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Manufacturing techniques and property evaluations of conductive composite yarns coated with polypropylene and multi-walled carbon nanotubes

Jia-Horng Lin [a,b,c], Zheng-Ian Lin [a], Yi-Jun Pan [d], Chien-Teng Hsieh [e], Mong-Chuan Lee [f], Ching-Wen Lou [g,*]

[a] Laboratory of Fiber Application and Manufacturing, Department of Fiber and Composite Materials, Feng Chia University, Taichung City 40724, Taiwan, ROC
[b] School of Chinese Medicine, China Medical University, Taichung City 40402, Taiwan, ROC
[c] Department of Fashion Design, Asia University, Taichung City 41354, Taiwan, ROC
[d] Department of Materials and Textiles, Oriental Institute of Technology, New Taipei City 22061, Taiwan, ROC
[e] Department of Fashion Design and Merchandising, Shih Chien University Kaohsiung Campus, Kaohsiung City 84550, Taiwan, ROC
[f] Graduate Institute of Biotechnology, Central Taiwan University of Science and Technology, Taichung City 40601, Taiwan, ROC
[g] Institute of Biomedical Engineering and Materials Science, Central Taiwan University of Science and Technology, Taichung City 40601, Taiwan, ROC

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ABSTRACT

This study uses a melt extrusion method, a method for producing wires, to coat polyester (PET) yarns with polypropylene (PP) and multi-walled carbon nanotubes (MWCNTs). The resulting PP/MWCNTs-coated PET conductive yarns are tested for their tensile properties, processability, morphology, melting and crystallization behaviors, electrical conductivity, and applications. The test results indicate that tensile strength of the conductive yarns increases with an increase in the coiling speed that contributes to a more single-direction-orientated MWCNTs arrangement as well as a greater adhesion between PP/MWCNTs and PET yarns. 8 wt% MWCNTs results in an 18 °C higher crystallization temperature (T_c) of PP and an electrical conductivity of 0.8862 S/cm. The test results of this study have proven that this form of processing technology can prepare PP/MWCNTs-coated PET conductive yarns that have satisfactory tensile properties and electrical conductivity, and can be used in functional woven fabrics and knitted fabrics.

1. Introduction

With attributes of high electrical conductivity, flexibility, and electromagnetic interference shielding functions [1–5], electrically conductive yarns can be applied to wearable electronics [6–9]. Electrically conductive yarns are composed of metallic fibers, carbon nanotubes (CNTs), graphene, and conductive polymers [1–14]. CNTs are featured by having satisfactory physical properties, in terms of low density, high mechanical properties, desired thermal stability and conductivity, and electrical conductivity [15–19], and they are thus applied in capacitors, fuel cells, and sensors [20–22]. In addition, CNTs are now capable of industrial mass production, and thus have a low production cost.

Polymer/CNTs fibers can be made by applying the melt spinning method and the electrospinning method [10,11,23–25], and the improvement of the strength and durability of polymer/CNTs fibers has become an increasingly important research topic. One approach to reinforce the properties of fibers is to incorporate the crystallization behavior of polymers. For example, Fang et al. combined the melt spinning method and various draw ratios to form high density polyethylene/CNTs fibers. The test results indicated that a high draw ratio caused the tensile strength of PE/CNT fibers to increase threefold. Such a result was ascribed to the shish kebab (SK) structure that contributed to the enhanced interfacial interaction [11]. Another approach to reinforce the properties of fibers is to coat high performance fibers with conductive materials. For example, Xiang et al. prepared carbon material-coated Kevlar fibers by incorporating a layer-by-layer spray coating. The test results showed that the coated fibers were electrically conductive (65 S/cm) and were also mechanically strong [26]. These properties were further stabilized as a result of the water washing cycles. Another approach is to reinforce the properties of fibers by using wet spinning to scatter the fillers. For examples, Gong et al. fabricated Kevlar/MWCNTs fibers by incorporating the aramid-assisted acid spinning. The fibers had a

* Corresponding author.
E-mail address: cwlou@ctust.edu.tw (C.-W. Lou).

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85 wt% MWCNTs, a tensile load of 360.24 mN, and an electrical conductivity of 154.43 S/cm [12]. The melt spinning method was limited by a certain amount of nano-fillers as nanofibers that have a high specific surface area and light specific gravity, which also sets limits to the processing and functions of the nanofibers [27]. The coating process and the wet spinning method require an organic solvent, which could possibly damage the structure of CNTs. As a result, this study does not functionally modify MWCNTs in order to prevent damage to the environment or the limits to the subsequent processing [12,26,28].

This study applies a melt extrusion method in order to coat the PET yarns in PP/MWCNTs melt. This experimental design does not require any specific core. In comparison to the melt spinning method, the melt extrusion method can provide the yarns with a PP/MWCNTs layer that contain more fillers. As a result, the melt extrusion method avoids the disadvantage of melt spinning that the yarns are subjected to breakage when the loading of fillers is high. In addition, the core can be freely adjusted. For example, glass fibers can be used when a high strength is preferred, while metallic wires can be used when electrical conductivity is preferred. In this study, PET yarns are used as the core in order to provide the conductive yarns with mechanical properties and ease of processing. Finally, the conductive yarns are tested for their tensile properties, processability, morphology, melting and crystallization behaviors, electrical conductivity, and applications in order to examine the influences of various amounts of MWCNTs and different coiling speeds.

2. Experimental

2.1. Materials

Polypropylene (PP) pellets (YUNGSOX 1080, Formosa Plastics Corp., Taiwan, R.O.C.) is a homopolymer that has a melt flow rate of 10 g/10 min (ISO1133). Multi-walled carbon nanotubes (MWCNTs; CF182C, Advanced Nanopower Inc. Taiwan, R.O.C) have a diameter of 10-30 nm and a length of 5–20 μm. Polyester (PET) yarns (Universal Textile Co., Ltd. Taiwan, R.O.C.) have a specification of 500 D/96 F, and is composed of a total of 96 PET filaments. The diameter of each filament is 0.02 mm, as indicated in Fig. 1.

2.2. Preparation of PP/MWCNTs pellets

MWCNTs (0.5, 1, 2, 4, or 8 wt%) and PP pellets are blended and then dried in an oven at 60 °C for eight hours in order to remove the moisture. The PP/MWCNTs Pellets are then processed by incorporating a brabender mixer (Tzung Wei Plastic Machinery Co., Ltd., Taiwan, R.O.C.) at 200 °C with a rotor speed of 50 rpm for 5 min.

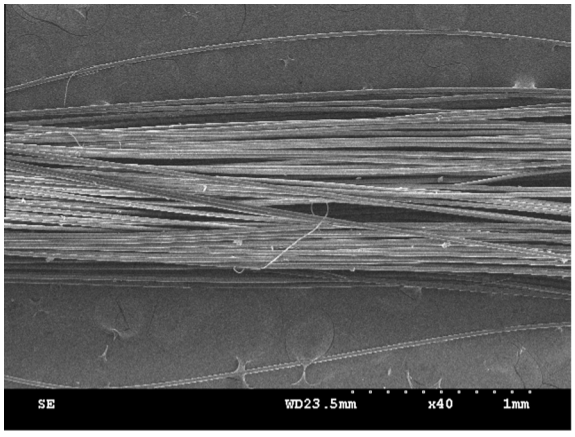

Fig. 1. SEM image (40×) of PET yarns.

2.3. Preparation of PP/MWCNTs-coated PET yarns

PET yarns that serve as the core are fed into the yarn coating machine through its die (SEVC-45, Sun Ying Machinery Co., Ltd. Taiwan, R.O.C.), with PP/MWCNTs composite pellets being extruded from the melt extrusion in order to coat PET yarns. The temperatures of four barrels of the yarn coating machine are 180 °C, 200 °C, 230 °C, 230 °C with its die at a temperature of 220 °C. The PP/MWCNTs-coated PET yarns are then cooled via a cooling tank, and are coiled through a rewinder (Tai Ho Machinery Co., Ltd. Taiwan, R.O.C.) with various coiling speeds of 100 rpm, 150 rpm, and 200 rpm in order to provide PP/MWCNTs-coated PET yarns with various diameters.

2.4. Testings

2.4.1. Tensile properties

The tensile properties of samples are measured by using an automatic tensile tester (FPA/M, Statimat-M, Textechno Ltd., Western-Germany), as indicated in Fig. 2. A total of ten samples for each specification are used for the measurement and their means are recorded. The distance between the upper and lower grips is 250 mm, and the crosshead speed is 50 mm/min.

2.4.2. Scanning electron microscope (SEM)

The fractured samples collected from tensile tests are collected and affixed to the sample holder by applying carbon paste. Samples are then coated with a thin gold layer, and their fractured surface morphology is observed by using a scanning electron microscope (S3000N, Hitachi, Japan) with an operating voltage of 15 kV.

2.4.3. Differential scanning calorimeter (DSC)

8-10 mg of PP/MWCNTs coating layers are placed in a DSC (Q200, TA Instruments, USA), and are then heated from 40 °C to

Fig. 2. Illustration of the automatic tensile tester. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)