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(54) Title: VERIFYING STRUCTURAL INTEGRITY OF MATERIALS USING REACTIVE PARAMETER MEASUREMENTS

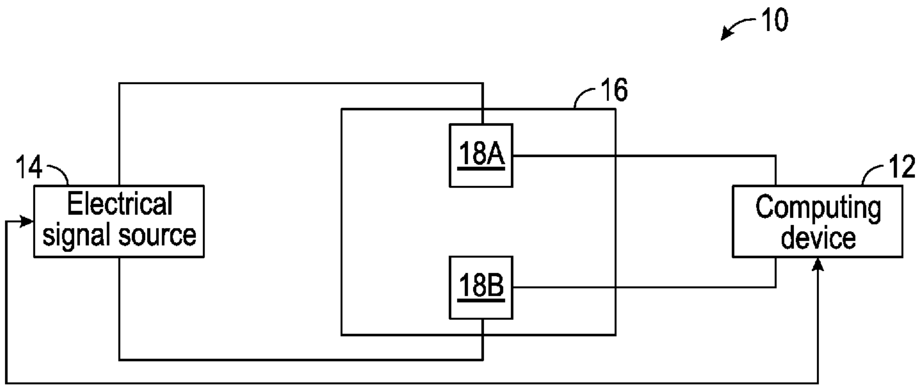

FIG. 1

(57) Abstract: The disclosure describes techniques and systems for detecting a crack or defect in a material. In some examples, a method for detecting a crack or defect in a material may include applying an electrical signal across an electrode pair electrically coupled to the material; determining a reactive parameter between the electrode pair; and determining whether the material includes a crack or other defect based on the reactive parameter. In some examples, the reactive parameter may include a capacitance, an electrical phase difference, or the like.

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VERIFYING STRUCTURAL INTEGRITY OF MATERIALS USING REACTIVE PARAMETER MEASUREMENTS

TECHNICAL FIELD

The disclosure relates to techniques for verifying structural integrity of 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 using reactive parameter measurements. Cracks in a material may have a capacitive property, storing electrical energy. Hence, a reactive parameter measurement may be used to determine if the material includes a crack. The reactive parameter may include capacitance, electrical phase difference, or the like. For example, by comparing the resulting reactive parameter measurement to a control reactive parameter measurement corresponding to the same measurement electrode pair when the material or a similar material or set of materials is known to be intact (undamaged), the reactive parameter 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 across an electrode pair electrically coupled to the material; determining a reactive parameter between the electrode pair; and determining whether the material includes a crack or other defect based on the reactive parameter.

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 across the respective pair of drive electrodes. The method also may include, for each respective pair of drive electrodes, determining a respective reactive parameter 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. 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 reactive parameters.

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 across a pair of drive electrodes, wherein the pair of drive electrodes are from the set of N electrodes; determine a reactive parameter between a pair of measurement electrodes, wherein at least one measurement electrode from the pair of measurement electrodes is from the set of N electrodes; and determine whether the material includes a crack or other defect based on the reactive parameter.

The techniques described herein may provide one or more advantages. For example, a reactive parameter measurement crack detection 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. Additionally or alternatively, a reactive parameter measurement crack detection system may be relatively insensitive to changes in material temperature. In some examples, a reactive parameter measurement crack detection system may allow relatively computationally cheap analysis techniques to be used to analyze the reactive parameter measurements and determine whether the material includes a crack or other defect.

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 conceptual and schematic diagram block illustrating an example system for determining presence of a crack or other defect in a material using a reactive parameter measurement.

FIG. 2 is flow diagram illustrating an example technique for determining presence of a crack or other defect in a material using a reactive parameter measurement.

FIG. 3 is conceptual and schematic block diagram illustrating an example system for determining presence of a crack or other defect in a material using a reactive parameter measurement.

FIG. 4 is flow diagram illustrating an example technique for determining presence of a crack or other defect in a material using a reactive parameter measurement.

FIG. 5 is a drawing illustrating an example ceramic sample including a sixteen element electrical contact array and a flex circuit.

FIG. 6 is a drawing illustrating the example ceramic sample of FIG. 5 attached to a flex circuit, a breakout board, and a set of leads.

FIG. 7 is a drawing illustrating the example ceramic sample of FIG. 5 including an electrode array and a location of a crack.

FIG. 8 is a diagram illustrating an example false color output of the reconstruction algorithm for the example ceramic sample of FIG. 7.

DETAILED DESCRIPTION

The disclosure describes systems and techniques for verifying structural integrity of a material. The techniques may utilize a reactive parameter measurement to determine whether the material includes a crack or other defect. In the reactive parameter measurement, an electrical signal source may apply an electrical signal to the material via a pair of drive electrodes and the resulting reactive parameter, if any, may be measured via a pair of measurement electrodes. The reactive parameter may include, for example, capacitance, electrical phase difference, or the like. Presence of a reactive parameter above a threshold value may indicate that the material is damaged or cracked.

A reactive parameter measurement for verifying structural integrity may provide advantages compared to resistivity measurements and other techniques for verifying structural integrity. A resistivity 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 contact between the leads and the material, in temperature of the material, or the like. In some examples, variations in electrical properties of these components may complicate measurement of resistivity of 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 resistivity in the material due to a crack, which may obscure the change in resistivity in the material due to a crack. By using a reactive parameter measurement, the contributions of the electrical leads connecting the pair of measurement electrodes to the measurement device, any contact resistance between the pair of measurement electrodes and the material, and any changes in temperature may be reduced or substantially eliminated. Hence, a reactive parameter measurement may facilitate detection of cracks or other defects in a material compared to measurements of resistivity.

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 and computationally expensive.

In contrast, a reactive parameter 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. In some examples, a reactive parameter measurement crack detection system may allow relatively computationally cheap analysis techniques to be used to analyze the reactive parameter measurements and determine whether the material includes a crack or other defect.

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 reactive parameter measurement. The system 10 of FIG. 1 includes a computing device 12, an electrical signal source 14, a first of electrode 18A, and a second electrode 18B (collectively, "electrodes 18"). Electrodes 18 are electrically coupled to material 16, which is being tested using a reactive parameter 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, 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. In other examples, material 16 may include a dielectric material.

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), or the like.

Material 16 may define any geometry, and the geometry of material 16 may be based at least in part on the 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 a current signal or a voltage signal. In some examples, the electrical signal may include an alternating current (AC) voltage or a stepped voltage. In other examples, the electrical signal may include an AC current or a stepped current. 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 an electrical signal from the power source and modify the electrical signal into a format suitable for output to electrodes 18, e.g., to a selected electrical signal, including frequency, amplitude, phase, and the like.

Electrodes 18 include a first electrode 18A and a second electrode 18B electrically coupled to material 16. In some examples, as shown in FIG. 1, each electrode may be electrically coupled to electrical signal source 14, e.g., by a respective lead wire, and electrically coupled to computing device 12, e.g., by a respective lead wire. Each of electrodes 18 may be electrically coupled to material 16 using any suitable type of electrical coupling, including, direct conductive coupling, capacitive coupling, or the like. Example materials that may be used to electrically couple electrodes 18 to material 16 may include, for example, an electrically conductive adhesive, an electrically conductive solder, an electrically nonconductive adhesive, embedding electrodes 18 in material 16, or the like.

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

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 within material 16. Cracks or other defects may affect the magnitude of the reactive parameter more significantly when the electrical field extends across a plane of the crack (e.g., normal to a surface of the crack).

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 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 and placing electrodes 18 based on the predicted locations, 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 electrodes 18 to three orthogonal surfaces, the electrical field 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 the electrical field 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, embedded 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 first electrode 18A and computing device 12 and between second electrode 18B and computing device 12. The ADC may measure a reactive parameter across material 16 using electrodes 18A and 18B, e.g., under control of computing device 12.

Computing device 12 is electrically coupled to the pair of electrodes 18A and 18B, 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 across the pair of electrodes 18A and 18B. Computing device 12 also may be configured to determine a reactive parameter across material 16 using electrodes 18A and 18B in response to the electrical signal. The reactive parameter may include, for example, capacitance, electrical phase difference, or the like.

Computing device 12 may be configured to determine the reactive parameter of material 16 (between first electrode 18A and second electrode 18B) in any manner. For example, computing device 12 may include cap sense circuitry configured to detect a reactive component between two electrodes. As another example, computing device 12 may be configured to control electrical signal source 14 to generate a step voltage or current, and computing device 12 may determine voltage across electrodes 18A and 18B or the current through material 16 bounded by electrodes 18A and 18B, as a function of time. The capacitance of material 16 is related to the change in voltage or current over time. As another example, computing device 12 may determine capacitance of material 16 using a bridge circuit, one branch of which includes material 16 and electrodes 18, and the other of which includes a reference capacitor. As another example, computing device 12 may be configured to determine an electrical phase difference between measured voltage and drive current across electrodes 18A and 18B. Computing device 12 may be configured to use any other measurement technique for determining a reactive parameter.

Computing device 12 may be configured to determine whether material 16 includes a crack or other defect based on the reactive parameter. For example, computing device 12 may compare the measured reactive parameter to a threshold reactive parameter value, and determine that material 16 includes a crack or other defect in response to the measured reactive parameter exceeding the threshold reactive parameter value. The threshold reactive parameter value may depend on the reactive parameter being measured by system 10. For example, in implementations in which system 10 measures a capacitance of material 16, the threshold reactive parameter value may be a threshold capacitance value, which may be selected to be a meaningful capacitance value dividing materials that include cracks or other defects from materials that are intact (do not include cracks or other defects). As another example, in implementations in which system 10 determines an electrical phase difference between drive current and measured voltage across material 16, the threshold reactive parameter value may be a threshold phase difference value, which may be selected to be a meaningful capacitance value dividing materials that include cracks or other defects from materials that are intact (do not include cracks or other defects).

In some examples, when intact, material 16 may be unitary, with no cracks, intentional gaps, or other features that would produce capacitance. Because of this, in some examples, any capacitance in material 16 may be due to presence of a crack or other defect. Thus, in some examples, the threshold reactive parameter value may be selected to be substantially equal to or slightly greater than a reactive parameter noise floor of system 10. By selecting the threshold reactive parameter value as substantially equal to or slightly greater than the reactive parameter noise floor of system 10, any non-zero reactive parameter that is reliably measured using system 10 is identified by computing device 12 as indicating that material 16 includes a crack or other defect.

In other examples, rather than comparing the measured reactive parameter to a threshold reactive parameter value, computing device 12 may be configured to compare the measured reactive parameter to a control reactive parameter or a threshold reactive parameter value. In some examples, computing device 12 or another similar device may have measured the control reactive parameter at a first time. The first time may be a time at which material 16 is known to be intact, undamaged, or to not include a crack. For example, the first time may be 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. In other examples, the control reactive parameter may be determined (e.g., by computing device 12) using a model of material 16 in an intact (undamaged) state, or the control reactive parameter 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 threshold reactive parameter value may be selected so that a reactive parameter value above the threshold reactive parameter value is indicative of a crack or other defect and a reactive parameter value below the threshold reactive parameter value is not indicative of a crack or other defect. This control reactive parameter or threshold reactive parameter value 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 measured reactive parameter. For example, computing device 12 may control electrical signal source 14 to apply an electrical signal to electrodes 18A and 18B and determine a reactive parameter across the pair of electrodes 18A and 18B. Computing device 12 may then determine whether material 16 includes a crack or other defect based on the measured reactive parameter, for example, by comparing the measured reactive parameter to the control reactive parameter. As one example, computing device 12 may determine a difference between a magnitude of the measured reactive parameter to a magnitude of the control reactive parameter. Computing device 12 then may compare this difference to a threshold difference value, and may determine that material 16 includes a crack or other defect in response to the difference being greater than the threshold difference value. The threshold difference value may be selected to be a meaningful difference value dividing materials that include cracks or other defects from materials that are intact (do not include cracks or other defects).

In this way, by using a reactive parameter measurement, the contributions of the electrical leads coupling the pair of measurement electrodes to the measurement device, any contact resistance between the pair of measurement electrodes and the material, and any changes in temperature may be reduced or substantially eliminated. A reactive parameter measurement may facilitate detection of cracks or other defects in a material compared to measurements of resistivity. Further, a reactive parameter measurement utilizes relatively smaller, relatively less expensive equipment, which may be portable and be used to detect cracks in materials *in situ* rather than requiring removing the materials to be tested to the testing equipment. Additionally or alternatively, a reactive parameter measurement crack detection system may allow relatively computationally cheap analysis techniques to be used to analyze the reactive parameter measurements and determine whether the material includes a crack or other defect.

FIG. 2 is flow diagram illustrating an example technique for determining presence of a crack or other defect in a material using a reactive parameter 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 an electrode pair, such as electrodes 18A and 18B, electrically coupled to material 16 (22). For example, computing device 12 may control electrical signal source 14 to generate an electrical signal with a predetermined voltage or current. The predetermined voltage or current may include an AC voltage or current or a stepped voltage or current. In some examples, the type of electrical signal may depend on the type of reactive parameter measurement. For example, an AC voltage or current may be used when determining the reactive parameter measurement using a bridge circuit, a frequency sweep, or the like, while a stepped voltage or current may be used when measuring a charging rate of material 16 (if any). Computing device 12 also may control electrical signal source 14 to generate the electrical signal with a selected amplitude, duration, phase, frequency, and other signal characteristics.

The technique of FIG. 2 also includes, while applying the electrical signal to the electrode pair, such as electrodes 18A and 18B, determining a reactive parameter between an electrode pair, such as electrodes 18A and 18B, electrically coupled to material 16 (24). In some examples, the electrodes may be the same, as shown in FIG. 1. In other examples, the pair of electrodes through which the electrical signal is applied may be different than the pair of electrodes through which the computing device 12 determines the reactive parameter. For example, computing device 12 may control electrical signal source 14 to apply the electrical signal through a first pair of drive electrodes and may determine the reactive parameter via a first pair of measurement electrodes. Further details regarding examples of utilizing four-point measurement techniques to determine the reactive parameter will be described below with reference to FIG. 3.

The technique of FIG. 2 further includes determining whether material 16 includes a crack or other defect based on the reactive parameter (26). For example, computing device 12 may compare the measurement reactive parameter to a control reactive parameter or to a threshold reactive parameter value. The control reactive parameter may have been determined by system 10 or another similar system by applying a similar electrical signal to the pair of electrodes 18A and 18B and determining the reactive parameter across the pair of electrodes 18A and 18B. The control reactive parameter may have been determined at a time when material 16 was known to be defect-free, e.g., as verified using a different detection method such as X-ray radiography and X-ray computed tomography. In other examples, the control reactive parameter may be determined (e.g., by computing device 12) using a model of material 16 in an intact (undamaged) state, or the control reactive parameter 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).

As another example, computing device 12 may compare the measured reactive parameter to a threshold reactive parameter value, and determine that material 16 includes a crack or other defect in response to the measured reactive parameter exceeding the threshold reactive parameter value. The threshold reactive parameter value may depend on the reactive parameter being measured by system 10. For example, in implementations in which system 10 measures a capacitance of material 16, the threshold reactive parameter value may be a threshold capacitance value, which may be selected to be a meaningful capacitance value dividing materials that include cracks or other defects from materials that are intact (do not include cracks or other defects). As another example, in implementations in which system 10 determines an electrical phase difference between drive current and measured voltage across material 16, the threshold reactive parameter value may be a threshold phase difference value, which may be selected to be a meaningful capacitance value dividing materials that include cracks or other defects from materials that are intact (do not include cracks or other defects). In some examples, the threshold reactive parameter value may be selected to be substantially equal to or slightly greater than a reactive parameter noise floor of system 10. By selecting the threshold reactive parameter value as substantially equal to or slightly greater than the reactive parameter noise floor of system 10, any non-zero reactive parameter that is reliably measured using system 10 is identified by computing device 12 as including that material 16 includes a crack or other defect.

In some examples, rather than including a single pair of electrodes 18A and 18B, 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 reactive parameter 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 reactive parameter 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. In some examples, material 36 may include a dielectric material.

Electrical signal source 34 may include any device configured to output an electrical signal to electrodes 38. The electrical signal may include an AC voltage or current or a stepped voltage or current. 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 coupling, including, for example, an electrically conductive adhesive, an electrically conductive solder, embedding electrodes 38 in material 36, capacitive coupling across a dielectric material such as an adhesive, 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, embedded 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 analog-to-digital converter (ADC), or system 30 may include an ADC separate from computing device 32. In examples in which the ADC is separate from computing device 32, the ADC may be electrically coupled between switch network 40 and computing device 32. The ADC may measure a reactive parameter across material 36 using electrodes 38, e.g., under control of computing device 32.

Computing device 32 is communicatively coupled to electrical signal source 34 and electrically coupled to switch network 40. 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 couple 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 coupled pair of drive electrodes.

Computing device 32 is also configured to cause switch network 40 to couple a selected pair of electrodes 38 to computing device 32 to serve as a pair of measurement electrodes. In this way, computing device 32 may determine a reactive parameter 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 whether a material includes a crack or other defect using a reactive parameter 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 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 pair of drive electrodes electrically coupled to material 36 (42), e.g., via switch network 40. The electrical signal may include an AC voltage or current or a stepped voltage or current. In some examples, the type of electrical signal may depend on the measurement technique used to determine the reactive parameter. For example, an AC voltage or current may be used when measuring the reactive parameter measurement using a bridge circuit, a frequency sweep, or the like, while a stepped voltage or current may be used when measuring a charging rate of material 36 (if any). Computing device 32 also may control electrical signal source 34 to generate the predetermined voltage signal with a selected amplitude, duration, frequency, phase, and other signal characteristics.

The technique of FIG. 4 also includes, while applying the electrical signal to the pair of drive electrodes, determining reactive parameter 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. In some examples, the selected pair of measurement electrodes may be the same two electrodes as are in the selected pair of drive electrodes. In other examples, the selected pair of measurement electrodes may share exactly one electrode with the selected pair of drive electrodes. In other examples, neither of the electrodes in the pair of measurement electrodes is shared with the pair of drive 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 measurement of the reactive parameter, but may reduce an area of material 36 for which the reactive parameter is measured. Regardless of the particular electrodes coupled to computing device 32, computing device 32 may determine a reactive parameter 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).

Computing device 32 may be configured to determine the reactive parameter of material 36 (between the first pair of measurement electrodes) in any manner. For example, computing device 32 may include cap sense circuitry configured to detect a capacitance between two electrodes.

As another example, computing device 32 may be configured to control electrical signal source 34 to generate a step voltage through a resistor in series with material 36, and computing device 32 may measure voltage as a function of time at a location between the resistor and material 36. The measured voltage is related to the capacitance by the expression $V_{out} = V_{max} * (1 - e^{t/RC})$, where Vout is the measured voltage, t is time, R is the resistance of the resistor (neglecting parasitic series resistance), and C is the capacitance of material 36.

As another example, computing device 32 may be configured to control electrical signal source 34 to generate a step current to the material 36, and computing device 32 may measure voltage as a function of time across the material 36. The measured voltage is related to the capacitance by the expression $V_{out} = I_{step} * t / C$, where V_{out} is the measured voltage, I_{step} is the current step magnitude, t is time, and C is the capacitance of material 36.

As another example, computing device 32 may determine reactance of material 36 using a bridge circuit. In some examples, the bridge circuit includes a first circuit branch that includes a first resistor in series with the pair of measurement electrodes, and a second circuit branch that includes a second resistor in series with a reference reactance. Computing device 32 may measure a first voltage at a point between the first resistor and the pair of measurement electrodes and a second voltage at a point between the second resistor and the reference reactance. Computing device 32 then may compare the first voltage and the second voltage to measure the difference in reactance of material 36. In some examples, rather than measuring a value of the reactance, computing device 32 may simply determine whether material 36 exhibits any measurable reactance based on the first and second voltages.

As an additional example, computing device 32 may measure reactance of material 36 using a bridge circuit in which both branches include material 36. For example, computing device 32 may apply in parallel a voltage to a first circuit branch that includes a first resistor in series with a first pair of electrodes from electrodes 38 and a second circuit branch that includes a second resistor in series with a second pair of electrodes from electrodes 38. The first pair of electrodes and the second pair of electrodes may be different any may not share any common electrodes. Computing device 32 may measure a first voltage at a point between the first resistor and the pair of measurement electrodes and a second voltage at a point between the first resistor and the reference reactance. Computing device 32 then may compare the first voltage and the second voltage to determine if the portion of material across which the voltage is applied in the first circuit branch, the portion of material across which the voltage is applied in the second circuit branch, or both exhibits any reactance.

As another example, computing device 32 may measure capacitance of material 36 using an LC circuit. For example, computing device may apply an AC voltage or current of varying frequency to a circuit including an inductor of known inductance and material 16 (e.g., a pair of electrodes from electrodes 38). Computing device 32 may determine a capacitance of material 16 by determining the resonant frequency of the LC circuit.

As a further example, computing device 32 may be configured to determine an electrical phase difference between measured voltage and drive current across an electrode pair from electrodes 38. In general, computing device 32 may be configured to use any measurement technique for measuring a reactive parameter, such as capacitance, electrical phase difference, or the like.

Regardless of the technique by which computing device 32 determines the reactive parameter, in some examples, computing device 32 may be configured to measure a respective reactive parameter 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 reactive parameter (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). Additionally, in some examples, the pair of drive electrodes is the same as the 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 reactive parameter across the selected additional pair of electrodes.

Computing device 32 may repeat this determination (46), coupling of selected pairs of measurement electrodes, and measurement of a respective reactive parameter (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 which to apply the electrical signal (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 reactive parameter between the selected pair of measurement electrodes (44). In some examples, the pair of drive electrodes is the same as the pair of measurement electrodes. Again, computing device 32 may determine whether there is an additional pair of measurement electrodes at which to determine a respective reactive parameter (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 reactive parameter 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 reactive parameter (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 material 36 includes a crack or other defect based on the respective reactive parameters (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 reactive parameters. 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. In other examples, the control reactive parameter may be determined (e.g., by computing device 12) using a model of material 16 in an intact (undamaged) state, or the control reactive parameter 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). These respective control reactive parameters may be stored (e.g., in a memory device associated with computing device 32) for later use. For example, the respective control reactive parameters may be stored in a data structure in which each respective control reactive parameter is associated with a pair of drive electrodes to which the electrical signal was applied during the reactive parameter measurement and a pair of measurement electrodes with which the respective control reactive parameter was measured.

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

The threshold difference value may be selected so that a reactive parameter difference above the threshold difference value is meaningful (e.g., indicative of a crack or other defect) and a reactive parameter difference below the threshold difference value is not meaningful (e.g., is not indicative of a crack or other defect). In some examples, the threshold difference value may be selected to be a reactive parameter value that is slightly greater than a noise floor of the measurement, such that any reactive parameter 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 measured reactive parameter against a corresponding control reactive parameter and comparing the difference to the threshold difference value to determine if the respective measured reactive parameter is indicative of a crack or other defect, computing device 36 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 that material 36 includes a crack of other defect in response to at least one respective reactive parameter difference being greater than the threshold reactive parameter.

In some examples, rather than utilizing differences between respective measurement reactive parameters and respective control reactive parameters, computing device 32 may compare each respective measured reactive parameter to a threshold reactive parameter value, and determine that material 36 includes a crack or other defect in response to at least one of the respective measured reactive parameters exceeding the threshold reactive parameter value. The threshold reactive parameter value may depend on the reactive parameter being measured by system 30. For example, in implementations in which system 30 measures a capacitance of material 36, the threshold reactive parameter value may be a threshold capacitance value, which may be selected to be a meaningful capacitance value dividing materials that include cracks or other defects from materials that are intact (do not include cracks or other defects). As another example, in implementations in which system 30 measures an electrical phase difference between drive current and measured voltage across material 36, the threshold reactive parameter value may be a threshold phase difference value, which may be selected to be a meaningful capacitance value dividing materials that include cracks or other defects from materials that are intact (do not include cracks or other defects).

In some examples, when intact, material 36 may be unitary, with no cracks, intentional gaps, or other features that would produce a reactive component. Because of this, in some examples, any reactive component in material 36 may be due to presence of a crack or other defect. Thus, in some examples, the threshold reactive parameter value may be selected to be substantially equal to or slightly greater than a reactive parameter noise floor of system 30. By selecting the threshold reactive parameter value as substantially equal to or slightly greater than the reactive parameter noise floor of system 30, any non-zero reactive parameter that is reliably measured using system 30 is identified by computing device 32 as indicating that material 36 includes a crack or other defect. In some examples, computing device 32 may determine that material 36 includes a crack or other defect in response to at least one reactive parameter value exceeding the threshold reactive parameter value. In other examples, computing device 32 may determine that material 36 includes a crack or other defect in response to at least a threshold number of reactive parameter values exceeding the threshold reactive parameter value.

In some examples, computing device 32 may compare each respective measured reactive parameter to each other respective measured reactive parameter to determine whether any of the measured reactive parameters are outliers (e.g., different than the other respective measured reactive parameter by greater than a threshold amount). The presence of any outlying measured reactive parameter values may indicate that material 36 includes a crack or other defect. In some examples, computing device 32 may determine that material 36 includes a crack or other defect in response to at least one reactive parameter value being an outlier. In other examples, computing device 32 may determine that material 36 includes a crack or other defect in response to at least a threshold number of reactive parameter values being outliers (e.g., a threshold number of reactive parameter values associated with the same pair of measurement electrodes and different pairs of drive electrodes).

In other examples, 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** and 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 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 impedance change within the material. In some examples, only the imaginary portion of the impedance—

the reactance—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. Again, in some examples, only the imaginary portion of the impedance—the reactance—may be used by computing device 32 to determine whether material 36 includes a crack or other defect.

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 an approximate impedance distribution 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 the reactive parameter overlaid on a representation of material 16. Examples of such outputs are shown below in FIG. 8.

In this way, by using a reactive parameter measurement, the contributions of the electrical leads coupling the pair of measurement electrodes to the measurement device, any contact resistance between the pair of measurement electrodes and the material, and any changes in temperature may be reduced or substantially eliminated. A reactive parameter measurement may facilitate detection of cracks or other defects in a material compared to measurements of resistivity. Further, a reactive parameter measurement utilizes relatively smaller, relatively less expensive equipment, which may be portable and be used to detect cracks in materials *in situ* rather than requiring removing the materials to be tested to the testing equipment. Additionally or alternatively, a reactive parameter measurement crack detection system may allow relatively computationally cheap analysis techniques to be used to analyze the reactive parameter measurements and determine whether the material includes a crack or other defect.

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 across an electrode pair electrically coupled to the material; determining a reactive parameter between the electrode pair; and determining whether the material includes a crack or other defect based on the reactive parameter.

Clause 2: The method of clause 1, wherein the reactive parameter comprises at least one of a capacitance, an electrical phase difference, a rise time of a response signal, or a fall time of a response signal.

Clause 3: The method of clause 1 or 2, wherein the electrical signal is at least one of an alternating current voltage, a stepped voltage, a stepped current, a pulsed voltage, or a pulsed current.

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 reactive parameter comprises determining that the material includes the crack or other defect in response to the reactive parameter exceeding a threshold reactive parameter value.

Clause 5: The method of any one of clauses 1 to 4, wherein a plurality of electrodes are distributed across a surface area of the material, and wherein the plurality of electrodes include the electrode pair.

Clause 6: The method of any one of clauses 1 to 4, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the electrode pair.

Clause 7: The method of any one of clauses 1 to 6, wherein: the electrode pair is a first electrode pair; the reactive parameter is a first capacitance; the method further comprises: applying an electrical signal across a second electrode pair electrically coupled to the material; and determining a second reactive parameter between the second electrode pair; and determining whether the material includes the crack or other defect based on the reactive parameter comprises determining whether the material includes the crack or other defect based on the first reactive parameter and the second reactive parameter.

Clause 8: The method of clause 7, wherein determining whether the material includes the crack or other defect based on the first reactive parameter and the second reactive parameter comprises determining that the material includes the crack or other defect in response to the first reactive parameter being different than the second capacitance.

Clause 9: The method of any one of clauses 1 to 8, wherein: the electrode pair is a first electrode pair; applying the electrical signal across the electrode pair electrically coupled to the material comprises applying the electrical signal in parallel to a first circuit branch comprising a first resistor in series with the first electrode pair and a second circuit branch comprising a second resistor in series with a second electrode pair electrically coupled to the material; and determining the reactive parameter between the first electrode pair comprises comparing a first voltage measured at a first point between the first resistor and the first electrode pair to a second voltage measured at a second point between the second resistor and the second electrode pair.

Clause 10: The method of any one of clauses 1 to 8, wherein: applying the electrical signal across the electrode pair electrically coupled to the material comprises applying the electrical signal in parallel to a first circuit branch comprising a first resistor in series with the first electrode pair and a second circuit branch comprising a second resistor in series with a capacitor; and determining the reactive parameter between the first electrode pair comprises comparing a first voltage measured at a first point between the first resistor and the first electrode pair to a second voltage measured at a second point between the second resistor and the capacitor.

Clause 11: The method of any one of clauses 1 to 10, wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a dielectric material.

Clause 12: 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 across the respective pair of drive electrodes; for each respective pair of drive electrodes, determining a respective reactive parameter 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 reactive parameters.

Clause 13: The method of clause 12, wherein the reactive parameter comprises at least one of a capacitance, an electrical phase difference, a rise time of a response signal, or a fall time of a response signal.

Clause 14: The method of clause 12 or 13, wherein the electrical signal is at least one of an alternating current voltage signal, a stepped voltage, a stepped current, a pulsed voltage, or a pulsed current.

Clause 15: The method of any one of clauses 12 to 14, wherein determining whether the material includes the crack or other defect based on the respective reactive parameters comprises determining that the material includes the crack or other defect in response to at least one of the respective capacitances exceeding a threshold reactive parameter value.

Clause 16: The method of clause 15, wherein determining that the material includes the crack or other defect in response to at least one of the respective reactive parameters exceeding the threshold reactive parameter value comprises determining that the material includes the crack or other defect in response to at least a threshold number of the respective reactive parameters exceeding the threshold reactive parameter value.

Clause 17: The method of any one of clauses 12 to 14, wherein determining whether the crack or other defect is present in the material based on the respective reactive parameters comprises: determining an approximate distribution of an imaginary portion of impedance 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 respective measured voltages; and determining whether the material includes the crack or other defect based on the distribution of the imaginary portion of the impedance.

Clause 18: The method of clause 17, wherein calculating the approximate change in the imaginary portion of the impedance 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 distribution of the imaginary portion of the impedance, 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.

Clause 19: The method of any one of clauses 12 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 pairs of drive electrodes and the at least one electrode of each of the plurality of respective pairs of measurement electrodes.

Clause 20: The method of any one of clauses 12 to 19, wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a dielectric material.

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 across a pair of drive electrodes, wherein the pair of drive electrodes are from the set of N electrodes; determine a reactive parameter between a pair of measurement electrodes, wherein at least one measurement electrode from the pair of measurement electrodes is from the set of N electrodes; and determine whether the material includes a crack or other defect based on the reactive parameter.

Clause 22: The system of clause 21, wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a dielectric material.

Clause 23: The system of clause 21 or 22, wherein the reactive parameter comprises at least one of a capacitance, an electrical phase difference, a rise time of a response signal, or a fall time of a response signal.

Clause 24: The system of any one of clauses 21 to 23, wherein the pair of measurement electrodes is different than the pair of drive electrodes.

Clause 25: The system of any one of clauses 21 to 23, wherein the pair of measurement electrodes is the same as the pair of drive electrodes.

Clause 26: The system of any one of clauses 21 to 25, wherein the electrical signal is at least one of an alternating current voltage, a stepped voltage, a stepped current, a pulsed voltage, or a pulsed current.

Clause 27: The system of any one of clauses 21 to 26, wherein the computing device is configured to determine whether the material includes the crack or other defect by at least comparing the reactive parameter to a control reactive parameter and determining that the material includes the crack or other defect in response to the reactive parameter exceeding the control reactive parameter.

Clause 28: The system of any one of clauses 21 to 27, wherein: the pair of measurement electrodes is a first pair of measurement electrodes; the reactive parameter is a first reactive parameter; the computing device is further configured to: determine a second reactive parameter between a second pair of measurement electrodes while applying the electrical signal across the first pair of drive electrodes, wherein at least one measurement electrode of 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 reactive parameter and the second reactive parameter.

Clause 29: The system of clause 28, wherein the computing device is configured to determine that the material includes the crack or other defect in response to the first reactive parameter being different than the second reactive parameter.

Clause 30: The system of clause 28, wherein the second pair of measurement electrodes shares exactly one electrode with the first pair of measurement electrodes.

Clause 31: The system of clause 28, wherein the second pair of measurement electrodes does not share any electrodes with the first pair of measurement electrodes.

Clause 32: The system of any one of clauses 21 to 31, wherein the set of N electrodes are distributed across a surface area of the material.

Clause 33: The system of any one of clauses 21 to 31, wherein the set of N electrodes are distributed are distributed around a perimeter of the material.

Clause 34: The system of any one of clauses 21 to 27, wherein: the pair of measurement electrodes is the same as the pair of drive electrodes and comprises a first electrode pair; the computing device is configured to: cause the electrical signal source to apply the electrical signal in parallel to a first circuit branch comprising a first resistor in series with the first electrode pair and a second circuit branch comprising a second resistor in series with a second electrode pair, wherein the set of N electrodes comprises the second electrode pair; and determine the reactive parameter between the pair of measurement electrodes by at least comparing a first voltage measured at a first point between the first resistor and the first electrode pair to a second voltage measured at a second point between the second resistor and the second electrode pair.

Clause 35: The system of any one of clauses 21 to 27, wherein: the pair of measurement electrodes is the same as the pair of drive electrodes and comprises an electrode pair; the computing device is configured to: cause the electrical signal source to apply the electrical signal in parallel to a first circuit branch comprising a first resistor in series with the electrode pair and a second circuit branch comprising a second resistor in series with a capacitor; and determine the reactive parameter between the first electrode pair by at least comparing a first voltage measured at a first point between the first resistor and the first electrode pair to a second voltage measured at a second point between the second resistor and the capacitor.

Clause 36: The system of any one of clauses 21 to 35, wherein the computing device is configured to: for each respective pair of drive electrodes of a plurality of respective pairs of drive electrodes, cause the electrical signal source to 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, determine a respective reactive parameter 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 reactive parameters.

Clause 37: The system of clause 36, wherein the computing device is configured to determine that the material includes the crack or other defect in response to at least one of the respective reactive parameters exceeding a threshold reactive parameter value.

Clause 38: The method of clause 37, wherein the computing device is configured to determine that the material includes the crack or other defect in response to at least a threshold number of the respective reactive parameters exceeding the threshold reactive parameter value.

Clause 39: The system of clause 36, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the respective reactive parameters by at least: determining an approximate distribution of an imaginary portion of impedance 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 respective measured voltages; and determining whether the material includes the crack or other defect based on the distribution of the imaginary portion of the impedance.

Clause 40: The system of clause 39, wherein calculating the approximate change in the imaginary portion of the impedance 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 distribution of the imaginary portion of the impedance, 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

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. 5 is a drawing illustrating the ceramic sample including the sixteen element electrical contact array and the flex circuit. FIG. 6 is a drawing illustrating the ceramic sample 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. 7 is a drawing illustrating the ceramic sample including an electrode array and the location of a crack. FIG. 7 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 algorithms. 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. EIDORS is available at eidors3d.sourceforge.net. MATLAB® is available from MathWorks®, Inc., Natick, Massachusetts, United States. An L-Curve method of hyperparameter selection and a Laplace filter penalty function was utilized in the EIDORS package.

Rather that inputting the simple voltage or real portion of the measured voltage (or the complex voltage) to the EIDORS algorithm, only the magnitude of the imaginary component of the complex voltage was input to the EIDORS algorithm. FIG. 8 is a diagram illustrating an example false color output of the EIDORS algorithm for the example ceramic sample of FIG. 7. The result in FIG. 8 shows that the imaginary component alone has sufficient information to correctly identify and locate the crack in this ceramic sample.

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 across an electrode pair electrically coupled to the material;

determining a reactive parameter between the electrode pair; and

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

2. The method of claim 1, wherein the reactive parameter comprises at least one of a capacitance, an electrical phase difference, a rise time of a response signal, or a fall time of a response signal.

3. The method of claim 1, wherein the electrical signal is at least one of an alternating current voltage, a stepped voltage, a stepped current, a pulsed voltage, or a pulsed current.

4. The method of claim 1, wherein determining whether the material includes the crack or other defect based on the reactive parameter comprises determining that the material includes the crack or other defect in response to the reactive parameter exceeding a threshold reactive parameter value.

5. 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 electrode pair.

6. 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 electrode pair.

7. The method of claim 1, wherein:

the electrode pair is a first electrode pair;

the reactive parameter is a first capacitance;

the method further comprises:

applying an electrical signal across a second electrode pair electrically coupled to the material; and

determining a second reactive parameter between the second electrode pair; and

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

8. The method of claim 7, wherein determining whether the material includes the crack or other defect based on the first reactive parameter and the second reactive parameter comprises determining that the material includes the crack or other defect in response to the first reactive parameter being different than the second capacitance.

9. The method of claim 1, wherein:

the electrode pair is a first electrode pair;

applying the electrical signal across the electrode pair electrically coupled to the material comprises applying the electrical signal in parallel to a first circuit branch comprising a first resistor in series with the first electrode pair and a second circuit branch comprising a second resistor in series with a second electrode pair electrically coupled to the material; and

determining the reactive parameter between the first electrode pair comprises comparing a first voltage measured at a first point between the first resistor and the first electrode pair to a second voltage measured at a second point between the second resistor and the second electrode pair.

10. The method of claim 1, wherein:

applying the electrical signal across the electrode pair electrically coupled to the material comprises applying the electrical signal in parallel to a first circuit branch comprising a first resistor in series with the first electrode pair and a second circuit branch comprising a second resistor in series with a capacitor; and

determining the reactive parameter between the first electrode pair comprises comparing a first voltage measured at a first point between the first resistor and the first electrode pair to a second voltage measured at a second point between the second resistor and the capacitor.

11. The method of claim 1, wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a dielectric material.

12. 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 across the respective pair of drive electrodes;

for each respective pair of drive electrodes, determining a respective reactive parameter 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 reactive parameters.

13. The method of claim 12, wherein the reactive parameter comprises at least one of a capacitance, an electrical phase difference, a rise time of a response signal, or a fall time of a response signal.

14. The method of claim 12, wherein the electrical signal is at least one of an alternating current voltage signal, a stepped voltage, a stepped current, a pulsed voltage, or a pulsed current.

15. The method of claim 12, wherein determining whether the material includes the crack or other defect based on the respective reactive parameters comprises determining that the material includes the crack or other defect in response to at least one of the respective capacitances exceeding a threshold reactive parameter value.

16. The method of claim 15, wherein determining that the material includes the crack or other defect in response to at least one of the respective reactive parameters exceeding the threshold reactive parameter value comprises determining that the material includes the crack or other defect in response to at least a threshold number of the respective reactive parameters exceeding the threshold reactive parameter value.

17. The method of claim 12, wherein determining whether the crack or other defect is present in the material based on the respective reactive parameters comprises:

determining an approximate distribution of an imaginary portion of impedance 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 respective measured voltages; and

determining whether the material includes the crack or other defect based on the distribution of the imaginary portion of the impedance.

18. The method of claim 17, wherein calculating the approximate change in the imaginary portion of the impedance 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 distribution of the imaginary portion of the impedance, 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 12, wherein a plurality of electrodes are distributed around a perimeter of the material, and wherein the plurality of electrodes include the plurality of respective pairs of drive electrode and the at least one electrode of each of the plurality of respective pairs of measurement electrodes.

20. The method of claim 12, wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a dielectric material.

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 across a pair of drive electrodes, wherein the pair of drive electrodes are from the set of N electrodes;

determine a reactive parameter between a pair of measurement electrodes, wherein at least one measurement electrode from the pair of measurement electrodes is from the set of N electrodes; and

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

22. The system of claim 21, wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a dielectric material.

23. The system of claim 21, wherein the reactive parameter comprises at least one of a capacitance, an electrical phase difference, a rise time of a response signal, or a fall time of a response signal.

24. The system of claim 21, wherein the pair of measurement electrodes is different than the pair of drive electrodes.

25. The system of claim 21, wherein the pair of measurement electrodes is the same as the pair of drive electrodes.

26. The system of claim 21, wherein the electrical signal is at least one of an alternating current voltage, a stepped voltage, a stepped current, a pulsed voltage, or a pulsed current.

27. 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 reactive parameter to a control reactive parameter and determining that the material includes the crack or other defect in response to the reactive parameter exceeding the control reactive parameter.

28. The system of claim 21, wherein:

the pair of measurement electrodes is a first pair of measurement electrodes;

the reactive parameter is a first reactive parameter;

the computing device is further configured to:

determine a second reactive parameter between a second pair of measurement electrodes while applying the electrical signal across the first pair of drive electrodes, wherein at least one measurement electrode of 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 reactive parameter and the second reactive parameter.

29. The system of claim 28, wherein the computing device is configured to determine that the material includes the crack or other defect in response to the first reactive parameter being different than the second reactive parameter.

30. The system of claim 28, wherein the second pair of measurement electrodes shares exactly one electrode with the first pair of measurement electrodes.

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

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

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

34. The system of claim 21, wherein:

the pair of measurement electrodes is the same as the pair of drive electrodes and comprises a first electrode pair;

the computing device is configured to:

cause the electrical signal source to apply the electrical signal in parallel to a first circuit branch comprising a first resistor in series with the first electrode pair and a second circuit branch comprising a second resistor in series with a second electrode pair, wherein the set of N electrodes comprises the second electrode pair; and

determine the reactive parameter between the pair of measurement electrodes by at least comparing a first voltage measured at a first point between the first resistor and the first electrode pair to a second voltage measured at a second point between the second resistor and the second electrode pair.

35. The system of claim 21, wherein:

the pair of measurement electrodes is the same as the pair of drive electrodes and comprises an electrode pair;

the computing device is configured to:

cause the electrical signal source to apply the electrical signal in parallel to a first circuit branch comprising a first resistor in series with the electrode pair and a second circuit branch comprising a second resistor in series with a capacitor; and

determine the reactive parameter between the first electrode pair by at least comparing a first voltage measured at a first point between the first resistor and the first electrode pair to a second voltage measured at a second point between the second resistor and the capacitor.

36. 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, cause the electrical signal source to 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, determine a respective reactive parameter 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 reactive parameters.

37. The system of claim 36, wherein the computing device is configured to determine that the material includes the crack or other defect in response to at least one of the respective reactive parameters exceeding a threshold reactive parameter value.

38. The method of claim 37, wherein the computing device is configured to determine that the material includes the crack or other defect in response to at least a threshold number of the respective reactive parameters exceeding the threshold reactive parameter value.

39. The system of claim 36, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the respective reactive parameters by at least:

determining an approximate distribution of an imaginary portion of impedance 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 respective measured voltages; and

determining whether the material includes the crack or other defect based on the distribution of the imaginary portion of the impedance.

40. The system of claim 39, wherein calculating the approximate change in the imaginary portion of the impedance 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 distribution of the imaginary portion of the impedance, 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.

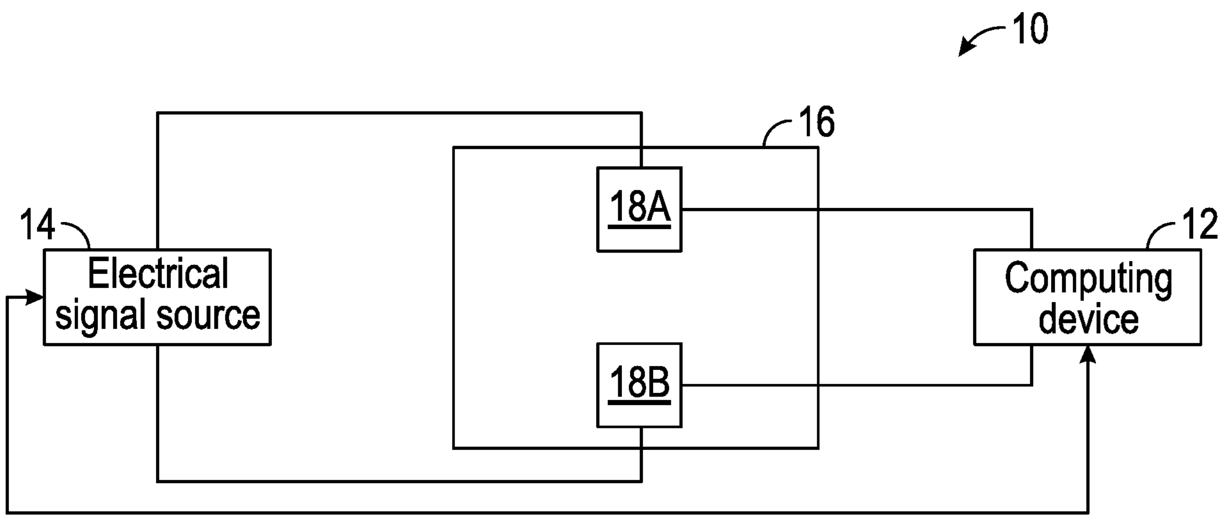

10
16
18A
18B
14
Electrical signal source
12
Computing device

FIG. 1

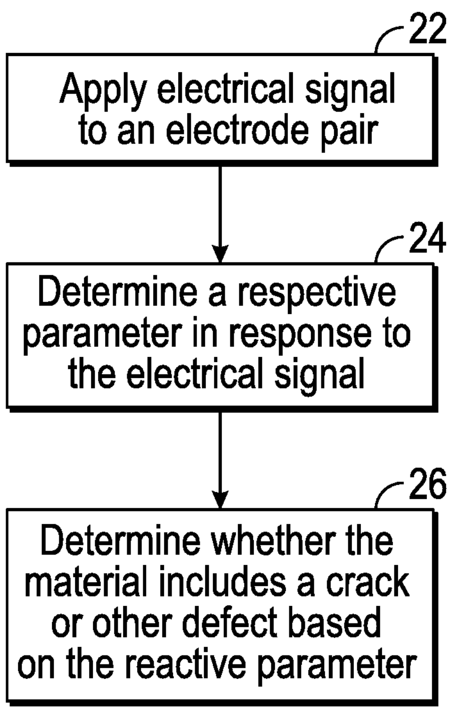

22
Apply electrical signal to an electrode pair
24
Determine a respective parameter in response to the electrical signal
26
Determine whether the material includes a crack or other defect based on the reactive parameter

FIG. 2

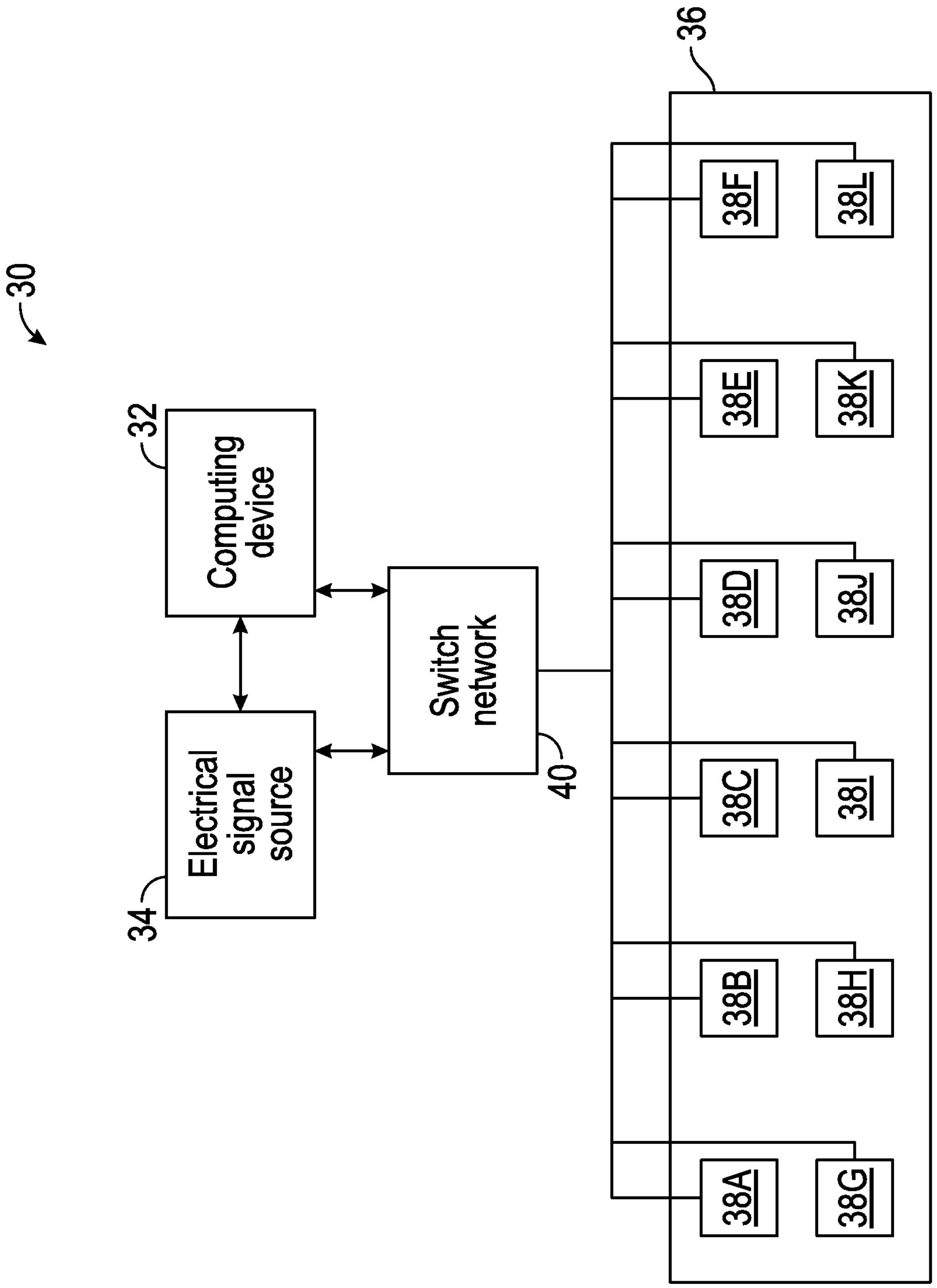
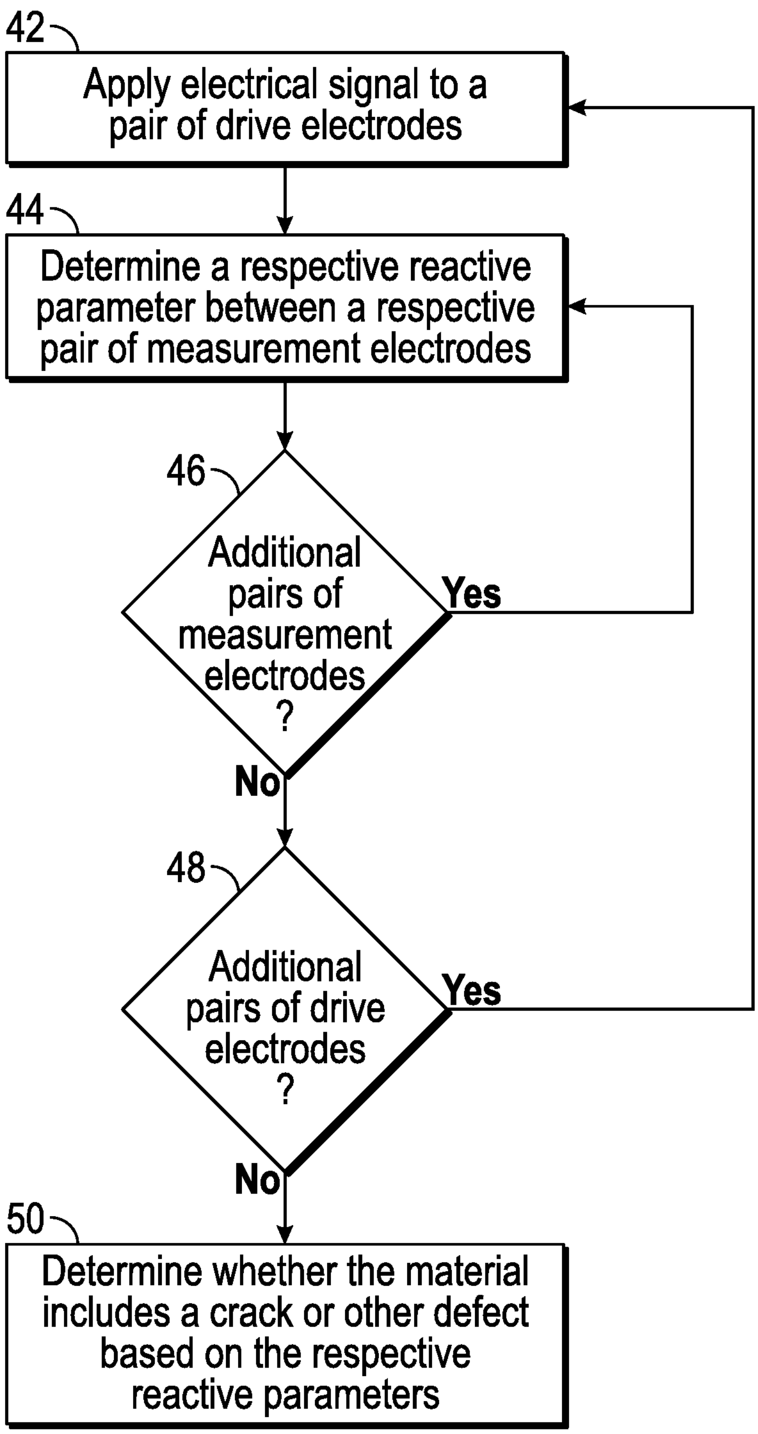

30
32
Computing device
34
Electrical signal source
Switch network
40
36
38A
38B
38C
38D
38E
38F
38G
38H
38I
38J
38K
38L

FIG. 3



42
Apply electrical signal to a pair of drive electrodes
44
Determine a respective reactive parameter 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 reactive parameters

FIG. 4

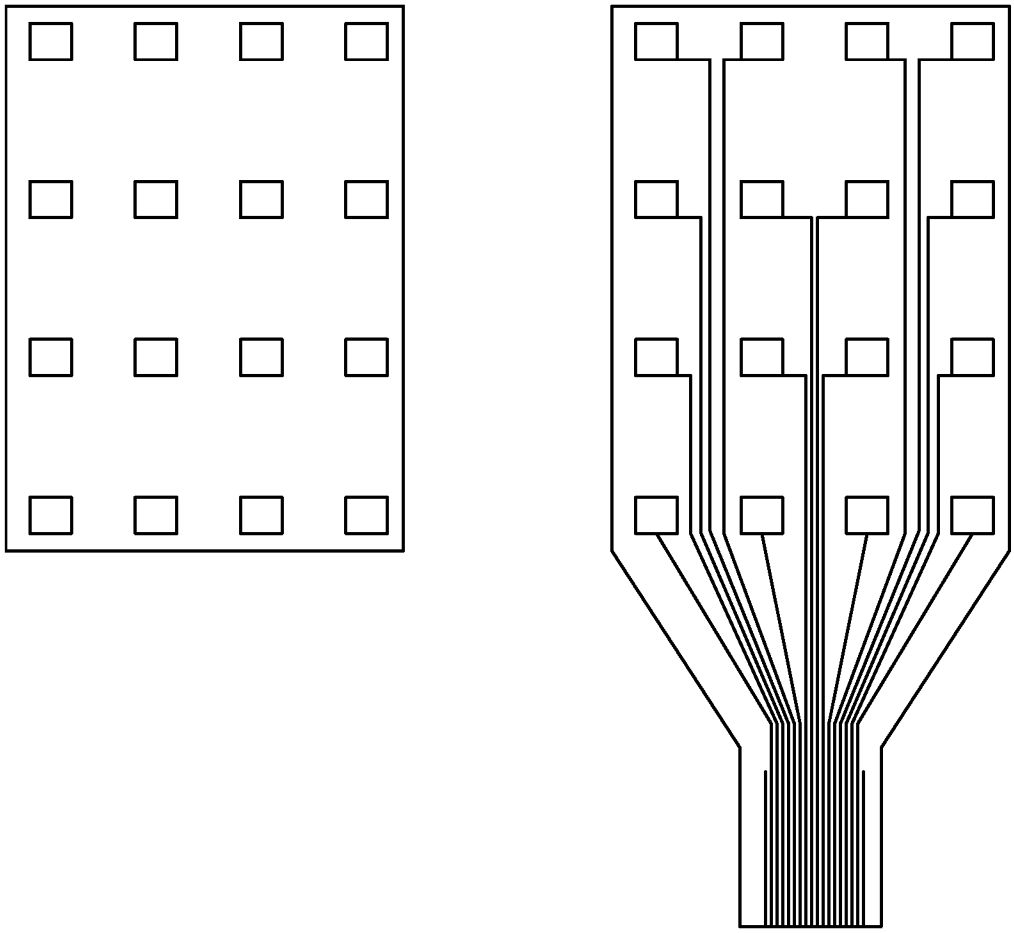


FIG. 5

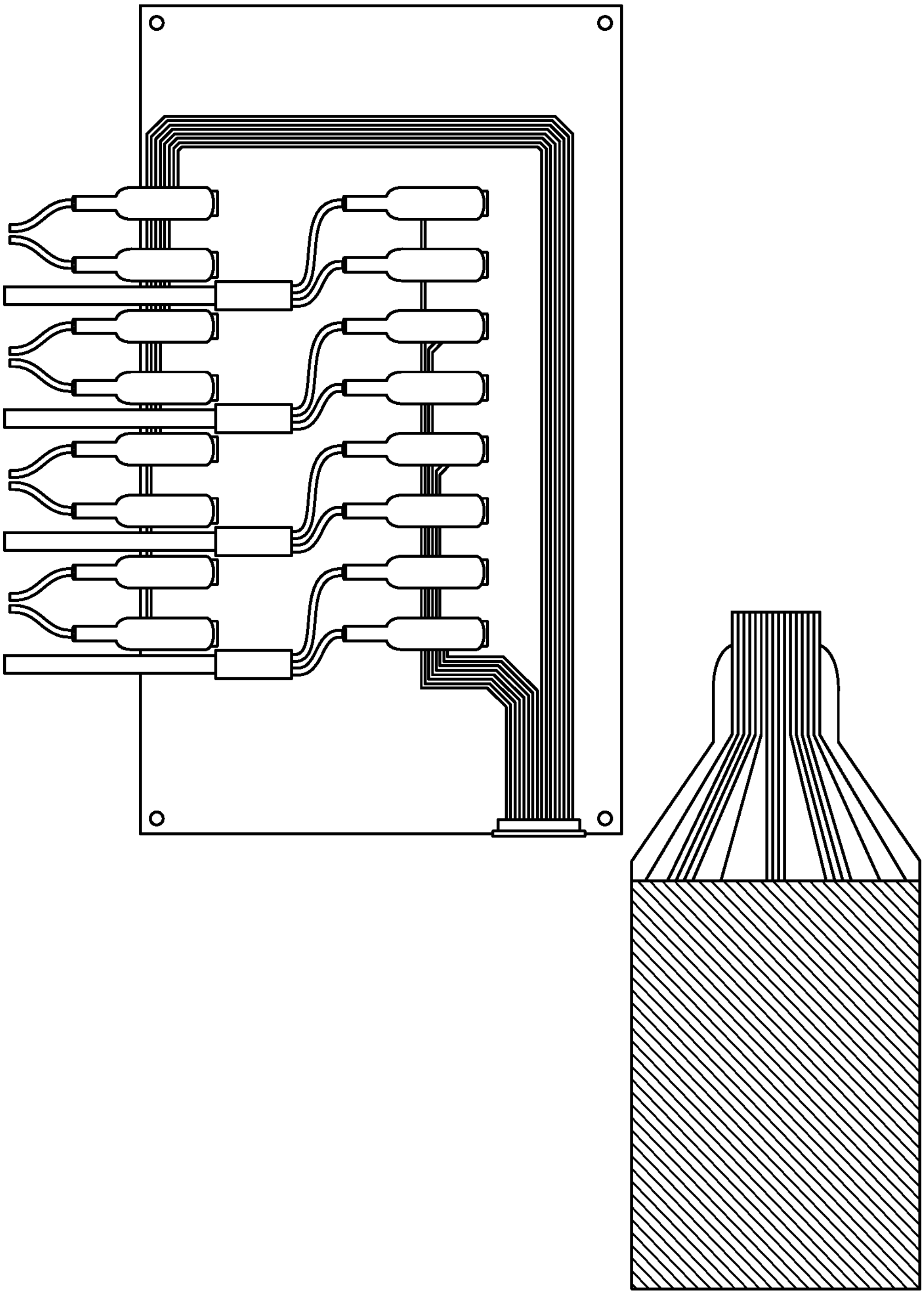


FIG. 6

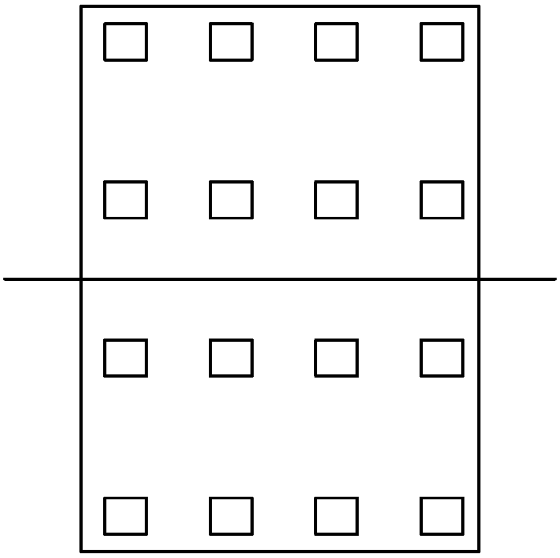


FIG. 7

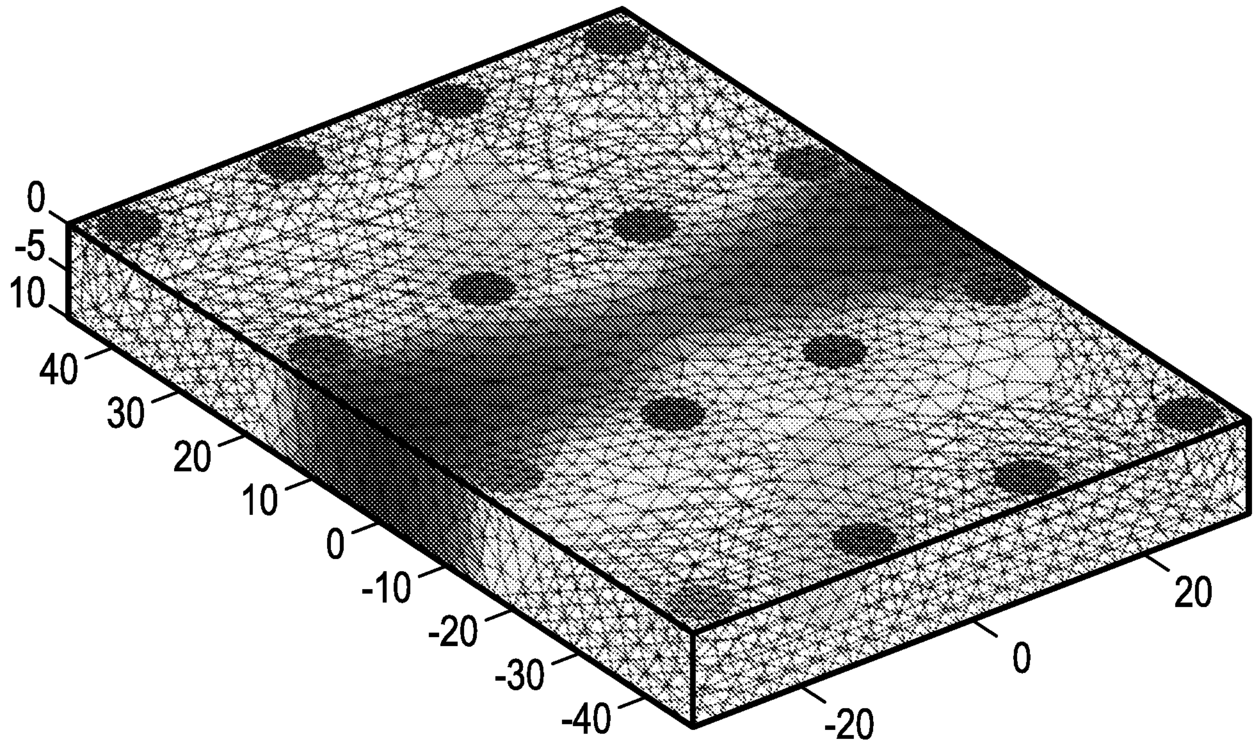


FIG. 8