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Electrical conductivity investigation of a nonwoven fabric composed of carbon fibers and polypropylene/polyethylene core/sheath bicomponent fibers

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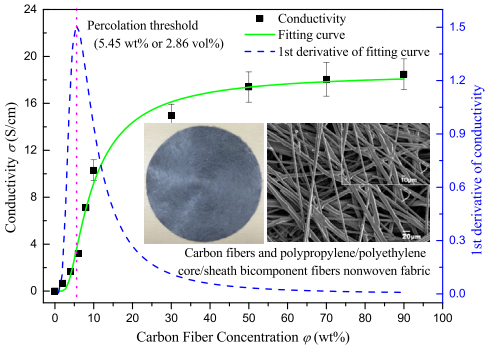
HIGHLIGHTS

- Nonwoven fabrics composed of carbon fibers and polypropylene/polyethylene core/sheath bicomponent fibers were fabricated.
- Heat pressing process is a key step in determining the electrical conductivity of the novel nonwoven fabrics.
- The electrical conductivity of the novel nonwoven fabric increases as the carbon fiber length increases.
- The electrical conductivity in the novel nonwoven fabrics can be modeled by the percolation theory.

GRAPHICAL ABSTRACT



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ABSTRACT

Carbon fiber (CF) nonwoven fabric, due to its mechanical robustness, compact structure and remarkable electrical properties, can be used as an electrode for energy storage devices and as a functional layer for electromagnetic interference (EMI) shielding equipment. To enhance the flexibility of CF nonwoven fabrics, a polypropylene/polyethylene (PP/PE) core/sheath bicomponent fiber (commercially known as PP/PE side by side fiber, simplified as ESF) was incorporated into the fabric to form a CF-ESFs composite. Using a two-step wet papermaking/thermal bonding process, we synthesized a highly flexible, and highly conductive nonwoven fabric, called CF-ESF nonwoven fabric (CEF-NF). Pure CF nonwoven fabrics and CEF-NFs were fully characterized via scanning electron microscopy, to understand and validate the improvement in tensile strength due to the incorporation of ESFs. The electrical conductivity of the CEF-NF was measured to elucidate the effect of heat pressing and to investigate its importance in enhancing the electrical conductivity of a CEF-NF. Lastly, we found the electrical conductivity of CEF-NFs increased with increasing fiber lengths and higher CF volume density. A theoretical model was established to express the relation between the electrical conductivity and CF concentration. From this model, we located the percolation threshold for the CF concentration of a CEF-NF.

1. Introduction

Porous nonwoven fabrics are a classic functional material characterized by high specific surface area [1], light weight [2] and ease of

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processing [3]. Among such fabrics, carbon fiber (CF) nonwoven fabric (known also as CF paper) is one representative fabric due to its excellent electrical conductivity, exceptional mechanical strength-to-weight ratio, and remarkable chemical resistance. As such, CF nonwoven fabrics have found extensive uses in industries where the aforementioned properties are collectively of critical importance, such as high-performance energy storage devices [4] and electromagnetic interference (EMI) shielding equipment [5,6]. Energy storage devices, including supercapacitors [4], lithium ion batteries [7,8] and fuel cells [9], routinely employ CF nonwoven fabrics as electrodes for redox charge transport, as catalyst support, and electrolytes transfer [10]. For EMI shielding equipment, CF nonwoven fabric is often used as a functional material layer to eliminate reflection and interference of EM waves [11].

When applied to energy storage device or EMI shielding equipment [12], it is essential that a CF nonwoven fabric possesses good electrical conductivity. Yang et al. [10] presented a tailored CF nonwoven fabric for high-capacity pseudocapacitors. They indicated that the internal electrical resistance critically influenced the power density of capacitors. To enhance the performance of CF nonwoven fabric, they suggested an optimal structure composing of numerous long CFs. Wong et al. [13] compared the EMI shielding performance of CF nonwoven fabric made of virgin and recycled CFs. They pointed out that the long length and even distribution of CFs would enhance the performance due to improved electrical conductivity. This conclusion has also been verified by Hong et al. [14] in CF composites to provide EMI shielding property. In summary, CF nonwoven fabrics with good performance for energy storage device or EMI shielding equipment should be composed of relatively long CFs—such as chopped CFs (at millimeters length scale)—that are homogeneously distributed [13], rather than carbon powders [9].

With the advent of portable and wearable electronics, polymeric binding materials have been incorporated into CF nonwoven fabrics with the aim of increasing its bendability and flexibility [15–18]. Nevertheless, polymeric binders could easily and irreversibly coat and clog the pores in a CF nonwoven fabric, restricting the diffusion of electrolyte ions, thereby compromising the performance when used in energy storage [2,19]. To overcome these disadvantages, a unique polypropylene/polyethylene (PP/PE) core/sheath bicomponent fiber [20–21], known by its trade name as PP/PE side by side fiber (ESF), could be an ideal additive to significantly enhance the flexibility and bendability of a CF nonwoven fabric without compromising its porosity and large active surface area.

A unique aspect of an ESF is the lower melting point of its sheath PE as compared to the core PP, allowing thermal bonding of ESFs and CFs to be readily and economically accomplished at the melting point of PE to form a point-bonded fabric. Wang et al. [21] carried out experiments to analyze the tensile properties of ESF nonwoven fabrics, they discovered that the bond points in these fabrics can undergo large deformations during uniaxial tensile loading before fracturing, demonstrating excellent ductility and stretchability. Ban et al. [17] numerically and analytically analyzed the stiffness of nonwoven fabrics composed of different types of fibers. Their findings indicated that the stiffness of nonwoven fabrics can be improved using a mixture of different fibers, allowing the structural integrity of the porous fabrics to be maintained during bending. Furthermore, ESFs have good chemical resistance [22–23]; and their surface can be modified by further post-processes [24]. As ESFs are a commercially available polymer and are already employed in several current applications [25,26], its inclusion in CF nonwoven fabrics for the purpose of promoting flexibility and bendability holds great promise.

Among available techniques to manufacture nonwoven fabrics, Martin et al. [27] claimed that papermaking technique—in which fibers are first dispersed in water to form a pulp, then deposited on a mesh and dried by suction—was a most effective one. In the papermaking process, a porous structure is formed initially by the fiber-to-fiber hydrogen bonds acted by residual water. During the final drying stage, the porous structure is kept because of the friction force among fibers or plus bonding force acted by additional agents. Using papermaking technique, Zhang and Shen [9] successfully fabricated fuel cell electrode with CF nonwoven fabric that exhibit appreciable electrical resistance and tensile strength. The damage resistance of CF nonwoven fabric could be further enhanced by mixing resin with CFs followed by heat pressing to material solidification. Their results showed that the heat pressing temperature was an important parameter in determining the properties of CF nonwoven fabric, i.e., density, specific resistance, electrical conductivity, etc.

In this paper, a structurally compact and flexible, and electrically conductive nonwoven fabric consisted of CFs/ESFs fibers (called CF-ESF nonwoven fabric, simplified as CEF-NF) was fabricated by a two-step process—a wet papermaking process followed by a thermal bonding process. To satisfy the requirements of energy storage devices and EMI shielding equipment, the influences of material structure and processing parameters on the mechanical and electrical properties of a CEF-NF were investigated in detail with tests that included mechanical deformation and a four-point probe technique [28].

2. Experimental procedures

2.1. Materials

The CEF-NF used in this work mainly consists of two different types of fibers—polyacrylonitrile (PAN)-based CFs and ESFs. The PAN-based CFs in continuous state are T700SC (Toray, Japan) with a tow of 12 K standard, comprising 12,000 bundled CF filaments. Some of the important properties of the CFs are listed in Table 1.

6 mm-long ESFs were purchased from Qianhai Fiber Technology Company (Hangzhou, China). ESFs are thermoplastic resin fibers with a PE/PP sheath-core structure, the sheath melting point ranges from 130 to 150 °C, the core melting point ranges from 180 to 200 °C. Important properties of the short ESF fiber are listed in Table 2.

1.2 wt% hydroxyethyl cellulose ($C_2H_6O_2 \cdot X$) aqueous solution, procured from Hengyu Chemical Company (Guangzhou, China), was used as dispersing agent.

2.2. Manufacturing process of CEF-NF

The CEF-NF was fabricated by a wet papermaking method followed by a thermal bonding procedure. The complete manufacturing process consisted of five steps (Fig. 1), which included: (i) CF chopping, (ii) CFs and ESFs mixing and dispersion, (iii) fabrication of wet preformed CEF-NF, (iv) drying of preformed CEF-NF, and (v) heat pressing. The final sample was a circular disc with a diameter of 200 mm.

First, a continuous CF tow was chopped into short pieces by a radial chopping technology as described by Shen et al. [29]. Chopped CFs at lengths of 2, 4, 6, 8, and 10 mm, respectively, were obtained. Second, based on the sample area, areal density and desired CF concentration, CFs and ESFs were weighed with an electronic balance and prepared separately. Next, the as-prepared chopped CFs and short ESFs of a predetermined ratio were dispersed in a circular container full of aqueous hydroxyethyl cellulose solution. A mixer was used to stir the solution at a rate of 700 rpm for 4 min followed by at least 5 min of holding. It is worth noting that the stirring procedure should be carefully controlled to avoid breaking the fibers. To ensure sufficient dispersion of mixed fibers, as much as 10 L of aqueous hydroxyethyl cellulose solution was used. Third, the dispersed solution containing CFs and ESFs was poured through a stainless-steel filter net with #80 mesh to form a circular preformed CEF-NF sample spreading across the net. Since fibers were bonded by hydrogen bonds and friction force in wet state [27], the wet preformed CEF-NF could be separated from the filter and be obtained as a stable porous structure. Fourth, the wet preformed CEF-NF sample was dried in an oven at 80 °C for 30 min. Lastly, the dried sample was heat-pressed using a thermal bonding procedure with a plate