Electric permittivity of carbon fiber

Asma A. Eddib, D.D.L. Chung[*]

Composite Materials Research Laboratory, Department of Mechanical and Aerospace Engineering, University at Buffalo, The State University of New York, Buffalo, NY, 14260-4400, USA

ARTICLE INFO

ABSTRACT

The electric permittivity is a fundamental material property that affects electrical, electromagnetic and electrochemical applications. This work provides the first determination of the permittivity of continuous carbon fibers. The measurement is conducted along the fiber axis by capacitance measurement at 2 kHz using an LCR meter, with a dielectric film between specimen and electrode (necessary because an LCR meter is not designed to measure the capacitance of an electrical conductor), and with decoupling of the contributions of the specimen volume and specimen-electrode interface to the measured capacitance. The relative permittivity is 4960 ± 662 and 3960 ± 450 for Thornel P-100 (more graphitic) and Thornel P-25 fibers (less graphitic), respectively. These values are high compared to those of discontinuous carbons, such as reduced graphite oxide (relative permittivity 1130), but are low compared to those of steels, which are more conductive than carbon fibers. The high permittivity of carbon fibers compared to discontinuous carbons is attributed to the continuity of the fibers and the consequent substantial distance that the electrons can move during polarization. The P-100/P-25 permittivity ratio is 1.3, whereas the P-100/P-25 conductivity ratio is 67. Thus, defects associated with a low degree of graphitization hinder conduction more than polarization.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Carbon fibers are outstanding among reinforcements in their combination of high strength, high elastic modulus, low density, and wide availability. In addition, they are attractive for their low coefficient of thermal expansion, high electrical and thermal conductivity, resistance to high temperatures, and biocompatibility. Therefore, carbon fibers and their composites (mostly commonly with polymer matrices) are used for lightweight structures (particularly in aircraft), lightning protection, electromagnetic interference (EMI) shielding (e.g., for computer cases), Stealth (low observability), antistatic structures, biomedical prosthetics, heat sinks, resistance (Joule) heating elements, current collectors, electrochemical electrodes (e.g., for batteries and supercapacitors), fluid filtration media (particularly in the form of activated carbon fiber), etc. [1].

Many of the applications exploit the electrical properties of the carbon fibers. Even for structural applications, the electrical properties are valuable for rendering the structure multifunctional. For

example, the electrical conductivity is used to render the structural composite capable of sensing its own condition (e.g., strain, stress, temperature and damage) through the dependence of the condition on the electrical resistance [2,3]. Since no embedded or attached sensor is involved, this capability is known as self-sensing. Advantages of self-sensing compared to the use of embedded or attached sensors include low cost, high durability, large sensing volume and absence of mechanical property loss. For electrochemical electrodes, which are commonly in the form of a fiber felt, the electronic conductivity of the fiber is utilized.

The electrical behavior of a material is described in terms of the electrical conductivity and the electric permittivity. The conductivity relates to the electrical resistance, whereas the permittivity relates to the polarization, which results in a capacitance. Much attention has been given to the conductivity of carbon fibers. The conductivity increases with increasing degree of graphitization of the fiber. However, relatively little attention has been given to the permittivity, in spite of the effect of polarization on the charge carrier movement and the fact that the capacitance causes signal propagation delay, as commonly described in terms of the RC time constant.

The permittivity governs the polarization, which is relevant to the piezoelectric and pyroelectric behavior. Thus, the

---

* Corresponding author.
E-mail address: ddlchung@buffalo.edu (D.D.L. Chung).
URL: http://alum.mit.edu/www/ddlchung

characterization of the permittivity opens the door to applications which have not been previously considered for carbon fibers.

The sensing or monitoring of stress/strain and damage is important for structural vibration control and structural health monitoring. The stress dependence of the permittivity (not addressed in this work) enables capacitance-based stress/strain self-sensing. The damage dependence of the permittivity (not addressed in this work) enables capacitance-based damage self-sensing. Prior work on stress/strain self-sensing of carbon fibers and their composites is limited to resistance-based self-sensing [2]. Prior work on damage self-sensing of carbon fiber composites has involved both resistance-based [2] and capacitance-based [4] self-sensing. In general, capacitance-based sensing is advantageous over resistance-based sensing in that the electrodes do not need to be in intimate electrical contact with the specimen. In practical structural implementation of the self-sensing technology, the fiber composite structure may be covered with a layer of paint. Removal of the paint is not necessary for capacitance measurement, but is necessary for resistance measurement.

A pitfall in the measurement of the permittivity of an electrically conductive material relates to the fact that an LCR meter used to measure the capacitance is not designed to measure the capacitance of an electrical conductor. To circumvent this problem, a dielectric film should be positioned between the specimen and an electrode. The paint mentioned above may serve as the dielectric film.

A relative permittivity value of 700 (10 kHz) has been previously reported for a short carbon fiber (14.7 vol%) polymer-matrix composite, with the polymer being acrylic-polyurethane [5]. Since the electrical resistivity of 100 Ω cm (10 kHz) [5] is not low, this permittivity value is probably correct, even though it was measured using an LCR meter in the absence of a dielectric film at the interface between the specimen and electrode.

A relative permittivity value of 2000 (100 Hz) has been previously reported for a short carbon nanofiber (0.15 μm diameter, 15.55 vol%) polymer-matrix composite, with the polymer being an ethylene-octene copolymer [6]. The resistivity of this composite is 2.34 Ω cm (DC), which is low. The high value of 2000 [6] is questionable, due to the substantial conductivity and the absence of a dielectric film at the interface between the specimen and electrode.

A relative permittivity value of 10,000 (100 Hz) has been previously reported for a carbon nanotube (0.02 μm diameter, 21.40 vol%) polymer-matrix composite, with the polymer being an ethylene-octene copolymer [6]. The resistivity of this composite is 11.6 Ω cm (DC), which is low. The high value of 10,000 [6] is questionable, due to the substantial conductivity and the absence of a dielectric film at the interface between the specimen and electrode. The error source is similar to that resulting in the erroneous high relative permittivity of 4×10^9 (20 Hz) previously reported for reduced graphite oxide [7].

A high relative permittivity of 110,000 (60 Hz) has been previously reported for a continuous carbon fiber epoxy-matrix composite in the through-thickness direction (with electrical resistivity 20 Ω cm), and an even higher value of 200,000 (60 Hz) has been reported for a corresponding composite with carbon nanotubes grafted on the carbon fibers (with resistivity 15 Ω cm) [8]. These high permittivity values are said to correspond to colossal permittivity [8], but their correctness is questionable, due to the conductivity of the specimens and the absence of a dielectric film in the use of an LCR meter.

The frequency used in this work (kHz) is much lower than that of the microwave regime (GHz), which is relevant to EMI shielding and Stealth [3]. In the microwave regime, the testing uses a vector network analyzer rather than an LCR meter. The mechanism of electromagnetic wave propagation involves radiation rather than conduction in the microwave regime. Furthermore, the ability of an electric dipole to respond to an AC electric field varies with the frequency. Therefore, comparison of the permittivity obtained in this work with the values of prior work in the microwave regime is not very suitable. Nevertheless, at 8 GHz, the axial complex relative permittivity (with the continuous carbon fibers parallel to the electric field) and the transverse complex relative permittivity (with the fibers perpendicular to the electric field) have been reported to be 27 and 29, respectively [9]; the axial value is lower than the transverse value. In contrast, at 2.6–8.2 GHz, the axial permittivity (with the fibers preferentially parallel to the electric field) of short fiber (3 mm long) epoxy-matrix composite has been reported to be about five times that of the transverse permittivity (with the fibers preferentially perpendicular to the electric field) [10]. At 8.2 GHz, a very high axial relative permittivity value of 32,000 has been reported for carbon fibers, based on the measurement of the permittivity of short (10 mm long) carbon fiber epoxy-matrix composites [11]. The permittivity increases with increasing fiber length [11], suggesting the importance of the testing of continuous carbon fibers.

This paper is directed at providing the first measurement of the permittivity of continuous carbon fiber. Prior work was limited to the measurement of the permittivity of a polyacrylonitrile (PAN) based carbon fiber polymer-matrix composite, for which the relative permittivity (2 kHz) is 2160 ± 510 and 1640 ± 330 for the longitudinal and transverse directions, respectively [4]. In particular, this work addresses the fiber's axial direction at low frequencies (below radio wave, microwave and optical frequencies). The axial direction is the important direction for most applications of carbon fibers. The low-frequency regime is important for electrochemical, self-sensing and resistance heating applications. In addition, this paper is aimed at studying the effect of the degree of graphitization on the permittivity, as indicated by comparison of the permittivity of mesophase-pitch-based fibers with different degrees of graphitization.

2. Methodology of permittivity measurement

In order to circumvent the problem of an LCR meter being not designed to measure the capacitance of an electrically conductive material, a dielectric film is positioned at the interface between the specimen and each of the two electrodes. In this work, the dielectric film is in the form of multiple layers of double-sided adhesive tape. The number of layers needs to be adequate to provide enough resistance for the purpose of circumventing the problem mentioned above. However, the number of layers should not be excessive, as this would result in too large a voltage drop across the layers and hence too small a voltage drop across the specimen. By using a dielectric film in the form of multiple layers of the adhesive tape, the dielectric film can be suitably tailored. In general, the lower is the resistance of the specimen, the more is the number of layers needed.

The contribution of the specimen-electrode interface (with the interface including the dielectric film) to the measured capacitance can be decoupled from the contribution of the specimen itself to the measured capacitance by conducting the capacitance measurement at three or more different lengths of the specimen between the two electrodes. As the two interfacial capacitances (for the two specimen-electrode interfaces) and the specimen volumetric capacitance are three capacitors in series, the measured capacitance C_m is given by

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

where C is the specimen volumetric capacitance, and C_i is the

interfacial capacitance for one interface. The C relates to the relative permittivity κ of the specimen in the direction along the above-mentioned length l of the specimen by the equation

$$C = \varepsilon_o \kappa A / l \qquad (2)$$

where ε_o is the permittivity of free space, and A is the area of the specimen in the plane perpendicular to the length l of the specimen. Combining Eqs. (1) and (2) gives

$$1/C_m = l/(\varepsilon_o \kappa A) + 2/C_i \qquad (3)$$

Based on Eq. (3), in case that l is a variable, a plot of $1/C_m$ vs. l gives a line of slope equal to $1/(\varepsilon_o \kappa A)$ (Fig. 1). Hence, from the slope, κ is obtained.

The abovementioned method of permittivity measurement involving the dielectric film and the decoupling has been previously applied to the study of a variety of discontinuous carbon materials [12–17]. These carbon materials include reduced graphite oxide [12], graphite oxide [13,14], exfoliated graphite [15,16], activated carbon [16], natural graphite [16] and carbon black [16,17], but they do not include carbon fibers.

3. Experimental methods

3.1. Materials

Two types of carbon fiber are studied, labeled type A and type B. They are both mesophase-pitch-based, unsized, without twist, with 10-μm diameter and 2000 filaments in a tow, as manufactured by Amoco Performance Products, Inc., presently owned by Cytec Industries Inc. (Woodland Park, New Jersey, U.S.A.).

Type A is Thornel P-100, with density $2.130 \pm 0.005 \, \text{g/cm}^3$, tensile modulus 760 GPa, tensile strength 2.4 GPa, tensile ductility 0.30% [18] and axial electrical resistivity $1.8 \times 10^{-4} \, \Omega \, \text{cm}$ (as measured for a single fiber using the four-probe method) [19]. Type B is Thornel P-25, with density $1.920 \pm 0.005 \, \text{g/cm}^3$, tensile modulus 159 GPa, tensile strength 1.56 GPa, tensile ductility 0.9% and axial electrical resistivity $1.2 \times 10^{-3} \, \Omega \, \text{cm}$ [20]. Compared to type B, type A exhibits higher modulus, higher strength, lower ductili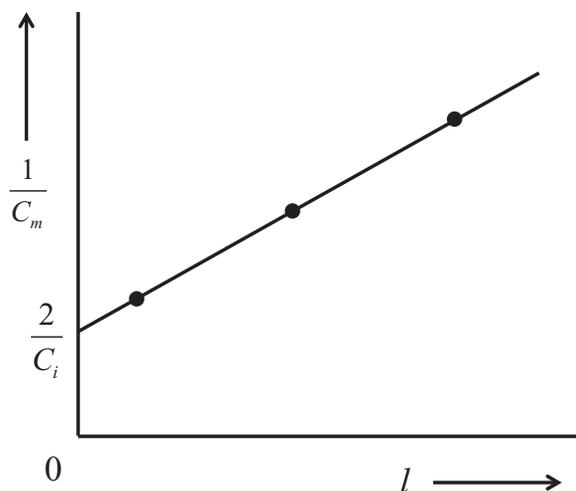ty, higher density, lower electrical resistivity, and higher degree of graphitization. The ratio of the conductivity of the P-100 fiber to that of the P-25 fiber is 67.

The difference in structure between the two types of fiber is shown in Table 1. Compared to P-25, P-100 has lower interlayer spacing d_{002}, smaller azimuthal spread, and higher values of L_c, L_a (the crystallite sizes along the c-axis and a-axis, respectively) and the graphitization parameter. The difference in structure is consistent with the higher conductivity and higher modulus of the P-100 fiber compared to the P-25 fiber.

The P-100 fiber is in the carbon fiber category known as ultra-high modulus carbon fiber, whereas the P-25 fiber is in the category known as low-modulus carbon fiber. This means that these two types of fiber differ greatly in the modulus, when the modulus range of various grades of carbon fibers is considered. With the same carbon precursor (mesophase pitch), these two types of carbon fibers are obtained by using different heat treatment temperatures. Due to the much higher heat-treatment temperature used for fabricating the P-100 fiber, the degree of graphitization is much greater for P-100 than P-25.

Two specimens are tested for each type of fiber. The two specimens of type A are labeled A1 and A2. The two specimens of type B are labeled B1 and B2. The specimen configuration for permittivity measurement is described in Sec. 3.2.

3.2. Permittivity measurement method

The experimental method for permittivity measurement is an extension of the method used in the prior work of Chung et al. [12–17]. The method involves the presence of a dielectric film between the specimen and each electrode and the decoupling of the interfacial capacitance from the volumetric capacitance, as explained Sec. 2. However, the specimen configuration in this work is different from that in the prior work [12–17]. In the prior work [12–17], the specimen dimension is small in the direction of capacitance measurement. In the present work, the specimen dimension is large in the direction of capacitance measurement.

In the prior work [12–17], measurement is conducted with two electrodes for three specimen thicknesses in order to provide the data for the plot in Fig. 1. In the present work, four electrodes in the form of tin-coated copper wires are positioned on the top surface of the specimen at four points (essentially equally spaced at a distance ranging from 25.40 to 26.15 mm, with the exact distance between every two adjacent electrodes measured for each specimen) along the length of the specimen (Fig. 2). Each electrode is adhered to the top surface of the specimen by using three layers of double-sided adhesive tape, which serves as the dielectric film between the specimen and the electrode. Each electrode is 0.97 mm wide in the direction of the length of the specimen, such that it extends all the way along the 0.50-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 ~26, ~52 and ~78 mm. The configuration of Fig. 2 had been previously used for measuring the in-plane permittivity of steel foil [21], which is even more conductive than carbon fibers.

A rectangular alumina mold cavity is manually assembled by

Fig. 1. Schematic plot of $1/C_m$ vs. l, for the determination of the relative permittivity κ based on Eq. (3). The slope equals $1/(\varepsilon_o \kappa A)$. 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_i is the specimen-electrode interfacial capacitance. (A colour version of this figure can be viewed online.)

Table 1
Structural parameters of the two types of carbon fiber [24].

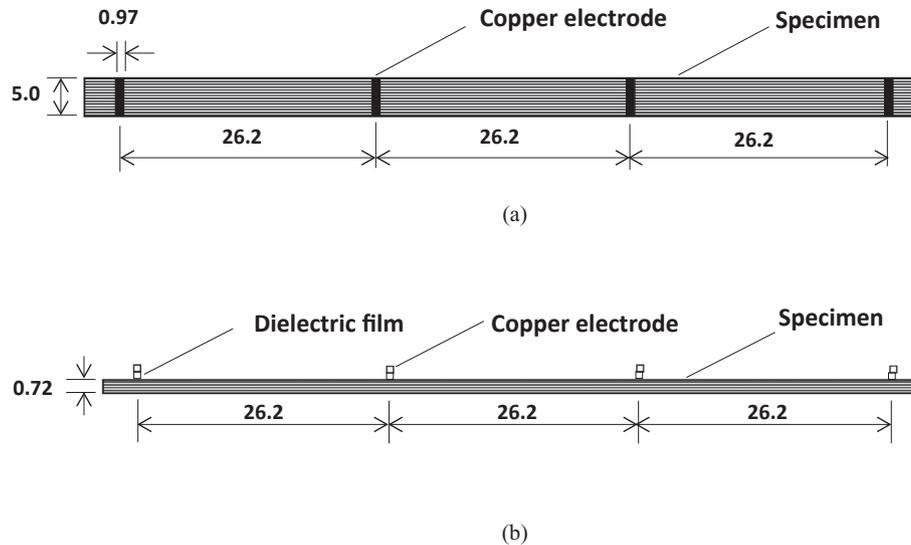| Structural parameter	P-100	P-25
Interlayer spacing (Å)	3.382	3.439
Azimuthal spread	5.6°	32°
L_c (Å)	227	26
L_a (Å)	235	28
Graphitization parameter	0.674	0.011

Fig. 2. Configuration for measuring the axial permittivity of carbon fiber. All dimensions are in mm. The dimensions shown are those for Specimen A1. The vertical dimensions in (b) are not to scale, as the thickness is much smaller than the length. (a) Top view. (b) Side view. (A colour version of this figure can be viewed online.)

using a large number of alumina (96 wt% Al_2O_3) substrates of size $25.4 \times 25.4 \times 0.6$ mm and through-thickness relative permittivity 8.5 (10 kHz) [22] that are oriented in the plane of the bottom surface of the mold cavity, and (ii) conventional adhesive tape to hold the substrates together. The mold cavity is used to contain the aligned fibers, the axis of which is along the longest dimension of the mold cavity. Multiple tows are packed to fill the mold cavity. The fiber length extends for the entire length of the mold cavity (at least 128 mm), which is substantially longer than the distance (~78 mm) between the outermost (1st and 4th) electrodes. The width of the mold cavity is 5.0 ± 0.3 mm for Specimens A1 and A2, and is 6.510 ± 0.030 mm for Specimens B1 and B2. The thickness of the mold cavity is ~0.71 mm and ~1.56 mm (with the exact thickness measured for each specimen) for Specimens A1/A2 and Specimens B1/B2, respectively.

The fiber volume fraction is obtained by dividing the fiber volume (obtained from the measured fiber mass and known fiber density) by the mold cavity volume. The fiber volume fraction is $(66.5 \pm 6.1)\%$ and $(61.5 \pm 5.7)\%$ for Specimens A1 and A2, respectively, and is $(26.49 \pm 0.16)\%$ and $(25.52 \pm 0.18)\%$ for Specimens B1 and B2, respectively. The relatively low fiber volume fraction for Specimens B1 and B2 compared to Specimens A1 and A2 is due to the fact that the P-100 fibers are macroscopically straighter than the P-25 fibers, as shown by visual inspection.

The capacitance between the two 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 voltage is adjusted so that the electric field is the same for different distances between the electrodes. The electric field is obtained by dividing the applied AC voltage amplitude by the distance between the electrodes. It is kept constant for the different pairs of electrodes for the same specimen, as enabled by adjusting the voltage, and is essentially the same for all the specimens. The electric field is 16.06 ± 0.04 and 15.93 ± 0.04 V/m for Specimens A1 and A2, respectively, and is 15.85 ± 0.04 V/m and 15.95 ± 0.04 V/m for Specimens B1 and B2, respectively. The capacitance is that for the LCR meter setting for the equivalent electrical circuit of a capacitance and a resistance in parallel.

The relative permittivity κ_f of the fibers is calculated from the measured value κ of the specimen in the mold by using the Rule of Mixtures with the fibers and air in parallel along the axis of the fibers. The parallel model (as opposed to the series model) is consistent with the physical configuration in which the fibers are electrically in parallel. In other words, κ_f is obtained by using the equation

$$\kappa = v_f \kappa_f + (1 - v_f) \kappa_a, \tag{4}$$

where κ_a is the relative permittivity of air (equal to 1.000) and v_f is the fiber volume fraction.

The relative permittivity of carbon materials decreases monotonically with increasing frequency, but it does not vary greatly with the frequency. For example, the relative permittivity of natural graphite is 53 at 50 Hz and 44 at 1 kHz [16]; the relative permittivity of reduced graphite oxide is 1130 at 50 Hz and 200 at 2 MHz [12]; the relative permittivity of graphite oxide is 915 at 50 Hz and 91 at 2 MHz [13]. The permittivity reported in this paper is for a single frequency (2 kHz), which represents the low-frequency regime (i.e., frequencies below those of the radio wave, microwave and optical regimes). The low-frequency regime, which includes commonly used frequencies, such as 60 Hz (the U.S. utility frequency), is relevant to the vast majority of the electrical applications and all electrochemical applications.

The method of this work is not impedance spectroscopy, which involves measurement over a wide range of frequencies and analyzing the frequency dependence (e.g., in the form of a Nyquist plot) by fitting it with the calculated frequency dependence for assumed equivalent circuit models. Due to the fact that the equivalent circuit model obtained from the fitting is not unique, the circuit parameters expressed by the circuit model are not very meaningful scientifically.

4. Results and discussion

Fig. 3 shows the plot of $1/C_m$ vs. length l for the carbon fibers (plus air) in accordance with Eq. (3). The plot is linear for all specimens investigated (A1, A2, B1 and B2). From the slope of the plot, κ is determined to be 3276 ± 195 and 3072 ± 244 for Specimens A1 and A2, respectively, and is 1019 ± 114 and 1029 ± 120 for
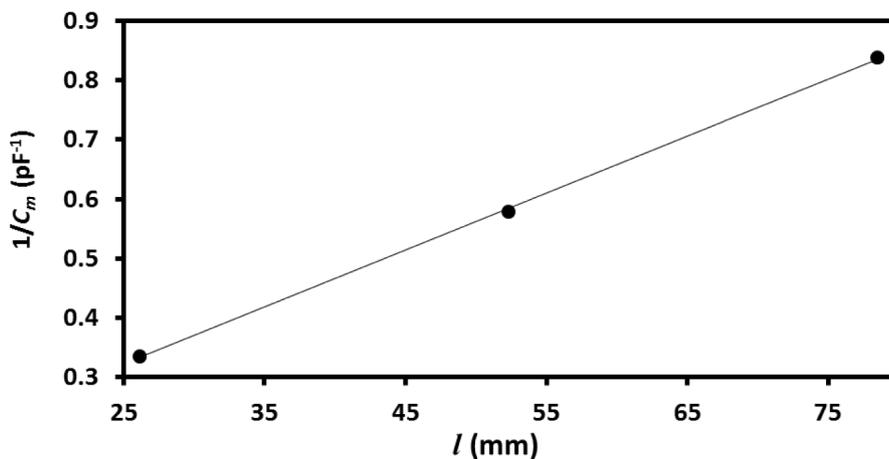
(a)
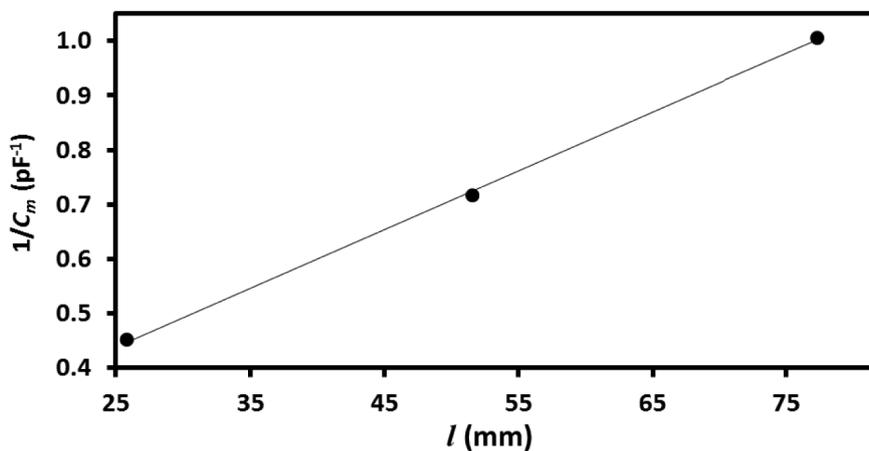
(b)

Fig. 3. Representative plots of $1/C_m$ vs. length l for the carbon fibers (plus air) for permittivity measurement in accordance with Eq. (3). (a) Specimen A1 (P-100 fiber). (b) Specimen B1 (P-25 fiber). (A colour version of this figure can be viewed online.)

Specimens B1 and B2, respectively. The error of the slope is determined by considering the slope values obtained from different pairs of data points in the plot. Using Eq. (4), κ_f is determined, as shown in Table 2.

The error in the κ_f value for each fiber type is substantial, as shown in Table 2. The ranges of the values for the two fiber types overlap to a minor degree. Nevertheless, the average κ_f value is higher for P-100 fiber than P-25 fiber, as expected due to the higher mobility of the electrons in P-100 — a consequence of the lower defect concentration due to the higher degree of graphitization. The ratio of the average permittivity of the P-100 fiber to that of the P-

25 fiber is 1.3. In contrast, the ratio of the conductivity of the P-100 fiber to that of the P-25 fiber is 67. This means that the electron mobility affects the conductivity more than the permittivity. In other words, the defects associated with a low degree of graphitization (such as those associated with a small crystallite size or a low degree of preferred orientation of the carbon layers) affect the conduction more than polarization. This is partly due to the larger distance of charge movement in conduction than polarization.

The relative permittivity values of both P-100 and P-25 are much higher than those previously reported for carbons in discontinuous forms (up to 1130, which is the value for reduced graphite oxide [12]). The high value for reduced graphite oxide is due to the functional groups [12]. In contrast, the high value obtained in this work for continuous carbon fibers is due to the long length and the consequent large distance that the charged species can move during polarization. The positive effect of dimensions on the permittivity is also supported by the higher permittivity in the longitudinal direction than the transverse direction for a continuous carbon fiber polymer-matrix composite [4], and by the increase of the permittivity of carbon black upon compressive

Table 2
Relative permittivity (κ_f) of carbon fibers at 2 kHz.

Fiber type	1st specimen	2nd specimen	Combined value[a]
P-100	4922 ± 535	4998 ± 788	4960 ± 662
P-25	3842 ± 430	4027 ± 471	3961 ± 450

[a] Value based on the results of both 1st and 2nd specimens.

squishing, which causes increase of the dimension [17]. It is also supported by the very high permittivity of monolithic steels [21], as discussed below.

By using a method that is essentially identical to that of this work, the relative permittivity (also at 2 kHz) of low carbon steel and stainless steel (both in the in-plane direction) has been reported by the research group of this paper to be 1.1×10^6 and 2.3×10^6, respectively [21]. These values of steels are much higher than the value of 4960 ± 662 obtained in this work for the P-100 fiber. This is due to the greater abundance and higher mobility of the free electrons in the steels compared to the carbon fibers, as supported by the fact that the chemical bonding in steels is purely metallic, whereas that in carbon fibers is not. In spite of the preferred orientation of the carbon layers along the axis of a carbon fiber, the carbon layers are not all aligned. Thus, the chemical bonding along the axis of a carbon fiber is partly metallic, partly covalent and partly Van der Waals, with the metallic and covalent aspects of the bonding being associated with the in-plane bonding of a carbon layer, and the Van der Waals' aspect of the bonding being associated with the out-of-plane bonding between the carbon layers.

Although the permittivity values are higher for steels than carbon fibers, the values are high for both types of material. The high values for both steels in the in-plane direction and those for carbon fibers in the axial direction are due to the availability of charge carriers (electrons in the case of steels and electrons and holes in the case of carbon fibers), the long length and continuity of the specimen in the direction of capacitance measurement, and the consequent large distance that the charge carriers can move during polarization. The importance of long length for a high value of the permittivity is supported by the fact that the permittivity of steel foils is much lower in the through-thickness direction than the in-plane direction, with the through-thickness value being 28 and the corresponding in-plane value being 2×10^6 [23].

5. Conclusion

The electric permittivity is a fundamental material property that is important to the numerous electrical and electrochemical applications. This work provides the first determination of the permittivity of continuous carbon fibers. The measurement is conducted by capacitance measurement at 2 kHz using an LCR meter, with the presence of a dielectric film between the specimen and each copper electrode (the dielectric film being necessitated by the fact that an LCR meter is not designed to measure the capacitance of an electrical conductor), and with decoupling of the contributions of the specimen volume and the specimen-electrode interface to the measured capacitance. The decoupling is enabled by capacitance measurement at three different length segments of each specimen.

Each specimen is in the form of multiple fiber tows that are packed along the direction of capacitance measurement in an alumina mold cavity. No matrix material is used with the fibers. The fiber permittivity is calculated from the measured specimen permittivity by using the Rule of Mixtures for dielectric components in parallel.

The relative permittivity in the axial direction is 4960 ± 662 and 3960 ± 450 for the P-100 (more graphitic) and P-25 fibers (less graphitic), respectively. These ranges overlap to a minor degree, but the average value is higher for the P-100 fiber than the P-25 fiber.

The ratio of the average permittivity of the P-100 fiber to that of the P-25 fiber is 1.3, compared to the corresponding conductivity ratio of 67. This means that the defects associated with a low degree of graphitization affect the conduction more than polarization.

Based on the Rule of Mixtures, the relative permittivity of the

PAN-based carbon fiber in a carbon fiber polymer-matrix composite is 4352 ± 510 for the longitudinal (axial) direction [4]. The relative permittivity values obtained in this work for the axial direction of the pitch-based P-100 and P-25 fibers (not in the form of a composite) are in line with this value based on a composite.

The relative permittivity values mentioned above for the P-100 and P-25 fibers are high compared to previously reported values of discontinuous carbon materials, such as reduced graphite oxide, the relative permittivity of which is 1130. However, they are low compared to previously reported values of steels, which are more conductive than carbon fibers. The high values of the continuous carbon fibers compared to discontinuous carbons are attributed to the continuity of the fibers and the consequent relatively large distance that the electrons can move during polarization.

References

[1] D.D.L. Chung, Carbon Materials, World Scientific, 2019 (Chapter 6).
[2] D.D.L. Chung, Processing-structure-property relationships of continuous carbon fiber polymer-matrix composites, Mater. Sci. Eng. R 113 (2017) 1–29.
[3] D.D.L. Chung, Carbon materials for structural self-sensing, electromagnetic shielding and thermal interfacing, Carbon 50 (2012) 3342–3353.
[4] A.A. Eddib, D.D.L. Chung, First report of capacitance-based self-sensing and in-plane electric permittivity of carbon fiber polymer-matrix composite, Carbon 140 (2018) 413–427.
[5] S. Pan, Z. Wang, M. Chen, Y. Liu, R. Fan, Enhanced permittivity in flexible carbon-fiber and acrylic-polyurethane composites, Mater. Lett. 205 (2017) 44–47.
[6] R. Theravalappil, P. Svoboda, J. Vilcakova, S. Poongavalappil, P. Slobodian, D. Svobodova, A comparative study on the electrical, thermal and mechanical properties of ethylene-octene copolymer based composites with carbon fillers, Mater. Des. 60 (2014) 458–467.
[7] S. Sarkar, A. Mondal, K. Dey, R. Ray, Defect driven tailoring of colossal dielectricity of reduced graphene oxide, Mater. Res. Bull. 74 (2016) 465–471.
[8] X. Wang, C. Wang, Z. Wang, Y. Wang, R. Lu, J. Qin, Colossal permittivity of carbon nanotubes grafted carbon fiber reinforced epoxy composites, Mater. Lett. 211 (2018) 273–276.
[9] R. Zoughi, B. Zonnefeld, Permittivity characteristics of Kevlar, carbon composites, E-glass, and rubber (33% carbon) at X-band (8-12 GHz), in: D.O. Thompson, D.E. Chimenti (Eds.), Review of Progress in Quantitative Nondestructive Evaluation, l0B, Plenum Press, New York, 1991, pp. 1431–1436.
[10] J. Fu, D. Zhu, W. Zhou, F. Luo, Anisotropic dielectric properties of short carbon fiber composites, Wuji Cailiao Xuebao 27 (11) (2012) 1223–1227.
[11] W. Hong, P. Xiao, H. Luo, Z. Li, Microwave axial dielectric properties of carbon fiber, Sci. Rep. 5 (2015) 14927.
[12] X. Hong, W. Yu, D.D.L. Chung, Electric permittivity of reduced graphite oxide, Carbon 111 (2017) 182–190.
[13] X. Hong, W. Yu, A. Wang, D.D.L. Chung, Graphite oxide paper as a polarizable electrical conductor in the through-thickness direction, Carbon 109 (2016) 874–882.
[14] X. Hong, W. Yu, D.D.L. Chung, Significant effect of sorbed water on the electrical and dielectric behavior of graphite oxide, Carbon 119 (2017) 403–418.
[15] X. Hong, D.D.L. Chung, Exfoliated graphite with relative dielectric constant reaching 360, obtained by exfoliation of acid-intercalated graphite flakes without subsequent removal of the residual acidity, Carbon 91 (2015) 1–10.
[16] A. Wang, D.D.L. Chung, Dielectric and electrical conduction behavior of carbon paste electrochemical electrodes, with decoupling of carbon, electrolyte and interface contributions, Carbon 72 (2014) 135–151.
[17] M. Moalleminejad, D.D.L. Chung, Dielectric constant and electrical conductivity of carbon black as an electrically conductive additive in a manganese-dioxide electrochemical electrode, and their dependence on electrolyte permeation, Carbon 91 (2015) 76–87.
[18] http://www.matweb.com/search/datasheet.aspx?matguid=dd21d18e267044a79df3e8d09de9a420&ckck=1 (as viewed on May 5, 2018).
[19] M. Ramirez, D.D.L. Chung, Electromechanical, self-sensing and viscoelastic behavior of carbon fiber tows, Carbon 110 (2016) 8–16.
[20] https://cytec.com/sites/default/files/datasheets/THORNEL_P25_052112.pdf (as viewed on July 6, 2018).
[21] D.D.L. Chung, K. Shi, Sensing the stress in steel by capacitance measurement, Sensor. Actuator. A 274 (2018) 244–251.
[22] S. Wen, D.D.L. Chung, Effect of stress on the dielectric constant of alumina, J. Electron. Packag. 127 (2005) 235–236.
[23] K. Shi, D.D.L. Chung, Unprecedented capacitance-based nondestructive evaluation of steels, J. Mater. Eng. Perf. (2018) in press.
[24] Ferguson JB, Anderson DP, Strong KL. Thermoelectric properties of carbon fibers. Thermal Conductivity 30, Thermal Expansion 18, Joint Conferences, August 29 - September 2, 2009, Pittsburgh, Pennsylvania, USA, pp. 768-773.