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Sensing the stress in steel by capacitance measurement

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ABSTRACT

This paper provides the first report of the sensing of stress in a metal (namely steel and stainless steel) by capacitance measurement. The method involves the measurement of the in-plane capacitance (2 kHz) between two coplanar electrodes that are on the same surface of the specimen. The capacitance decreases with increasing normal compressive stress. The fractional decrease in capacitance (up to 20%) is higher than the compressive strain calculated based on the elastic modulus by orders of magnitude. The capacitance decrease is essentially reversible and is attributed to the direct piezoelectric effect. Because an LCR meter is not designed to measure the capacitance of an electrical conductor, it is essential for a dielectric film to be positioned between the electrode and specimen. Two configurations are used for the electrodes. Configuration I involves aluminum foil as the electrode and a stack of 3 layers of double-sided adhesive tape as the dielectric film; no pressure is used. Configuration II involves copper sheet as the electrode and a glass fiber polymer-matrix composite film as the dielectric film, with normal pressure applied to the stack. The fractional decrease in capacitance per unit stress is much greater for configuration I than configuration II. Configuration I is better for sensing low stresses, whereas configuration II is better for sensing high stresses. Configuration I is less expensive and more practical than configuration II.

1. Introduction

A structure encounters stresses due to live loads, static loads, temperature variation, wind, ocean waves, earthquakes, etc. The sensing of stress allows load monitoring, operation control and condition monitoring. In the elastic regime, which is the regime for normal structural operation, stress is proportional to the strain. Hence, stress sensing is intimately related to strain monitoring. Stress sensing is to be distinguished from damage sensing, as the stress can be in the elastic regime in the absence of damage. The sensing of stress is typically more subtle than that of damage, particularly when the stress is in the elastic regime. In general, the sensing is preferably fast enough (short enough in the response time), so that it is suitable for real-time monitoring.

Steel is a dominant structural material that is used in construction, machinery, transportation, automobile, furniture, defense, medicine, etc. Stainless steel (a steel alloy with a minimum of 10.5 wt.% Cr) is well-known for its corrosion resistance, low maintenance, and luster. It is used for architecture, locomotion, cookware, household hardware, appliances, surgical instruments, industrial equipment, storage tanks, tankers, guns, rail passenger vehicles, etc. Applications of the stress sensing in steel include the monitoring of the stress in steel constructions, transport vehicles, oil and gas wells and platforms, pipelines, farm vehicles, machinery, and storage tanks (e.g., natural gas storage and carbon dioxide storage).

Sensing is most commonly performed in a structure by the attachment or embedment of sensors, which may be strain gages (commonly in the form of a metal film), optical fibers and piezoelectric sensors. In contrast, self-sensing refers to the ability of a structural material to sense its own condition without the need for embedded or attached sensors. In other words, a self-sensing structural material is a multifunctional material that is capable of both structural and sensing functions. Such a material is also said to be intrinsically smart.

Compared to the use of attached or embedded sensors, the advantages of self-sensing include low cost, high durability, large sensing volume and absence of mechanical property loss. This is because structural materials are necessarily low in cost and high in durability. Attached sensors tend to be not durable, as they can be detached. Embedded sensors tend to degrade the mechanical properties of the structural material.

Self-sensing has been reported in continuous carbon fiber polymer-matrix structural composites [1,2] and short carbon fiber

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cement-matrix composites [3–5], as achieved by measuring the electrical resistance. The resistance relates to the stress, strain, damage and temperature, due to the electrical conductivity of the carbon fibers compared to the polymer or cement matrix and the effect of these parameters on the fiber arrangement in a microscopic level. These fibers are not the sensors, but the composites are. The phenomenon of the resistivity changing with strain is known as piezoresistivity, which is exhibited by both continuous carbon fiber polymer-matrix structural composites and short carbon fiber cement-matrix composites. The implementation of the self-sensing involves the application of electrical contacts, which are not sensors.

Due to the high and spatially uniform electrical conductivity of a metal, a metal does not exhibit piezoresistivity. The dimensional changes associated with strain change the resistance of a metal, while the resistivity is not affected. Due to the absence of piezoresistivity, self-sensing based on resistance measurement is not effective.

The methods of nondestructive evaluation of the damage of metals include eddy current inspection, ultrasonic inspection, acoustic emission and magnetic particle inspection [6–12]. These methods are not suitable for strain/stress sensing. In addition, they involve the installation of devices or materials for providing the sensing function. These methods do not render the metal self-sensing.

Self-sensing has been recently reported by us in relation to the sensing of damage in steel by capacitance measurement [13]. The method involves the use of two coplanar electrodes on the surface of the steel, such that each electrode is separated from the steel by a dielectric film. This film is critical, because without it, the resistance of the system would be too low for an LCR meter (impedance meter) to provide a reliable measurement of the capacitance. An LCR meter is not designed for measuring the capacitance of an electrical conductor. Because of the conductivity of the steel, the electric field lines between the coplanar electrodes do not only reside in the region between the two electrodes, but extend to considerable distances in the steel away from the electrodes. Thus, the in-plane capacitance obtained by using the coplanar electrodes is sensitive to the damage in the steel even for the parts of the steel that are at considerable distances from the electrodes.

In the implementation of the self-sensing technology, electrodes can be wrapped around a steel pipe and positioned at various points along the length of the pipe, for example. By using an array of electrodes, the stress distribution can be obtained from the capacitance distribution.

This paper extends the prior work on the capacitance-based self-sensing of steel [13] from damage sensing to stress sensing. The objectives of this work are (i) to demonstrate the feasibility of capacitance-based stress self-sensing in steel, (ii) to provide the methodology for measuring the capacitance that relates to the stress, (iii) to compare the self-sensing performance of steel and stainless steel, and (iv) the elucidate the scientific origin of the self-sensing behavior. The comparison in (iii) is scientifically meaningful, because steel is more conductive than stainless steel and the conductivity affects the extent of spreading of the electric field lines associated with the capacitance measurement. The stress studied in this work is uniaxial compressive stress. The effect of flexural stress is addressed in a follow-on publication [14].

2. Experimental methods

2.1. Materials

Two types of steel foil (low carbon steel and stainless steel), both of thickness 25 μm, are used, as provided by Precision Brand Products, Downers Grove, IL. The low carbon steel is C1010 (full hard), with 99.43 wt.% Fe, 0.35 wt.% Mn and 0.06 wt.% C. The stainless steel is 302 (full hard, austenitic, nonmagnetic), with 18 wt.% Cr, 8 wt.% Ni, 1.5 wt.% Mn and 0.02 wt.% C.

The electrical resistivity is 1.43×10^{-5} and 7.2×10^{-5} Ω.cm for C1010 and 302, respectively [11]. The relative magnetic permeability is 100 [15] and 1 [16] for C1010 and 302, respectively. Based on the resistivity and magnetic permeability, the skin depth at 2 kHz (the frequency used in this work) is 426 and 9549 μm for C1010 and 302, respectively [17]. These values of the skin depth much exceed the specimen thickness of 25 μm. Hence, the AC current injected from the specimen surface penetrates the complete thickness of the specimen for both C1010 and 302, with negligible decay as it penetrates.

For the 302 steel, the yield strength is 1190 MPa, the tensile strength is 1300 MPa, and the elastic modulus is 200 GPa. For the C1010 steel, the yield strength is 741 MPa, the tensile strength is 750 MPa, and the elastic modulus is 200 GPa.

2.2. Capacitance measurement method

The in-plane capacitance is measured using coplanar electrodes. The steel or stainless steel foil has in-plane dimensions 75 mm x 25 mm. Two electrodes are on the same surface of the specimen. The entire 25 mm x 25 mm surface of each electrode is in contact with the steel foil and positioned at an end of the 75-mm length of the steel foil (Fig. 1 and 2). The parallel proximate edges of the two electrodes are 25 mm apart. Thus, the area between the two electrodes is 25 mm x 25 mm. This is the area that receives the compressive stress in the study of stress sensing.

Two configurations (designated configurations I and II) are used for measuring the capacitance. In configuration I (Fig. 1), aluminum foil is used as the electrode. Commercial double-sided adhesive tape (stack of 3–4 layers, 3 layers unless noted otherwise, 54 μm thick per layer) is positioned between the aluminum foil and the specimen in order to adhere the specimen to the electrode. The tape also serves as a dielectric film, as needed due to the high conductivity of steel and the unsuitability of the LCR meter for measuring the capacitance of materials of low resistance. If a single layer of the tape is used, the capacitance is higher, but the fractional decrease in capacitance due to the stress increase is lower. No pressure is applied to the electrodes, due to the adhesion provided by the tape.

Configuration II (Fig. 2) uses copper sheets (4.91 mm thick) as the electrodes. Between each of the two electrodes and the specimen is positioned a dielectric Teflon-coated glass fiber composite film (thickness 58 μm, relative permittivity 1.5 at 2 kHz). In order to tighten up the stack, a compressive stress of 3.23 kPa is applied to the stack (over the area of each of the electrodes only) in the direction perpendicular to the layers in the stack by using a known weight.

Because of the absence of pressure on the electrodes, configuration I is more convenient for practical implementation than configuration II. In addition, the costs of materials and installation are lower for configuration I than configuration II.

The in-plane capacitance between the two coplanar electrodes is measured using a precision LCR meter (Instek LCR-816 High Precision LCR Meter, 100 Hz-2 kHz). The frequency used is 2 kHz, because this is the highest frequency provided by the meter and a frequency in the kHz range is commonly available and widely used. The use of frequencies below 2 kHz gives similar results. The error in the capacitance measurement is ± 0.1 pF. The electric field is in the plane of the specimen and corresponds to a voltage of 0.25 V over the gap of 25 mm between the proximate edges of the two electrodes. The capacitance reported is that for the equivalent electrical circuit of a capacitance and a resistance in parallel. In the stress