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High performance infrared heaters using carbon fiber filaments decorated with alumina layer by microwave-assisted method

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ABSTRACT

This study adopts an efficient microwave-assisted (MA) route to deposit Al_2O_3 layer onto microscaled carbon fabrics (CFs) as a filament for infrared (IR) heater. The MA deposition is able to coat different densities of alumina on the surface of CFs by adjusting ionic concentration of Al^{3+}. The highly-crystalline Al_2O_3 layers can be formed under microwave irradiation of 720 W. It has shown that both the heating rate and maximal temperature are increasing functions of the surface density of alumina. This improved thermal efficiency originates from the decoration of Al_2O_3 onto the CFs, liberating the IR-light illumination with different wavelengths and increasing the emissive surface area of CF filaments. Under the operating condition at 25 V, the heating rate and the maximal temperature of composite filaments can reach 36.6° C/min and 213° C, respectively. The composite heater displays the highest irradiation power of 49.2 W, approximately 2.6 times higher as compared to the original CF heater. This satisfactory result expresses that a robust design that combines with CF heaters and decoration of alumina deposits exhibits a potential feasibility for commercializing IR illuminators with high thermal irradiation performance.

1. Introduction

Infrared (IR) heating has attracted considerable attentions in a variety of practical applications such as surface coating, drying and curing of paints and coatings, moisture removal, and many practical applications [1]. So far, the IR induction heating is one of the popular methods to supply fast and consistent heat for drying and manufacturing applications. Accordingly, previous studies have adopted the IR heating technique to ignite chemical reaction on microchips [2] and to sinter ternary Li-ion battery materials [3], NiO buffer layer [4], and Ag nanoparticles [5]. It is generally recognized that IR radiation is a reliable heat source that transfers large amounts of energy in a short time. The IR ray could save energy efficiently because it can be switched on and off quickly and easily. Compared with traditional convective heating, the advantages of IR heater consist of (i) fast heat-up times, (ii) ability for programmable heating, (iii) good controllability, and (iv) high energy efficiency [1,6].

IR ray is an electromagnetic radiation with wavelength between visible light and microwave radiation [7]. Basically, two different types of IR heaters, medium-wave and short-wave electric IR heaters, dominate these applications mentioned above [8]. The medium-wave IR heaters have earned lots of sights because they allow the users to match temperatures to the optimal absorption wavelength for each application. Typical medium-wave IR heater is composed of one filament, which is carefully sealed in a quartz tube after vacuum suction process. The IR filaments are made of carbon fabrics (CFs) or ceramic, emitting IR rays with different wavelength regions, *e.g.*, IR-B (1.4–3 μm) and IR-C (3–1000 μm). The IR-B ray is capable of penetrating the human's skin to subcutaneous tissues with a depth of 4–5 cm, approximately 80 times deeper than general heat [7]. The IR radiation of CF heaters is ideally matched to the spectrum of water absorption, improving the blood circulation in human body as a vibration shaking more than 2000 times per minute. It is generally recognized that the spectral distribution of IR heaters strongly depends on the type of filament materials, affecting the thermal radiation efficiency. However, there are few reports focusing on the enhancement of thermal radiation efficiency for medium-wave IR heaters.

Within the above scope, this study aims at the decoration of alumina (Al_2O_3) on CF filaments for improving the irradiation performance of IR heaters. Recently, microwave-assisted (MA) deposition has become an indispensable route to synthesize various nanomaterials [9]. The MA heating shows many advantages over the conventional heating, such as high heating rate, easy control of heating process, and energy saving [10]. The MA heating not only

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shortens chemical reaction period by several orders of magnitude but also avoid side reactions, thereby increasing the yield and reproducibility of a specific synthesis protocol [11]. Indeed, the MA method has been confirmed to successfully deposit precious metals (*e.g.*, Pt [12,13]) and metal oxides (*e.g.*, TiO_2 [14]) on carbon supports. Pioneering study has pointed out that the carbon-based support could serve as a proper microwave absorbent to efficiently convert microwave energy to heat, inducing the following surface reaction [15]. The research achievements direct us at one efficient way to coat alumina onto CF filaments. To inspect the thermal emissive power, the weight loading of Al_2O_3 serves as a controlling factor in determining the performance of IR heaters. Both the thermal radiation powers and heat capacities are systematically examined. This present work would explore the relationship between the surface loading of metal oxide and the thermal efficiency, based on the IR heating equipment.

2. Experimental

The MA deposition concerning the alumina coating onto CFs was similar to our previous studies [16,17]. The CF filaments, made from polyacrylonitrile (PAN) precursor, were composed of approximately 3000 single fibers. First, the bundle of CF filament was carefully cut into a length of 20 cm. Then the CF filaments were chemically oxidized by impregnating them in 1 N nitric acid. The chemical oxidation was carried out at 90° C for 3 h, ensuring the implantation of surface oxide groups (*e.g.*, carboxylic and hydroxyl groups) onto the surface of CFs. Afterward, the treated CF filaments were dehydrated at 85° C in vacuum oven overnight.

Prior to the MA deposition, aqueous Al^{3+} solutions were prepared by dissolving $Al(NO_3)_3 \bullet 9H_2O$ in distilled water. The Al^{3+} solutions with five ionic concentrations (2, 2.5, 3, 3.5, 4.5 mM) were adjusted to the pH value at 10 by using 0.5 M KOH solution. The oxidized CFs was impregnated in the Al-containing solution (volume: 50 mL) at ambient temperature for 2 h. The CF slurries were then put into a household microwave oven (Tatung Co., 900 W, 2.45 GHz). The MA process started from room temperature to 80° C with a heating rate of 5° C/min, followed by isothermally keeping at 80° C for 0.1 h. The microwave oven was equipped with a thermocouple and proportion-integration-differentiation temperature controller, capable of controlling this reaction temperature program. After that, the treated CF filaments were dried at 85°C in a vacuum oven overnight.

The crystalline structure of alumina crystals was studied by using X-ray diffraction (XRD) with Cu-Kα radiation, using an automated X-ray diffractometer (Shimadzu Labx XRD-6000). The microstructure of the resulting alumina deposits onto CF samples were characterized by a field-emission scanning electron microscope (FE-SEM, JEOL JSM-6701F). The thermal conversion performance of Al-coated CF heaters was evaluated in a quartz tube with an inner diameter of 3 cm and a length of 20 cm (see Fig. 1). One thermocouple (*K*-type, Maximum Electronic Co.) was used to detect real temperature of CF filaments heaters. The thermocouple with a diameter of 0.38 mm was unsheathed type, suitable for pin-point measurement. The thermocouple was well positioned by a fitting apparatus, controlled by a Teflon screw nail. The distance between the CF filaments and the thermocouple was 1 cm. For accuracy, the distance between the CF filaments and the thermocouple was adjusted for each experimental run. The applied potential was set at 25 V, controlled by a galvanostat/potentiastat instrument (Kuan Ming Co.). To prevent any oxidation of CF filament from air, a vacuum pump was applied 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 alumina-coated CFs was investigated using XRD analysis, as depicted in Fig. 2. First of all, the fresh and acid-treated CF samples are named as CF and ACF, respectively. The Al_2O_3-coated ACF samples fibers are designated to AACF-1, AACF-2, AACF-3, AACF-4, and AACF-5, according to the order of Al^{3+} solutions (*i.e.*, 2, 2.5, 3, 3.5, 4.5 mM), respectively. The XRD patterns clearly indicate the presence of Al_2O_3 crystals over the CF samples, well identical with α-Al_2O_3 structure [18,19]. This result reflects that the MA method provides a pathway to deposit highly-crystalline alumina onto the surface of CF filaments at low temperature. To inspect the influence of ionic concentration, the weight loading of Al_2O_3 crystals onto the CF filaments as a function of Al^{3+} ionic concentration is figured out, as shown in Fig. 3. A linear relation between the weight loading and the ionic concentration can be observed, indicating that the ionic concentration favors the deposition of Al_2O_3 crystals under microwave irradiation. This finding can be inferred from one possible reason that the Al^{3+} ions and their hydration molecules would occupy functional oxygen groups, created from chemical oxidation treatment. The adsorbed Al^{3+} ions are then nucleated, and the nuclei tend to be grown with the aid of microwave. Meanwhile, the MA method imparts a dipole change in polar molecules (*e.g.*, water and hydration molecules) with uniform temperature distribution [20], facilitating the growth of alumina crystals. Since the number of ions

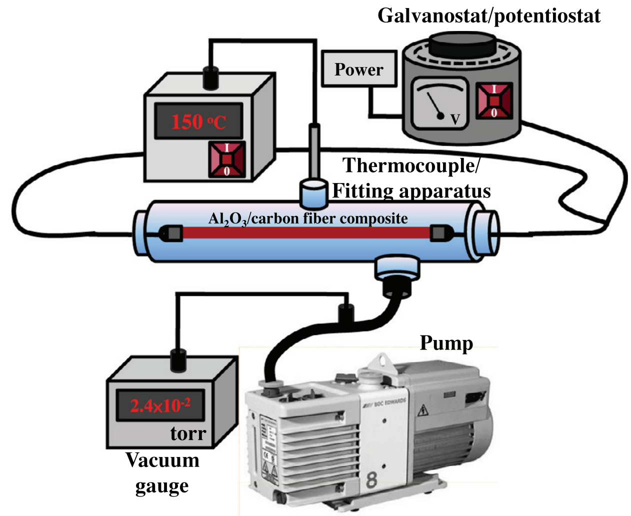

Fig. 1. The schematic diagram for illustrating the assembly of IR heater.

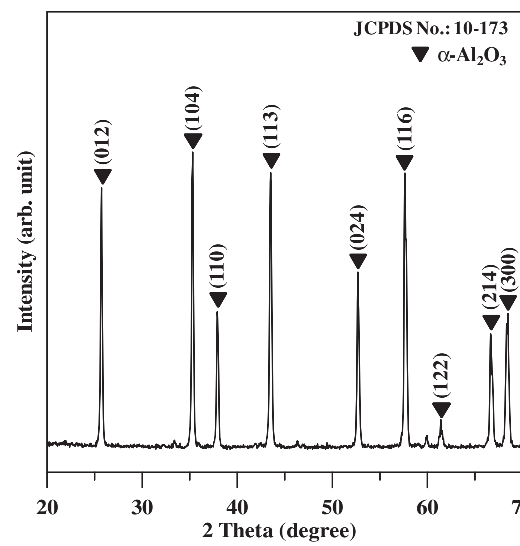

Fig. 2. Typical XRD patterns of Al_2O_3-coated CF filaments with different amounts of alumina coating.