lnterlaminar resistive heating behavior of ZnO nanorods/woven carbon fiber composites

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ABSTRACT

This paper addressed the interlaminar region characterization complying with electrical resistive heating behavior of ZnO/woven carbon fiber laminae reinforced composites. The interlaminar region is composed of ZnO nanostructure arrays embedded on woven carbon fibers interacted with the thermoset vinyl ester resin. The ZnO nanostructure arrays are formed to the nanorods synthesized using hydrothermal process. In order to investigate the electrical resistive heating behavior of the interlaminar region, three different zones have been classified as heating zone, maximum temperature zone, and the cooling zone. The electrical resistive heating temperature was shown effectively at the interlaminar region due to the intrinsic plain weaved carbon fiber multiple junctions as well as the multi-junctions of ZnO nanorods. In room zone, the contact resistance of ZnO/woven carbon fiber laminae reinforced composites was increased as the ZnO molar concentration was became higher from 10mM to 110mM.

Keywords: ZnO, electrical resistive heating behavior

1 INTRODUCTION

Over the past decades, fiber reinforced polymer composites have been widely used in many industrial applications owing to the high specific strength-to-weight and stiffness-to-weight ratios compared to other engineering materials. In particular, polymer composites reinforced by carbon fiber (CF) have still been drawn a high degree of attention from academia as well as a large number of industries due to excellent mechanical properties and light weight. Recently, emerging interest on nanoscale carbon-based fillers such as carbon nanotube (CNT) [1, 2], graphene/graphite nanoplatelets [3, 4], carbon nanofiber (CNF) [5, 6] and carbon black [7, 8] reinforcement of composites is intensely attractive due to their noticeable performance in thermal stability, electrical conductivity as well as enhanced mechanical properties. However, these nanoscale carbon-based fillers are confronted to the uniform dispersion techniques due to the strong intermolecular van der Walls interactions for CNTs and graphene or a lot bundle of branches for CNFs and carbon blacks, thereby, having aggregation in some parts of composites. To overcome these drawbacks, whiskerization of material was introduced as to get desired interfacial reinforcement that determines performance of composites and grows a secondary reinforcement directly on the fiber surface. In particular, ZnO nanostructure as one of the whiskerization materials has been researched ceaselessly up to date due to unique exceptional piezoelectric, optical, electrical, mechanical, dielectric and microwave absorption properties. It is because ZnO nanostructure arrays enhance load transfer from the fiber to the matrix in accompanying with preserving the fiber strength and reduces stress concentrations and increases the surface area for bonding with the polymer matrix.

This research intends to investigate the electrical resistive heating behavior of interlaminar region of composites, fabricated with woven CFs covered with ZnO secondary reinforcement and vinyl ester matrix. With outstanding of fiber junctions, it is estimated that woven carbon fibers have been capable of intrinsic electrical resistive heating element containing with fiber junctions.

2 EXPERIMENTAL PART

The vinyl ester resin and initiator were bisphenol A epoxy based vinyl ester and methyl ethyl ketone peroxide, with respectively. The accelerating agent, dimethyl aniline was used to shorten the curing time and reduce the curing temperature of vinyl ester resin. These are chemicals for as matrix components of composites purchased from Kukdo chemical Co. Ltd., Korea. T-300 woven CFs were used as reinforcement provided from Toray Industries Inc.. Analytical grade zinc acetate dehydrate ($Zn(CH_3COO)_2{\cdot}2H_2O$), NaOH, zinc nitrate hexahydrate ($Zn(NO_3)_2{\cdot}6H_2O$), and hexamethylenetetramine ($C_6H_{12}N_4$, HMTA) were purchased from Sigma Aldrich and used for ZnO NR growth. Ethanol (J.T. Baker, reagent grade) was used as a solvent and also used together with zinc acetate dehydrate chemical to obtain a stable colloidal suspension of seeds for ZnO growth.

2.1 Electrical resistive heating experimental setup

In this research, the electrical resistive heating behavior was characterized by the schematic experimental diagram as shown in Fig. 1. The sample was connected to an electrical power supply, and the temperature distribution on the surface of it was monitored using an infrared camera (H2640, manufactured by Joowon Industrial Co., Ltd, Korea). The temperature of thermocouple and infrared thermographic analysis of temperature were simultaneously compared, and an amount of temperature gap was compensated. The inter-probe resistance of a sample was monitored using a digital multimeter (Model 2002 manufactured by Keithley, U.S.A.). The electrical resistance was measured by two-probe method.

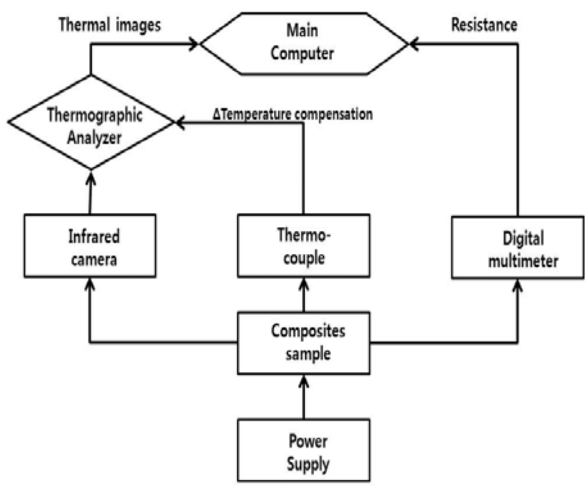

Fig. 1. Schematic experimental diagram and signal flow

In order to investigate the electrical resistive heating behavior, silver wires were integrated on the surface of ZnO NRs embedded on woven CFs prior to VARTM process. The ends of silver wires were connected to the electrical power supply. Temperature distribution in the areas between the two electrodes was monitored because large temperature distribution was observed in the vicinity of the electrodes.

2.2 Characterization

The morphology of ZnO NRs on woven CFs with different ZnO concentrations was obtained by the SEM study. The structural order of the ZnO NRs on woven CFs was examined by using a X-ray diffractometer (Bruker) with crystal monochromated CuK_α radiation (0.154nm). XRD patterns were obtained at the rate of 1^o/min in the angular range of 30 - 60^o (2θ) with a 40 kV operating voltage and 20 mA current. DSC was carried out using a DSC Q200 from TA instruments under nitrogen flow. Initial sample weight was set as 20-21 mg for each operation. The specimen was heated from room temperature to 100^oC at a heating rate of 10^oC/min.

3 RESULTS AND DISCUSSION

The synthesis and growth of ZnO NRs on woven CFs were already mentioned in the experimental section. ZnO growth rate in the axial direction (c-axis direction) was affected by the molar concentration of the zinc nitrate hexhahydrate and HMTA. ZnO NRs were grown at the uniform and well-distributed morphology having higher specific area of the ZnO NRs as the molar concentration of zinc nitrate hexhahydrate and HMTA is increased from 10-110 mM. Thus, Fig. 2 shows that the mass of ZnO NRs was enhanced as increasing the molar concentration of ZnO.

The XRD patterns shows the characteristic crystalline peaks and its intensities of ZnO NRs embedded on woven CFs. ZnO NR was observed as showing the crystalline peaks at $2\theta=31.7^o$, 34.4^o, 36.2^o, 47.5^o and 56.5^o, which matches well to the hexagonal structure as referenced in JCPDS NO. 36-1451 with lattice constants of a = 3.25 Å and c = 5.21 Å. In addition, (002) diffraction peak among the board crystalline peaks were indicated that the ZnO NRs have grown along the c-axis. The intensity of XRD patterns has been unique according to the ZnO molar concentration. It was observed that intensity of the diffraction peaks corresponds higher as the molar concentration of ZnO increased.

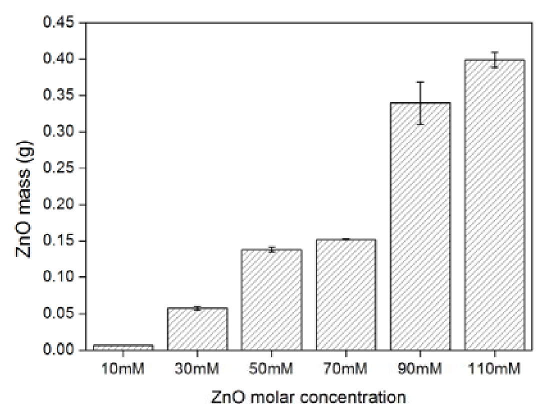

Fig. 2. The mass of ZnO NRs growth on woven CFs at ZnO molar concentrations (10mM-110mM)

In this research, by utilizing a joint contact, two laminae of ZnO/woven CF reinforced composites were bonded with the adhesive insulating material, thermoset vinyl ester. Another attraction of the use of interlaminar region is the ZnO NRs that grown on the surface of woven CFs. The contact resistance of the interlaminar region can be distinguished by controlling the molar concentration of ZnO NRs, in the whole fabricated by the VARTM process. The fiber-fiber contact is increased by embedded ZnO NRs, thus increasing the contact resistance. Moreover, branched ZnO

NRs have a role of reducing the charge carrier in the composite mixture, so the conductivity is decreased. It is well agreement to the experimental results. The contact resistance of ZnO/woven CF-vinyl ester matrix composites was higher as accompanied by ZnO molar concentration and combined with ZnO mass. Thereby, the resistance is proportionally corresponded by the mass of material. Thus, the interlaminar region of composites can be a heating element.

The electrical resistive heating behavior was investigated by observing infrared thermographic analysis of the time-dependent temperature changes in the interlaminar region of composites at different applied current of 1-3A. The examples of infrared images of samples were shown in Fig. 3. As considering the average temperature of selective area, the sample of combination with two laminae of ZnO/woven CF reinforced composites was shown higher heating temperature than of bare woven CF reinforced composites.

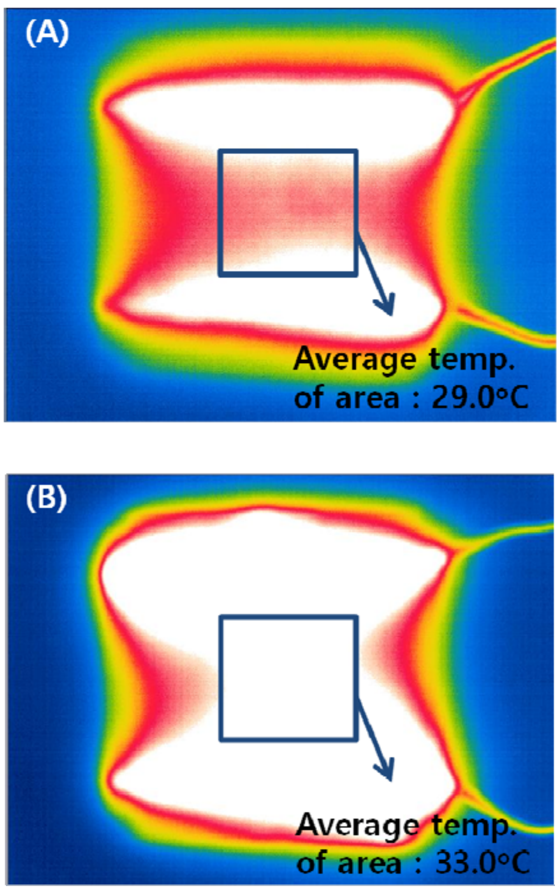

Fig. 3. For example, infrared thermographic analysis of temperature during heating time (20min) at an applied current 2A: (A) bare woven CF laminae reinforced composites , (B) ZnO(30mM)/woven CF laminae reinforced composites.

4 CONCLSUION

The interlaminar region characterization of ZnO/woven CF laminae reinforced composites was shown to be effective electrical resistive heating in this work. By investigating the infrared thermographic analysis of the time-dependent temperature changes, electrical resistive heating temperature was increased for the interlaminar region as ZnO molar concentration became higher. The multi-joint junctions of interlaminar region were obviously functionalized for the tendency of electric heating behavior. The use of the interlaminar region as a heating element is attractive not only because of the effectiveness of the heating, but is also because of the part of a conventional structural composite material. Since carbon fiber polymer matrix composites are lightweight structural materials, it is also allowed for serving as a heating element while maintaining the structural function.

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