Sensors and Actuators A 160 (2010) 87–93

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Modeling of piezoresistivity of carbon black filled cement-based composites under multi-axial strain

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ARTICLE INFO

Article history:
Received 7 October 2009
Received in revised form 30 April 2010
Accepted 30 April 2010
Available online 10 May 2010

Keywords:
Smart materials
Electrical properties
Modeling

ABSTRACT

A tunnel effect theory-based piezoresistivity model is proposed to predict the strain-sensing property of carbon black filled cement-based composite (CBCC[1]) whose CB concentration is near percolation threshold and the conductive mechanism is dominated by tunnel effect. The conductive network in CBCC is assumed to be composed of randomly distributed tunnel resistors which are formed by each adjacent CB particles. According to tunnel effect theory, tunnel resistance is an exponential function of tunnel width (distance between two adjacent CB particles). The width change of an individual tunnel resistor under external strain is first quantified to obtain the consequent resistance change. Then, the conductive network is modeled based on SEM imaging, enabling us to combine the change of individual tunnel resistances to obtain the macro-resistance behavior of a CBCC specimen. Comparative analysis on experimental and theoretical results indicates that the proposed model is able to predict the resistance behavior and strain gauge factors of CBCC under various loading and environmental conditions.

1. Introduction

Sensors are a fundamental component in structural health monitoring systems and allow us to monitor structural damage caused by fatigue load, environmental corrosion or natural disasters. Recently, CBCC were found to have a strain self-sensing ability that could lead to the material being utilized as a strain sensor candidate material for long-term health monitoring of infrastructures [1–5]. As a new generation of cement-based strain-sensing materials developed from carbon fiber reinforced concrete (CFRC) [6–10], CBCC is more suitable for infrastructural health monitoring because of its compatibilities with concrete structures compared with other polymer-based composites [11–13]. To be used as a strain sensor, the piezoresistivity of CBCC should be firstly calibrated to obtain the strain gauge factor. However, the loading and environmental conditions of civil structures are usually too complicated to be thoroughly simulated in lab, making the applicability of the calibrated strain gauge factor questionable given the many modes of real application. Therefore, a piezoresistivity model that can help us understand and predict the resistance behavior and strain gauge factors of CBCC under complex loading and environmental conditions is required to improve the application of CBCC-based strain sensors in structural health monitoring.

The origins of piezoresistivity differ for composites filled with different fillers. For carbon fiber reinforced composites, piezoresistivity is considered to originate from the slight pull-out of crack-bridging fibers during crack opening and the consequent increase in the contact electrical resistivity of the fiber–matrix interface [14], or the conduction network degeneration resulting from fiber reorientation under finite strain [15]. However, fiber pull-out and reorientation do not exist in CBCC. The existing models for carbon fiber reinforced composite are inapplicable for CBCC. For carbon black filled composites, piezoresistivity models were generally proposed based on percolation theory [16,17] or tunnel effect theory [18]. The percolation theory-based models were established by converting strain resulted deformation into changes of CB concentration [16] or by considering each two adjacent CB particles as a resistor and converting resulting strain deformation into changes of resistor concentration, then obtaining the relationship between resistance and strain based on percolation theory [17]. However, resistance behavior under complex strain cannot be predicted with such models because of the assumptions that loading is due to hydrostatic pressure or that composite volume is unchanging. For CBCC, when CB concentration is near percolation threshold (i.e. 8.79% and 11.39% by volume of composite), the dominated conductive mechanism and the origin of piezoresistivity are attributed to tunnel effect theory [1], which consider the electrical tunnel effect (tunnel resistance) between two adjacent

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[1] CBCC – Carbon black filled cement-based composites whose conductive mechanism are dominated by tunnel effect.

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doi:10.1016/j.sna.2010.04.027

conductive particles separated by thin insulating film is an exponent function of the thickness of the insulating film [19]. Hence, the tunnel effect theory-based piezoresistivity model is appropriate for CBCC. However, an existing tunnel effect theory-based model [18] can only quantify the effect of uniaxial strain on resistance because the conductive network was oversimplified to be formed by well aligned tunnel resistors. This paper is intent to establish a tunnel effect theory-based piezoresistivity model that can predict the resistance behavior and strain gauge factors of CBCC under complex loading conditions, and by transforming the environmental conditions change into multi-axial strain, the proposed model can predict the strain gauge factors under various environmental conditions.

Since the proposed model in this paper is based on tunnel effect theory, it is only fit for the conductive composites whose conductive mechanism is dominated by tunnel effect.

2. Model derivation

2.1. Origin of piezoresistivity of CBCC

Electrical conductivity of CBCC is dominated by the tunnel effect [1]. According to tunnel effect theory [19], current density in a tunnel resistor formed by two adjacent CB particles at a low voltage region can be depicted by the following equation:

$$J = \left[\frac{3(2m\varphi)^{1/2}}{2S_0}\right]\left(\frac{e}{h}\right)^2 U \exp\left[-\left(\frac{4\pi S_0}{h}\right)(2m\varphi)^{1/2}\right], \qquad (1)$$

where J is current density, m, e and h are the electron mass, charge on an electron and Planck's constant, respectively, φ, S_0 and U are the height of tunnel potential barrier, tunnel width (i.e. distance between conductive fillers) and voltage applied across tunnel resistor, respectively. R_{t0} denotes the tunnel resistor and A denotes the section area of the resistor, respectively. Then the resistance of the resistor can be obtained as

$$R_{t0} = k_1 S_0 \exp(k_2 S_0), \qquad (2)$$

where $k_1 = (2/3)(2m\varphi)^{-1/2}(e/h)^{-2}A^{-1}$ and $k_2 = (4\pi/h)(2m\varphi)^{1/2}$.

For a given composite, k_1 and k_2 are constants. S_0 can be obtained as follows [20]:

$$S_0 = D\left[\left(\frac{\pi}{6}\right)^{1/3} V_c{}^{-1/3} - 1\right], \qquad (3)$$

where V_c and D are the volume concentration and diameter of CB particle, respectively. Eq. (2) indicates that even a slight change of S_0 may cause a large change of resistance. Conductive networks in CBCC are composed of a large number of R_{t0} and the change in resistance of CBCC is the integrated result of the change of each R_{t0}. Therefore, the piezoresistivity model of CBCC will be established based on the resistance behavior of each R_{t0}. The resistance of each R_{t0} under strain can be quantified with Eq. (2); hence, the key task of the modeling is to obtain the deformation of each R_{t0} under external strain.

2.2. Characteristics of conductive network in composites

Cement-based composite filled with CB particles (average size of 120 nm) in the amount of 15% by weight of cement (i.e. 8.79% by volume of composite, near percolation threshold) has good electromechanical property [1] and is employed in this study. Therefore, it was prepared with the same materials and procedure as shown in [1], and the microstructure was observed with SEM to study the characteristics of the conductive network of CBCC. Fig. 1(a) shows the microstructure of CBCC, in which the bright spherical objects and rounded hollowness denotes CB particles. To see the pattern of conductive network clearly, CB particles are emphasized in a white background, as shown in Fig. 1(b). The conductive path is formed by adjacent CB particles and is presented in Fig. 1(b) by joining the CB particles. Based on the schematic characteristics of a conductive network, a conductive model is proposed, as shown in Fig. 1(c). First, R_{t0} is connected in series to form a resistor element R_0. Then, R_0 forms the conductive network by connections in parallel and then series. It can be easily derived that the fractional change of resistance of CBCC is equal to that of R_0. Therefore, piezoresistivity modeling of CBCC is focused on the behavior of R_0 under external loading.

The resistance value of each R_{t0} can be calculated based on Eqs. (2) and (3). The orientation direction of each R_{t0} is assumed to be uniformly distributed by considering the infinite and randomly distributed CB particles in CBCC. Fig. 2(a) and (b) shows the schematics of orientation and distribution of tunnel resistor, respectively. Assume that there are a total $4 \times 3(M+1)^2$ of R_{t0} in the space and each $4(M+1)^2$ of R_{t0} surround a coordinator. For example, $4(M+1)^2$ of R_{t0} is first defined by θ_z and φ_z, as shown in Fig. 2(a). Both θ_z and φ_z should be over the range of [0,2π]; however, considering the symmetrical characteristic of R_{t0} in each quadrant, $\theta_z, \varphi_z \in [0, \pi/2]$ is sufficient to represent the orientation character of R_{t0} and is adopted in this paper. Therefore, θ_z and φ_z are in

$$\theta_z, \varphi_z = \left[0, \frac{\pi}{2M}, \frac{\pi}{M}, \frac{3\pi}{2M}, \cdots, \frac{\pi}{2(M-1)}, \frac{\pi}{2}\right], \qquad (4)$$

where θ_x, φ_x, and θ_y, φ_y are defined in the same way as that of θ_z, φ_z. Hence, the resistance behavior of CBCC can be described by the $3(M+1)^2$ of R_{t0}. As shown in Fig. 2(b), the distribution of CB particles defined by above method is not uniform in space that the distribution density is higher near each coordinate, but it is uniform in calculating the effect of multi-axial strain on resistance.

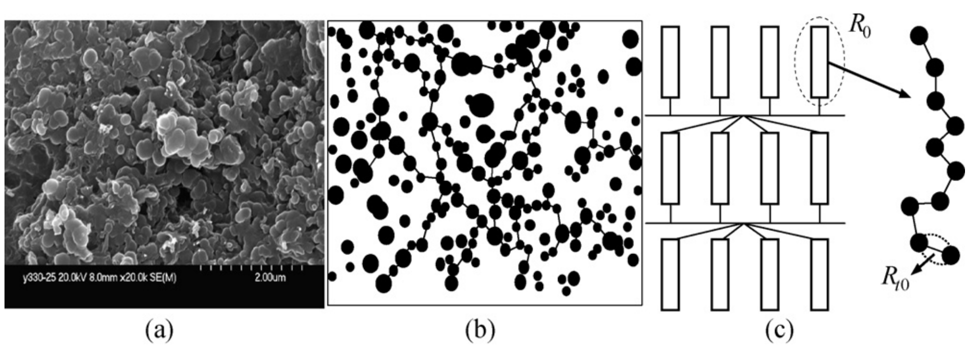

Fig. 1. Schematic of conductive network in CBCC. (a) SEM picture, (b) schematic picture, and (c) conductive network model.