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Mechanical and thermo-mechanical properties of short carbon fiber reinforced polypropylene composites using exfoliated graphene nanoplatelets coating

Alireza Ashori [a,*], Saman Menbari [b], Reza Bahrami [a]

[a] Department of Chemical Technologies, Iranian Research Organization for Science and Technology (IROST), P.O. Box 33535111, Tehran, Iran
[b] Department of Mechanical Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran

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ABSTRACT

This work reports an improvement in the mechanical and thermo-mechanical properties of short carbon fiber (SCF)/polypropylene (PP) composite, resulting from coating of the SCFs with exfoliated graphene nanoplatelets (xGnPs). Firstly, the xGnPs were coated on the SCFs surface by a simple physical absorption method, and then the composites were manufactured by melt blending and hot-press processing. The amount of SCFs was kept constant at 15 wt% and the amount of xGnP was varied up to 3 wt%. Results of tensile and impact measurements indicated that, for the xGnP–SCF/PP composite, maximum tensile strength, tensile modulus and impact strength were 43.4 MPa, 1.052 GPa, and 38.1 J/m, respectively, corresponding to 13.6%, 41.7%, and 7.3% enhancement compared to the untreated SCF/PP composite. In addition, the results of dynamic mechanical thermal analyses indicated enhancement in storage modulus and damping capacity for the treated samples; however, no significant difference was observed in the glass transition temperature. The xGnP–SCF/PP interface adhesion enhancement was clearly shown by scanning electron microscopy (SEM) images of the tensile failure surfaces. Finally, the optimal xGnP content for effectively improving the overall composite mechanical and thermo-mechanical performance was found to be 1 wt%.

Introduction

Polymer composites reinforced with short fibers (such as glass and carbon fibers) have been widely used as structural materials for automobiles, aerospace, marine, and other industrial applications due to their high stiffness and strength to weight ratios compared to metal alloys [1,2]. Compared to short glass fibers, short carbon fibers (SCF) are attractive due to their excellent mechanical properties, high thermal and electrical conductivity, high resistance to corrosive environment, and low density [3]. However, the mechanical properties of SCF reinforced polymer composites critically depend on the fiber–matrix interfacial adhesion, fiber amount, aspect ratio, orientation with respect to loading direction, etc [4]. Among these, fiber–matrix interfacial adhesion is extremely important since carbon fibers (CFs) have chemical inertness and poor wettability with most of the polymeric matrices [5]. Hence, it is necessary to improve the fiber–matrix adhesion to enhance the mechanical properties. Many methods have been developed for improving the carbon fiber–polymer matrix interfacial adhesion to enhance mechanical interlocking, including electrochemical, chemical, thermal, grafting, coating (sizing) and discharge plasma treatments, etc. [6–9].

In recent years, the fiber coating technologies have been developed for various purposes [5,6,10–12], and carbon nanomaterials such as carbon nanotube (CNT), graphene, graphene oxide (GO) have given rise to significant improvements in tensile strength, electrical properties and barrier performance of fiber [13–16]. Huang et al. [17] coated GO onto the surface of CF by electrophoretic deposition and reduced the GO by a subsequent annealing process, which improved the interfacial adhesion and mechanical properties of CF/polymer composites. Furthermore, little research has concerned the shielding mechanisms of GO-CF and rGO-CF reinforced polymer composites [11].

Since the cost and strength of these composites depend on the fabrication method, fiber coating has attracted a lot of attention due to ease of preparation and good performance. A substantial

* Corresponding author. Tel.: +98 2156275192; fax: +98 2156275191.
E-mail address: ashori@irost.ir (A. Ashori).

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increase in the fiber–matrix adhesion using nanoparticle coating has been reported in literatures [5,14,15,18]. Li et al. [5] prepared and characterized GO-coated SCF reinforced polysulfone (GO-SCF/PES) composites by a simple physical absorption method and obtained significant improvement in the tensile and flexural properties of the composites due to obviously enhanced SCF/PES interfacial adhesion. Qin et al. [13] investigated the effects of exfoliated graphene nanoplatelet (xGnP)-coated CFs on the mechanical properties of epoxy matrix. Their results showed 52%, 7%, and 19% increase in comparison with non-coated CFs/epoxy composites, for 90° flexural strength, 0° flexural strength, and interlaminar shear strength, respectively. Agnihotri et al. [18] studied CNT-coated CF/polyester composites and found that presence of CNT on the surface of CF results in the enhancement of fiber–matrix adhesion.

Polypropylene (PP) is a polyolefin polymer used in a wide variety of applications. It has been used as the matrix material in commercial form because of its many attractive properties, such as low weight, relatively low cost, excellent heat distortion temperature (above 100 °C) and its recyclability [19,20]. Accordingly, PP was used in this study as the polymer matrix of a composite material in order to investigate its mechanical properties. The research further aimed at studying the effect of xGnP-coated SCFs on the mechanical and the thermo-mechanical properties of composites.

Materials and methods

Materials

Polypropylene (PP, V30S trade name) with melt flow index of 18 g/10 min (190 °C/2.16 kg) and density of 0.918 g/cm^3, was supplied by Arak Petrochemical Co. (Iran). The PAN-based carbon fiber T300, made by Japan Toray Co., was used in this study. The physical and mechanical properties of the carbon fiber are illustrated in Table 1. The fibers were chopped into 5 ± 1 mm lengths and then the pyrolytical sizing agent on the fibers was removed by heating in an aerated furnace at 500 °C for 30 min. The exfoliated graphene nanoplatelet (xGnP-C750) was a product of XG Sciences Inc. (USA). The average surface area of xGnP was 750 m^2/g. As received, the particles are agglomerated into a few microns size aggregates, but, when dispersed properly in the appropriate solvent, their diameter was less than 100 nm. An X-ray photoelectron spectroscopy (XPS) analysis gave elemental concentrations for oxygen and carbon of 7% and 93%, respectively.

Preparation of xGnP-coated SCF/PP composites

The xGnP was subsequently dispersed in deionized water to form a suspension of 0.1 mg/mL. The resulted suspension was treated by an ultrasonic technique (600 W) for 2 h to exfoliate the nanoplatelets and form the homogeneous xGnP aqueous solution. Then, an appropriate amount of SCFs was added to the xGnP aqueous solution in the ratio shown in Table 2 and stirred for 24 h.

Table 1
Physical and mechanical properties of the used carbon fiber.

Specification	Value
Diameter of fiber (μm)	5.2
Number of filament	12 000
Tensile strength (MPa)	4400
Tensile modulus (GPa)	377
Elongation (%)	1.2
Mass per unit length (g/1000 m)	454.5
Density (g/cm^3)	1.75

Table 2
Formulation and components weight ratio of the composites.

Code	PP (wt%)	SCF (wt%)	xGnP (wt%)
A	100	0	0
B	85	15	0
C	84.5	15	0.5
D	84	15	1.0
E	82	15	3.0

Subsequently, the resultant mixtures were dried at 100 °C to remove water and then cooled naturally to room temperature. Finally, the xGnP-coated SCFs were obtained. The PP and xGnP–SCF were compounded by melt blending using a Brabender internal mixer at a rotor speed of 80 rpm and temperature of 180 °C for 10 min. Samples for characterizations and measurements were prepared by hot-press molding using a square steel mold at 190 °C. The blends were first added to the cold mold. The platens were pre-heated to 190 °C and a minimum pressure was applied during the pre-heating step to maintain the contact between the platens and mold. The pressure was then increased slowly to 2.5 MPa for 2 min and was held at this pressure for an additional 5 min. The mold was then removed from the hot-press and cooled down to room temperature in a separate cold-press under the same pressure (2.5 MPa).

Measurements

Tensile test was carried out using Zwick/Roell machine model z100 at the crosshead speed of 5 mm/min and room temperature according to ASTM D-638. Notched Izod impact tests were conducted with a Santam pendulum impact tester (model SIT-20D), according to ASTM D-256. Each measurement was repeated for five times. The morphology of the samples was studied by scanning electron microscopy (SEM, model WEGA-III TESCAN) on the fracture surfaces from the tensile tests. The samples were coated with a thin film (15 nm) of gold to avoid electrical charge accumulation during the examination and then analyzed at an accelerating voltage of 20 kV. Dynamic mechanical thermal analyses (DMTA) were performed using a DMA 8000 analyzer (Perkin Elmer) and single cantilever configuration. The test was run at 1 Hz frequency, 10 °C/min heating rate in range of −100–140 °C according to ASTM D-4065. Samples were in rectangular form with dimensions of 1 mm × 10 mm × 36 mm.

Results and discussion

Morphology of xGnP–SCF

The changes of SCF surface morphology after the coating process of xGnP were verified using the SEM. Fig. 1 shows the SEM images of the CFs coated with different amounts of xGnP nanoparticles. As shown in Fig. 1a, virgin (un-coated) SCF has a relatively smooth and glassy surface due to the commercial sizing. The rough morphological surface of SCFs, after treatment by xGnP, can be clearly observed in Fig. 1b–d. The treated SCFs with 0.5 wt% xGnP are partially coated by nanoparticles, and there still exist bare surface areas as shown in Fig. 1b. For SCFs coated with 1 wt% xGnP, more uniform coverage of SCF surface can be seen from the micrograph shown in Fig. 1c, while in the 3 wt% xGnP, non-uniform coverage and xGnP agglomeration is clearly visible (Fig. 1d).

Mechanical properties

Stronger interfacial interactions between SCF and the PP matrix have a significant effect on the mechanical properties. As described