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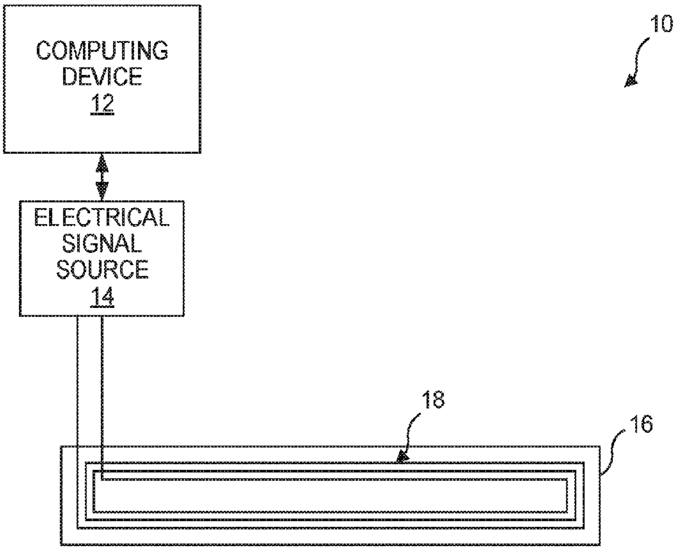

FIG. 1

(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 to an inductor adjacent to the material; determining an electrical loss in the inductor due to the material; and determining whether the material includes a crack or other defect based on the electrical loss. In other examples, a method for detecting a crack or defect in a material may include applying an electrical signal to an inductor adjacent to a material; determining an induced voltage or current across a pair of electrical contacts, where at least one of the electrical contacts is electrically coupled to the material; and determining whether the material includes a crack or other defect based on the induced voltage or current.

[Continued on next page]

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VERIFYING STRUCTURAL INTEGRITY OF MATERIALS USING MAGNETIC FIELD STIMULATION

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 magnetic field stimulation. Cracks in a material may affect conductivity (and resistivity) of the material, which in turn may affect parameters of the material induced using magnetic field stimulation, including electrical loss and formation of induced currents in the material. Hence, a magnetic field stimulation-based measurement may be used to determine if the material includes a crack or other defect. The parameter measured using magnetic field stimulation may include electrical loss of the inductor, induced voltages, induced currents, or the like. For example, by comparing the resulting parameter measurement induced using magnetic field stimulation to a control parameter corresponding to the same electrode pair or inductor when the material or a similar material or set of materials is known to be intact (undamaged) or a predetermined threshold parameter value, the parameter measurement induced using magnetic field stimulation may be used to determine whether the material is damaged or intact.

In some examples, the disclosure describes a method for detecting a crack or defect in a material. The method may include applying an electrical signal to an inductor adjacent to the material; determining an electrical loss in the inductor due to the material; and determining whether the material includes a crack or other defect based on the electrical loss.

In some examples, the disclosure describes a system including a material; an inductor adjacent to the material; an electrical signal source configured to apply an electrical signal to the at least one inductor; and a computing device. The computing device may be configured to determine an electrical loss in the inductor due to the material and determine whether the material includes a crack or other defect based on the electrical loss.

In some examples, the disclosure describes a system including an electrical signal source; an inductor electrically coupled to the electrical signal source; a pair of electrical contacts; and a computing device. The computing device may be configured to cause the electrical signal source to apply an electrical signal to the inductor when a material is adjacent to the inductor. The computing device also may be configured to determine an induced voltage or current across the pair of electrical contacts, wherein the electrical contacts are electrically coupled to a pair of electrodes electrically coupled to the material. Further, the computing device may be configured to determine whether the material includes a crack or other defect based on the induced voltage or current.

In some examples, the disclosure describes a method for detecting a crack or defect in a material. The method may include applying an electrical signal to an inductor adjacent to a material; determining an induced voltage or current across a pair of electrical contacts electrically coupled to the material; and determining whether the material includes a crack or other defect based on the induced voltage or current.

The techniques described herein may provide one or more advantages. For example, a crack detection system utilizing magnetic field stimulation may offer at least one of improved portability, speed, or 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. In some examples, a crack detection system utilizing magnetic field stimulation may allow relatively computationally cheap analysis techniques to be used to analyze the 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 a conceptual and schematic diagram block illustrating an example system for determining whether a material includes a crack or other defect using magnetic field stimulation.

FIG. 2 is a conceptual and schematic diagram block illustrating another example system for determining whether a material includes a crack or other defect using magnetic field stimulation.

FIG. 3 is a conceptual and schematic diagram block illustrating another example system for determining whether a material includes a crack or other defect using magnetic field stimulation.

FIG. 4 is flow diagram illustrating an example technique for determining whether a material includes a crack or other defect using magnetic field stimulation.

FIG. 5 is a conceptual and schematic diagram block illustrating another example system for determining whether a material includes a crack or other defect using magnetic field stimulation.

FIG. 6 is a conceptual and schematic diagram block illustrating another example system for determining whether a material includes a crack or other defect using magnetic field stimulation.

FIG. 7 is flow diagram illustrating another example technique for determining whether a material includes a crack or other defect using magnetic field stimulation.

DETAILED DESCRIPTION

The disclosure describes systems and techniques for verifying structural integrity of a material. The techniques may utilize magnetic field stimulation to induce voltage or current in a material and determine a related parameter to determine whether the material includes a crack or other defect. In the magnetic field stimulation-related parameter measurement, an electrical signal source may apply an electrical signal to an inductor adjacent to the material and a computing device may determine the resulting magnetic field stimulation-related parameter. The magnetic field stimulation-related parameter may include, for example, electrical loss in the inductor due to the material, induced voltage in the material, induced current in the material, or the like. A reduction in the electrical loss in the inductor compared to a control electrical loss or a reduction in induced voltage or current in the material compared to a control voltage or current may indicate that the material includes a crack or other defect. The control electrical loss and the control induced voltage or current may be determined using one or more techniques. For example, the electrical loss and the control induced voltage or current may be determined for the material when the material is known to be intact (undamaged), the control electrical loss and the control induced voltage or current may be determined using a model of the material in an intact (undamaged) state, or the control electrical loss and the control induced voltage or current 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, instead of comparing the determined magnetic field stimulation-related parameter to a control magnetic field stimulation-related parameter, the determined magnetic field stimulation-related parameter may be compared to a predetermined threshold magnetic field stimulation-related parameter. In some examples, the predetermined threshold magnetic field stimulation-related parameter may be selected so that a determined magnetic field stimulation-related parameter below the threshold magnetic field stimulation-related parameter value is indicative of a crack or other defect and a determined magnetic field stimulation-related parameter above the threshold magnetic field stimulation-related parameter value is not indicative of a crack or other defect.

A magnetic field stimulation-related parameter measurement for verifying structural integrity may provide advantages compared to other techniques for verifying structural integrity. Using resistivity measurement using a current directly applied to the material 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, 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 an induced voltage or current measurement or electrical loss measurement, the contributions of the electrical leads connecting the pair of measurement electrodes (if any) to the measurement device and any contact resistance between the measurement electrodes (if any) and the material may be reduced or substantially eliminated. Hence, a magnetic field stimulation-related parameter measurement may facilitate detection of cracks or other defects in a material.

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 magnetic field stimulation-related parameter measurement utilizes relatively smaller, relatively less expensive equipment. As such, in some examples, 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 magnetic field stimulation-related parameter measurement crack detection system may allow relatively computationally cheap analysis techniques to be used to analyze the magnetic field stimulation-related 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 magnetic field stimulation-related parameter measurement. System 10 of FIG. 1 includes a computing device 12, an electrical signal source 14, and an inductor 18. Inductor 18 is adjacent to material 16, which is being tested using the inductor-related 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 material, an electrically semiconductive material, or a magnetically permeable material. For example, material 16 may include a metal, an alloy, a metalloid, a semiconductor, an electrically conductive or semiconductive ceramic, or the like. In some examples, material 16 may include a ceramic such as boron carbide (B_4C), silicon carbide (SiC), alumina (Al_2O_3), composites thereof, or the like.

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

Material 16 may define any geometry, and the geometry of material 16 may be based at least in part on the 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 inductor 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 an AC 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 inductor 18, e.g., to a selected electrical signal, including frequency, amplitude, phase, and the like.

Inductor 18 may include an electrical conductor arranged in any geometry suitable for an inductor. In some examples, inductor 18 may include a substantially planar coil, as shown in FIG. 1. In examples in which inductor 18 includes a coil, inductor 18 may include any number of windings. Inductor 18 may include any suitable electrically conductive material, including, for example, copper, aluminum, silver, gold, or the like. Inductor 18 may be any size, and in some examples, may be shaped and sized to that a perimeter of inductor 18 is approximately the same size and shape as a perimeter of the surface of material 16 near which inductor 18 will be positioned. This may allow relatively complete coverage of material 16 when testing for a crack or other defect.

Inductor 18 may be mechanically attached to material 16. For example, inductor 18 may be mechanically attached to material 16 using an adhesive. In some examples, inductor 18 may be mechanically attached directly to material 16 with no intervening materials (except any adhesive used to mechanically attach inductor 18 to material 16). In other examples, one or more layers of material may be between inductor 18 and material 16. For example, the object of which material 16 is a part may include one or more layers of other materials on a surface of material 16, and inductor 18 may be indirectly mechanically attached to material 16, i.e., may be mechanically attached to a layer of material that is attached to material 16.

Inductor 18 may be attached to any surface of material 16. The surface to which inductor 18 is attached may affect the direction in which induced electrical current (also referred to as eddy current) flows within material 16. Cracks or other defects may affect the magnitude of the induced electrical current more significantly when the induced electrical current flows 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 may be predicted based on the use for material. In some of these examples, inductor 18 may then be attached to material 16 so that the induced current within material 16 from current conducted through inductor 18 flows 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 inductor 18 based on the predicted location of the crack or other defect, an inductor 18 may be attached to more than one surface of material 16. For example, if material 16 is in the shape of a cube, a respective inductor 18 may be attached to three orthogonal surfaces of the cube. By attaching a respective inductor 18 to three orthogonal surfaces, current may be induced to flow in one of three orthogonal directions depending on the inductor 18 through which current is driven. This may increase a likelihood that induced current will flow 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 inductor 18 and computing device 12.

Computing device 12 is electrically coupled to the pair of inductor 18 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 to inductor 18. Computing device 12 also may be configured to determine a magnetic field stimulation-related parameter in response to the electrical signal. For example, computing device 12 may be configured to determine electrical loss in inductor 18 due to material 16 being adjacent to inductor 18.

Computing device 12 may be configured to determine the electrical loss in inductor 18 due to material 16 in any manner. For example, computing device 12 using a resonant circuit including inductor 18 in series with a capacitor and electrical signal source 14. One terminal of electrical signal source 14 may be coupled to ground and one terminal coupled to the inductor. Similarly, one terminal of the capacitor may be attached to ground and one terminal attached to inductor 18. Computing device 12 may measure an input voltage amplitude output by electrical signal source 14 and an output voltage amplitude across the capacitor. Computing device 12 then may estimate the electrical losses in inductor 18 due to material 16 according to the following equation (1), shown in Han et al., "Evaluation of Magnetic Materials for Very High Frequency Power Applications," *IEEE Power Elecgtronics Specialists Conference*, June 2008, pp. 4270–4276:

$$R_{core} = \frac{V_{in}}{V_{out}}\left(R_C + \frac{1}{\omega_s C}\right) - R_{cu} - R_c \qquad (1),$$

in which R_{core} is the core loss due to material 16, V_{in} is the input voltage amplitude output by electrical signal source 14, V_{out} is the output voltage amplitude across the capacitor, R_c is the resistance across the capacitor, ω_s is the angular frequency of the input voltage, C is the capacitance of the capacitor, and R_{cu} is the resistance across inductor 18. Assuming that R_c is small compared to $R_{cu} + R_{core}$ and $1/\omega_s C$, equation (1) may be approximated as equation (2):

$$R_{core} \approx \frac{V_{in}}{V_{out}}\left(\frac{1}{\omega_s C}\right) - R_{cu} \quad (2).$$

Further, assuming that R_{cu} is constant between electrical loss measurements for material 16 or is small compared to R_{core}, the electrical loss, $R_{inductor}$, used by computing device 12 for determining whether material 16 includes a crack or other defect may be simplified to equation (3):

$$R_{inductor} \approx \frac{V_{in}}{V_{out}}\left(\frac{1}{\omega_s C}\right) \quad (3)$$

Equations (1), (2), and (3) and the resonant circuit are one example for determining electrical loss through inductor 18 due to material 16. Other techniques also may be used to determine electrical loss through inductor 18 due to material 16.

Computing device 12 may be configured to determine whether material 16 includes a crack or other defect based on the determined electrical loss (e.g., either R_{core} in equation (2) or $R_{inductor}$ in equation (3)). For example, computing device 12 may be configured to compare the determined electrical loss to a control electrical loss. In some examples, computing device 12 or another similar device may have determined the control electrical loss 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, computing device 12 or another device may determine the control electrical loss using a model of the material in an intact (undamaged) state, or may determine the control electrical loss as an average (e.g., mean) of a plurality of similar materials (e.g., in geometry and composition) that are known to be intact (undamaged). This control electrical loss 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 an electrical loss of inductor 18 due to material 16 at the later time. For example, computing device 12 may control electrical signal source 14 to apply an electrical signal to inductor 18 and determine the electrical loss, for example, using the voltage measurements and equation (2) or (3) described above. Computing device 12 may then determine whether material 16 includes a crack or other defect based on the determined electrical loss, for example, by comparing determined electrical loss to the control electrical loss. As one example, computing device 12 may determine a difference between a magnitude of the determined electrical loss and a magnitude of the control electrical loss. If material 16 includes a crack or other defect, the electrical loss may be less than when material 16 is intact or undamaged, as eddy currents may not flow as easily through material 16 when material 16 includes a crack or other defect. Computing device 12 then may compare the difference between the determined electrical loss and the control electrical loss 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 some examples, instead of computing device 12 comparing the determined electrical loss to a control electrical loss, computing device 12 may compare the determined electrical loss to a predetermined threshold electrical loss. In some examples, the predetermined threshold electrical loss may be selected so that a determined electrical loss below the threshold electrical loss value is indicative of a crack or other defect and a determined electrical loss above the threshold electrical loss value is not indicative of a crack or other defect.

In this way, using an electrical loss measurement may utilize 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, an electrical loss measurement crack detection system may allow relatively computationally cheap analysis techniques to be used to analyze the electrical loss measurements and determine whether the material includes a crack or other defect.

In some examples, a single inductor may not provide sufficient coverage for detecting cracks having at all locations and with all orientations within material 16. As described above, in some examples, system 10 may include a respective inductor 18 attached to each of two or more surfaces of material 16, which may improve detection of cracks having different orientations within material 16. In some examples, a system may include at least two inductors attached to a single surface of material 16. For example, FIG. 2 is a conceptual and schematic diagram block illustrating another example system 20 for determining whether a material 16 includes a crack or other defect using an electrical loss measurement.

Similar to system 10 shown in FIG. 1, system 20 in FIG. 2 includes computing device 12, electrical signal source 34, and material 16. Each of computing device 12, electrical signal source 34, and material 16 may be similar to or substantially the same as computing device 12, electrical signal source 14, and material 16 described with reference to FIG. 1, aside from electrical signal source 14 in FIG. 2 including four terminals instead of the two terminals illustrated in FIG. 1. In general, electrical signal source 14 may include any number of terminals, or may include two terminals that are electrically coupled to inputs of a switch network whose outputs are coupled to leads of respective inductors.

Unlike system 10 in FIG. 1, system 20 in FIG. 2 includes a plurality of inductors. In the example of FIG. 2, system 20 includes a first inductor 28A and a second inductor 28B (collectively, "inductors 28"). In general, system 20 may include any number of inductors 28, e.g., at least two inductors 28. In the example of FIG. 2, each of first inductor 28A and second inductor 28B are positioned adjacent to the same surface of material 16. Each of inductors 28 may include any suitable inductor geometry, as described above with respect to inductor 18 of FIG. 1. In some examples, each of inductors 28 may have a similar construction (e.g., geometry, material composition, or the like), or at least one of inductors 28 may have a different construction than at least one other of inductors 28. Each of inductors 28 may be mechanically attached directly to material 16 or to a layer on material 16.

As shown in FIG. 2, first inductor 28A partially overlaps second inductor 28B. In particular, a portion of the coil of first inductor 28A overlaps the coil of second inductor 28B. By having first inductor

28A partially overlap second inductor 28B, the sensitivity of system 20 to crack lying in a region near the end of the coils (where the coils overlap) may be increased compared to examples in which first inductor 28A does not overlap second inductor 28B. This is because the portions of inductors 28 in which the coil is substantially vertical in FIG. 2 may have be less sensitive to cracks as the eddy currents may be less likely to flow normal to a plane of a crack. In examples in which first inductor 28A partially overlaps second inductor 28B, the portions of inductors 28 in which the coil is substantially vertical in FIG. 2 are overlapped by a horizontal portion of the other inductor.

In some examples, as described above with reference to FIG. 1, inductors 28 may be attached to multiple surfaces of material 16, e.g., orthogonal surfaces or surfaces for which normal vectors extending from the surfaces intersect. This may provide improved sensitivity for cracks at arbitrary orientations within material 16.

Computing device 12 may be configured to determine whether material 16 includes a crack or other defect based on the respective determined electrical loss (e.g., either R_{core} in equation (2) or $R_{inductor}$ in equation (3)) for each respective inductor of inductors 28. For example, computing device 12 may be configured to compare the respective determined electrical loss to a respective control electrical loss. In some examples, computing device 12 or another similar device may have determined the respective control electrical loss for each inductor of inductors 28 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, computing device 12 or another device may determine the control electrical loss using a model of the material in an intact (undamaged) state, or may determine the control electrical loss 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 electrical losses may be stored (e.g., in a memory device associated with computing device 12) for later use.

At a later time, system 20 then may be used to determine a respective electrical loss associated with each of inductors 28 due to material 16 at the later time. For example, computing device 12 may control electrical signal source 14 to apply a respective electrical signal to each inductor of inductors 28 and determine the respective electrical loss, for example, using the voltage measurements and equation (2) or (3) described above. Computing device 12 may then determine whether material 16 includes a crack or other defect based on the respective determined electrical losses, for example, by comparing the respective determined electrical loss to the respective control electrical loss.

As one example, computing device 12 may determine a difference between a magnitude of the respective determined electrical loss and a magnitude of the respective control electrical loss associated with the same inductor of inductors 28. If material 16 includes a crack or other defect in a volume in which eddy currents are induced, the respective electrical loss may be less than when material 16 is intact or undamaged, as eddy currents may not flow as easily through the volume of material 16 when material 16 includes a crack or other defect. Computing device 12 then may compare the respective differences between the respective determined electrical loss and the respective control electrical loss to a threshold difference value, and may determine that material 16 includes a crack or other defect in response to at least one of the differences being greater than the threshold difference value. For example, computing device 12 may determine that a volume of material 16 adjacent to the inductor for which the respective determined electrical loss is less than the respective control electrical loss by more than the threshold value includes a crack or other defect. 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 some examples, computing device 12 may determine that material 16 includes a crack or other defect in response to at least a threshold number of the differences being greater than the threshold difference value.

In some examples, instead of computing device 12 comparing the determined electrical loss to a control electrical loss, computing device 12 may compare the determined electrical loss to a predetermined threshold electrical loss. In some examples, the predetermined threshold electrical loss may be selected so that a determined electrical loss below the threshold electrical loss value is indicative of a crack or other defect and a determined electrical loss above the threshold electrical loss value is not indicative of a crack or other defect.

In some examples, including multiple inductors on a single surface of material 16 may result in a large number of electrical couplings to electrical signal source if each inductor is electrically coupled directly to electrical signal source 34, e.g., in parallel with the other inductors. To decrease the number of electrical couplings and complexity of wire traces or leads, in some examples, multiple inductors may be electrically coupled to electrical signal source 14 in series. FIG. 3 is a conceptual and schematic diagram block illustrating another example system 30 for determining whether a material 16 includes a crack or other defect using an electrical loss measurement.

Similar to system 10 shown in FIG. 1, system 30 in FIG. 3 includes computing device 12, electrical signal source 14, and material 16. Each of computing device 12, electrical signal source 14, and material 16 may be similar to or substantially the same as computing device 12, electrical signal source 14, and material 16 described with reference to FIG. 1. In general, electrical signal source 14 may include any number of terminals, or may include two terminals that are electrically coupled to inputs of a switch network whose outputs are coupled to leads of respective inductors.

Unlike systems 10 and 20 shown in FIGS. 1 and 2, system 30 includes a first inductor 38A and a second inductor 38B (collectively, “inductors 38”) electrically coupled in series. This may reduce the number of electrical couplings between electrical signal source 14 and inductors 38 compared to examples in which each inductor of inductors 38 are electrically coupled to electrical signal source in parallel.

In general, system 30 may include any number of inductors 38 electrically coupled in series, e.g., at least two inductors 38. In the example of FIG. 3, each of first inductor 38A and second inductor 38B are positioned adjacent to the same surface of material 16. Each of inductors 38 may include any suitable inductor geometry, as described above with respect to inductor 18 of FIG. 1. In some examples, each of inductors 38 may have a similar construction (e.g., geometry, material composition, or the like), or at least one of inductors 38 may have a different construction than at least one other of inductors 38. Each of inductors 38 may be mechanically attached directly to material 16 or to a layer on material 16.

In some examples, as described above with reference to FIG. 1, inductors 38 may be attached to multiple surfaces of material 16, e.g., orthogonal surfaces or surfaces for which normal vectors extending from the surfaces intersect. This may provide improved sensitivity for cracks at arbitrary orientations within material 16. In some examples, inductors 38 on a single surface of material 16 are electrically coupled to electrical signal source 14 in series, and inductors on one surface of material 16 are electrically coupled to electrical signal source 14 in parallel with inductors on another surface of material 16. In other examples, inductors 38 on multiple surfaces of material 16 are electrically coupled to electrical signal source 14 in series.

As shown in FIG. 3, first inductor 38A does not overlap second inductor 38B. However, in other examples, first inductor 38A may partially overlap second inductor 38B, e.g., as shown with inductors 28 of FIG. 2.

Computing device 12 may be configured to determine whether material 16 includes a crack or other defect based on the determined electrical loss (e.g., either R_{core} in equation (2) or $R_{inductor}$ in equation (3)) for inductors 38. As inductors 38 are coupled in series, inductors 38 may not be individually addressable. For example, computing device 12 may be configured to compare the determined electrical loss to a control electrical loss. In some examples, computing device 12 or another similar device may have determined the respective control electrical loss for inductors 38 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. In other examples, computing device 12 or another device may determine the control electrical loss using a model of the material in an intact (undamaged) state, or may determine the control electrical loss as an average (e.g., mean) of a plurality of similar materials (e.g., in geometry and composition) that are known to be intact (undamaged). This control electrical loss may be stored (e.g., in a memory device associated with computing device 12) for later use.

At a later time, system 30 then may be used to determine an electrical loss associated with inductors 38 due to material 16 at the later time. For example, computing device 12 may control electrical signal source 14 to apply an electrical signal to inductors 38 and determine the respective electrical loss, for example, using the voltage measurements and equation (2) or (3) described above. Computing device 12 may then determine whether material 16 includes a crack or other defect based on the determined electrical loss, for example, by comparing the determined electrical loss to the control electrical loss. Computing device 12 then may compare the difference between the determined electrical loss and the control electrical loss 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.

In some examples, instead of computing device 12 comparing the determined electrical loss to a control electrical loss, computing device 12 may compare the determined electrical loss to a predetermined threshold electrical loss. In some examples, the predetermined threshold electrical loss may be selected so that a determined electrical loss below the threshold electrical loss value is indicative of a crack or other defect and a determined electrical loss above the threshold electrical loss value is not indicative of a crack or other defect.

FIG. 4 is flow diagram illustrating an example technique for determining presence of a crack or other defect in a material using a magnetic field stimulation-related parameter measurement. The technique of FIG. 4 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. 4 may be performed by other systems and computing devices (such as system 20 of FIG. 2 or system 30 of FIG. 3), and that system 10 and computing device 12 may be used to perform other techniques.

The technique of FIG. 4 includes applying an electrical signal to an inductor 18 adjacent to (e.g., mechanically attached to) material 16 (42). For example, computing device 12 may be configured to cause 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. 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. 4 also includes, while applying the electrical signal to inductor 18, determining an electrical loss in inductor 18 due to material 16 (44). For example, computing device 12 may be configured determine the electrical loss in inductor 18 using the voltages and equation (2) or (3) described with reference to FIG. 1.

The technique of FIG. 2 further includes determining whether material 16 includes a crack or other defect based on the electrical loss (46). For example, computing device 12 may be configured to determine whether material 16 includes a crack or other defect by comparing the determined electrical loss to a control electrical loss determined for material 16 when material 16 is known to be intact or undamaged. Computing device 12 may compare the difference between the determined electrical loss and the control electrical loss to a threshold difference value, and may determine that material 16 includes a crack or other defect if the difference between the determined electrical loss and the control electrical loss is greater than the threshold difference value. For example, computing device 12 may determine that material 16 includes a crack or other defect if the determined electrical loss is less than the control electrical loss by more than the threshold difference value.

In some examples, instead of computing device 12 comparing the determined electrical loss to a control electrical loss, computing device 12 may compare the determined electrical loss to a predetermined threshold electrical loss. In some examples, the predetermined threshold electrical loss may be selected so that a determined electrical loss below the threshold electrical loss value is indicative of a crack or other defect and a determined electrical loss above the threshold electrical loss value is not indicative of a crack or other defect.

In some examples, rather than determining the electrical loss associated with an inductor attached to the material, a system may determine whether a material includes a crack or other defect based on another magnetic field stimulation-related parameter, such as an induced current or voltage. For example, instead of the inductor being mechanically attached to the material, the inductor may be physically separate from the material, and the material may include at least one electrode at which an induced voltage or current is measured. FIG. 5 is a conceptual and schematic diagram block illustrating another example system 50 for determining whether a material 16 includes a crack or other defect using a magnetic field stimulation-related parameter measurement, in this case, an induced voltage or current.

System 50 includes computing device 52, electrical signal source 14, switch network 54, enclosure 56, and inductor 60. Electrical signal source 14 may be similar to or substantially the same as electrical signal source 14 of FIGS. 1–3.

Material 16 may be similar to or substantially the same as material 16 described with reference to FIGS. 1–3. In the example of FIG. 5, plurality of electrodes 62 are attached to material 16.

In addition to the functionality described with reference to computing device 12 of FIGS. 1–4, computing device 52 in FIG. 5 may be configured to control switch network 54 to selectively couple a pair of electrodes from plurality of electrodes 62 to computing device 52 to allow computing device 52 to measure a voltage across the pair of electrodes.

Plurality of electrodes 62 are electrically coupled to material 16, which is being tested using an inductor -related parameter measurement. Each electrode of plurality of electrodes 68 is electrically coupled to material 16 using any suitable type of electrical coupling, including, for example, an electrically conductive adhesive, an electrically conductive solder, embedding electrodes 62 in material 16, a dielectric adhesive and capacitive coupling, or the like. Each electrode of plurality of electrodes 62 is electrically coupled to switch network 54 using a respective electrically conductive lead. In some examples, the plurality of electrodes 62 are distributed across a surface of material 16, as shown in FIG. 5. In other examples, the plurality of electrodes 62 may be distributed around a perimeter of material 16 (e.g., on multiple sides of material 16). In some examples, plurality of electrodes 62 may be referred to as a set of N electrodes 62.

In some examples, system 50 may include one or more electrodes not electrically coupled to material 16, which may be used as a reference electrode for single-ended voltage measurements between one electrode or plurality of electrodes 62 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 16 includes a crack or other defect. In other examples, computing device 52 may determine differential voltages between two electrodes 62 electrically coupled to material 16 by comparing (e.g., subtracting) single ended voltages associated with the two electrodes, and computing device 52 may utilize these differential voltages in the techniques described herein to determine whether material 16 includes a crack or other defect.

Switch network 54 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 54 may include a pair of inputs electrically coupled to electrical signal source 14, and at least a pair of inputs electrically coupled to computing device 52. Switch network 54 may include at least as many outputs are there are electrodes 62. For example, in the example shown in FIG. 5, system 50 includes seven electrodes, and switch network 54 thus includes at least seven outputs. Each electrode of electrodes 62 is electrically coupled to a respective output of switch network 54.

Computing device 52 is configured to control operation of system 50, including electrical signal source 14 and switch network 54. Computing device 52 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 52 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.

Computing device 52 is communicatively coupled to electrical signal source 14 and electrically coupled to switch network 54. Computing device 52 may be configured to control electrical signal source 14 to output an electrical signal, and may be configured to control switch network 54 to couple a selected pair of electrodes from plurality of electrodes 62 to computing device 52 to serve as a pair of measurement electrodes. In this way, computing device 32 may measure a magnetic field stimulation-related parameter (e.g., induced voltage or current) across material 16 in response to the electrical signal output by electrical signal source 14.

Electrical signal source 14 is electrically coupled to inductor 60, which is part of support 56. Support 56 provides support for inductor 60 so that inductor 60 may be positioned adjacent to material 16. In some examples, as shown in FIG. 5, support 56 may define a slot 58 or other area in which material 16 may be positioned. In some examples, the shape of slot 58 may be complementary to the shape of material 16, support 56 may include one or more locating features, of the like, to facilitate positioning of material 16 relative to inductor 60. In some examples, support 56 is sized and shaped so that, when material 16 is positioned correctly relative to support 56, inductor 60 is contacting or nearly contacting a surface of material 16. This may result in a better signal-to-noise ratio than if inductor 60 is further from material 16.

Inductor 60 may include an electrical conductor arranged in any geometry suitable for an inductor. In some examples, inductor 60 may include a substantially planar coil, as shown in FIG. 5. In examples in which inductor 60 includes a coil, inductor 60 may include any number of windings. Inductor 60 may include any suitable electrically conductive material, including, for example, copper, aluminum, silver, gold, or the like. Inductor 60 may be any size, and in some examples, may be sized and shaped so that a perimeter of inductor 60 is approximately the same size as a perimeter of the surface of material 16 near which inductor 60 will be positioned. This may allow relatively complete coverage of material 16 when testing for a crack or other defect. In other examples, inductor 60 may include another shape or size, such as a solenoid sized so that material 16 may be placed in the bore of the solenoid. The solenoid may have any shape, such as rectangular prism, cylindrical, elliptical cylinder, or the like.

In some examples, although not shown in FIG. 5, support 56 may include a plurality of electrical contacts, which are arranged on support so that, when material 16 is positioned properly with respect to inductor 60, respective ones of the electrical contacts contact respective electrodes of plurality of electrodes 62. This may facilitate electrical coupling of plurality of electrodes 62 to switch network 54 and computing device 52.

By including a support 56 that includes inductor 60 separate from material 16, system 50 may facilitate sequential testing of multiple samples of material 16 using the same system 50. This may be useful in manufacturing contexts, e.g., for quality control, for testing of large numbers of samples of materials 16, e.g., by an end user of material 16 after use of material 16, or the like. However, in some examples, inductor 60 may be attached to material 16, as shown in FIG. 6. FIG. 6 is a conceptual and schematic diagram block illustrating another example system 70 for determining whether a material includes a crack or other defect using a magnetic field stimulation-related parameter measurement. System 70 is similar to system 50 of FIG. 5, but does not include support 56. Rather, inductor 72 is mechanically attached to material 16, e.g., using an adhesive.

FIG. 7 is flow diagram illustrating an example technique for determining whether a material includes a crack or other defect using a magnetic field stimulation-related parameter measurement, in this case induced voltage or current. The technique of FIG. 7 will be described with reference to system 50 of FIG. 5 for clarity. However, it will be appreciated that the technique of FIG. 7 may be performed by other systems and computing devices (such as system 70 of FIG. 6), and that system 50 may be used to perform other techniques.

The technique of FIG. 7 includes applying an electrical signal to an inductor 60 (82). For example, computing device 52 may cause electrical signal source 14 to apply the electrical signal to inductor 60 (82). The electrical signal may include an AC voltage or current. Computing device 52 also may control electrical signal source 14 to generate the AC voltage or current with a selected amplitude, duration, frequency, phase, and other signal characteristics.

The technique of FIG. 7 also includes, while applying the electrical signal to inductor 60, measuring a respective induced voltage or current between a respective pair of electrodes 62 electrically coupled to material 16 (84). For example, computing device 52 may cause switch network 54 to electrically couple computing device 52 to a selected pair of electrodes from plurality of electrodes 62. The selected pair of electrodes may be any two electrodes from plurality of electrodes 62. In some examples, the two electrodes in the selected pair of electrodes may be directly adjacent to each other with no other electrodes in between. In other examples, the two electrodes in the selected pair of electrodes may be spaced apart from each other with one or more electrodes in between. Using adjacent electrodes as the pair of electrodes may result in a higher signal-noise-ratio in the measurement of the magnetic field stimulation-related parameter, but may reduce an area of material 16 for which the induced voltage or current is measured. Regardless of the particular electrodes coupled to computing device 52, computing device 52 may measure a respective induced voltage or current across the selected pair of electrodes (84) while electrical signal source 14 is applying the electrical signal to inductor 60 (82).

In some examples, computing device 32 may be configured to measure a respective magnetic field stimulation-related parameter for a plurality of pairs of electrodes from electrodes 62. Hence, in some examples, the technique of FIG. 7 further includes determining whether there is an additional pair of electrodes at which to measure a respective induced voltage or current (86). In some examples, each pair of measurement electrodes is a unique pair of electrodes. In some examples, no two pairs of measurement electrodes share a common electrode. For example, a first pair of electrodes may not share any electrodes with a second, different pair of electrodes. In other examples, different pairs of electrodes may include one common electrode. For example, a first pair of electrodes may share exactly one electrode with a second, different electrode pair.

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 86), computing device 52 may control switch network 54 to couple the selected additional pair of electrodes to computing device 52. Computing device 52 then may measure the induced voltage or current across the selected additional pair of electrodes (84).

Computing device 52 may repeat this determination (86), coupling of a selected pair of electrodes, and measurement of a respective induced voltage or current across the selected pair of electrodes (84) until computing device 52 determines there are no more additional pairs of electrodes from plurality of electrodes 62 to be used as a pair of measurement electrodes

Once computing device 52 has determined that there are no more additional pairs of electrodes from plurality of electrodes 62 to be used as a pair of measurement electrodes (the "NO" branch of decision block 86), computing device 52 may determine whether material 16 includes a crack or other defect based on the respective induced voltages or currents (88). In some examples, computing device 52 may determine whether material 36 includes a crack or other defect based on a comparison between respective induced voltages or currents. For example, computing device 52 or another computing device may perform steps (82)–(86) of the technique of FIG. 7 on material 16 at a first time at which it is known that material 16 is intact, i.e., does not include a crack or other defect. 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. As other examples, computing device 52 or another device may determine the control induced voltages or currents using a model of material 16 in an intact (undamaged) state, or computing device 12 or another device may determine the control induced voltages or currents 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 induced voltages or current may be stored (e.g., in a memory device associated with computing device 52) for later use. For example, the respective control induced voltages or currents may be stored in a data structure in which each respective control induced voltage or current is associated with a pair of electrodes with which the respective control induced voltage or current was measured.

Computing device 52 then may compare the respective measured induced voltages or currents to respective control induced voltages or currents and determine whether material 16 includes the crack or other defect based on the comparison. For example, computing device 52 may compare each respective measured induced voltage or current with a corresponding (i.e., associated with the same pair of electrodes) control induced voltage or current. As an example, computing device 52 may subtract the respective measured induced voltage or current from the corresponding control induced voltage or current. In some examples, computing device 52 may compare the respective induced voltage or current difference (between the respective measurement induced voltage or current and the respective control induced voltage or current) to a threshold difference value.

The threshold difference value may be selected so that an induced voltage or current difference above the threshold difference value is meaningful (e.g., indicative of a crack or other defect) and an induced voltage or current 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 difference value that is slightly greater than a noise floor of the measurement, such that any induced voltage or current difference that exceeds the noise floor is determined by computing device 52 to be indicative of a crack or other defect.

In some examples, after comparing each respective measured induced voltage or current against a corresponding control induced voltage or current and comparing the difference to the threshold difference value to determine if the respective measured induced voltage or current is indicative of a crack or other defect, computing device 52 may determine whether a crack or other defect is present in material 16 based on the plurality of indications. For example, computing device 52 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 16 includes a crack or other defect. As another example, computing device 52 may determine that material 16 includes a crack of other defect in response to at least one respective magnetic field stimulation-related parameter difference being greater than the threshold magnetic field stimulation-related parameter.

In some examples, instead of comparing the measured induced voltages or currents to control induced voltages or currents, computing device 52 may compare the measured induced voltages or currents to a predetermined threshold induced voltage or current. In some examples, the predetermined induced voltage or current threshold may be selected so that a measured induced voltage or current below the threshold induced voltage or current value is indicative of a crack or other defect and a measured induced voltage or current above the threshold induced voltage or current value is not indicative of a crack or other defect.

In other examples, computing device 52 may calculate an approximate impedance distribution utilizing the respective control induced voltages or currents, and the respective measured induced voltages or currents to determine whether material 16 includes a crack or other defect (88). 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 52 may be programmed with a finite element model (FEM) of material 16 which implements the physics-based simulation. The FEM of material 16 may include substantially accurate (e.g., accurate or approximately accurate) geometry of material 16 (e.g., the shape and volume of material 16), and also may include substantially accurate (e.g., accurate or approximately accurate) locations of electrodes 38 attached to material 36 and position of inductor 60 relative to material 16. In some examples, the FEM of material 16 may additionally include representative properties of material 16, including, for example, conductivity, resistivity, other related electrical properties, and the like. The FEM of material 16 may include representative properties of material 16 for each respective node representing material 16.

Calculating the approximate impedance distribution to determine whether material 16 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 16 that produce the outputs are unknown. Moreover, more than one set of properties of material 16 may produce the outputs. Hence, computing device 52 may utilize a regularization technique to constrain the solution to solutions more likely to represent the properties of material 16 that would produce the respective measurement voltages.

In particular, computing device 52 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:

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

where **x** is the approximate change in impedance distribution, f is an operator calculating the simulated difference in voltages based on input **x** utilizing the physics-based simulation, **y** is the measured difference in voltages, l_2 is a chosen norm, **R** is the regularization matrix, and λ is the chosen weight of the regularization or regularization parameter. Computing device 52 may determine respective model control voltages based on the physics-based model and inputs representative of the electrical signal(s) applied to inductor 60. The respective model control voltages may be associated with respective pairs of measurement electrodes used to collect the control voltages from material 16. Computing device 52 then may determine, using the physics-based model and inputs representative of the electrical signal(s) applied to inductor 60, respective model measurement voltages. The respective model measurement voltages may be associated with respective pairs of measurement electrodes used to collect the measurement voltages from material 16. For each respective model measurement voltage, computing device 52 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 52 also may determine a respective difference between the respective measurement voltage and the respective control voltage for each respective measurement voltage measured using material 16 to generate a set of actual voltage differences (**y** in the equation above).

Computing device 52 then may minimize the objective function by updating one or more parameters of the physics-based model. Computing device 52 may continue to iterate the model until a stopping criterion is reached. Computing device 52 then may determine the approximate impedance distribution (or approximate change in impedance distribution) that is representative of the condition of material 16. When iteration completes the input to the model is the approximate impedance distribution.

Computing device 52 may then determine whether material 16 includes a crack or other defect based on the approximate change in impedance distribution. For example, computing device 52 may determine whether material 16 includes a crack or other defect based on the magnitude and location of the approximate impedance change within the material. In some examples, only the real portion of the impedance—the conductivity or resistivity—may be used by computing device 52 to determine whether material 16 includes a crack or other defect.

In some examples, rather than utilizing respective control voltages and respective model control voltages, computing device 52 may determine an approximate impedance distribution using an absolute form of the objective function, in which **x** is the impedance distribution, f is an operator calculating a set of the simulated voltages based on input **x** utilizing the physics-based simulation, **y** is a set of the measured voltages, l_2 is a chosen norm, **R** is the regularization matrix, and λ is the chosen weight of the regularization or regularization parameter.

Computing device 52 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 52 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 52 utilizes a FEM and physics-based model to determine the existence of a crack or other defect, computing device 52 may output a visual representation of material 16 and locations of the crack or other defect. For example, computing device 52 may output a false-color representation of the inductor-related parameter overlaid on a representation of material 16.

In these ways, a magnetic field stimulation-related parameter measurement may facilitate detection of cracks or other defects in a material utilizing 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 magnetic field stimulation-related parameter measurement crack detection system may allow relatively computationally cheap analysis techniques to be used to analyze the magnetic field stimulation-related 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 to an inductor adjacent to the material; determining an electrical loss in the inductor due to the material; and determining whether the material includes a crack or other defect based on the electrical loss.

Clause 2: The method of clause 1, wherein determining whether the material includes the crack or other defect based on the electrical loss comprises determining that the material includes the crack or other defect in response to the electrical loss being less than a threshold electrical loss value.

Clause 3: The method of clause 1, wherein determining whether the material includes the crack or other defect based on the electrical loss comprises determining that the material includes the crack or other defect in response to the electrical loss being less than a control electrical loss.

Clause 4: The method of any one of clauses 1 to 3, wherein: the inductor comprises a first inductor; the electrical loss comprises a first electrical loss; the method further comprises: applying the electrical signal to a second inductor adjacent to the material; and determining a second electrical loss in the second inductor due to the material; and determining whether the material includes the crack or other defect comprises determining whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss.

Clause 5: The method of clause 4, wherein determining whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss comprises determining that the material includes the crack or other defect in response to the first electrical loss being different than the second electrical loss.

Clause 6: The method of clause 4, wherein determining whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss comprises: determining that the material includes the crack or other defect in response to at least one of the first electrical loss or the second electrical loss being less than a threshold electrical loss value.

Clause 7: The method of clause 4, wherein determining whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss comprises: determining that the material includes the crack or other defect in response to at least one of the first electrical loss being less than a first control electrical loss or the second electrical loss being less than a second control electrical loss.

Clause 8: The method of any one of clauses 1 to 7, wherein the inductor comprises at least two inductors electrically coupled in series.

Clause 9: The method of any one of clauses 1 to 8, wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a magnetically permeable material.

Clause 10: The method of clause 9, wherein the material comprises a semiconductive ceramic armor piece or an electrically conductive ceramic armor piece.

Clause 11: A system comprising: a material; an inductor adjacent to the material; an electrical signal source configured to apply an electrical signal to the at least one inductor; and a computing device configured to: determine an electrical loss in the inductor due to the material; and determine whether the material includes a crack or other defect based on the electrical loss.

Clause 12: The system of clause 11, wherein the computing device is configured to determine whether the material includes the crack or other defect in response to the electrical loss being less than a threshold electrical loss value.

Clause 13: The system of clause 11, wherein the computing device is configured to determine whether the material includes the crack or other defect in response to the electrical loss being less than a control electrical loss.

Clause 14: The system of any one of clauses 11 to 13, wherein: the inductor comprises a first inductor; the electrical loss comprises a first electrical loss; the electrical signal source is further configured to applying the electrical signal to a second inductor adjacent to the material; and the computing device is further configured to: determine a second electrical loss in the second inductor due to the material; and determine whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss.

Clause 15: The system of clause 14, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss in response to the first electrical loss being different than the second electrical loss.

Clause 16: The system of clause 14, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss in response to at least one of the first electrical loss or the second electrical loss being less than a threshold electrical loss value.

Clause 17: The system of clause 14, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss in response to at least one of the first electrical loss being less than a first control electrical loss or the second electrical loss being less than a second control electrical loss.

Clause 18: The system of any one of clauses 11 to 17, wherein the inductor comprises at least two inductors coupled in series.

Clause 19: The system of any one of clauses 11 to 18, wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a magnetically permeable material.

Clause 20: The system of clause 19, wherein the material comprises a semiconductive ceramic armor piece or an electrically conductive ceramic armor piece.

Clause 21: A system comprising: an electrical signal source; an inductor electrically coupled to the electrical signal source; a pair of electrical contacts; and a computing device configured to: cause the electrical signal source to apply an electrical signal to the inductor when a material is adjacent to the inductor; determine an induced voltage or current across the pair of electrical contacts, wherein the electrical contacts are electrically coupled to a pair of electrodes electrically coupled to the material, and wherein at least one electrode of the pair of electrodes is; determine whether the material includes a crack or other defect based on the induced voltage or current.

Clause 22: The system of clause 21, further comprising the material and the pair of electrodes electrically and mechanically coupled to the material, each respective electrode electrically contacting a respective electrical contact of the pair of electrical contacts, and wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a magnetically permeable material.

Clause 23: The system of clause 22, wherein the material comprises a semiconductive ceramic armor piece or an electrically conductive ceramic armor piece.

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

Clause 25: The system of any one of clauses 21 to 24, wherein: the pair of electrical contacts comprises a plurality of electrical contacts; and the computing device is further configured to: determine a respective induced voltage or current between each respective pair of electrical contacts of a plurality of unique pairs of electrical contacts while applying the electrical signal to the inductor; and determine whether the material includes the crack or other defect based on the respective induced voltages or currents.

Clause 26: The system of clause 25, further comprising the material, and wherein: a plurality of electrodes are distributed across a surface area of the material and are positioned on the material to electrically contact a respective electrical contact of the plurality of electrical contacts.

Clause 27: The system of clause 25, further comprising the material, and wherein: a plurality of electrodes are distributed around a perimeter of the material and are positioned on the material to electrically contact a respective electrical contact of the plurality of electrical contacts.

Clause 28: The system of any one of clauses 25 to 27, wherein the computing device is configured to determine whether the material includes the crack or other defect by at least comparing the respective induced voltages or currents to respective control induced voltages or currents.

Clause 29: The system of any one of clauses 25 to 28, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the respective induced voltages or currents by at least: calculating an approximate change in impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the inductor, the respective induced voltages or currents, and respective control induced voltages or currents; and determining that the material includes the crack or other defect based on the approximate change in the impedance distribution.

Clause 30: The system of clause 29, wherein calculating the approximate change in impedance distribution within the material comprises minimizing an output of an objective function:

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

, wherein **x** is the approximate change in impedance distribution, f is an operator calculating a set of simulated differences in induced voltages or currents based on input **x** utilizing the physics-based simulation, **y** is a set of differences between the respective induced voltages or currents and the respective control induced voltages or currents, 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 31: The system of any one of clauses 21 to 30, wherein the inductor is mechanically attached to the material.

Clauses 32: The system of any one of clauses 21 to 30, wherein the inductor is not mechanically attached to the material.

Clause 33: A method comprising: applying an electrical signal to an inductor adjacent to a material; determining an induced voltage or current across a pair of electrical contacts, wherein at least one of the electrical contacts is electrically coupled to the material; and determining whether the material includes a crack or other defect based on the induced voltage or current.

Clause 34. The method of clause 33, further comprising the material and a pair of electrodes, wherein at least one electrode of the pair of electrodes is electrically and mechanically coupled to the material, each respective electrode positioned to electrically contact a respective electrical contact of the pair of electrical contacts, and wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a magnetically permeable material.

Clause 35: The method of clause 34, wherein the material comprises a semiconductive ceramic armor piece or an electrically conductive ceramic armor piece.

Clause 36: The method of any one of clauses 33 to 35, wherein determining whether the material includes the crack or other defect based on the induced voltage or current comprises determining whether the material includes the crack or other defect by at comparing the induced voltage or current to a control induced voltage or current.

Clause 37: The method of any one of clauses 33 to 38, wherein: the pair of electrical contacts comprises a plurality of electrical contacts; and the method further comprises: determining a respective induced voltage or current between each respective pair of electrical contacts of a plurality of unique pairs of electrical contacts while applying the electrical signal to the inductor; and determining whether the material includes the crack or other defect based on the respective induced voltages or currents.

Clause 38: The method of clause 37, further comprising the material, and wherein: a plurality of electrodes are distributed across a surface area of the material and are positioned on the material to electrically contact a respective electrical contact of the plurality of electrical contacts.

Clause 39: The method of claim 37, further comprising the material, and wherein: a plurality of electrodes are distributed around a perimeter of the material and are positioned on the material to electrically contact a respective electrical contact of the plurality of electrical contacts.

Clause 40: The method of any one of clauses 37 to 39, wherein determining whether the material includes the crack or other defect comprises comparing the respective induced voltages or currents to respective control induced voltages or currents.

Clause 41: The system of any one of clauses 37 to 40, wherein determining whether the material includes the crack or other defect based on the respective induced voltages or currents comprises: calculating an approximate change in impedance distribution within the material based on a physics-based simulation, inputs representative of the electrical signal(s) applied to the inductor, the respective induced voltages or currents, and respective control induced voltages or currents; and determining that the material includes the crack or other defect based on the approximate change in the impedance distribution. .

Clause 42: The method of claim 41, wherein calculating the approximate change in impedance distribution within the material comprises minimizing an output of an objective function:

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

, wherein **x** is the approximate change in impedance distribution, f is an operator calculating a set of simulated differences in induced voltages or currents based on input **x** utilizing the physics-based simulation, **y** is a set of differences between the respective induced voltages or currents and the respective control induced voltages or currents, 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 43: The method of any one of clauses 33 to 42, wherein the inductor is mechanically attached to the material.

Clause 44: The method of any one of clauses 33 to 42, wherein the inductor is not mechanically attached to the material.

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

WHAT IS CLAIMED IS:

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

applying an electrical signal to an inductor adjacent to the material;

determining an electrical loss in the inductor due to the material; and

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

2. The method of claim 1, wherein determining whether the material includes the crack or other defect based on the electrical loss comprises determining that the material includes the crack or other defect in response to the electrical loss being less than a threshold electrical loss value.

3. The method of claim 1, wherein determining whether the material includes the crack or other defect based on the electrical loss comprises determining that the material includes the crack or other defect in response to the electrical loss being less than a control electrical loss.

4. The method of claim 1, wherein:

the inductor comprises a first inductor;

the electrical loss comprises a first electrical loss;

the method further comprises:

applying the electrical signal to a second inductor adjacent to the material; and

determining a second electrical loss in the second inductor due to the material; and

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

5. The method of claim 4, wherein determining whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss comprises determining that the material includes the crack or other defect in response to the first electrical loss being different than the second electrical loss.

6. The method of claim 4, wherein determining whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss comprises:

determining that the material includes the crack or other defect in response to at least one of the first electrical loss or the second electrical loss being less than a threshold electrical loss value.

7. The method of claim 4, wherein determining whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss comprises:

determining that the material includes the crack or other defect in response to at least one of the first electrical loss being less than a first control electrical loss or the second electrical loss being less than a second control electrical loss.

8. The method of claim 1, wherein the inductor comprises at least two inductors electrically coupled in series.

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

10. The method of claim 9, wherein the material comprises a semiconductive ceramic armor piece or an electrically conductive ceramic armor piece.

11. A system comprising:

a material;

an inductor adjacent to the material;

an electrical signal source configured to apply an electrical signal to the at least one inductor; and

a computing device configured to:

determine an electrical loss in the inductor due to the material; and

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

12. The system of claim 11, wherein the computing device is configured to determine whether the material includes the crack or other defect in response to the electrical loss being less than a threshold electrical loss value.

13. The system of claim 11, wherein the computing device is configured to determine whether the material includes the crack or other defect in response to the electrical loss being less than a control electrical loss.

14. The system of claim 11, wherein:

the inductor comprises a first inductor;

the electrical loss comprises a first electrical loss;

the electrical signal source is further configured to applying the electrical signal to a second inductor adjacent to the material; and

the computing device is further configured to:

determine a second electrical loss in the second inductor due to the material; and determine whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss.

15. The system of claim 14, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss in response to the first electrical loss being different than the second electrical loss.

16. The system of claim 14, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss in response to at least one of the first electrical loss or the second electrical loss being less than a threshold electrical loss value.

17. The system of claim 14, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the first electrical loss and the second electrical loss in response to at least one of the first electrical loss being less than a first control electrical loss or the second electrical loss being less than a second control electrical loss.

18. The system of claim 11, wherein the inductor comprises at least two inductors coupled in series.

19. The system of claim 11, wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a magnetically permeable material.

20. The system of claim 19, wherein the material comprises a semiconductive ceramic armor piece or an electrically conductive ceramic armor piece.

21. A system comprising:

an electrical signal source;

an inductor electrically coupled to the electrical signal source;

a pair of electrical contacts; and

a computing device configured to:

cause the electrical signal source to apply an electrical signal to the inductor when a material is adjacent to the inductor;

determine an induced voltage or current across the pair of electrical contacts, wherein the electrical contacts are electrically coupled to a pair of electrodes, and wherein at least one electrode of the pair of electrodes is electrically coupled to the material;

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

22. The system of claim 21, further comprising the material and the pair of electrodes electrically and mechanically coupled to the material, each respective electrode electrically contacting a respective electrical contact of the pair of electrical contacts, and wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a magnetically permeable material.

23. The system of claim 22, wherein the material comprises a semiconductive ceramic armor piece or an electrically conductive ceramic armor piece.

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

25. The system of claim 21, wherein:

the pair of electrical contacts comprises a plurality of electrical contacts; and

the computing device is further configured to:

determine a respective induced voltage or current between each respective pair of electrical contacts of a plurality of unique pairs of electrical contacts while applying the electrical signal to the inductor; and

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

26. The system of claim 25, further comprising the material, and wherein:

a plurality of electrodes are distributed across a surface area of the material and are positioned on the material to electrically contact a respective electrical contact of the plurality of electrical contacts.

27. The system of claim 25, further comprising the material, and wherein:

a plurality of electrodes are distributed around a perimeter of the material and are positioned on the material to electrically contact a respective electrical contact of the plurality of electrical contacts.

28. The system of claim 25, wherein the computing device is configured to determine whether the material includes the crack or other defect by at least comparing the respective induced voltages or currents to respective control induced voltages or currents.

29. The system of claim 25, wherein the computing device is configured to determine whether the material includes the crack or other defect based on the respective induced voltages or currents by at least:

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

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

30. The system of claim 29, wherein calculating the approximate change in impedance distribution within the material comprises minimizing an output of an objective function:

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

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

31. The system of claim 21, wherein the inductor is mechanically attached to the material.

32. The system of claim 21, wherein the inductor is not mechanically attached to the material.

33. A method comprising:

applying an electrical signal to an inductor adjacent to a material;

determining an induced voltage or current across a pair of electrical contacts, wherein at least one of the electrical contacts is electrically coupled to the material; and

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

34. The method of claim 33, further comprising the material and a pair of electrodes, wherein at least one electrode of the pair of electrodes is electrically and mechanically coupled to the material, each respective electrode positioned to electrically contact a respective electrical contact of the pair of electrical contacts, and wherein the material comprises at least one of a semiconductive ceramic material, an electrically conductive ceramic material, or a magnetically permeable material.

35. The method of claim 34, wherein the material comprises a semiconductive ceramic armor piece or an electrically conductive ceramic armor piece.

36. The method of claim 33, wherein determining whether the material includes the crack or other defect based on the induced voltage or current comprises determining whether the material includes the crack or other defect by at comparing the induced voltage or current to a control induced voltage or current.

37. The method of claim 33, wherein:

the pair of electrical contacts comprises a plurality of electrical contacts; and

the method further comprises:

determining a respective induced voltage or current between each respective pair of electrical contacts of a plurality of unique pairs of electrical contacts while applying the electrical signal to the inductor; and

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

38. The method of claim 37, further comprising the material, and wherein:

a plurality of electrodes are distributed across a surface area of the material and are positioned on the material to electrically contact a respective electrical contact of the plurality of electrical contacts.

39. The method of claim 37, further comprising the material, and wherein:

a plurality of electrodes are distributed around a perimeter of the material and are positioned on the material to electrically contact a respective electrical contact of the plurality of electrical contacts.

40. The method of claim 37, wherein determining whether the material includes the crack or other defect comprises comparing the respective induced voltages or currents to respective control induced voltages or currents.

41. The system of claim 37, wherein determining whether the material includes the crack or other defect based on the respective induced voltages or currents comprises:

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

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

42. The method of claim 41, wherein calculating the approximate change in impedance distribution within the material comprises minimizing an output of an objective function:

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

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

43. The method of claim 33, wherein the inductor is mechanically attached to the material.

44. The method of claim 33, wherein the inductor is not mechanically attached to the material.

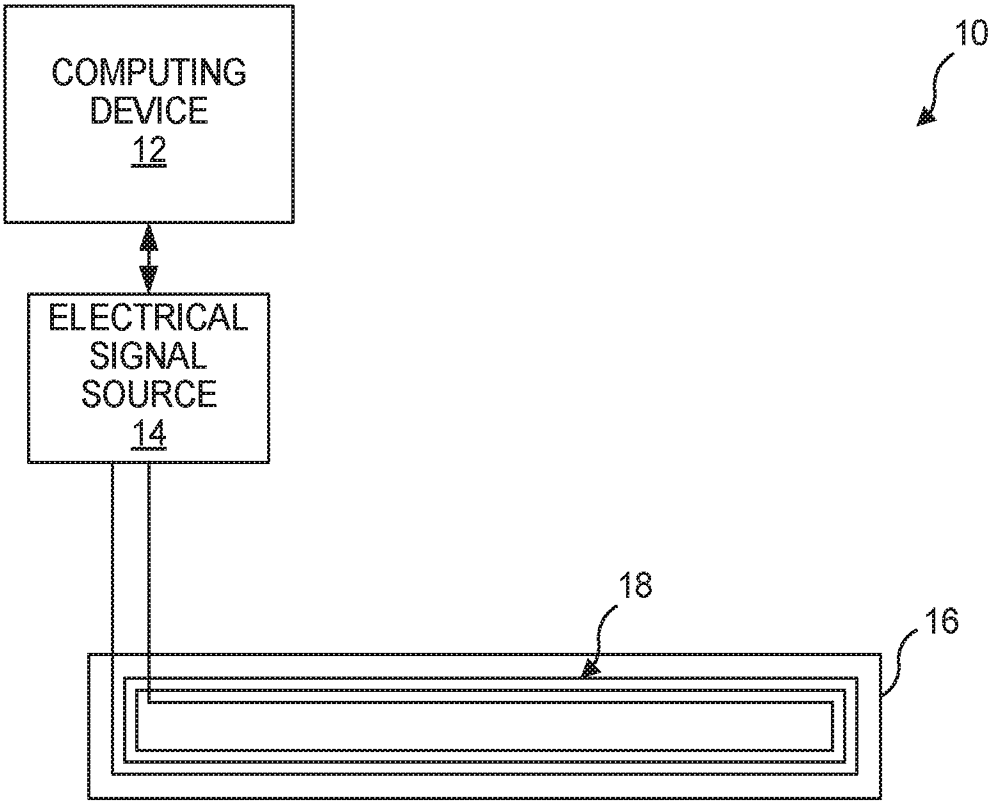

FIG. 1

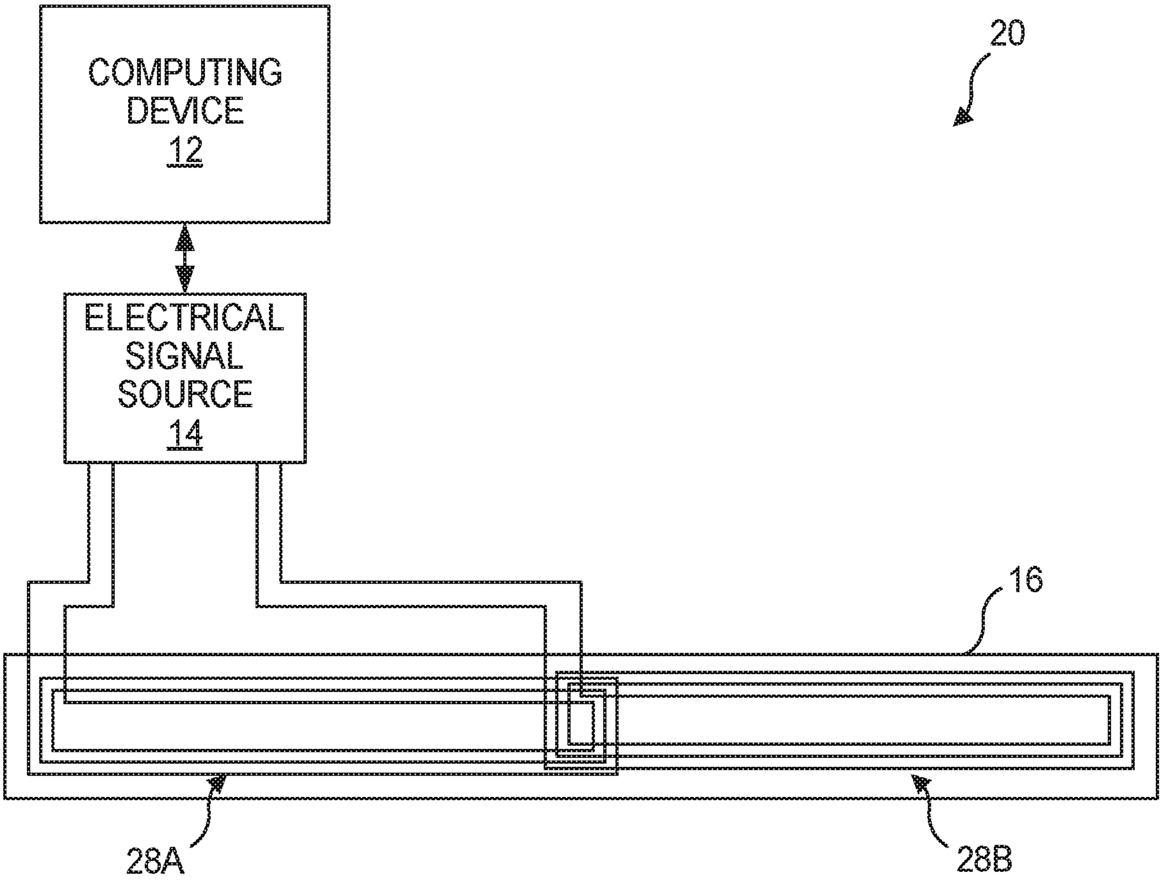
COMPUTING DEVICE 12
ELECTRICAL SIGNAL SOURCE 14
20
16
28A
28B

FIG. 2

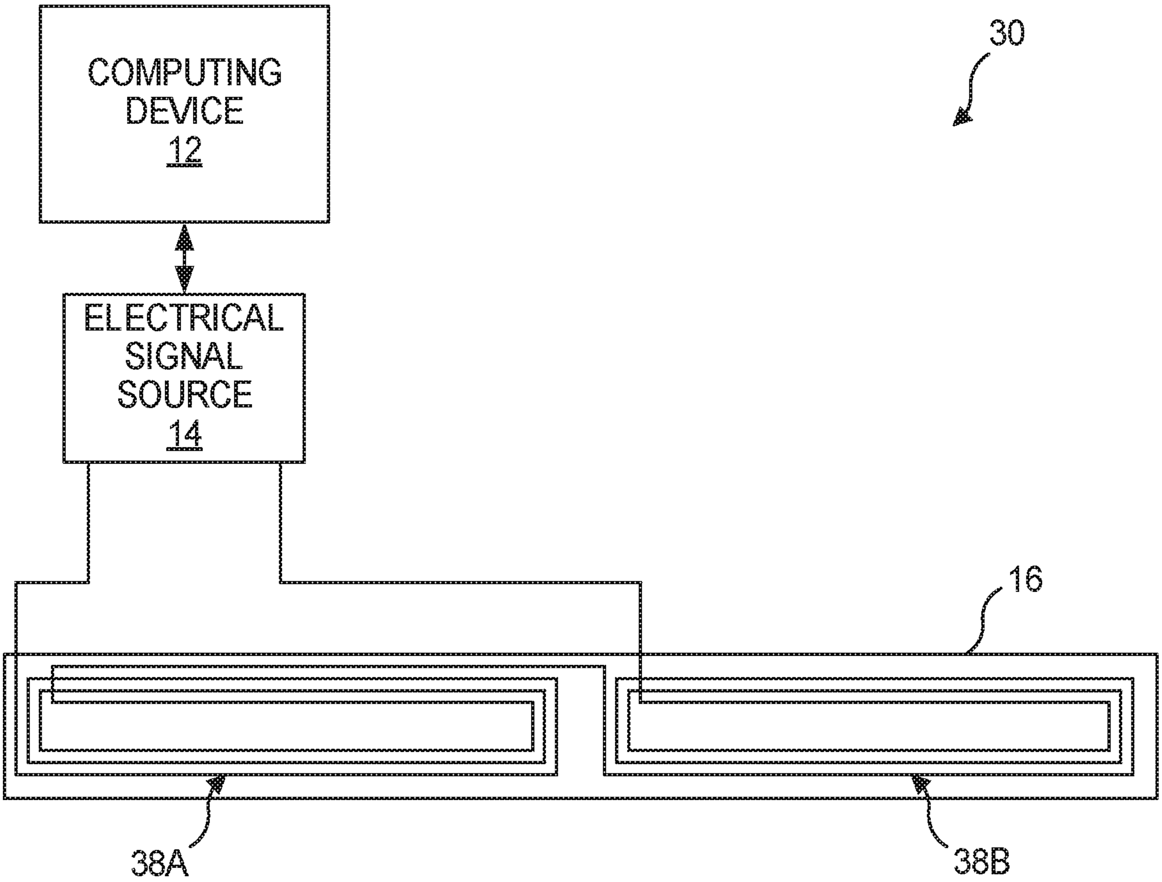
COMPUTING
DEVICE
12
ELECTRICAL
SIGNAL
SOURCE
14
30
16
38A
38B

FIG. 3

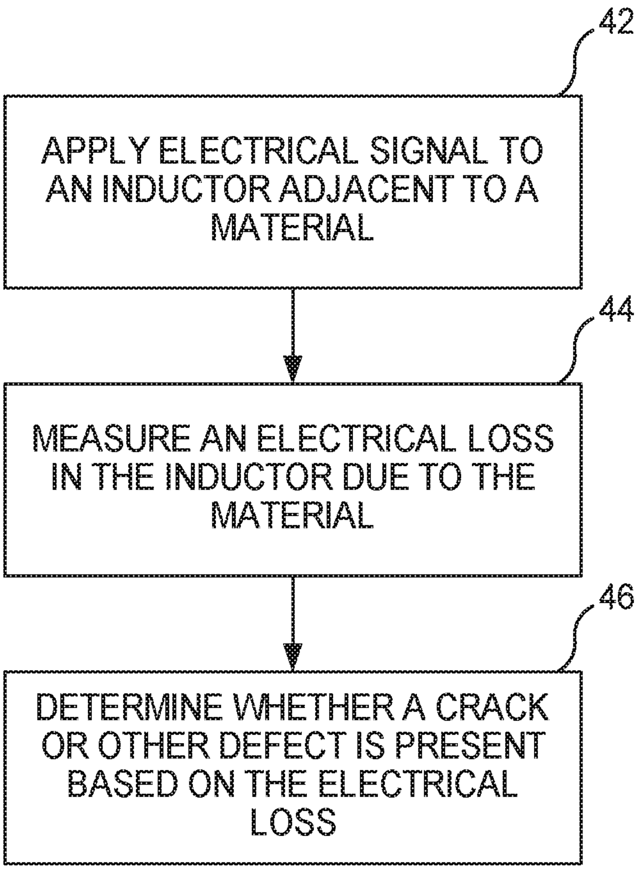
42
APPLY ELECTRICAL SIGNAL TO AN INDUCTOR ADJACENT TO A MATERIAL
44
MEASURE AN ELECTRICAL LOSS IN THE INDUCTOR DUE TO THE MATERIAL
46
DETERMINE WHETHER A CRACK OR OTHER DEFECT IS PRESENT BASED ON THE ELECTRICAL LOSS

FIG. 4

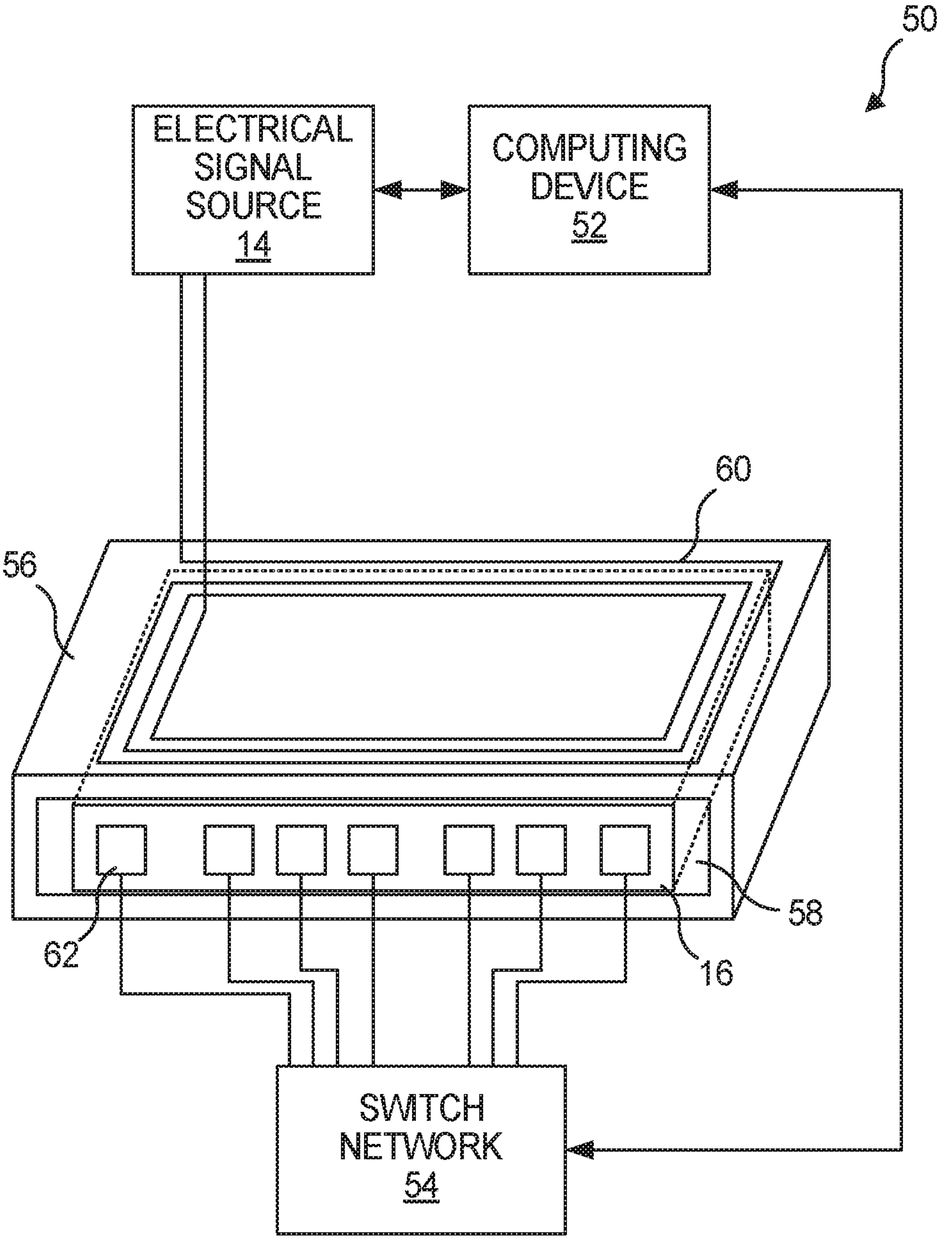
50
ELECTRICAL SIGNAL SOURCE 14
COMPUTING DEVICE 52
60
56
58
62
16
SWITCH NETWORK 54

FIG. 5

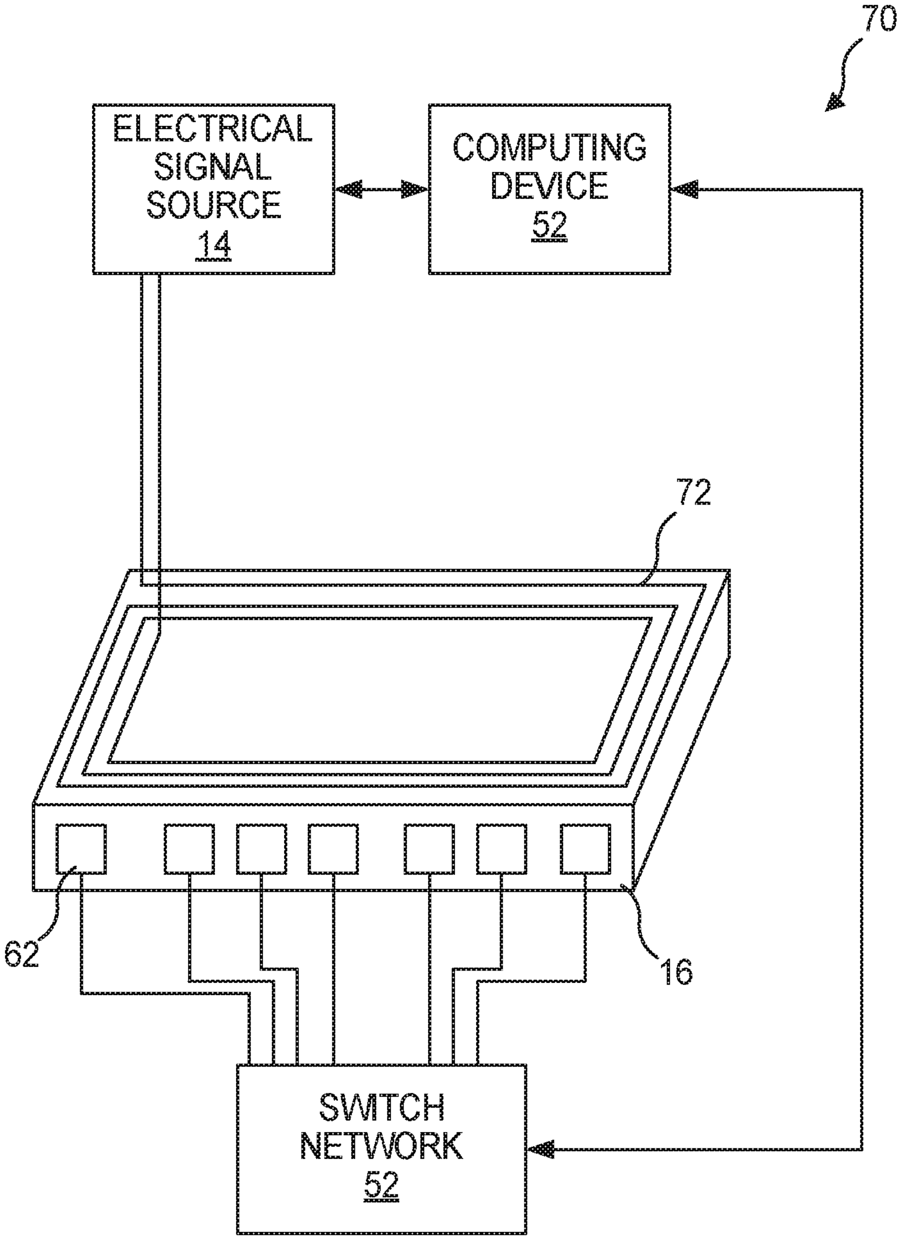
70
ELECTRICAL SIGNAL SOURCE 14
COMPUTING DEVICE 52
72
62
16
SWITCH NETWORK 52

FIG. 6

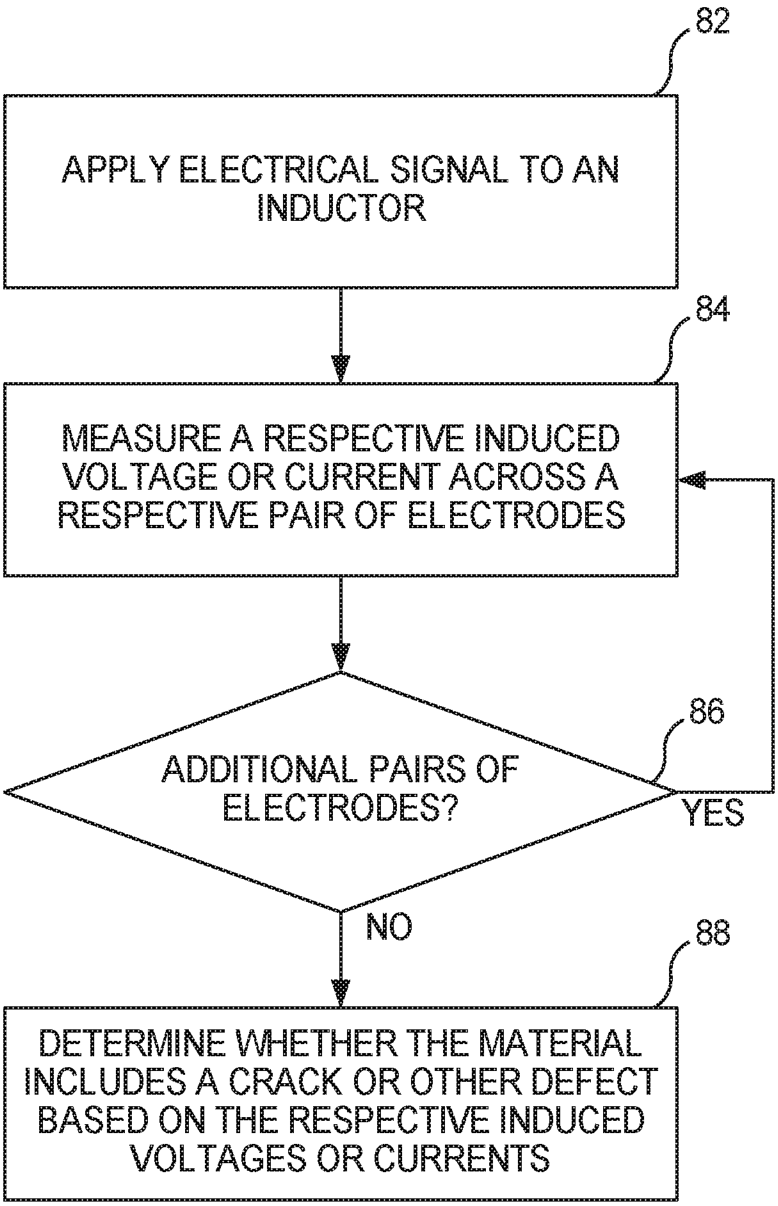
82
APPLY ELECTRICAL SIGNAL TO AN INDUCTOR
84
MEASURE A RESPECTIVE INDUCED VOLTAGE OR CURRENT ACROSS A RESPECTIVE PAIR OF ELECTRODES
86
ADDITIONAL PAIRS OF ELECTRODES?
YES
NO
88
DETERMINE WHETHER THE MATERIAL INCLUDES A CRACK OR OTHER DEFECT BASED ON THE RESPECTIVE INDUCED VOLTAGES OR CURRENTS

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US17/61737

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I: Claims 1-20 are directed towards detecting a crack or defect in material based on an electrical loss.

Group II: Claims 21-44 are directed towards detecting a crack or defect in material based on an induced voltage or current.

-***-Continued Within the Next Supplemental Box-***-

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US17/61737

A. CLASSIFICATION OF SUBJECT MATTER

IPC - G01N 27/02, 27/20, 27/22, 27/24, 27/72, 27/82, 27/87, 27/90, 35/00 (2017.01)

CPC - G01N 27/02, 27/023, 27/025, 27/20, 27/22, 27/24, 27/72, 27/82, 27/87, 27/90, 27/9006, 27/9033, 27/904, 27/9046, 35/00

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y	US 7,705,589 B2 (KIM, YJ et al.) 27 April 2010; abstract; column 4, lines 20-26, 35-47; column 5, lines 52-65; column 7, lines 58-68	1, 4-5 -- 2-3, 6-20
X -- Y	US 6,150,809 A (TIERNAN, TC et al.) 21 November 2000; abstract; column 7, lines 62-67; column 8, lines 2-12; column 9, lines 36-41; column 10, lines 22-26, 33-38; column 15, lines 45-49; column 16, lines 3-5; claim 1	11 -- 21-44
Y	US 2011/0060536 A1 (FENG, MQ) 10 March 2011; abstract; paragraphs [0007], [0012], [0014], [0040], [0043], [0047]; claim 1	2-3, 6-7, 9-20, 23-24, 28, 35-36, 40
Y	US 4,785,243 A (ABRAMCZYK, RF et al.) 15 November 1988; abstract; figure 2; column 2, lines 50-58; column 3, lines 23-26; column 4, lines 15-25, 29-30	8, 18
Y	CN 101,832,970 B (UNIV JIANGSU) 29 August 2012; see machine translation; abstract; claims 1, 3-4; paragraphs [0002], [0007], [0033], [0039]	21-44
Y	US 2015/0308980 A1 (HALLIBURTON ENERGY SERVICES, INC.) 29 October 2015; abstract; figure 1; paragraphs [0003], [0018]	27, 39
Y	ZAOUI, A et al.) Inverse Problem in Nondestructive Testing Using Arrayed Eddy Current Sensors. Sensors, Vol. 10, pp. 8696-8707. 10 September 2010; abstract; pages 8697-8703	29-30, 32, 41-42, 44

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 21 February 2018 (21.02.2018)	Date of mailing of the international search report 05 MAR 2018
Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US17/61737

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	(RUAN, T) Development of an Automated Impedance Tomography System and Its Implementation in Cementitious Materials. Clemson University, A dissertation, [Retrieved from the internet on 20 February 2018], <URL: https://tigerprints.clemson.edu/cgi/viewcontent.cgi?article=2758&context=all_dissertations>; August 2016; pages 46-47	30, 42
Y	CN 205,003,121 U (HANGZHOU ZHEJIANG UNIV JINGYI ELECTROMECHANICAL TECH ENG CO LTD) 27 January 2016; see machine translation; abstract; paragraphs [0002], [0004], [0039]	31, 43

-***-Continued from Box III: Observations where unity of invention is lacking-***-

The special technical features of Group I include a method and a system for detecting a crack or defect in a material, the method comprising: determining an electrical loss in the inductor due to the material; and determining whether the material includes a crack or other defect based on the electrical loss, which are not present in Group III; and the special technical features of Group II include a method and a system determining whether the material includes a crack or other defect based on the induced voltage or current, comprising: a pair of electrical contacts; determine an induced voltage or current across a pair of electrical contacts, wherein at least one of the electrical contacts is electrically coupled to the material; and determining whether the material includes a crack or other defect based on the induced voltage or current, which are not present in Group I.

The common technical features between Groups I-II are: detecting a crack or defect in a material, comprising: an inductor adjacent to the material; an electrical signal source configured to apply an electrical signal to the at least one inductor; and determining whether the material includes a crack or other defect

These common technical features are disclosed by US 6,150,809 A to Tiernan, et al. (hereinafter "Tiernan")

Tiernan discloses detecting a crack or defect in a material, comprising: an inductor adjacent to the material (one or more giant magnetoresistance sensors comprising an electrically conductive coil (an inductor) which is proximal to the material under test; abstract; figure 1a; column 9, lines 36-41; column 10, lines 22-26); an electrical signal source configured to apply an electrical signal to the at least one inductor (applying an electrical field (an electrical signal source) to the electrically conductive coil; abstract; column 9, lines 36-41; column 10, lines 22-26); and determining whether the material includes a crack or other defect (using determined changes in the resistance signal to detect defects in electrically conductive materials; abstract; column 10, lines 33-38).

Since the common technical features are previously disclosed by Tiernan, these common features are not special and so Groups I-II lack unity.