CARBON 2019
LEXINGTON, KY

DISCOVERY OF CARBONS AS ELECTRETS, PIEZOELECTRETS AND ELECTRET-BASED ELECTRIC POWER SOURCES

Xiang Xi[1], D.D.L. Chung[1*]

[1]*Department of Mechanical and Aerospace Engineering, Composite Materials Research Laboratory, University at Buffalo, The State University of New York, Buffalo, NY 14260-4400, U.S.A.*

*Presenting author's e-mail: ddlchung@buffalo.edu

Introduction

In spite of the large variety of existing power sources, energy remains a significant issue all over the world. Examples of issues include the greenhouse gas emission, oil spills, oil/gas leakage, environmental pollution, fire hazard, nuclear reactor safety inadequacy and high cost.

A common method of achieving structural self-powering and structural self-sensing involves the embedment of relevant devices or device components in the structure. However, the embedment results in the loss in mechanical performance, which is critically important to structures.

For obtaining a self-sensing structural material, a structural material can be rendered piezoresistive or piezoelectric by the incorporation of functional fillers. However, the absence of the functional fillers in conventional structural materials causes this approach to be applicable to new structures (not existing structures). Moreover, the functional filler incorporation increases the material cost.

This paper provides a new class of electric power source that are fundamentally different from any of the existing power sources. In addition, it provides a new class of structural sensor. Both are electrically conductive electrets in the form of monolithic electronic conductors. Electrets are permanent electric dipoles. Because the conductive electrets include structural carbons (such as carbon fibers), they enable a new form of structural self-sensing and a new form of structural self-powering. As the behavior stems from the mobile charge carriers in the carbon materials, comparison is made with metals, which have free electrons.

The electret differs from all prior electrets (polymers and ceramics [4-9]) in its electrical conductivity, which enables the electret to function as a DC power source. All prior electrets are nonconductive and behave as capacitors, as for piezoelectric devices, thus requiring the stimulus to be sensed and to be converted to electricity to be time-varying. As a result, a nonconductive electret cannot function as a DC power source. In contrast, a conductive electret functions as a resistor and does not require a time-varying stimulus, so it can function as a DC power source.

The effect of stress on the electret enables stress sensing that is based on measurement of either the electric field or the capacitance. This means that the carbon material senses itself in the absence of any attached or embedded sensor. This is in contrast to piezoresistivity, which enables sensing that is based on the measurement of the electrical resistance.

Materials and Methods

The carbons include PAN-based carbon fiber, nickel-coated PAN-based carbon fiber, continuous carbon fiber polymer-matrix composite (in-plane), carbon-carbon composite (in-plane), isotropic graphite and exfoliated-graphite-based flexible graphite (in-plane). The metals used in the comparative study include steels, aluminium and copper.

The dielectric behavior is studied at 2 kHz. The electret, piezoelectret and piezoresistive behavior is studied under DC condition. No poling is involved. All testing is performed in-plane in the elastic regime.

Results and Discussion

The conductive electrets (carbons and metals) can be enhanced by microstructural and composition modification. For example, the nickel coating of carbon fiber enhances the power density of the carbon fiber electret due to the resistivity decrease. For both carbons and metals, the electric field in the electret increases linearly with increasing inter-electrode distance l, which affects the amount of carriers that participate. The linearity has been shown up to l = 1280 m in case of copper. Discharge occurs upon short-circuiting; charge occurs upon open-circuiting. The electric field (voltage) and permittivity (capacitance) of a conductive electret are affected by stress, strain or damage, thus enabling the electret to sense itself. For example, the electric field and permittivity are both increased reversibly by tensile stress in the elastic regime for both PAN-based carbon fiber and isotropic graphite. For isotropic graphite, at the stress amplitude of 6.78 MPa, the fractional changes in electric field and permittivity are 52% and 10%, respectively. A reversible stress-induced microstructural change is probably involved.

The electrets are supported by electric field measurement and the observed polarization-induced increase in the apparent resistance[1-3]. The apparent resistance increase correlates positively with the relative permittivity κ. This increase is undesirable for conduction-related applications. The electrets are also supported by the directional asymmetry in the polarization-induced increase in the apparent resistance upon polarity reversal. The electric field increases monotonically with the permittivity, resistivity and asymmetry degree. The piezoelectrets are supported by the change of the electric field and capacitance with the applied tensile stress.

The polarization is due to charge carrier movement, with the fraction of carriers that participate decreasing with increasing inter-electrode distance. It is also supported by the measurement of κ, which is high (10^3-10^6) for all the carbons and changes with the stress. High permittivity and resistivity correlate among the metals, but not for the carbons, due to the large differences in structure among the carbons. The electric field, capacitance, permittivity and resistivity all change reversibly with the stress in the elastic regime, thus allowing stress/strain self-sensing. The reversibility applies to all the carbons except flexible graphite, which has slight irreversibility in the κ increase when the stress exceeds 2.1 MPa, due to a microstructural change that does not affect the strain or resistivity reversibility, but increases κ.

For 37%-cold-worked copper, E reaches 2.81×10^{-3} V/m and the power density reaches 530 W/m^3 for l = 1200 m, with short-circuit discharge taking 300 s and open-circuit charge taking 400 s.

Cold work (rolling) greatly strengthens the electret, as shown by a large increase in the electric field. The positive end of the electret voltage is where the rolling-induced plastic flow originates. These observations show the interaction of the carriers with the atoms, particularly the microstructure.

Among the carbons, carbon fiber polymer-matrix composite gives the highest power density (55 W/m^3). The nickel coating of carbon fiber increases with power density from 1.14 to 31.6 W/m^3.

Conclusions

Electronically conductive electrets are found to constitute a new class of electric power source (direct current), as demonstrated for metals and carbons, all without poling. In addition, they serve as piezoelectrets, thereby allowing them to serve as sensors of their own stress/strain and damage. Due to the fact that these electrets include dominant structural materials (carbon fiber composites, steel, etc.), they enable structural self-powering and structural self-sensing.

References

1. Chung D.D.L. (2010). Functional Materials, World Sci. Pub., 2010, Ch. 3.
2. Wen S, Chung D.D.L. (2001). Electric polarization in carbon fiber reinforced cement. Cem. Concr. Res. 31(2), 141-14.
3. Cao J., Chung D.D.L. (2004). Electric polarization and depolarization in cement-based materials, studied by apparent electrical resistance measurement. Cem. Concr. Res. 34(3), 481-485
4. Erhard D.P., Lovera D., von Salis-Soglio C., Giesa R., Altstaedt V., Schmidt H. (2010). Recent advances in the improvement of polymer electret films. Adv. Polymer Sci. 228(Complex Macromolecular Systems II), 155-207
5. Pillai P.K.C. (1995). Polymeric electrets. Plastics Engineering (New York, NY, United States) 28, 1-61
6. Sessler. G.M. (2001). Electrets: recent developments. J Electrostatics 51-52, 137-145
7. Kressmann R., Sessler G.M., Guenther P. (1996). Space-charge electrets. IEEE Trans. Dielectrics Electrical Insulation 3(5), 607-623
8. Liu Y., Aoyagi Y., Chung D.D.L. (2008). Development of epoxy-based electrets. J. Mater. Sci. 43(5), 1650-1663
9. Huang C., Chung D.D.L. (2009). Controlling and increasing the inherent voltage in cement paste. Adv. Cem. Res. 21(1), 31-37