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Decoration of zinc oxide nanoparticles onto carbon fibers as composite filaments for infrared heaters

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ABSTRACT

This study examines the thermal properties of ZnO-coated carbon fiber (CF) filaments for high-performance infrared (IR) heaters. An efficient pulse microwave (PM) method is applied to deposit different morphologies of ZnO crystals at various pH values of Zn^{2+} solutions, i.e., fragments (pH = 9), thin films (pH = 10), bulky islands (pH = 11), and nanoparticles (pH = 12). Under the applied voltage of 25 V, the CF composite filament, prepared by the PM route at pH = 10, offers the highest thermal radiation power and superior heat-storage capability among these IR heaters. Its saturation temperature and heating rate of ZnO-coated CF heater can reach to 184 °C and 28 °C/min, respectively. The enhanced thermal performance can be ascribed to the facts (i) the ZnO crystals create more emissive surface area and (ii) the composite filament illuminate more homogeneous spectral IR rays, showing the synergetic effect.

1. Introduction

Infrared (IR) heaters have been recognized as a promising heating source in thermal treatment and drying operation, such as dehydration of fibrils and paints [1], synthesis of metallic nanoparticles [2], ignition of chemical reaction on microchips [3], sintering of cathode materials for Li-ion batteries [4], inactivation of bacterial spores [5], and so on. Theoretically, IR ray is an electromagnetic radiation with wavelength between visible light and microwave radiation [6]. It is generally known that the IR ray can be divided into three regions: IR-A (0.7–1.4 μm), IR-B (1.4–3 μm), and IR-C (3–1000 μm), based on its wavelength. The wavelength range and thermal radiation efficiency of IR heaters basically depend on the filament of emitting elements. So far, two commonly-used types of IR filaments dominate the practical applications, i.e., ceramic and carbon fiber (CF). The IR heaters equipped with ceramic (e.g., alumina) illuminate the IR ray with a wavelength region of 3–18 μm, whereas the wavelength of IR heaters fabricated with CFs falls into the IR-B region. Therefore, the IR radiation of CF heaters is ideally matched to the spectrum of water absorption. This finding reveals that the IR radiation is capable of penetrating the skin to subcutaneous tissues, transforming the light energy into thermal energy. This heat transfer induces an improvement in blood circulation and a reduction of toxins from the human body by sweat production [6]. Accordingly, the CF heater emits rays that are beneficial for human's health and healing. However, improving the thermal efficiency of CF filaments is still a challenge and rarely discussed in literatures.

Traditionally, commercial IR heaters are fabricated by using CF as filament, which is carefully sealed in a quartz tube after vacuum suction process. The power consumption of IR heaters strongly depends on the heater size and applied voltage. One strategy concerning an improved thermal efficiency is to directly modify the CF filaments. The CF filaments are typically composed of thousands of carbon fibers, having an average diameter of 8–10 μm. The purpose of this work is to deposit metal oxide nanoparticles (i.e., zinc oxide (ZnO)) onto the surface of CFs. It is expected that (i) the ZnO-coated CF filament emit irradiation with a wider wavelength range and (ii) the decoration of ZnO nanostructures facilitates heating surface area, thus, imparting an improved thermal efficiency of IR heaters. In fact, ZnO materials have received considerable attentions in a variety of applications such as photocatalysts, gas sensors, solar cells, transparent conductors, and piezoeletronic materials due to their excellent electronic, mechanical, and optical performance [7–10]. Many efforts have been made to synthesize ZnO structures such as spray pyrolysis [11], electrochemical deposition [12–15], hydrothermal method [16], and template electrosynthesis [17]. More recently, our previous work has proposed a novel perspective to rapidly synthesize ZnO crystals, using a pulse microwave (PM) method [18]. The PM method displays a great potential to deposit ZnO crystals onto different carbon supports (e.g., carbon nanotubes and carbon black) at low

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temperatures (e.g., 80 °C). The PM method only takes a short period of 8–12 min, showing a commercial feasibility.

Within the above scope, this present work adopts the PM method to coat ZnO layers onto the CFs, forming a composite filament. The pH value of Zn^{2+} solution was chosen as a controlling factor in affecting the morphology of ZnO structures. The composite IR filaments were assembled as IR heaters, operated at a fixed applied potential. The heating rate and maximal heating temperature were systematically investigated. This work would shed some lights on how the introduction of ZnO crystals on CF filament enhances the thermal radiation efficiency of IR heaters.

2. Experimental

In the present work, commercial CF, made from polyacrylonitrile (PAN) precursor, served as heating filament for IR heaters. Each CF filament consisted of a bundle of individual fiber, and total number of fiber was approximately 3000. Each CF filament was carefully cut into a length of 20 cm. Before the deposition of ZnO, the CF filaments were impregnated in distilled water and placed in an ultrasonic bath for 0.5 h. Then the wetted CF filaments were dried at 105 °C in a vacuum oven overnight.

Herein an aqueous Zn^{2+} solution was prepared for the ZnO deposition by the PM method, in which an optimal synthesis conditions have been reported previously [18]. The Zn^{2+} solution was composed of 2 M $(CH_3COO)_2Zn{\cdot}2H_2O$ solution and distilled water. The pH value of the solution was adjusted to pH = 9, 10, 11, and 12, respectively, by using 0.5 M KOH. Afterward, the cleaned CF was impregnated into the Zn-containing solution (volume: 50 mL) at ambient temperature for 2 h. Then the CF slurries were placed in the center of household microwave oven (Tatung Co., 900 W, 2.45 GHz). The microwave oven was equipped with a thermocouple and temperature controller. The reaction temperature program started from 25 to 80 °C with a heating rate of 5 °C/min. The PM deposition temperature was maintained at 80 °C for 8 min. The power-on and power-off periods were set at 3 s and 3 s, respectively. After the PM deposition, the treated CF filaments were dehydrated at 105 °C in a vacuum oven overnight.

The microstructural observation of the resulting ZnO deposits onto CF samples was characterized by a field-emission scanning electron microscope (FE-SEM, JEOL JSM-6701F). The crystalline structure of ZnO crystals was examined by X-ray diffraction (XRD) with Cu-Kα radiation, using an automated X-ray diffractometer (Shimadzu Labx XRD-6000). The thermal efficiency of IR heaters was investigated in a quartz tube with an inner diameter of 3 cm and a length of 20 cm. The CF filaments could be fixed in the center of quartz tube by using fixtures. One thermal couple (K-type) was also equipped in the center of quartz tube to detect the real temperature of IR heaters. A galvanostat-potentiastat instrument was adopted to apply stable potential difference between both ends of CF filaments. The potential differences were set at 25 V in the present work. To avoid any oxidation on CFs, a vacuum pump was used to ensure the low-pressure operation of IR heaters, i.e., the operating pressure $<$0.001 torr.

3. Results and discussion

The crystallographic structure of ZnO-coated CFs was inspected using XRD analysis, as shown in Fig. 1. The XRD patterns confirm the presence of well-crystalline ZnO, which is good agreement with wurtzite structure [19,20]. The result reflects that the PM method is capable of growing ZnO wurzite crystals at low temperature of 80 °C. Our preliminary studies also confirm the low-temperature growth of ZnO crystals on graphene sheets [21] and metal oxides [22] under microwave irradiation. This can be attributed to the fact that PM synthesis induces a dipole change in

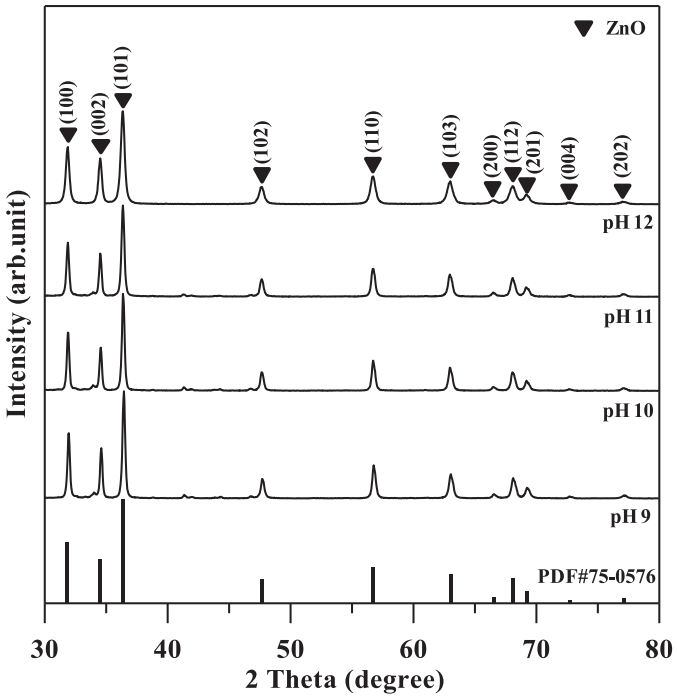

Fig. 1. Typical XRD patterns for ZnO-coated CF filaments prepared by the PM method at different pH values.

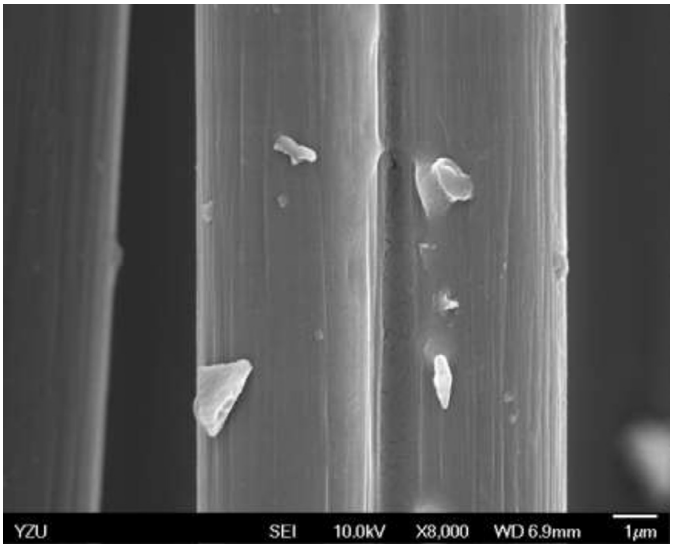

Fig. 2. FE-SEM image of original CFs.

polar molecules (e.g., water and hydration molecules) with uniform temperature distribution, thus leading to highly crystalline ZnO [23].

SEM photo of original CF sample in Fig. 2 reflects that an individual fiber possesses a smooth surface. Each fiber has an average diameter of 8 μm. To inspect the dispersion of ZnO over CF filaments, SEM was also adopted to observe the morphology of ZnO-coated CF samples, as depicted in Fig. 3(a)–(d). The SEM images clearly show the CFs decorated with different topographies of ZnO crystals, indicating the importance of pH value on the formation of ZnO crystals, e.g., fragments (pH = 9), thin films (pH = 10), bulky islands (pH = 11), and nanoparticles (pH = 12). This finding reveals that the pH value plays a vital role in determining the shape formation of ZnO crystals during the PM process. A growth mechanism of ZnO crystals onto CFs under microwave irradiation has