



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.

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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) to 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} $\Omega\cdot\text{cm}$ 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 \times 25 mm. Two electrodes are on the same surface of the specimen. The entire 25 mm \times 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 \times 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

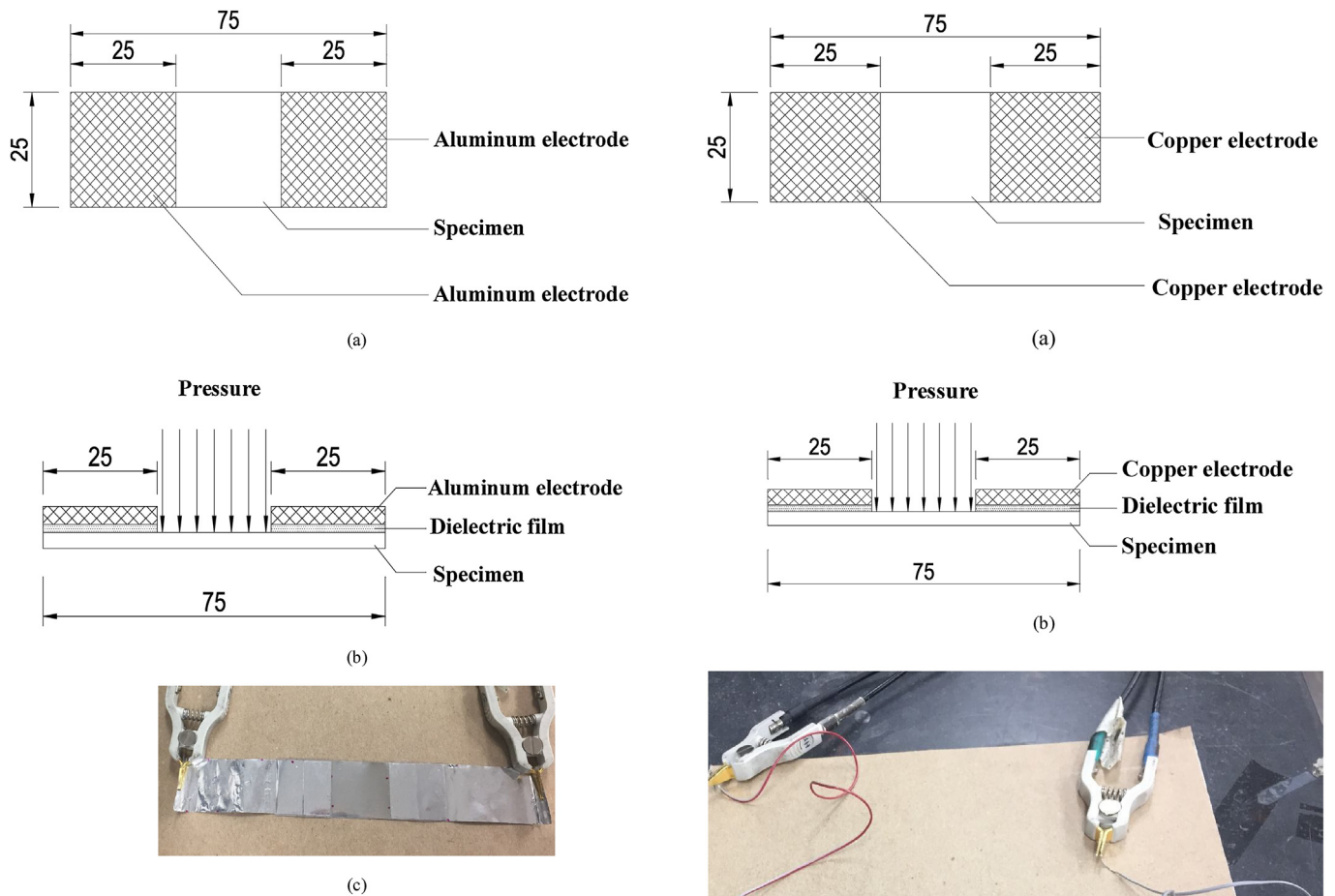


Fig. 1. Testing configuration I for in-plane capacitance measurement. The aluminum foil electrode is held to the specimen by using 3–4 layers (3 layers unless noted otherwise) of double-sided adhesive tape, which also serves as a dielectric film positioned between each electrode and the specimen. No pressure is applied to the electrodes. All dimensions are in mm. The vertical dimensions are not to scale, as the thickness is much smaller than the length. (a) Top view. (b) Side view. (c) Photograph of the setup without the weight on the steel specimen (silver color at the center) and with the aluminum electrodes (more shiny regions) on both sides of the specimen.

sensing investigation, the capacitance is measured during loading and subsequent unloading.

2.3. Method of measuring the capacitance as a function of the stress

In the stress sensing investigation, the stress up to 144 kPa is provided by known weights. The compressive stress is calculated by dividing the force by the area on which the force is applied. This stress is applied to the 25 mm x 25 mm region between the two electrodes. The highest stress of 144 kPa is much below the yield strength of either type of steel. For either type of steel, according to the modulus of 200 GPa, the stress of 144 kPa gives a strain of 7×10^{-9} , which corresponds to a negligible strain-induced capacitance fractional change of 7×10^{-9} .

2.4. Permittivity measurement method

The in-plane permittivity of steel and stainless steel is measured by using four electrodes, each in the form of aluminum foil that is adhered to the specimen by using 4–7 layers of double-sided adhesive tape, which serves as the dielectric film. The specimen is a strip of width 10 mm (Fig. 3). The four electrodes are regularly spaced at a distance of 50 mm along the length of the strip. Each electrode

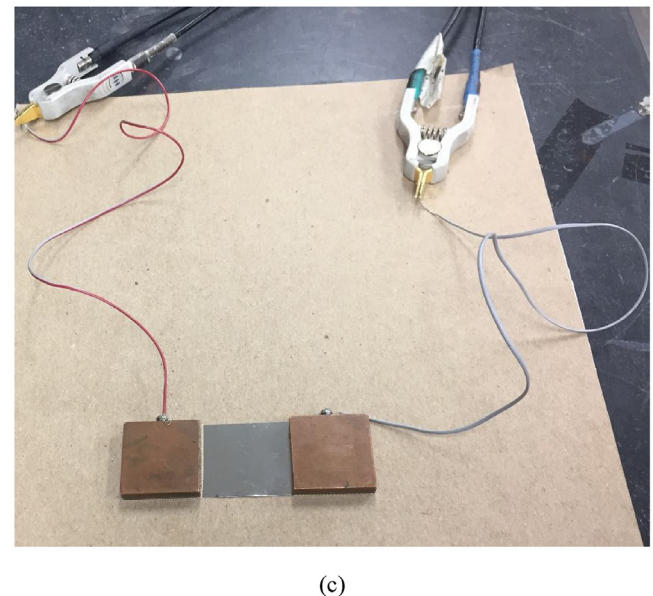


Fig. 2. Testing configuration II for in-plane capacitance measurement. The copper sheet electrode is held to the specimen by using an applied pressure. A dielectric film in the form of Teflon-coated glass fiber composite is positioned between each electrode and the specimen. All dimensions are in mm. The vertical dimensions are not to scale, as the thickness is much smaller than the length. (a) Top view. (b) Side view. (c) Photograph of the setup without the weights on the steel specimen (silver color) and copper electrodes (copper color).

is 5 mm wide in the direction of the length of the strip, such that it extends all the way along the 10-mm width of the specimen. By using different pairs of electrodes (i.e., the 1st and 2nd, the 1st and 3rd, and the 1st and 4th), measurement of the capacitance is conducted over distances of 50, 100 and 150 mm.

The interface between an electrode and the specimen is associated with a capacitance (C_i). The part of the specimen between the two electrodes and the two electrode-specimen interfaces constitute three capacitors in series. The equation for capacitors in series gives

$$1/C_m = 1/C + 2/C_i, \quad (1)$$

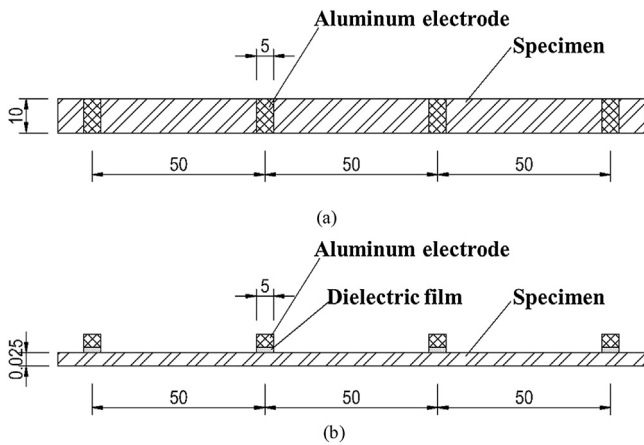


Fig. 3. Configuration for measuring the in-plane permittivity. All dimensions are in mm. The vertical dimensions are not to scale, as the thickness is much smaller than the length. (a) Top view. (b) Side view.

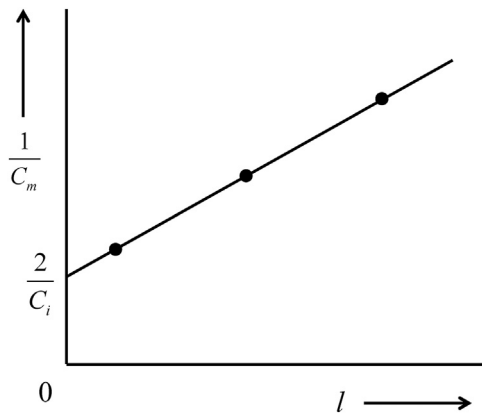


Fig. 4. Schematic plot of $1/C_m$ vs. l for the determination of C_i and κ based on Eq. (1), where C_i is the capacitance of a specimen-contact interface and κ is the relative permittivity of the specimen. The slope equals $1/(\epsilon_0\kappa A)$. The l is the thickness of the specimen and A is the area of the specimen. The intercept on the vertical axis equals $2/C_i$.

where C_m is the measured capacitance and C relates to the relative permittivity κ of the specimen by the equation

$$C = \epsilon_0\kappa A/l, \tag{2}$$

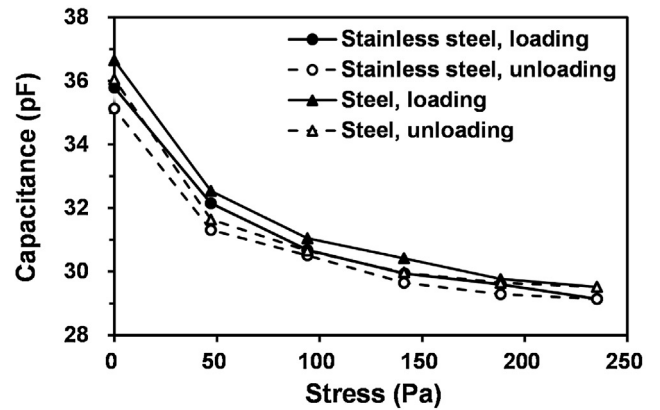
where ϵ_0 is the permittivity of free space (8.85×10^{-12} F/m), κ is the in-plane relative permittivity (real part) of the specimen, A is the specimen cross-sectional area, and l is the distance over which the capacitance is measured. Due to the small thickness (25 μ m) and high conductivity of the specimen, the in-plane AC current injected by the two electrodes used to measure the capacitance is assumed to penetrate the entire thickness of the specimen. By measuring the capacitance for various values of l and plotting $1/C_m$ vs. l , κ is obtained from the slope of the linear plot and C_i is obtained from the intercept of the line with the vertical axis at $l=0$ (Fig. 4). The slope of the line is equal to $1/(\epsilon_0\kappa A)$.

3. Results and discussion

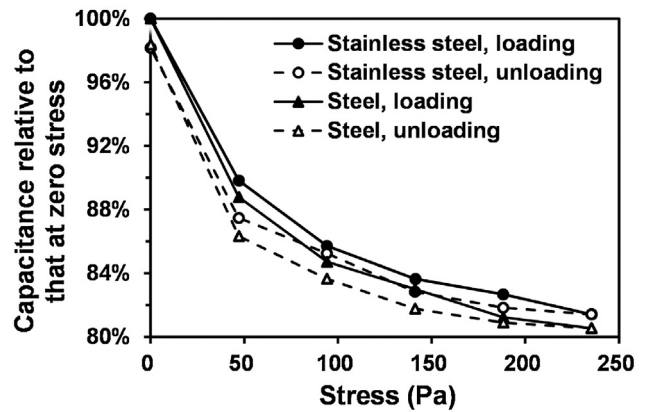
3.1. Effect of stress on the capacitance

3.1.1. Configuration I

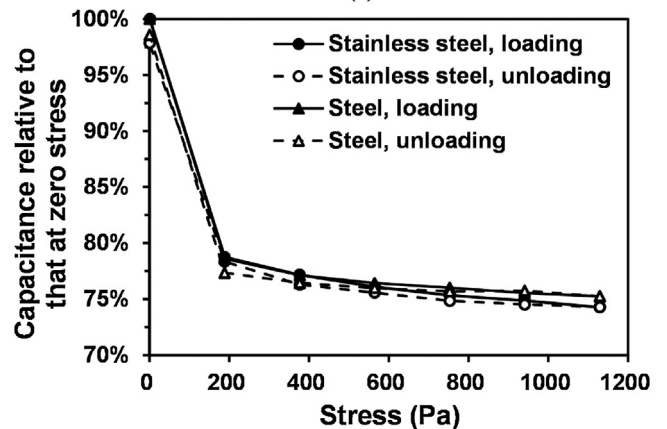
Fig. 5 shows that, for configuration I, 3 layers of adhesive tape, and a maximum stress of 235 Pa, the measured capacitance decreases monotonically with increasing stress. The capacitance decrease is more abrupt in the low-stress regime than the high-



(a)



(b)



(c)

Fig. 5. Stress-sensing results for configuration I, using three layers of adhesive tape as the dielectric film. (a) The measured capacitance during loading and subsequent unloading for a maximum stress of 235 Pa. (b) The measured capacitance relative to that at zero stress during loading and subsequent unloading for a maximum stress of 235 Pa. (c) The measured capacitance relative to that at zero stress during loading and subsequent unloading for a maximum stress of 1129 Pa.

stress regime. For the same stress, the capacitance is lower during unloading than loading, though the difference is not large.

For configuration I and a maximum stress of 235 Pa, the capacitance decrease is essentially reversible, though the capacitance is slightly lower during unloading than during loading at the same stress (Fig. 5(a)). In case that the capacitance is divided by the value at zero stress, the hysteresis is negligible (Fig. 5(b)). The fractional decrease in capacitance is up to 20%. The behavior is similar for steel and stainless steel, though the capacitance is slightly lower for steel than stainless steel at the same stress (including zero stress)

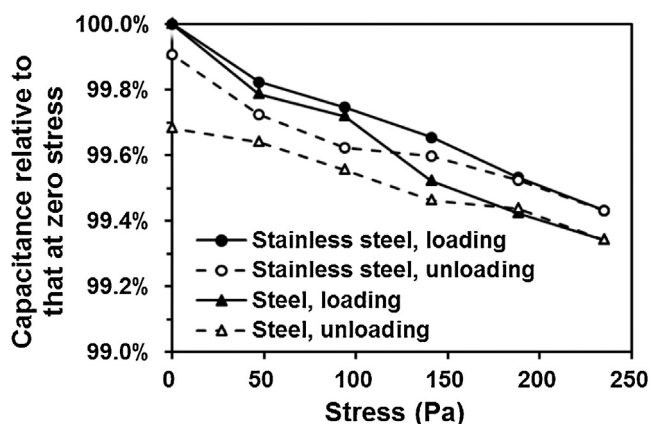


Fig. 6. Stress-sensing results for configuration I, using four layers of adhesive tape as the dielectric film.

(Fig. 5(a)). In case that the capacitance is divided by the value at zero stress, the difference between steel and stainless steel is negligible (Fig. 5(b)).

For a maximum stress of 1129 Pa, the capacitance decrease is abrupt up to a stress of about 200 Pa, about which the capacitance decreases gradually as the stress increases (Fig. 5(c)). Thus, the stress sensitivity is much greater at stresses below about 200 Pa.

When four layers of adhesive tape are used as the dielectric film, the capacitance-based stress sensing is not as sensitive. As shown in Fig. 6, the fractional change in capacitance due to the stress (up to 250 Pa) is up to 0.6% when four layers of tape are used, in contrast to a corresponding fractional change in capacitance of up to 19% when three layers of tape are used (Fig. 5(b)). The lower sensitivity in case of four layers of tape is due to the larger resistance associated with four layers and the consequent lower electric field across the steel specimen.

3.1.2. Configuration II

In relation to configuration II, Fig. 7 shows that the measured capacitance decreases with stress, as in the case of configuration I. For the same stress, the capacitance is lower during unloading than loading, though the difference is not large. The higher the stress, the less is the incremental capacitance decrease. At any stress, the capacitance is lower for steel than stainless steel. The scientific origin of the lower capacitance for steel is presently unclear. In case that the capacitance is divided by the value at zero stress, the difference between steel and stainless steel is small. At a given stress, the fractional decrease in capacitance is higher for steel than stainless steel. The greater fractional decrease for steel relates to the lower capacitance for steel.

Fig. 7(a) and (b) show that, for configuration II, the stress sensing is marginally effective for low stresses up to 50 Pa, but is ineffective in the range from 50 to 235 Pa. The largest fractional decrease in capacitance due to the stress is 5% and 3% for steel and stainless steel, respectively.

Fig. 7(c) and (d) show that, for configuration II, the sensing is effective in the range from 200 to 1129 Pa, such that the capacitance change is more significant below 200 Pa than above 200 Pa. The largest fractional decrease in capacitance is 11% and 8% for steel and stainless steel, respectively.

Fig. 7(e) and (f) show that, for configuration II, the sensing is effective in the range from 32 to 144 kPa, such that the capacitance change is more significant below 32 kPa than above 32 kPa; the largest fractional decrease in capacitance is 20% and 18% for steel and stainless steel, respectively.

3.1.3. Comparison of configurations I and II

The fractional decrease in capacitance is up to 20% for both configuration I (as observed at 235 Pa) and configuration II (as observed at 144 kPa). This means that the fractional decrease in capacitance per unit stress is much greater for configuration I than configuration II. The lower stress sensitivity for configuration II, particularly in the low-stress regime, is partly attributed to the pressure of 3.23 kPa applied to each of the two electrodes, which rest on the specimen. Although this pressure is applied only to the areas of the electrodes, it may affect the part of the specimen away from the electrodes. This is because the specimen is continuous as a single piece for both the areas of the electrodes and the area away from the electrodes. The greater stress sensitivity for configuration I is partly attributed to the flexibility of both aluminum foil and adhesive tape and the consequent better conformability of the electrodes to the specimen surface (which is never perfectly smooth) for this configuration. In contrast, the copper sheet is less flexible and less conformable than the aluminum foil, and the Teflon-coated glass fiber composite sheet is less flexible and less conformable than the adhesive tape, in spite of the presence of pressure. As a consequence, air voids are bound to occur at the interface between the copper sheet and the composite sheet and at the interface between the composite sheet and the specimen surface. The air voids are detrimental to the quality of the electrical contact.

Since the applied voltage amplitude is fixed, the superior electrical contact in configuration I results in less voltage drop across the contact and hence a greater voltage drop within the specimen between the two electrodes. The greater voltage drop in the specimen results in greater sensitivity to the applied stress in the low-stress regime. However, the insensitivity to relatively high values of the stress for configuration I is probably due to the high stress affecting negatively the quality of the electrical contact that involves thin flexible materials.

Configuration I is superior to configuration II in sensing low stresses, whereas configuration II is superior to configuration I in sensing relatively high stresses. The capacitance obtained using configuration I is not sensitive to stress exceeding about 200 Pa. In contrast, the capacitance obtained in configuration II is sensitive to stress up to at least 140 kPa. In other words, the capacitance obtained in configuration I is sensitive to stress only in the low-stress regime, whereas that obtained in configuration II is sensitive to a much wider range of stress.

For configuration I, the capacitance and fractional decrease in capacitance are both similar for steel and stainless steel. For configuration II, the capacitance is lower for steel than stainless steel, but the fractional decrease in capacitance is comparable. This suggests that configuration II is more sensitive to the conductivity of the specimen than configuration I. However, the scientific origin of this difference between the two configurations is presently not completely clear.

3.2. Permittivity

The number of layers of the tape needs to be optimum, as it must be sufficient to provide enough resistance to the system; otherwise the LCR meter will not give a meaningful value of the capacitance. However, the number of layers should not be excessive, as a larger number of layers would cause less electric field applied to the specimen, so that the permittivity would be less than the true value. Experimental work for various numbers of layers of the adhesive tape has shown that the use of 4 layers of the tape is optimum. As shown in Table 1, the use of 4 layers of tape gives the highest value of the relative permittivity, which decreases with increasing number of layers of the tape. The results are shown in Fig. 7 for 3, 4 and 5 layers of the tape. The plot of $1/C_m$ vs. distance is approximately linear in case of 4 or 5 layers of tape, as expected from Eq.

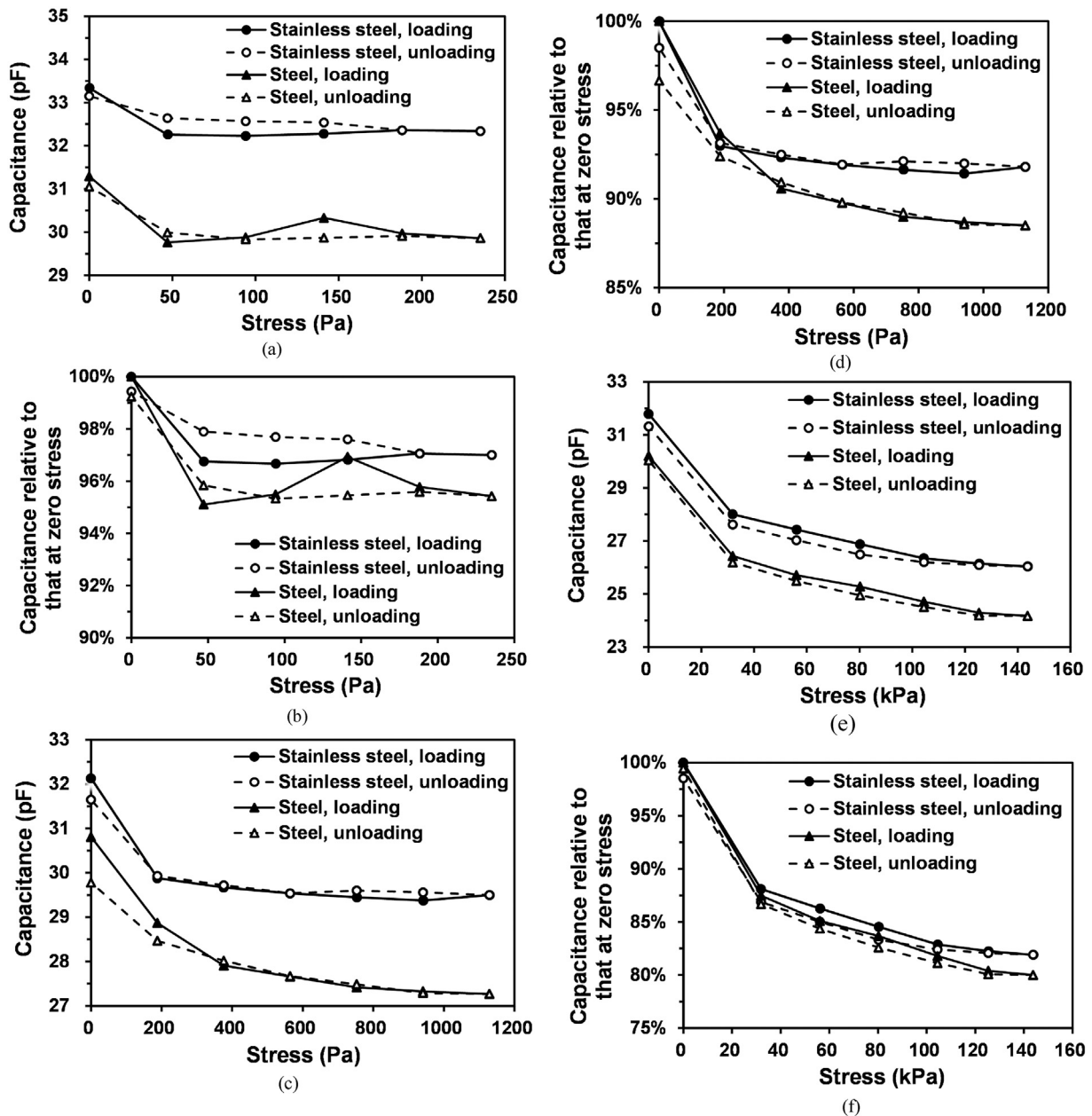


Fig. 7. Stress-sensing results for configuration II. (a) The measured capacitance during loading up to 235 Pa and subsequent unloading. (b) The measured capacitance relative to that at zero stress during loading up to 235 Pa and subsequent unloading. (c) The measured capacitance during loading up to 1129 Pa and subsequent unloading. (d) The measured capacitance relative to that at zero stress during loading up to 1129 Pa and subsequent unloading. (e) The measured capacitance during loading up to 144 kPa. (f) The measured capacitance relative to that at zero stress during loading up to 144 kPa.

(1), but is not linear in case of 3 layers of tape. The nonlinearity in case of three layers of tape is due to the inadequate resistance in the system for accurate measurement of the capacitance.

Table 1
Relative permittivity measured for steels using different numbers of layer of double-sided adhesive tape as the dielectric film between the specimen and the aluminum foil electrode.

No. of layers of adhesive tape	Relative permittivity at 2 kHz	
	Stainless steel	Low carbon steel
4	$(2.25 \pm 0.65) \times 10^6$	$(1.13 \pm 0.16) \times 10^6$
5	$(7.50 \pm 0.72) \times 10^5$	$(6.48 \pm 0.02) \times 10^5$
6	$(4.50 \pm 0.26) \times 10^5$	$(3.49 \pm 0.16) \times 10^5$
7	$(3.00 \pm 0.20) \times 10^5$	$(2.39 \pm 0.19) \times 10^5$

From the slope, based on Eq. (2), the in-plane relative permittivity κ is determined to be $(1.134 \pm 0.164) \times 10^6$ and $(2.249 \pm 0.649) \times 10^6$ for low carbon steel and stainless steel, respectively, for the case of four layers of tape. The error in the slope relates to the degree of linearity and this error is used to obtain the error in κ . The slightly higher permittivity for stainless steel relates to the slightly higher resistivity of this material.

In spite of the non-linearity, the use of three layers of tape gives more capacitance-based stress sensitivity than the use of four layers of tape. This means that there is a compromise between the capacitance accuracy and the stress sensitivity. The capacitance accuracy is better for four layers of tape than three layers of tape, but the stress sensitivity is greater for three layers of tape than four layers of tape. Permittivity measurement demands high accuracy of the capacitance measurement, so the use of four layers of tape is needed

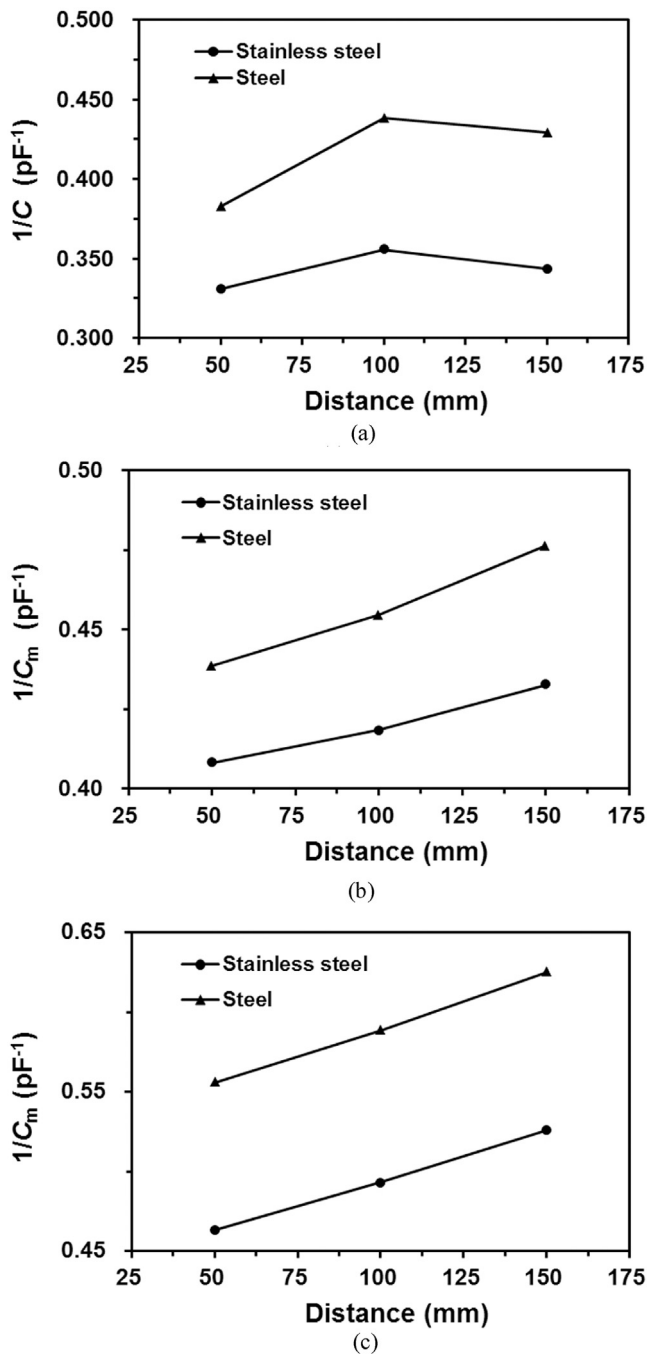


Fig. 8. Plot of $1/C_m$ vs. distance according to Eq. (1). (a) 3 layers of adhesive tape. (b) 4 layers of adhesive tape. (c) 5 layers of adhesive tape.

for this measurement. However, because (i) stress sensitivity is less demanding of the accuracy of the capacitance measurement and (ii) the higher electric field across the specimen in case of three layers of tape, the use of three layers of tape is more suitable for stress sensing than the use of four layers of tape.

3.3. Scientific origin

As shown in Sec. 3.2, the relative permittivity κ is 10^6 at 2 kHz for both types of steel. As shown in Fig. 8, the specimen capacitance C (to be distinguished from the measured capacitance C_m) is at least 30 pF and 20 pF for the cases of 4 and 5 layers of the tape, respectively. Consider the case of 4 layers of tape. The observed

fractional change in in-plane capacitance due to the normal compressive stress is up to -0.2 (Fig. 5(a)). Due to Eq. (2), the fractional change in in-plane distance l (i.e., the strain in the in-plane direction) is the negative of the fractional change in in-plane capacitance. Hence, the fractional change in l is $+0.2$. With respect to the applied normal stress, the in-plane direction is the transverse direction. The strain in the stress direction is related to that in the transverse direction by the Poisson ratio, which is 0.3 for both steels [18]. Hence, the strain in the stress direction is $-(0.2)/0.3 = -0.7$. This axial strain is unreasonably high, since the low stress used (up to 250 Pa) and the high elastic modulus (200 GPa) of the steels gives a strain of only 10^{-9} . In other words, the strain needed to explain the observed capacitance change is unreasonably high. This means that the strain cannot explain the observed capacitance change, even though a decrease in thickness would decrease the in-plane capacitance.

The decoupling of C and C_i (Eq. (1)) has been achieved for the purpose of measuring the relative permittivity (Sec. 3.2). This decoupling is not performed in studying the effect of stress on the capacitance (Sec. 3.1), because the capacitance rather than the permittivity is an attribute that is suitable for direct measurement in relation to sensing.

The direct piezoelectric effect is associated with the electric field resulting from strain. It converts mechanical energy to electrical energy. The change in capacitance due to stress is attributed to the direct piezoelectric effect of the steel, i.e., the applied stress causing polarization and hence a capacitance change. The piezoelectric effect is commonly observed in dielectric materials in the form of ceramics and polymers, but has not been previously suggested or observed for any metal. However, the dielectric (polarization) behavior of steel does occur, as shown by the measurement of the permittivity (Sec. 3.2). Due to the dielectric behavior, the occurrence of a degree of piezoelectric behavior is expected. Although the applied compressive stress is normal to the steel sheet and the capacitance is measured in the plane of the sheet, the piezoelectric effect is still reasonable, due to the transverse effect that is commonly characterized by the piezoelectric coupling coefficient known as d_{31} . Although the magnitude of d_{31} is lower than that of d_{33} (which is the piezoelectric coupling coefficient of the longitudinal effect), d_{31} describes an effect that is widely used in practice for piezoelectric devices.

The capacitance decreases with increasing compressive stress (Fig. 5). This means that the capacitance increases with increasing stress, where the stress is positive for tensile stress and negative for compressive stress. This in turn means that the piezoelectric coupling coefficient is positive. The curve of capacitance vs. compressive stress is not linear (Fig. 5). This means that the piezoelectric coupling coefficient decreases with increasing compressive stress, i.e., it increases with increasing stress, where the stress is positive for tensile stress and negative for compressive stress. This stress dependence may be due to the effect of strain on the material's piezoelectric behavior. Linearity between the capacitance and stress is expected for the direct piezoelectric effect. The non-linearity suggests that the origin of the phenomenon is more complex than a simple piezoelectric effect. Due to the quantity measured being the capacitance rather than the voltage, the piezoelectric coupling coefficient cannot be determined.

3.4. Difference from impedance spectroscopy

This work uses a technique which differs greatly from the widely used technique of impedance spectroscopy, which measures the impedance as a function of frequency and uses the frequency dependence to obtain information. Firstly, the technique of this work does not measure the impedance, but measures the capacitance, which relates to the imaginary part of the impedance. This work measures the capacitance with a test configuration in which a

dielectric film is positioned between the specimen and each of the two electrodes. The presence of this film ensures that the resistance of the system is high enough for the measured capacitance given by the LCR is correct. However, the presence of this film would cause the specimen resistance to be not effectively measured. Resistance measurement is not a part of this study. A dielectric film is not usually used in impedance spectroscopy, thus causing the capacitance measurement in the impedance spectroscopy to be questionable. Secondly, the technique of this work does not need to address the frequency dependence in order to obtain meaningful information. In contrast, impedance spectroscopy is focused on the frequency dependence of the impedance, as conventionally described in terms of the Nyquist plot, for the purpose of deriving by mathematical fitting of the plot an equivalent electrical circuit that is intended to describe the electrical/dielectric behavior of the material. The circuit model obtained by the curve fitting [19] tends to be not unique, so the determined values of the circuit elements in the model are not very meaningful [20,21].

Impedance spectroscopy is not suitable for real-time sensing, because of its requirement of making measurement as a function of frequency. In contrast, the method of work does not require studying the frequency dependence.

4. Conclusion

The sensing of stress in a metal (namely steel and stainless steel) by capacitance measurement is reported here for the first time. The method involves the measurement of the in-plane capacitance 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, with slight hysteresis. The scientific origin of the capacitance decrease 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 the specimen. Two configurations are used for the electrodes. Configuration I involves aluminum foil as the electrode and a stack of three 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, in addition to the use of normal pressure on the stack. Configuration I is less expensive and more convenient for practical implementation than configuration II.

The fractional decrease in capacitance per unit stress is much greater for configuration I than configuration II. Configuration I is superior in the sensitivity of low stresses below about 200 Pa (0.2 kPa), whereas configuration II is superior in the sensitivity of high stresses up to 140 kPa. For both configurations, the highest fractional decrease in capacitance due to the stress is 20% and 18% for steel and stainless steel, respectively. For configuration I, the capacitance and fractional decrease in capacitance are both similar for steel and stainless steel. For configuration II, the capacitance is lower for steel than stainless steel, but the fractional decrease in capacitance is comparable.

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