical contacts between the leads and the material, or the like. In some examples, variations in electrical properties of these components may complicate measurement of voltage across the material under test, as these electrical properties may vary differently (in magnitude, direction, or both) than the electrical properties of the material under test. In some examples, one or more of these electrical properties may actually vary to a greater extent than the change in electrical properties, such as resistivity, conductivity, or other related electrical properties, in the material due to a crack, which may obscure the change in electrical properties in the material due to a crack. By using a four-point voltage measurement, the contributions of the electrical leads coupling the pair of measurement electrodes to the measurement device and any contact-related error sources (e.g., contact resistance) between the pair of measurement electrodes and the material may be reduced or substantially eliminated, as little current flows to the measurement device. Hence, a four-point voltage measurement may facilitate measurement of voltage differences in the material and detection of cracks due to changes in electrical properties.

Other techniques also may be used to detect cracks in a material. For example, X-ray radiography or X-ray computed tomography (CT) may be used to detect cracks in a material. However, X-ray radiography and X-ray CT utilize relatively large, relatively expensive equipment to perform the crack detection. This may prevent X-ray radiography and X-ray CT from being portable, such as being used to test materials in the environments in which they are used. Moreover, X-ray radiography and X-ray CT may be relatively time consuming.

In contrast, a four-point voltage measurement utilizes relatively smaller, relatively less expensive equipment. As such, the equipment may enable portable crack detection systems, which may be used to detect cracks in materials *in situ* rather than requiring removing the materials to be tested to the testing equipment.

FIG. 1 is conceptual and schematic diagram block illustrating an example system 10 for determining presence of a crack or other defect in a material 16 using a four-point voltage measurement. The system 10 of FIG. 1 includes a computing device 12, an electrical signal source 14, and a plurality of electrodes 18A–18D (collectively, “electrodes 18”). Electrodes 18 are electrically coupled to material 16, which is being tested using a four-point voltage measurement.

Material 16 may be any material for which detection of a potential crack or other defect is desired. In some examples, material 16 may be an electrically conductive or an electrically semiconductive material. For example, material 16 may include a metal, an alloy, a metalloid, a semiconductor, an electrically conductive or semiconductive ceramic, or the like. In some examples, material 16 may include a ceramic such as boron carbide (B_4C), silicon carbide (SiC), alumina (Al_2O_3), composites thereof, or the like.

Material 16 may be used in any one of a wide variety of applications. For example, material 16 may be a ceramic that has relatively high hardness, a relatively high Young's modulus, a relatively high tensile strength, and may be used in ceramic armor plating. Ceramic armor plating may be used in body armor for military and police personnel, vehicle armor, or the like. Example materials for ceramic armor plating include boron carbide (B_4C), silicon carbide (SiC), alumina (Al_2O_3), composites thereof, or the like.

Material 16 may define any geometry, and the geometry of material 16 may be based at least in part on the intended use for material 16. For example, ceramic armor plating may have a geometry defined by the surface that the armor plating will be applied to. Example geometries for material 16 include, but are not limited to, polygonal solids, such as rectangular solids or solids with more sides.

Electrical signal source 14 may include any device configured to output an electrical signal to electrodes 18. The electrical signal may include an alternating current (AC) signal or a direct current (DC) signal. In some examples, electrical signal source 14 may output a current signal; in other examples, electrical signal source 14 may output a voltage signal. In some examples, electrical signal source 14 may include a power source, such as a battery, a capacitor, a supercapacitor, a transformer electrically connected to a mains voltage, or the like. In some examples, in addition to the power source, electrical signal source 14 may include analog or digital circuitry configured to receive the electrical signal from the power source and modify the electrical signal into a format suitable for output to electrodes 18.

Electrodes 18 include a plurality of electrodes electrically coupled to material 16. In some examples, as shown in FIG. 1, electrodes 18 may include a pair of drive electrodes 18A and 18B each electrically coupled to electrical signal source 14, e.g., by a respective lead wire, and a pair of measurement electrodes 18C and 18D each electrically connected to computing device 12, e.g., by a respective lead wire. Each of electrodes 18 may be electrically connected to material 16 using any suitable type of electrical connection, including, for example, an electrically conductive adhesive, an electrically conductive solder, embedding electrodes 18 in material 16, or the like.

In some examples, rather than both measurement electrodes 18C and 18D being electrically coupled to material 16, only one of the measurement electrodes (e.g., measurement electrode 18C) of the pair of measurement electrodes is electrically coupled to the material. The other measurement electrode of the pair of measurement electrodes may be at a reference voltage, such as ground or a selected offset voltage. In such examples, the determined voltage is the voltage difference between the first measurement electrode electrically coupled to the material and the second measurement electrode at the reference voltage.

In some examples, electrodes 18 may include more than one pair of drive electrodes, more than one pair of measurement electrodes, or both. In some examples, as described below with respect to FIG. 3, electrodes 18 may include a plurality of electrodes connected to a switch network, which allows any electrode of the plurality of electrodes to be selectively coupled to electrical signal source 14 or computing device 12.

Electrodes 18 may be attached to any surface of material 16. The surface to which electrodes 18 are attached may affect the direction in which the electrical field extends and current flows within material 16. Cracks or other defects may affect the magnitude of the voltage more significantly when the electrical field and current flow extends across a plane of the crack (e.g., normal to a surface of the crack). As such, in some examples, the likely locations of cracks or other defects and the likely orientation of cracks or other defects within material 16 may be predicted based on the use for material 16. In some of these examples, electrodes 18 may then be attached to material 16 so that the electrical field and current flow within material 16 extends substantially normal to a predicted orientation of the crack or other defect.

In some examples, rather than predicting a location of the crack or other defect within material 16 and placing electrodes 18 based on the prediction, electrodes 18 may be attached to more than one surface of material 16. For example, if material 16 is in the shape of a cube, electrodes 18 may be attached to three orthogonal surfaces of the cube. By attaching a respective electrode of electrodes 18 to three orthogonal surfaces, the electrical field and current flow may be caused to extend in one of three orthogonal directions depending on the electrodes 18 through which the electrical signal is applied. This may increase a likelihood that induced the electrical field and current flow will extend within material 16 normal to the plane of any crack in material 16. Other examples are possible for other shapes.

Computing device 12 is configured to control operation of system 10, including electrical signal source 14. Computing device 12 may include any of a wide range of devices, including computer servers, desktop computers, notebook (i.e., laptop) computers, tablet computers, and the like. In some examples, computing device 12 may include a processor. The processor may include one or more microprocessors, digital signal processors (DSP), application specific integrated circuits (ASIC), field programmable gate arrays (FPGA), or other digital logic circuitry. In some examples, computing device 12 may include an analog-to-digital converter (ADC), or system 10 may include an ADC separate from computing device 12. In examples in which the ADC is separate from computing device 12, the ADC may be electrically coupled between measurement electrode 18C and computing device 12 and between measurement electrode 18D and computing device 12. The ADC may measure the voltage across measurement electrodes 18C and 18D, e.g., under control of computing device 12.

Computing device 12 is electrically coupled to the pair of measurement electrodes 18C and 18D, and communicatively coupled to electrical signal source 14. Computing device 12 may be configured to cause electrical signal source 14 to apply an electrical signal (e.g., a voltage signal or current signal) to the pair of drive electrodes 18A and 18B. Computing device 12 also may be configured to determine a voltage across the pair of measurement electrodes 18C and 18D in response to the electrical signal, regardless of whether one or both of measurement electrodes 18C and 18D are electrically coupled to material 16. In some examples, computing device 12 includes an ADC that measures the voltage across the pair of measurement electrodes 18C and 18D. In other examples, computing device 12 controls an external ADC to measure the voltage across the pair of measurement electrodes 18C and 18D. In other examples, computing device 12 may measure or control another device to measure another electrical parameter (e.g., current) and may determine the voltage based on the measured electrical parameter.

By using a four-point voltage measurement, the contributions of the electrical leads coupling the pair of measurement electrodes 18C and 18D to computing device 12 and any contact resistance between measurement electrodes 18C and 18D and material 16 may be reduced or substantially eliminated, as little current flows to computing device 12. Hence, a four-point voltage measurement may facilitate measurement of voltages in material 16 and detection of cracks due to changes in electrical properties, such as resistivity, conductivity, or other related electrical properties.

In some examples, to determine whether material 16 includes a crack or other defect, computing device 12 may determine a control voltage. The control voltage may be based on material 16, a model, or an average of a plurality of materials that are similar to or substantially the same as material 16. For example, computing device 12 or another similar computing device may determine the control voltage at a time at which material 16 is manufactured, or a time at which an independent measurement (e.g., X-ray radiology or X-ray CT scan) may be used to verify that material 16 is intact, undamaged, or does not include a crack. Computing device 12 or the other similar computing device may determine by control voltage by applying the electrical signal to the pair of drive electrodes 18A and 18B and determining the voltage across the measurement electrodes 18C and 18D.

In other examples, the control voltage may be determined using a model of the material in an intact (undamaged) state. For example, computing device 12 may execute the model of material 16 and determine the control voltage based on the model. In some examples, the model may include a physics-based model of the electrical properties of material 16, such as the physics-based model described below. In some other examples, the control voltage may be determined as an average (e.g., mean) of a plurality of similar materials (e.g., in geometry and composition) that are known to be intact (undamaged). This control voltage may be stored (e.g., in a memory device associated with computing device 12) for later use.

At a later time, system 10 then may be used to determine a measurement voltage using the four-point measurement test described above. For example, computing device 12 may control electrical signal source 14 to apply an electrical signal (e.g., a voltage signal or a current signal) to a pair of drive electrodes 18A and 18B and measure a voltage across the pair of measurement electrodes 18C and 18D or determine the voltage across the pair of measurement electrodes 18C and 18D based on another electrical parameter measured across the pair of measurement electrodes 18C and 18D (e.g., current). Computing device 12 may then determine whether material 16 includes a crack or other defect based on the measurement voltage, for example, by comparing the measurement voltage to the control voltage. As one example, computing device 12 may determine a difference between a magnitude of the measurement voltage and a magnitude of the control voltage. Computing device 12 then may compare this difference to a threshold voltage value, and may determine that material 16 includes a crack or other defect in response to the difference being greater than the threshold voltage value. As another example, computing device 12 may compare the measurement voltage to a threshold voltage value, and may determine that material 16 includes a crack or other defect in response to the measurement voltage being less than the threshold voltage value.

In this way, a four-point voltage measurement may offer improved accuracy and sensitivity for detecting cracks or other defects in material 16 compared to a two-point voltage measurement. Additionally, a four-point voltage measurement system 10 may offer improved portability and cost compared to an X-ray radiography or X-ray computed tomography system, while offering sufficient accuracy and detail to enable detection of cracks or other defects in material 16 while material 16 is being used in the field.

FIG. 2 is flow diagram illustrating an example technique for determining presence of a crack or other defect in a material using a four-point voltage measurement. The technique of FIG. 2 will be described with reference to system 10 and computing device 12 of FIG. 1 for clarity. However, it will be appreciated that the technique of FIG. 2 may be performed by other systems and computing devices, and that system 10 and computing device 12 may be used to perform other techniques.

The technique of FIG. 2 includes applying an electrical signal to a first electrode pair, such as the pair of drive electrodes 18A and 18B, electrically coupled to a material 16 (22). For example, computing device 12 may control electrical signal source 14 to generate a predetermined electrical signal. The predetermined electrical signal may include an AC signal or a DC signal, and may be a current or a voltage. In some examples, the type of electrical signal may depend on the composition of material 16. For example, a DC signal may be used to measure a voltage of an electrically conductive or electrically semiconductive material, while an AC signal may be used to measure a voltage of an electrically conductive material, an electrically semiconductive material, or a dielectric material. Computing device 12 also may control electrical signal source 14 to generate the predetermined electrical signal with a selected amplitude, duration, frequency, and other signal characteristics.

The technique of FIG. 2 also includes, while applying the electrical signal to the first electrode pair, such as the pair of drive electrodes 18A and 18B, determining voltage between a second, different electrode pair, such as the pair of measurement electrodes 18C and 18D, electrically coupled to material 16 (24). For example, computing device 12 may measure or cause another device (e.g., an external ADC) to measure a voltage across the pair of measurement electrodes 18C and 18D or determine the voltage across the pair of measurement electrodes 18C and 18D based on another electrical parameter measured across the pair of measurement electrodes 18C and 18D (e.g., current).

The technique of FIG. 2 further includes determining whether a crack or other defect is present in material 16 based on the voltage (26). For example, computing device 12 may compare the measurement voltage to a control voltage. In some examples, the control voltage may have been measured by system 10 or another similar system by applying a similar electrical signal to the pair of drive electrodes 18A and 18B and measuring the voltage across the pair of measurement electrodes 18C and 18D. However, the control voltage may have been measured at a time when material 16 was known to be defect-free. In other examples, the control voltage may be determined using a model of the material in an intact (undamaged) state, or the control voltage may be determined as an average (e.g., mean) of a plurality of similar materials (e.g., in geometry and composition) that are known to be intact (undamaged).

In some examples, computing device 12 may determine whether material 16 includes a crack or other defect based on the voltage (26) by first determining a difference between a magnitude of the measurement voltage to a magnitude of the control voltage. For example, computing device 12 may subtract the magnitude of the control voltage from the magnitude of the measurement voltage to determine the difference. Computing device 12 then may compare this difference to a threshold voltage value. The threshold voltage value may be selected so that a voltage difference above the threshold voltage value is meaningful (e.g., indicative of a crack or other defect) and a voltage difference below the threshold voltage value is not meaningful (e.g., is not indicative of a crack or other defect). In some examples, the threshold voltage value may be selected to be a voltage value that is slightly greater than a noise floor of the measurement, such that any voltage difference that exceeds the noise floor is determined by computing device 12 to be indicative of a crack or other defect. In this way, in some examples, computing device 12 may compare the difference between the measurement voltage and the control voltage to a threshold voltage value, and may determine that material 16 includes a crack or other defect in response to the difference being greater than the threshold voltage value.

As another example, computing device 12 may compare the measurement voltage to a threshold voltage value, and may determine that material 16 includes a crack or other defect in response to the measurement voltage being less than the threshold voltage value. In some examples, the threshold voltage may be selected so that a voltage below the threshold voltage value is indicative of a crack or other defect and a voltage above the threshold voltage value is not indicative of a crack or other defect.

In some examples, rather than directly utilizing the measured voltages to determine whether material 16 includes a crack or other defect based on the voltage (26), computing device 12 may derive a parameter from the voltage, then utilize the derived parameter to determine whether material 16 includes a crack or other defect. As the derived parameter is derived based on the measurement voltages, such a determination is still based on the voltage. For example, computing device 12 may determine a resistance based on an applied current and the voltage, and may determine whether material 16 includes a crack or other defect based on the derived resistance.

In some examples, rather than including a single pair of drive electrodes 18A and 18B and a single pair of measurement electrodes 18C and 18D, a system may include a plurality of electrodes electrically coupled to a material to be tested. By including more electrodes, the system may utilize more data for determining whether the material includes a crack or other defect, which may provide more accuracy or precision, and, in some examples, may allow the system to estimate a position of the crack or other defect within the material.

For example, FIG. 3 is conceptual and schematic block diagram illustrating an example system 30 for determining presence of a crack or other defect in a material 36 using a four-point voltage measurement. System 30 of FIG. 3 includes a computing device 32, an electrical signal source 34, a plurality of electrodes 38A–38L (collectively, “electrodes 38”), and a switch network 40. Plurality of electrodes 38 are electrically coupled to material 36, which is being tested using a four-point voltage measurement.

Material 36 may include any material for which detection of a potential crack or other defect is desired. For example, material 36 may include any of the materials described above with reference to material 16 of FIG. 1. In some examples, material 36 may include an electrically conductive or electrically semiconductive material, such as a ceramic. Example ceramics include boron carbide (B_4C), silicon carbide (SiC), alumina (Al_2O_3), composites thereof, or the like.

Electrical signal source 34 may include any device configured to output an electrical signal to electrodes 38. The electrical signal may include an AC signal or a DC signal. In some examples, electrical signal source 34 may output a current signal; in other examples, electrical signal source 34 may output a voltage signal. In some examples, electrical signal source 34 may be similar to or substantially the same as electrical signal source 14 of FIG. 1.

In the example shown in FIG. 3, each electrode of plurality of electrodes 38 is electrically coupled to material 36 using any suitable type of electrical connection, including, for example, an electrically conductive adhesive, an electrically conductive solder, embedding electrodes 38 in material 36, dielectrically coupled via capacitive coupling, or the like. Each electrode of plurality of electrodes 38 is electrically coupled to switch network 40 using a respective electrically conductive lead. In some examples, the plurality of electrodes 38 are distributed across a surface area of material 36, as shown in FIG. 3. In other examples, the plurality of electrodes 38 are distributed around a perimeter of material 36. In some examples, plurality of electrodes 38 may be referred to as a set of N electrodes 38.

In some examples, one or more electrodes may not be electrically coupled to material 36 and may be used as a reference electrode for single-ended voltage measurements between one electrode or plurality of electrodes 38 and the reference electrode. The reference electrode may be at a selected voltage, such a ground or an offset voltage. In some examples, the single-ended voltages may be used in the techniques described herein to determine whether material 36 (or material 16) includes a crack or other defect. In other examples, differential voltages between two electrodes electrically coupled to material 36 (or material 16) may be determined by comparing (e.g., subtracting) single ended voltages associated with the two electrodes, and these differential voltages may be used in the techniques described herein to determine whether material 36 (or material 16) includes a crack or other defect.

Switch network 40 includes a plurality of inputs and a plurality of outputs, with respective inputs electrically coupled to each respective output by the network of switches. For example, switch network 40 may include a pair of inputs electrically coupled to electrical signal source 34, and at least a pair of inputs electrically coupled to computing device 32. Switch network 40 may include at least as many outputs are there are electrodes 38. For example, in the example shown in FIG. 3, system 30 includes twelve electrodes, and switch network 40 thus includes at least twelve outputs. Each electrode of electrodes 38 is electrically coupled to a respective output of switch network 40.

Computing device 32 is configured to control operation of system 30, including electrical signal source 34 and switch network 40. Computing device 32 may include any of a wide range of devices, including computer servers, desktop computers, notebook (i.e., laptop) computers, tablet computers, and the like. In some examples, computing device 32 may include a processor. The processor may include one or more microprocessors, digital signal processors (DSP), application specific integrated circuits (ASIC), field programmable gate arrays (FPGA), or other digital logic circuitry. In some examples, computing device 32 may include an ADC or system 30 may include a separate ADC. In examples in which the ADC is separate from computing device 12, the ADC may be electrically coupled between switch network 40 and computing device 12. The ADC may measure the voltage across respective pairs of measurement electrodes.

Computing device 32 is communicatively coupled to electrical signal source 34 and electrically coupled to switch network 40, e.g., either directly or indirectly via an external device, such as an ADC. Computing device 32 may be configured to control electrical signal source 34 to output an electrical signal, and may be configured to control switch network 40 to connect a selected pair of electrodes 38 to electrical signal source 34 to serve as a pair of drive electrodes, such that the electrical signal output by electrical signal source 34 is output to the pair of drive electrodes.

Computing device 32 is also configured to cause switch network 40 to connect a selected pair of electrodes 38 to computing device to serve as a pair of measurement electrodes. In this way, computing device 32 may determine a voltage across material 36 in response to the electrical signal output by electrical signal source 34. Further details regarding an example technique performed by system 30 are described below with respect to FIG. 4.

FIG. 4 is flow diagram illustrating an example technique for determining presence of a crack or other defect in a material using a four-point voltage measurement. The technique of FIG. 4 will be described with reference to system 30 of FIG. 3 for clarity. However, it will be appreciated that the technique of FIG. 4 may be performed by other systems and computing devices, and that system 30 may be used to perform other techniques.

The technique of FIG. 4 includes applying an electrical signal to a first pair of drive electrodes electrically coupled to material 36 (42). For example, computing device 32 may cause switch network 40 to electrically couple electrical signal source 34 to a selected pair of electrodes 38, which serves as a pair of drive electrodes. The selected pair of electrodes 38 may include any two electrodes of electrodes 38. In some examples, the selected pair of electrodes 38 may be adjacent to each other; in other examples, the selected pair of electrodes may be spaced apart. For example, in some instances, the selected pair of electrodes 38 may be substantially opposite each other in the array of electrodes, e.g., electrode 38A and electrode 38L or electrode 38F and electrode 38G.

Computing device 32 then may cause electrical signal source 34 to apply the electrical signal to the first pair of drive electrodes electrically coupled to material 36 (42), e.g., via switch network 40. The electrical signal may include an AC signal or a DC signal, and may include a current signal or a voltage signal. In some examples, the type of electrical signal may depend on the composition of material 36. For example, a DC signal may be used to measure a voltage of an electrically conductive or electrically semiconductive material, while an AC signal may be used to measure a voltage of an electrically conductive material, an electrically semiconductive material, or a dielectric material. Computing device 32 also may control electrical signal source 34 to generate the predetermined electrical signal with a selected amplitude, duration, frequency, and other signal characteristics.

The technique of FIG. 4 also includes, while applying the electrical signal to the first pair of drive electrodes, determining a voltage between a pair of measurement electrodes electrically coupled to material 36 (44). For example, computing device 32 may cause switch network 40 to electrically couple computing device 32 to a selected pair of measurement electrodes. The selected pair of measurement electrodes may be any two electrodes from electrodes 38, neither of which is being used as one of the electrodes in the drive pair of electrodes. In some examples, the two electrodes in the pair of measurement electrodes may be adjacent to each other, e.g., electrode 38B and electrode 38C, or electrode 38D and electrode 38J. In other example, the two electrodes in the pair of measurement electrodes may be spaced each other with one or more electrodes between, e.g., electrode 38B and electrode 38D, or electrode 38E and electrode 38H. Using adjacent electrodes as the pair of measurement electrodes may result in a higher signal-noise-ratio in the voltage measurement, but may reduce an area of material 36 for which the voltage is measured. Regardless of the particular electrodes coupled to computing device 32, computing device 32 may determine a voltage between the pair of measurement electrodes (44) while electrical signal source 34 is applying the electrical signal to the selected pair of drive electrodes (42).

In some examples, computing device 32 may be configured to determine a respective measurement voltage for a plurality of pairs of measurement electrodes for each pair of drive electrodes. Hence, in some examples, the technique of FIG. 4 further includes determining whether there is an additional pair of measurement electrodes at which to determine a measurement voltage (46) for the selected pair of drive electrodes. In some examples, each pair of measurement electrodes is a unique pair of electrodes (e.g., for the purposes of this the electrode pair 38A, 38B is the same as the electrode pair 38B, 38A). In some examples, no two pairs of measurement electrodes share a common electrode. For example, a third, different electrode pair (a second pair of measurement electrodes) may not share any electrodes with a second, different electrode pair (a first pair of measurement electrodes).

In other examples, different pairs of measurement electrodes may include one common electrode. For example, a third, different electrode pair (a second pair of measurement electrodes) may share exactly one electrode with the second, different electrode pair (a first pair of measurement electrodes).

In response to determining that there is an additional pair of electrodes to be used as a pair of measurement electrodes (the “YES” branch of decision block 46), computing device 32 may control switch network 40 to couple the selected additional pair of electrodes to computing device 32. Computing device 32 then may determine a measurement voltage across the selected additional pair of electrodes.

Computing device 32 may repeat this determination (46), coupling of selected pairs of measurement electrodes, and determination of a respective measurement voltage (44) until computing device 32 determines there are no more additional pairs of electrodes 38 to be used as a pair of measurement electrodes for the selected pair of drive electrodes (the "NO" branch of decision block 46). Computing device 32 then may determine whether there is an additional pair of drive electrodes to apply the electrical signal to (48). For example, computing device 32 may be configured to utilize each unique pair of electrodes as a pair of drive electrodes.

Upon selecting a new pair of drive electrodes (the "YES" branch of decision block 48), computing device 32 may control switch network 40 to electrically couple the selected pair of drive electrodes to electrical signal source 34. Computing device 32 then may cause electrical signal source 34 to apply the electrical signal to the new selected pair of drive electrodes (42). Computing device then may cause switch network 40 to electrically couple computing device 32 to a selected pair of measurement electrodes, and may determine a respective measurement voltage between the selected pair of measurement electrodes (44). Again, computing device 32 may determine whether there is an additional pair of measurement electrodes at which to measure a measurement voltage (46) for the selected pair of drive electrodes. In response to determining that there is an additional pair of electrodes to be used as a pair of measurement electrodes (the "YES" branch of decision block 46) for the selected pair of drive electrodes, computing device 32 may control switch network 40 to couple the selected additional pair of electrodes to computing device 32. Computing device 32 then may determine a measurement voltage across the selected additional pair of electrodes. Computing device 32 may repeat this determination (46), coupling of selected pairs of measurement electrodes, and determination of a respective measurement voltage (44) until computing device 32 determines there are no more additional pairs of electrodes 38 to be used as a pair of measurement electrodes for the selected pair of drive electrodes (the "NO" branch of decision block 46).

Computing device 32 then may determine whether there is an additional pair of electrodes 38 to be used as a pair of drive electrodes (48). Computing device 32 may repeat this algorithm until computing device 32 determines there are no more additional pairs of electrodes 38 to be used as a pair of drive electrodes (the "NO" branch of decision block 48).

Once computing device 32 has determined that there are no more additional pairs of electrodes 38 to be used as a pair of drive electrodes (the "NO" branch of decision block 48), computing device 32 may determine whether a crack or other defect is present in material 36 based on the respective voltages (50). In some examples, similar to the technique of FIG. 2, computing device 32 may determine whether material 36 includes a crack or other defect based on a comparison between voltages. For example, computing device 32 or another computing device may perform steps (42)–(48) of the technique of FIG. 4 on material 36 at a first time at which it is known that material 36 is intact, i.e., does not include a crack or other defect. For example, the first time may be a time at which material 36 is manufactured, or a time at which an independent measurement (e.g., X-ray radiology or X-ray CT scan) may be used to verify that material 36 is intact, undamaged, or does not include a crack. These respective control voltages may be stored (e.g., in a memory device associated with computing device 32) for later use. For example, the respective control voltages may be stored in a data structure in which each respective control voltage is associated with a pair of drive electrodes to which the electrical signal was applied during the voltage measurement and a pair of measurement electrodes with which the respective control voltage was measured. In other examples, the control voltage may be determined using a model of the material in an intact (undamaged) state, or the control voltage may be determined as an average (e.g., mean) of a plurality of similar materials (e.g., in geometry and composition) that are known to be intact (undamaged).

Computing device 32 then may compare the respective measurement voltages to respective control voltages and determine whether the crack or other defect is present in material 36 based on the voltage based on the comparison. For example, computing device 32 may compare each respective measurement voltage with a corresponding (i.e., associated with the same pair of drive electrodes and the same pair of measurement electrodes) control voltage. As an example, computing device 32 subtract the corresponding control voltage form the respective measurement voltage. In some examples, computing device 32 may compare the respective voltage difference (between the respective measurement voltage and the respective control voltage) to a threshold voltage value.

The threshold voltage value may be selected so that a voltage difference above the threshold voltage value is meaningful (e.g., indicative of a crack or other defect) and a voltage difference below the threshold voltage value is not meaningful (e.g., is not indicative of a crack or other defect). In some examples, the threshold value may be selected to be a voltage value that is slightly greater than a noise floor of the measurement, such that any voltage difference that exceeds the noise floor is determined by computing device 32 to be indicative of a crack or other defect.

In some examples, after comparing each respective measurement voltage against a corresponding control voltage and comparing the difference to the threshold voltage value to determine if the respective measurement voltage is indicative of a crack or other defect, computing device 32 may determine whether a crack or other defect is present in material 36 based on the plurality of indications. For example, computing device 32 may determine a number of differences that are indicative of a crack and compare this number of differences to a threshold number of differences to determine if material 36 includes a crack or other defect.

As another example, computing device 32 may determine whether material 36 includes a crack or other defect based on the respective measurement voltages (50) by comparing each respective measurement voltage to a threshold voltage value. For example, computing device 32 may compare the respective measurement voltage to the threshold voltage value, and may determine that the respective measurement voltage indicates that material 16 includes a crack or other defect in response to the respective measurement voltage being less than the threshold voltage value. In some examples, the threshold voltage may be selected so that a measurement voltage below the threshold voltage value is indicative of a crack or other defect and a measurement voltage above the threshold voltage value is not indicative of a crack or other defect. In some examples, after comparing each respective measurement voltage to the threshold voltage value to determine if the respective measurement voltage is indicative of a crack or other defect, computing device 32 may determine whether material 36 includes a crack or other defect based on the plurality of indications. For example, computing device 32 may determine a number of measurement voltages that are indicative of a crack and compare this number of measurement voltages to a threshold number of measurement voltages to determine if material 36 includes a crack or other defect.

In some examples, rather than utilizing differences between respective measurement voltages and respective control voltages or threshold voltage values directly, computing device 32 may calculate an approximate impedance distribution within material 36 to determine whether material 36 includes a crack or other defect (50). In some examples, reconstruction of the impedance distribution may be achieved by minimizing difference between the output of a physics-based simulation tool with the respective control voltages, and the respective measurement voltages. For example, computing device 32 may be programmed with a finite element model (FEM) of material 36 which implements the physics-based simulation. The FEM of material 36 may include substantially accurate (e.g., accurate or approximately accurate) geometry of material 16 (e.g., the shape and volume of material 36), and also may include substantially accurate (e.g., accurate or approximately accurate) locations of electrodes 38 attached to material 36. In some examples, the FEM of material 36 may additionally include representative properties of material 36, including, for example, conductivity, resistivity, other related electrical properties, and the like. The FEM of material 36 may include representative properties of material 36 for each respective node representing material 36.

Calculating the approximate impedance distribution to determine whether material 36 includes a crack of other defect is an ill-posed inverse problem, in which the outputs (the respective measurement voltages) are known but the properties of material 36 that produce the outputs are unknown. Moreover, more than one set of properties of material 36 may produce the outputs. Hence, computing device 32 may utilize a regularization technique to constrain the solution to solutions more likely to represent the properties of material 36 that would produce the respective measurement voltages.

In particular, computing device 32 may generate an objective function which combines outputs of the physics-based model, respective control voltages, the respective measurement voltages, and the regularization term. For example:

$$\arg\min_{\mathbf{x}} \left\{ \mathcal{F}(\mathbf{x}) := \frac{1}{2}||f(\mathbf{x}) - \mathbf{y}||_{\ell_2}^2 + \lambda\frac{1}{2}||\mathbf{R}\mathbf{x}||_{\ell_2}^2 \right\}$$

where **x** is the approximate change in impedance distribution, f is an operator calculating the simulated difference in voltages based on input **x** utilizing the physics-based simulation, **y** is the measured difference in voltages, l_2 is a chosen norm, **R** is the regularization matrix, and λ is the chosen weight of the regularization or regularization parameter. Computing device 32 may determine respective model control voltages based on the physics-based model and inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes. The respective model control voltages may be associated with respective pairs of measurement electrodes for each respective pair of drive electrodes used to collect the control voltages from material 36. Computing device 32 then may determine, using the physics-based model and inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes, respective model measurement voltages. The respective model measurement voltages may be associated with respective pairs of measurement electrodes for each respective pair of drive electrodes used to collect the measurement voltages from material 36. For each respective model measurement voltage, computing device 32 may determine a respective difference between the respective model measurement voltage and the respective model control voltage (f(x) in the equation above).

Computing device 32 also may determine a respective difference between the respective measurement voltage and the respective control voltage for each respective measurement voltage measured using material 36 to generate a set of actual voltage differences (**y** in the equation above).

Computing device 32 then may minimize the objective function by updating one or more parameters of the physics-based model. Computing device 32 may continue to iterate the model until a stopping criterion is reached. Computing device 32 then may determine the approximate impedance distribution (or approximate change in impedance distribution) that is representative of the condition of material 36. When iteration completes the input to the model is the approximate impedance distribution.

Computing device 32 may then determine whether material 36 includes a crack or other defect based on the approximate change in impedance distribution. For example, computing device 32 may determine whether material 36 includes a crack or other defect based on the magnitude and location of the approximate impedance change within the material. In some examples, only the real portion of the impedance—the conductivity or resistivity—may be used by computing device 32 to determine whether material 36 includes a crack or other defect.

In some examples, rather than utilizing respective control voltages and respective model control voltages, computing device 32 may determine an approximate impedance distribution using an absolute form of the objective function, in which **x** is the impedance distribution, f is an operator calculating a set of the simulated voltages based on input **x** utilizing the physics-based simulation, **y** is a set of the measured voltages, l_2 is a chosen norm, **R** is the regularization matrix, and λ is the chosen weight of the regularization or regularization parameter.

Computing device 32 may output a representation of the determination of whether material 16 includes a crack or other defect. In some examples, the representation may include a simplified output, such as an indication of "Yes" or "No," "Crack" or "No Crack," "Damaged" or "Intact," or the like. The representation may be textual, icon-based, color-based, or the like. For example, the representation may include a green light to represent that material 16 is still intact or a red light to represent that material 16 is damages or includes a crack or other defect.

As another example, computing device 32 may output a visual representation of the determination of whether material includes a crack or other defect. For example, in instances in which computing device 32 utilizes image reconstruction to determine the existence of a crack or other defect, computing device 32 may output a visual representation of material 16 and locations of the crack or other defect. For example, computing device 32 may output a false-color representation of conductivity or resistivity overlaid on a representation of material 16. Examples of such outputs are shown below in FIGS. 6 and 7.

In this way, computing device 32 may perform a four-point voltage measurement, which may offer improved accuracy and sensitivity for detecting cracks or other defects in material 36 compared to a two-point voltage measurement. Additionally, a four-point voltage measurement system 30 may offer improved portability and cost compared to an X-ray radiography or X-ray computed tomography system, while offering sufficient accuracy and detail to enable detection of cracks or other defects in material 36 while material 36 is being used in the field.

The techniques described in this disclosure may be implemented, at least in part, in hardware, software, firmware, or any combination thereof. For example, various aspects of the described techniques may be implemented within one or more processors, including one or more microprocessors, digital signal processors (DSPs), application specific integrated circuits (ASICs), field programmable gate arrays (FPGAs), or any other equivalent integrated or discrete logic circuitry, as well as any combinations of such components. The term "processor" or "processing circuitry" may generally refer to any of the foregoing logic circuitry, alone or in combination with other logic circuitry, or any other equivalent circuitry. A control unit including hardware may also perform one or more of the techniques of this disclosure.

Such hardware, software, and firmware may be implemented within the same device or within separate devices to support the various techniques described in this disclosure. In addition, any of the described units, modules or components may be implemented together or separately as discrete but interoperable logic devices. Depiction of different features as modules or units is intended to highlight different functional aspects and does not necessarily imply that such modules or units must be realized by separate hardware, firmware, or software components. Rather, functionality associated with one or more modules or units may be performed by separate hardware, firmware, or software components, or integrated within common or separate hardware, firmware, or software components.

The techniques described in this disclosure may also be embodied or encoded in an article of manufacture including a computer-readable storage medium encoded with instructions. Instructions embedded or encoded in an article of manufacture including a computer-readable storage medium encoded, may cause one or more programmable processors, or other processors, to implement one or more of the techniques described herein, such as when instructions included or encoded in the computer-readable storage medium are executed by the one or more processors. Computer readable storage media may include random access memory (RAM), read only memory (ROM), programmable read only memory (PROM), erasable programmable read only memory (EPROM), electronically erasable programmable read only memory (EEPROM), flash memory, a hard disk, a compact disc ROM (CD-ROM), a floppy disk, a cassette, magnetic media, optical media, or other computer readable media. In some examples, an article of manufacture may include one or more computer-readable storage media.

In some examples, a computer-readable storage medium may include a non-transitory medium. The term "non-transitory" may indicate that the storage medium is not embodied in a carrier wave or a propagated signal. In certain examples, a non-transitory storage medium may store data that can, over time, change (e.g., in RAM or cache).

Clause 1: A method for detecting a crack or defect in a material, the method comprising: applying an electrical signal to a first electrode pair electrically coupled to the material; while applying the electrical signal to the first electrode pair, determining a voltage between a second, different electrode pair, wherein at least one electrode of the second, different electrode pair is electrically coupled to the material; and determining whether the material includes a crack or other defect based on the voltage.

Clause 2: The method of clause 1, wherein the electrical signal is a voltage signal or a current signal.

Clause 3: The method of clause 1, wherein both electrodes of the second, different electrode pair are electrically coupled to the material.

Clause 4: The method of any one of clauses 1 to 3, wherein determining whether the material includes the crack or other defect based on the voltage comprises determining whether the material includes the crack or other defect by at comparing the voltage to a control voltage.

Clause 5: The method of any one of clauses 1 to 4, wherein: the voltage is a first voltage; the method further comprises determining a second voltage between a third, different electrode pair while applying the electrical signal to the first electrode pair, wherein at least one electrode of the third, different electrode pair is electrically coupled to the material, and determining whether the material includes the crack or other defect based on the voltage comprises determining whether the material includes the crack or other defect based on the first voltage and the second voltage.

Clause 6: The method of clause 5, wherein the third, different electrode pair shares exactly one electrode with the second, different electrode pair.

Clause 7: The method of clause 5, wherein the third, different electrode pair does not share any electrodes with the second, different electrode pair.

Clause 8: The method of any one of clauses 1 to 7, wherein the second, different electrode pair does not share any electrodes with the first electrode pair.

Clause 9: The method of any one of clauses 1 to 8, wherein a plurality of electrodes are distributed across a surface area of the material, and wherein the plurality of electrodes include the first electrode pair and the at least one electrode of the second, different electrode pair.

Clause 10: The method of any one of clause 1 to 8, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the first electrode pair and the at least one electrode of the second, different electrode pair.

Clause 11: A method for detecting a crack or defect in a material, the method comprising: for each respective pair of drive electrodes of a plurality of respective pairs of drive electrodes electrically coupled to the material, applying an electrical signal to the respective pair of drive electrodes; for each respective pair of drive electrodes, determining a respective voltage between each respective pair of measurement electrodes of a plurality of pairs of measurement electrodes while applying the electrical signal to the respective pair of drive electrodes, wherein at least one electrode of each respective pair of measurement electrodes is electrically coupled to the material; and determining whether the material includes a crack or other defect based on the respective voltages.

Clause 12: The method of clause 11, wherein the electrical signal is a voltage signal or a current signal.

Clause 13: The method of clause 12, wherein both electrodes of each respective pair of measurement electrodes are electrically coupled to the material.

Clause 14: The method of any one of clauses 11 to 13, wherein determining whether the material includes the crack or other defect based on the respective voltages comprises determining whether the material includes the crack or other defect by at least comparing the respective voltages to respective control voltages.

Clause 15: The method of any one of clauses 11 to 13, wherein determining whether the material includes the crack or other defect based on the respective voltages comprises: calculating an approximate change in impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes, the respective voltages, and respective control voltages; and determining that the material includes the crack or other defect based on the approximate change in impedance distribution.

Clause 16: The method of clause 15, wherein calculating the approximate change in impedance distribution within the material comprises minimizing an output of an objective function:

$$\arg\min_{\mathbf{x}} \left\{ \mathcal{F}(\mathbf{x}) := \frac{1}{2} \| f(\mathbf{x}) - \mathbf{y} \|_{\ell_2}^2 + \lambda \frac{1}{2} \| \mathbf{R}\mathbf{x} \|_{\ell_2}^2 \right\},$$

wherein **x** is the approximate change in impedance distribution, f is an operator calculating a set of simulated difference in voltages based on input **x** utilizing the physics-based simulation, **y** is a set of differences between the respective voltages and the respective control voltages, l_2 is a chosen norm, **R** is a regularization matrix, and λ is a chosen weight of the regularization or a regularization parameter.

Clause 17: The method of any one of clauses 11 to 13, wherein determining whether the material includes the crack or other defect based on the respective voltages comprises: calculating an approximate impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes, and the respective voltages; and determining that the material includes the crack or other defect based on the approximate impedance distribution.

Clause 18: The method of clause 17, wherein calculating the approximate impedance distribution within the material comprises minimizing an output of an objective function:

$$\arg\min_{\mathbf{x}} \left\{ \mathcal{F}(\mathbf{x}) := \frac{1}{2} \| f(\mathbf{x}) - \mathbf{y} \|_{\ell_2}^2 + \lambda \frac{1}{2} \| \mathbf{R}\mathbf{x} \|_{\ell_2}^2 \right\},$$

wherein **x** is the approximate impedance distribution, f is an operator calculating a set of simulated voltages based on input **x** utilizing the physics-based simulation, **y** is a set of the respective voltages, l_2 is a chosen norm, **R** is a regularization matrix, and λ is a chosen weight of the regularization.

Clause 19: The method of any one of clauses 11 to 18, wherein a plurality of electrodes are distributed across a surface area of the material, and wherein the plurality of electrodes include the plurality of respective drive electrode pairs and the at least one electrode of each of the plurality of respective measurement electrode pairs.

Clause 20: The method of any one of clauses 11 to 18, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the plurality of respective drive electrode pairs and the at least one electrode of each of the plurality of respective measurement electrode pairs.

Clause 21: A system comprising: a set of N electrodes electrically coupled to a material; an electrical signal source; and a computing device configured to: cause the electrical signal source to apply an electrical signal to a first pair of drive electrodes, wherein the first pair of drive electrodes are from the set of N electrodes; cause a voltage between a first pair of measurement electrodes to be determined, wherein at least one electrode from the first pair of measurement electrodes is from the set of N electrodes and both electrodes of the first pair of measurement electrodes are different than the first pair of drive electrodes; and determine whether the material includes a crack or other defect based on the voltage.

Clause 22: The system of clause 21, wherein the electrical signal is a voltage signal or a current signal.

Clause 23: The system of clause 21, wherein both electrodes of the first pair of measurement electrodes are from the set of N electrodes.

Clause 24: The system of any one of clauses 21 to 23, wherein the computing device is configured to determine whether the material includes the crack or other defect by at least comparing the voltage to a control voltage.

Clause 25: The system of any one of clauses 21 to 24, wherein: the voltage is a first voltage; the computing device is further configured to: measure a second voltage between a second pair of measurement electrodes while applying the electrical signal to the first pair of drive electrodes, wherein at least one electrode from the second pair of measurement electrodes is from the set of N electrodes; and determine whether the material includes the crack or other defect based on the first voltage and the second voltage.

Clause 26: The system of clause 25, wherein the second pair of measurement electrodes shares exactly one electrode with the first pair of measurement electrodes.

Clause 27: The system of clause 25, wherein the second pair of measurement electrodes does not share any electrodes with the first pair of measurement electrodes.

Clause 28: The system of any one of clauses 21 to 27, wherein the first pair of measurement electrodes does not share any electrodes with the first pair of drive electrodes.

Clause 29: The system of any one of clauses 21 to 28, wherein the set of N electrodes are distributed across a surface area of the material.

Clause 30: The system of any one of clauses 21 to 28, wherein the set of N electrodes are distributed are distributed around a perimeter of the material.

Clause 31: The system of any one of clauses 21 to 30, wherein the computing device is configured to: for each respective pair of drive electrodes of a plurality of respective pairs of drive electrodes, apply an electrical signal to the respective pair of drive electrodes, wherein each respective pair of drive electrodes is from the set of N electrodes; for each respective pair of drive electrodes, measure a respective voltage between each respective pair of measurement electrodes of a plurality of pairs of measurement electrodes while applying the electrical signal to the respective pair of drive electrodes, wherein at least one electrode from each respective pair of measurement electrodes is from the set of N electrodes; and determine whether the material includes the crack or other defect based on the respective voltages.

Clause 32: The system of clause 31, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the respective voltages by at least: calculating an approximate change in impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes, the respective voltages, and respective control voltages; and determining whether the material includes the crack or other defect based on the change in impedance distribution.

Clause 33: The system of clause 32, wherein calculating the approximate change in impedance distribution within the material comprises minimizing an output of an objective function:

$$\arg\min_{\mathbf{x}} \left\{ \mathcal{F}(\mathbf{x}) := \frac{1}{2}||f(\mathbf{x}) - \mathbf{y}||_{\ell_2}^2 + \lambda\frac{1}{2}||\mathbf{R}\mathbf{x}||_{\ell_2}^2 \right\},$$

wherein **x** is the approximate change in impedance distribution, f is an operator calculating a set of simulated difference in voltages based on input **x** utilizing the physics-based simulation, **y** is a set of differences between the respective voltages and the respective control voltages, l_2 is a chosen norm, **R** is a regularization matrix, and λ is a chosen weight of the regularization or a regularization parameter.

Clause 34: The system of clause 31, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the respective voltages by at least: calculating an approximate impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes, and the respective voltages; and determining whether the material includes the crack or other defect based on the approximate impedance distribution.

Clause 35: The system of clause 34, wherein calculating the approximate impedance distribution within the material comprises minimizing an output of an objective function:

$$\arg\min_{\mathbf{x}} \left\{ \mathcal{F}(\mathbf{x}) := \frac{1}{2}||f(\mathbf{x}) - \mathbf{y}||_{\ell_2}^2 + \lambda\frac{1}{2}||\mathbf{R}\mathbf{x}||_{\ell_2}^2 \right\},$$

wherein **x** is the approximate impedance distribution, f is an operator calculating a set of simulated voltages based on input **x** utilizing the physics-based simulation, **y** is a set of the respective voltages, l_2 is a chosen norm, **R** is a regularization matrix, and λ is a chosen weight of the regularization or a regularization parameter.

EXAMPLES

Example 1

FIG. 5 is a diagram illustrating an example fine-grained FEM of a material 52 that includes a simulated crack or other defect. The fine-grained FEM includes a thin 'crack' feature 54 of low conductivity (compared to the rest of the sample) buried below the top surface of the sample and almost touching the bottom. FIG. 5 also illustrates a set of sixteen electrodes 56 distributed around the upper surface of material 52 (four of which are labeled in FIG. 5). A forward solution of electrical conductivity using this fine-grained FEM was used to generate the measured voltages for the cracked material. A forward solution of the same fine-grained FEM, but excluding the thin 'crack" feature 54 was used to generate the control voltages.

A coarse-grained FEM, having a coarser mesh than the fine-grained FEM, was used to reconstruct the fine-grained FEM including the crack. The electrode placement and geometry of the coarse-grained FEM was the same as in the fine-grained FEM. The algorithm inv_solve_diff_GN_one_step in the package Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software (EIDORS) was used to solve the reconstruction problem in MATLAB®. MATLAB® is available from MathWorks®, Inc., Natick, Massachusetts, United States. EIDORS is available at eidors3d.sourceforge.net. An L-Curve method of hyperparameter selection and a Laplace filter penalty function was utilized in the EIDORS package.

FIG. 6 is a diagram illustrating an example false color model output overlaid on an example finite element model of a material that includes a simulated crack or other defect. The image shown in FIG. 6 is an output of the coarse-grained FEM with the physics-based model after solving the regularized least-squares minimization problem. The image shown in FIG. 6 is shown looking up at the bottom of the model. The defect is clearly detected in the sample in the center of the image. Cross-sectional images can be taken at any location within the model. FIG. 7 is a cross-sectional diagram illustrating an example false color output of a FEM that includes a simulated crack or other defect. This example utilized only one iteration of the Gauss-Newton algorithm and exhibits some noise surrounding the simulated crack. These artifacts can be reduced by running multiple iterations to refine the solution further (at the cost of computation time, for example between 2 and 20 iterations could be used).

Example 2

A ceramic sample included approximately 70% boron carbide and 30% silicon carbide. The back side of the ceramic sample was coated with a fiberglass/epoxy resin to keep the pieces in intimate contact after breaking. On the front side, sixteen approximately square electrical contacts were vapor deposited through a shadow mask. The electrical contacts included a first layer of titanium with a thickness of about 5 nanometers (nm) and a second layer of gold with a thickness of about 100 nm. A flex circuit was etched to match the locations of the electrical contacts, and a conductive silver-loaded epoxy was used to make electrical connections between the flex circuit and gold contacts. The flex circuit then was connected to a breakout board, which was connected to the switch matrixes. After the conductive epoxy was cured and the flex circuit attached to the electrical contacts, the ceramic sample was wrapped in tape to help further contain any pieces after breaking. FIG. 8 is a drawing illustrating the ceramic sample including the sixteen element electrical contact array and the flex circuit. FIG. 9 is a drawing illustrating an example ceramic material attached to a flex circuit, a breakout board, and a set of leads.

AC currents of 10mA were applied to pairs of electrodes. Electrical contacts were numbered 1–16 and drive pairs were six electrical contacts apart (e.g. 1 and 7, 2 and 9, etc.) using modulo 16 math. Measurement pairs were adjacent (e.g. 1 and 2) again modulo 16. For each drive pair, all possible measurements were taken according to the following rule: the measurement pairs may not contain either drive electrode. Frequencies of 50 kHz, 100 kHz, and 150 kHz were used.

A control dataset was taken prior to breaking the ceramic sample. After the initial dataset was taken, the sample was hit in approximately the center with a hammer, resulting in a crack located through the middle of the ceramic sample. FIG. 10 is a drawing illustrating the ceramic sample including an electrode array and the location of a crack. FIG. 10 illustrates the location of the crack as the horizontal line through the approximate center of the ceramic sample.

After breaking, a measurement data set was collected according to the rules described above. The control dataset and measurement data set were analyzed using electrical impedance tomography image reconstruction algorithms. In particular, the algorithm inv_solve_diff_GN_one_step in the package EIDORS was used to determine the approximate impedance change within the sample. MATLAB® is available from MathWorks®, Inc., Natick, Massachusetts, United States. EIDORS is available at eidors3d.sourceforge.net. An L-Curve method of hyperparameter selection and a Laplace filter penalty function was utilized in the EIDORS package.

FIG. 11 is a diagram illustrating an example false color output of the EIDORS algorithm for the example ceramic sample of FIG. 10. The crack creates a region of higher resistance, and this is shown in the figure below as a drop in conductivity (darker shading indicates lower conductivity than the initial dataset).

Various examples have been described. These and other examples are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A method for detecting a crack or defect in a material, the method comprising:

applying an electrical signal to a first electrode pair electrically coupled to the material;

while applying the electrical signal to the first electrode pair, determining a voltage between a second, different electrode pair, wherein at least one electrode of the second, different electrode pair is electrically coupled to the material; and

determining whether the material includes a crack or other defect based on the voltage.

2. The method of claim 1, wherein the electrical signal is a voltage signal or a current signal.

3. The method of claim 1, wherein both electrodes of the second, different electrode pair are electrically coupled to the material.

4. The method of claim 1, wherein determining whether the material includes the crack or other defect based on the voltage comprises determining whether the material includes the crack or other defect by at comparing the voltage to a control voltage.

5. The method of claim 1, wherein:

the voltage is a first voltage;

the method further comprises determining a second voltage between a third, different electrode pair while applying the electrical signal to the first electrode pair, wherein at least one electrode of the third, different electrode pair is electrically coupled to the material, and

determining whether the material includes the crack or other defect based on the voltage comprises determining whether the material includes the crack or other defect based on the first voltage and the second voltage.

6. The method of claim 5, wherein the third, different electrode pair shares exactly one electrode with the second, different electrode pair.

7. The method of claim 5, wherein the third, different electrode pair does not share any electrodes with the second, different electrode pair.

8. The method of claim 1, wherein the second, different electrode pair does not share any electrodes with the first electrode pair.

9. The method of claim 1, wherein a plurality of electrodes are distributed across a surface area of the material, and wherein the plurality of electrodes include the first electrode pair and the at least one electrode of the second, different electrode pair.

10. The method of claim 1, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the first electrode pair and the at least one electrode of the second, different electrode pair.

11. A method for detecting a crack or defect in a material, the method comprising:

for each respective pair of drive electrodes of a plurality of respective pairs of drive electrodes electrically coupled to the material, applying an electrical signal to the respective pair of drive electrodes;

for each respective pair of drive electrodes, determining a respective voltage between each respective pair of measurement electrodes of a plurality of pairs of measurement electrodes while applying the electrical signal to the respective pair of drive electrodes, wherein at least one electrode of each respective pair of measurement electrodes is electrically coupled to the material; and

determining whether the material includes a crack or other defect based on the respective voltages.

12. The method of claim 11, wherein the electrical signal is a voltage signal or a current signal.

13. The method of claim 12, wherein both electrodes of each respective pair of measurement electrodes are electrically coupled to the material.

14. The method of claim 11, wherein determining whether the material includes the crack or other defect based on the respective voltages comprises determining whether the material includes the crack or other defect by at least comparing the respective voltages to respective control voltages.

15. The method of claim 11, wherein determining whether the material includes the crack or other defect based on the respective voltages comprises:

calculating an approximate change in impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes, the respective voltages, and respective control voltages; and

determining that the material includes the crack or other defect based on the approximate change in impedance distribution.

16. The method of claim 15, wherein calculating the approximate change in impedance distribution within the material comprises minimizing an output of an objective function:

$$\underset{\mathbf{x}}{\arg\min}\left\{\mathcal{F}(\mathbf{x}) := \frac{1}{2}||f(\mathbf{x}) - \mathbf{y}||_{\ell_2}^2 + \lambda\frac{1}{2}||\mathbf{R}\mathbf{x}||_{\ell_2}^2\right\},$$

wherein **x** is the approximate change in impedance distribution, f is an operator calculating a set of simulated difference in voltages based on input **x** utilizing the physics-based simulation, **y** is a set of differences between the respective voltages and the respective control voltages, l_2 is a chosen norm, **R** is a regularization matrix, and λ is a chosen weight of the regularization or a regularization parameter.

17. The method of claim 11, wherein determining whether the material includes the crack or other defect based on the respective voltages comprises:

calculating an approximate impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes, and the respective voltages; and

determining that the material includes the crack or other defect based on the approximate impedance distribution.

18. The method of claim 17, wherein calculating the approximate impedance distribution within the material comprises minimizing an output of an objective function:

$$\underset{\mathbf{x}}{\arg\min}\left\{\mathcal{F}(\mathbf{x}) := \frac{1}{2}||f(\mathbf{x}) - \mathbf{y}||_{\ell_2}^2 + \lambda\frac{1}{2}||\mathbf{R}\mathbf{x}||_{\ell_2}^2\right\},$$

wherein **x** is the approximate impedance distribution, f is an operator calculating a set of simulated voltages based on input **x** utilizing the physics-based simulation, **y** is a set of the respective voltages, l_2 is a chosen norm, **R** is a regularization matrix, and λ is a chosen weight of the regularization or a regularization parameter.

19. The method of claim 11, wherein a plurality of electrodes are distributed across a surface area of the material, and wherein the plurality of electrodes include the plurality of respective drive electrode pairs and the at least one electrode of each of the plurality of respective measurement electrode pairs.

20. The method of claim 11, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the plurality of respective drive electrode pairs and the at least one electrode of each of the plurality of respective measurement electrode pairs.

21. A system comprising:

a set of N electrodes electrically coupled to a material;

an electrical signal source; and

a computing device configured to:

cause the electrical signal source to apply an electrical signal to a first pair of drive electrodes, wherein the first pair of drive electrodes are from the set of N electrodes;

cause a voltage between a first pair of measurement electrodes to be determined, wherein at least one electrode from the first pair of measurement electrodes is from the set of N electrodes and both electrodes of the first pair of measurement electrodes are different than the first pair of drive electrodes; and

determine whether the material includes a crack or other defect based on the voltage.

22. The system of claim 21, wherein the electrical signal is a voltage signal or a current signal.

23. The system of claim 21, wherein both electrodes of the first pair of measurement electrodes are from the set of N electrodes.

24. The system of claim 21, wherein the computing device is configured to determine whether the material includes the crack or other defect by at least comparing the voltage to a control voltage.

25. The system of claim 21, wherein:

the voltage is a first voltage;

the computing device is further configured to:

measure a second voltage between a second pair of measurement electrodes while applying the electrical signal to the first pair of drive electrodes, wherein at least one electrode from the second pair of measurement electrodes is from the set of N electrodes; and

determine whether the material includes the crack or other defect based on the first voltage and the second voltage.

26. The system of claim 25, wherein the second pair of measurement electrodes shares exactly one electrode with the first pair of measurement electrodes.

27. The system of claim 25, wherein the second pair of measurement electrodes does not share any electrodes with the first pair of measurement electrodes.

28. The system of claim 21, wherein the first pair of measurement electrodes does not share any electrodes with the first pair of drive electrodes.

29. The system of claim 21, wherein the set of N electrodes are distributed across a surface area of the material.

30. The system of claim 21, wherein the set of N electrodes are distributed are distributed around a perimeter of the material.

31. The system of claim 21, wherein the computing device is configured to:

for each respective pair of drive electrodes of a plurality of respective pairs of drive electrodes, apply an electrical signal to the respective pair of drive electrodes, wherein each respective pair of drive electrodes is from the set of N electrodes;

for each respective pair of drive electrodes, measure a respective voltage between each respective pair of measurement electrodes of a plurality of pairs of measurement electrodes while applying the electrical signal to the respective pair of drive electrodes, wherein at least one electrode from each respective pair of measurement electrodes is from the set of N electrodes; and

determine whether the material includes the crack or other defect based on the respective voltages.

32. The system of claim 31, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the respective voltages by at least:

calculating an approximate change in impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes, the respective voltages, and respective control voltages; and

determining whether the material includes the crack or other defect based on the change in impedance distribution.

33. The system of claim 32, wherein calculating the approximate change in impedance distribution within the material comprises minimizing an output of an objective function:

$$\arg\min_{\mathbf{x}} \left\{ \mathcal{F}(\mathbf{x}) := \frac{1}{2}||f(\mathbf{x}) - \mathbf{y}||_{\ell_2}^2 + \lambda\frac{1}{2}||\mathbf{R}\mathbf{x}||_{\ell_2}^2 \right\},$$

wherein **x** is the approximate change in impedance distribution, f is an operator calculating a set of simulated difference in voltages based on input **x** utilizing the physics-based simulation, **y** is a set of differences between the respective voltages and the respective control voltages, l_2 is a chosen norm, **R** is a regularization matrix, and λ is a chosen weight of the regularization or a regularization parameter.

34. The system of claim 31, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the respective voltages by at least:

calculating an approximate impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the respective pairs of drive electrodes, and the respective voltages; and determining whether the material includes the crack or other defect based on the approximate impedance distribution.

35. The system of claim 34, wherein calculating the approximate impedance distribution within the material comprises minimizing an output of an objective function:

$$\arg\min_{\mathbf{x}} \left\{ \mathcal{F}(\mathbf{x}) := \frac{1}{2}||f(\mathbf{x}) - \mathbf{y}||_{\ell_2}^2 + \lambda\frac{1}{2}||\mathbf{R}\mathbf{x}||_{\ell_2}^2 \right\},$$

wherein **x** is the approximate impedance distribution, f is an operator calculating a set of simulated voltages based on input **x** utilizing the physics-based simulation, **y** is a set of the respective voltages, l_2 is a chosen norm, **R** is a regularization matrix, and λ is a chosen weight of the regularization or regularization parameter.

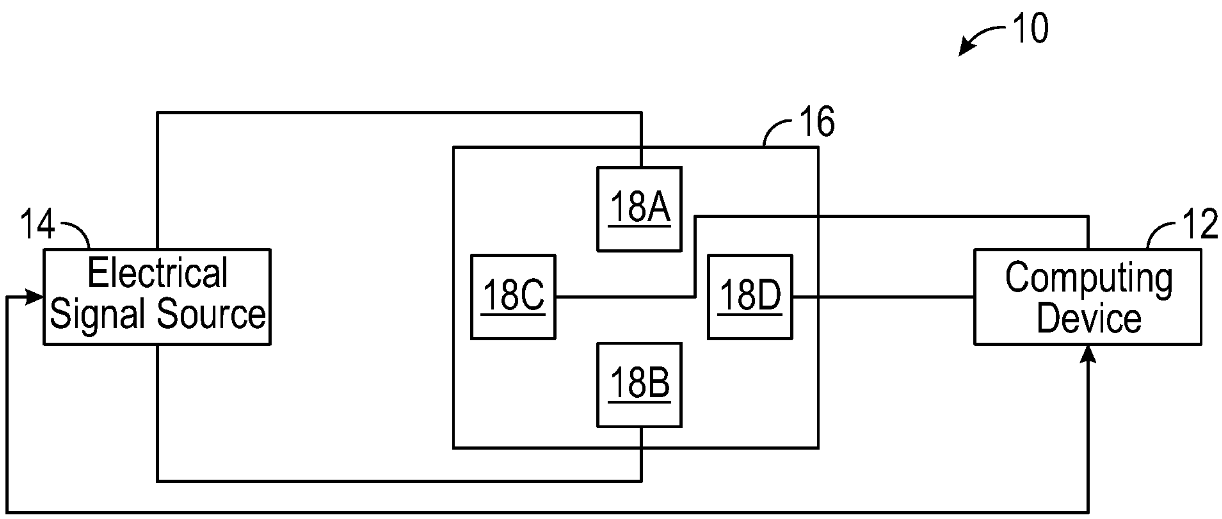
10
16
14
Electrical Signal Source
18A
18C
18D
18B
12
Computing Device

FIG. 1

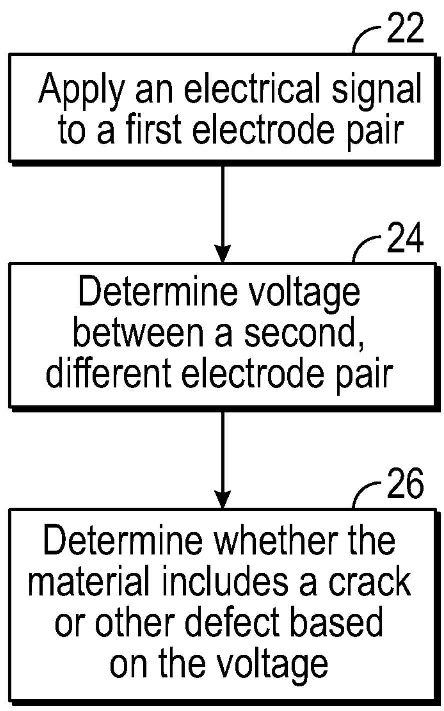
22
Apply an electrical signal to a first electrode pair
24
Determine voltage between a second, different electrode pair
26
Determine whether the material includes a crack or other defect based on the voltage

FIG. 2

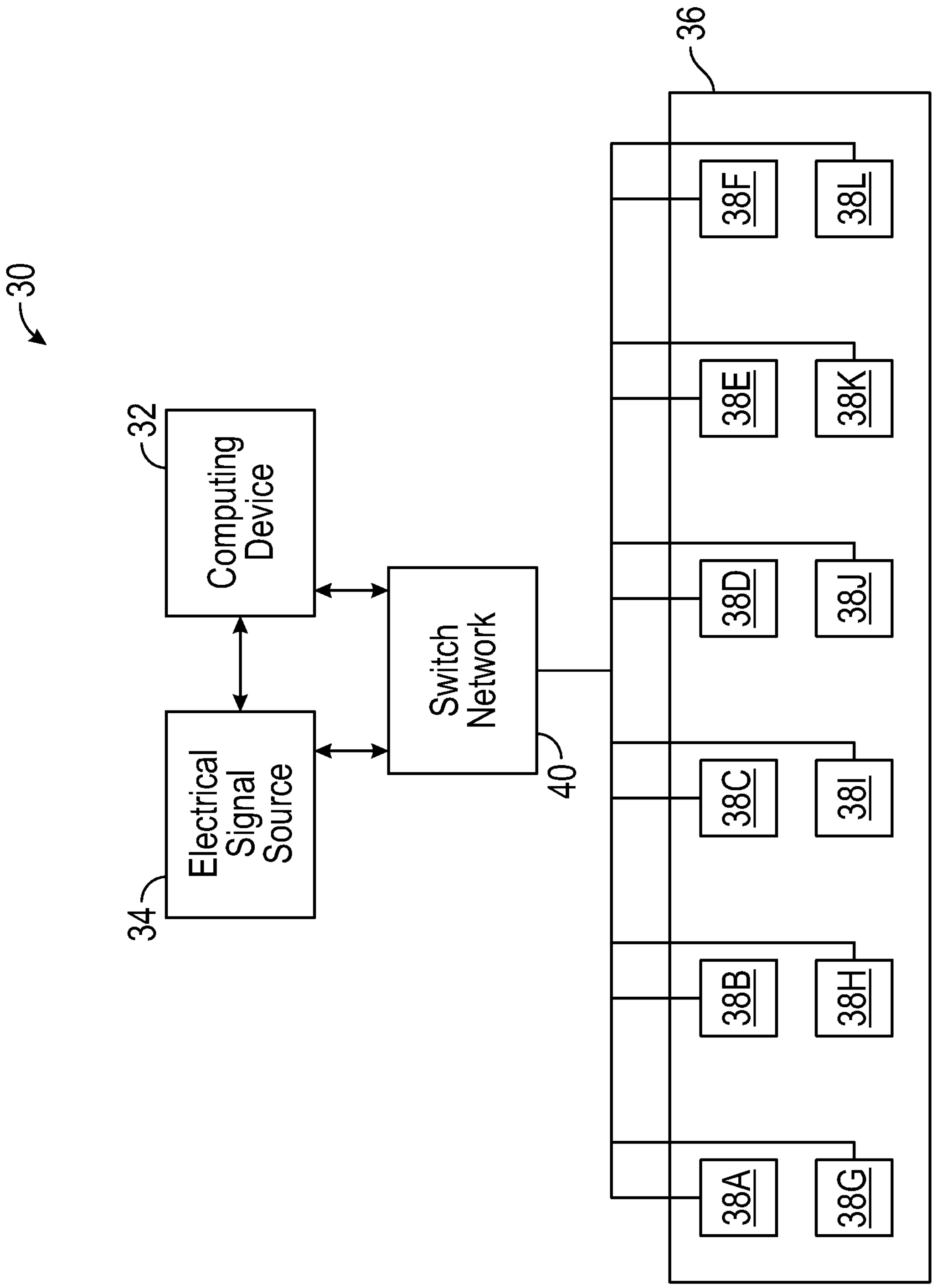
30
32
Computing Device
34
Electrical Signal Source
Switch Network
40
36
38A
38B
38C
38D
38E
38F
38G
38H
38I
38J
38K
38L

FIG. 3

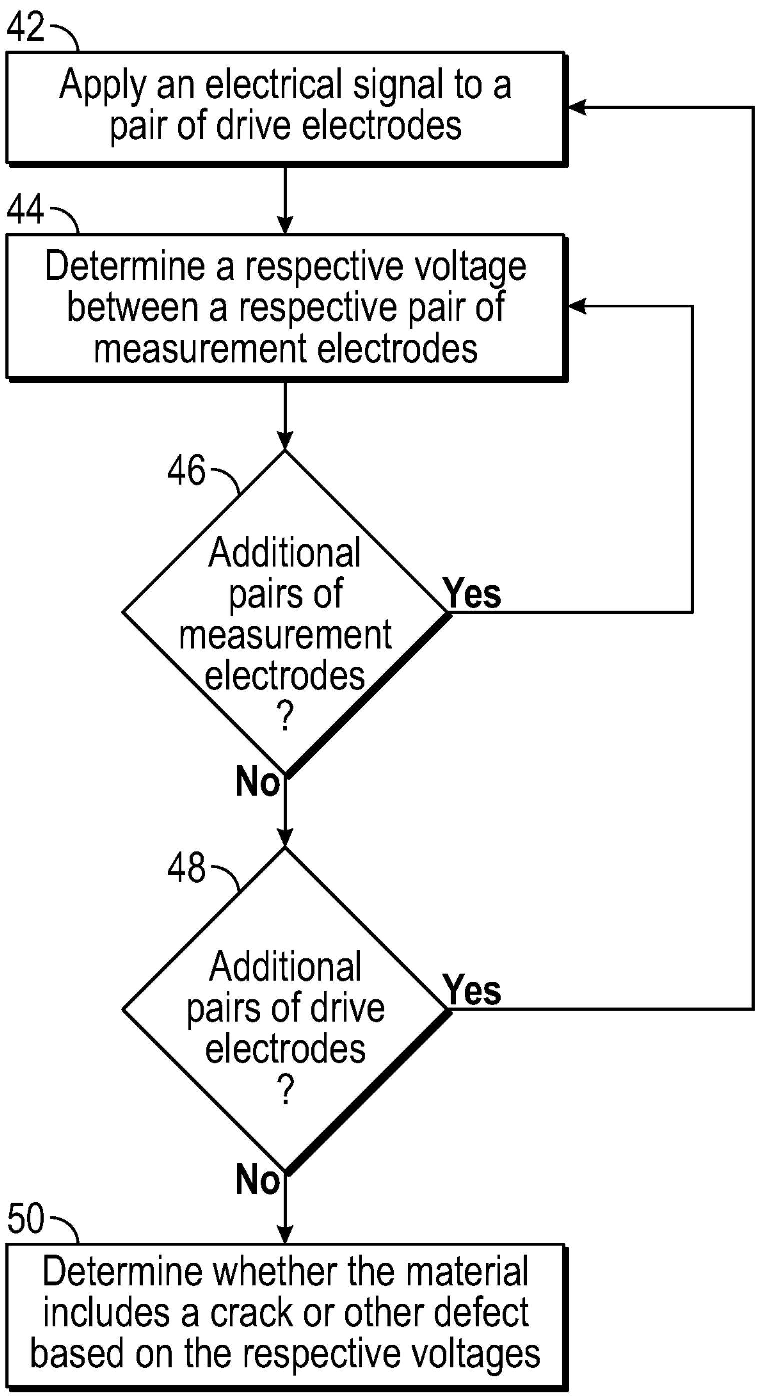
42
Apply an electrical signal to a pair of drive electrodes
44
Determine a respective voltage between a respective pair of measurement electrodes
46
Additional pairs of measurement electrodes ?
Yes
No
48
Additional pairs of drive electrodes ?
Yes
No
50
Determine whether the material includes a crack or other defect based on the respective voltages

FIG. 4

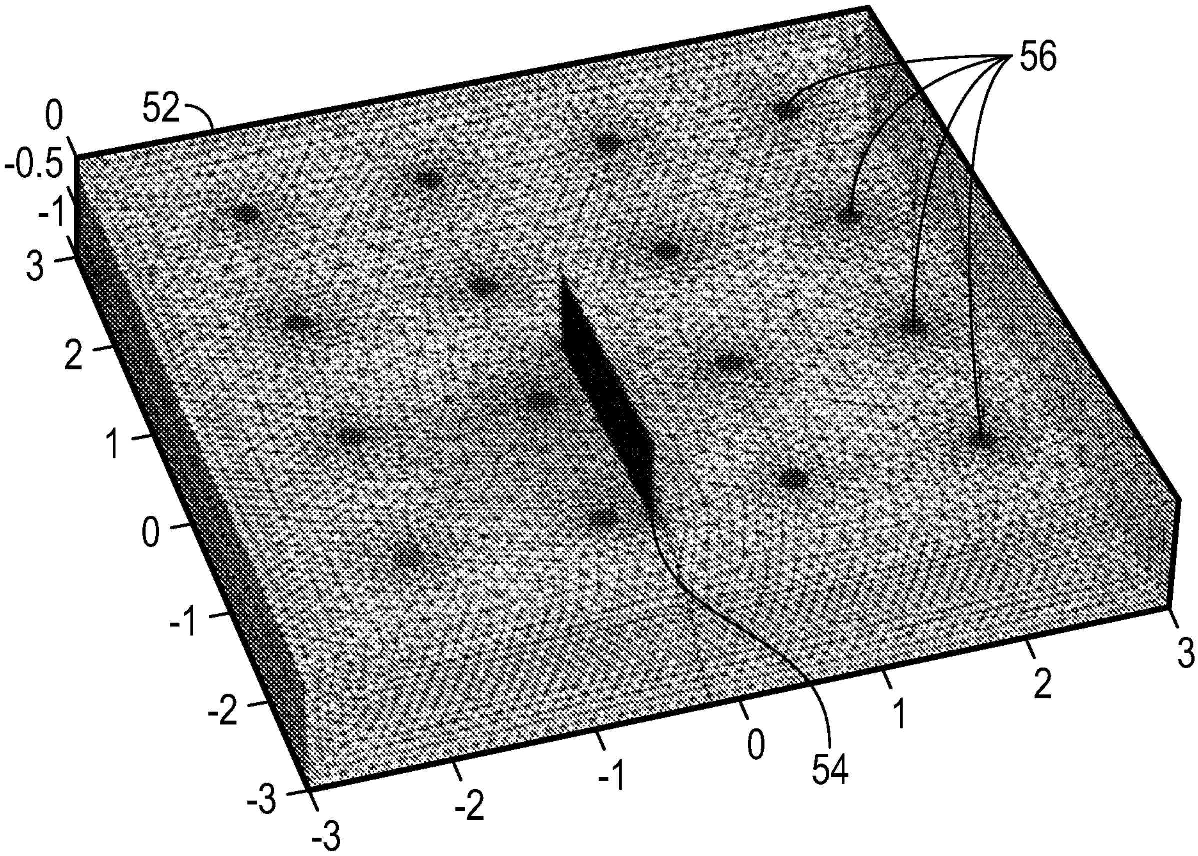

FIG. 5

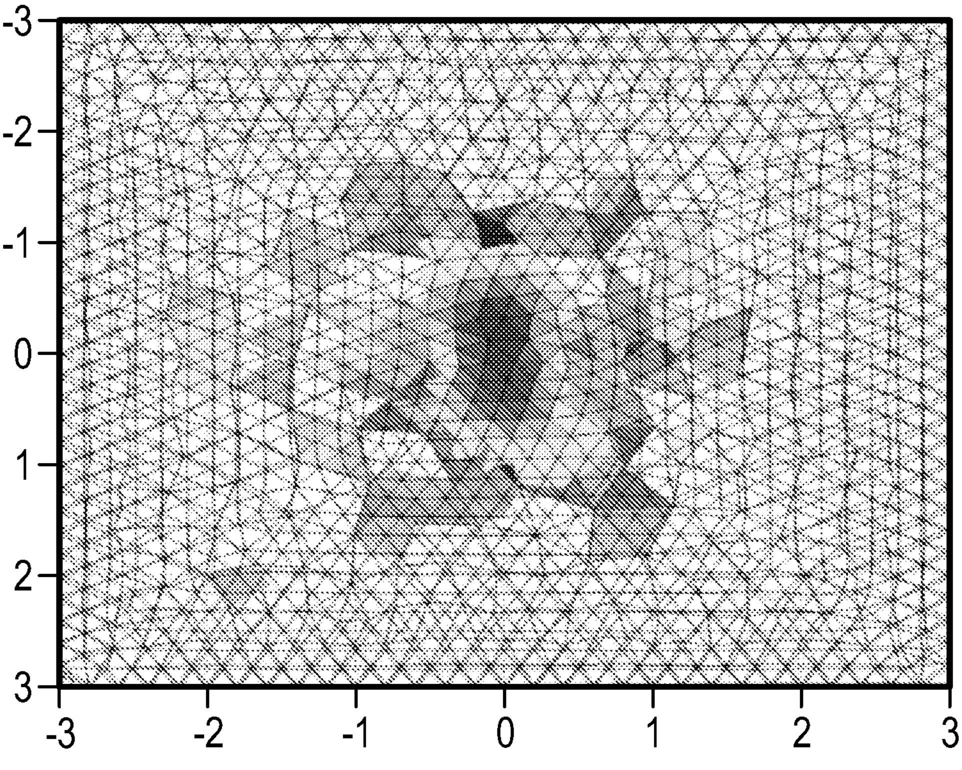

FIG. 6

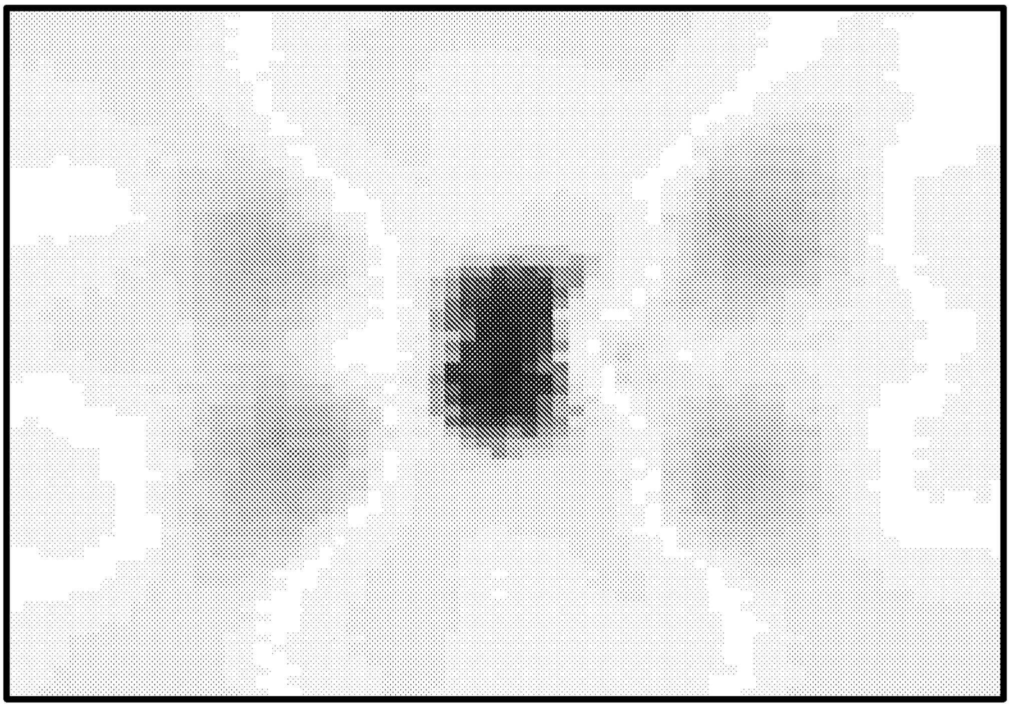

FIG. 7

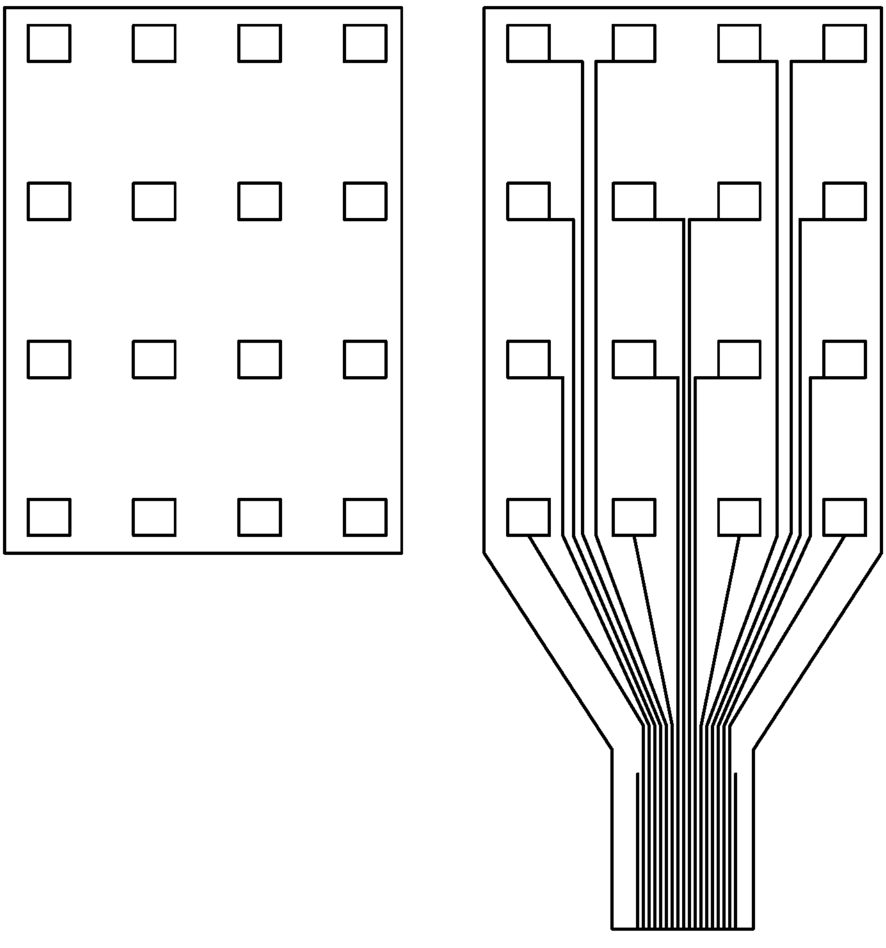

FIG. 8

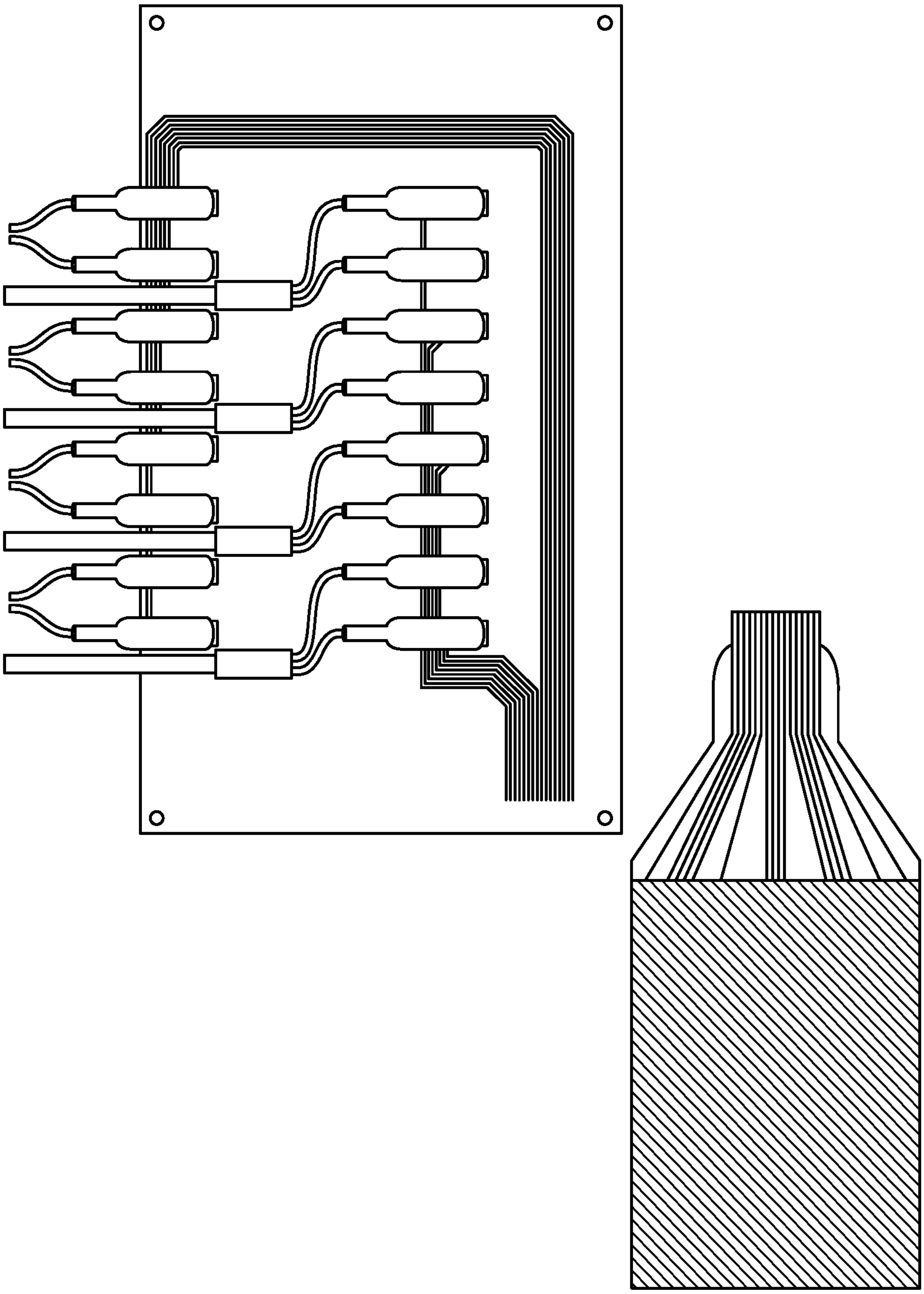

FIG. 9

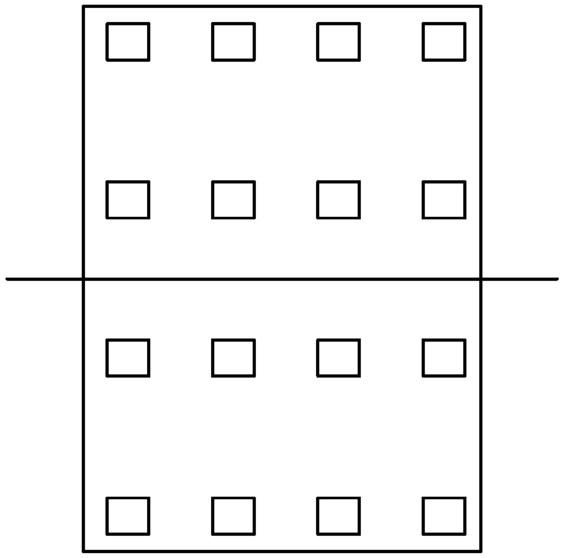

FIG. 10

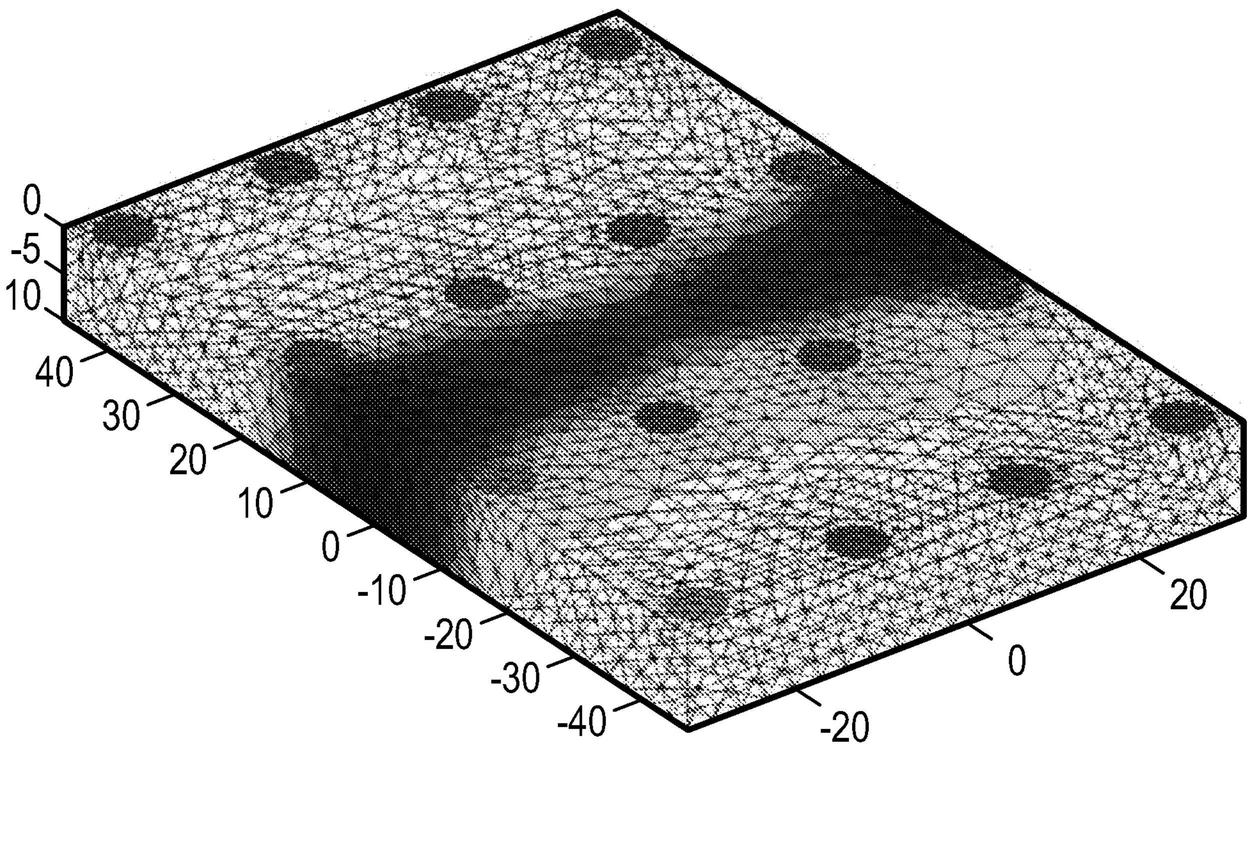

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/061763

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N27/20
ADD. G01R27/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 914 378 A (HAYASHI MAKOTO [JP] ET AL) 3 April 1990 (1990-04-03) abstract column 2, lines 7-55 column 4, line 21 - column 5, line 12 column 5, line 54 - column 6, line 8 column 7, lines 9-20 column 7, line 54 - column 8, line 15 figures 3, 28 -----	1-35
X	US 2012/235693 A1 (FENG HONG [US]) 20 September 2012 (2012-09-20) paragraphs [0011] - [0014], [0037] - [0047]; figure 3 -----	1-8, 10-14, 20-28, 30,31

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 January 2018	30/01/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Knoll, Stephan

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 218 846 B1 (LUDWIG REINHOLD [US] ET AL) 17 April 2001 (2001-04-17) column 4, lines 7-21 column 3, line 9 - column 5, line 46 column 6, line 45 - column 7, line 5 column 7, lines 50-58 -----	1-3, 5-13, 19-23, 25-31

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2017/061763

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
US 4914378	A	03-04-1990	DE	3751702	D1	21-03-1996
			DE	3751702	T2	13-06-1996
			EP	0289615	A1	09-11-1988
			US	4914378	A	03-04-1990
			WO	8802857	A1	21-04-1988
US 2012235693	A1	20-09-2012	NONE			
US 6218846	B1	17-04-2001	NONE			