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Preparation and tribological properties of 3D network polymer-based nanocomposites reinforced by carbon nanofibers

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ABSTRACT

A new robust three-dimensional (3D) network epoxy (EP)-based nanocomposite was fabricated via vacuum assisted resin transfer molding (VARTM) method. Carbon nanofibers (CNFs) and 3D polyimide (PI) fiber felt were utilized to improve the mechanical and tribological properties of the prepared EP nanocomposites. Results indicated that both the friction coefficients and wear rates of CNFs/PI/EP nanocomposites were lower than the other two comparative materials at various loads and velocities. CNFs/PI/EP nanocomposites obtained superior tribological properties, which enhanced the wear resistance by 18 times compared with pure EP under the applied load of 1.2 MPa. The worn surface and wear mechanism of composites were analyzed by a scanning electron microscope (SEM). Additionally, CNFs/PI/EP nanocomposites also exhibited remarkable improvements in the mechanical properties. These improved properties could be attributed to the synergistic effect between PI fiber felt and CNFs. The 3D PI fiber felt was used as structural skeleton reinforcing while the CNFs played its role in enhancing interface bonding strength between EP matrix and PI fiber felt. The CNFs could also act as solid lubrication and anti-friction agent in the composites.

1. Introduction

In recent years, three-dimensional (3D) network polymer-based nanocomposites as promising materials have attracted intensive interest in scientific and practical applications [1]. Compared with traditional composites, new-type composites reinforced by 3D textile fabrics can enhance mechanical strength to solve interlaminar fracture problem effectively [2–3]. Up to now, various three-dimensional (3D) network nanocomposites have been fabricated by means of different techniques, such as chemical spray deposition [4], template method [5] and microfluidic infiltration [6]. It is believed that the application of these 3D network nanocomposites can broaden the investigation of the mechanics and tribology in the materials field.

Epoxy resin (EP) has been widely used in engineering and construction industries owing to its excellent properties, such as high adhesion, good mechanical properties, high chemical corrosion resistance and dimensional stability [7–9]. However, the major defects of poor fracture resistance and high wear rate of EP are still urgently need to improve for many tribological applications [10,11]. Various kinds of EP composites reinforced by fillers have been developed for several decades. For instance, Allaoui et al. [12] found that adding 3 wt% multiwalled carbon nanotubes (MWCNTs) into epoxy composite decreased the wear rate by 77% compared to pure epoxy. The obtained better wear resistance of the MWCNTs/epoxy composite can be explained by the high mechanical property and dispersion quality of CNTs in epoxy matrix. Fan et al. [13] fabricated epoxy composites enhanced by strategically injecting MWCNT/epoxy suspensions into stationary glass fiber mats. This research contributes to an increase in the interlaminar shear strength (ILSS) by 33% of the prepared composites. Unfortunately, compared with organic polymer fibers, glass fiber with high brittleness is difficult to satisfy more rigorous demands in industrial application [14]. Organic polymer fibers with continuous macromolecular chain possess of excellent flexibility especially in high temperature, which can enhance the mechanical and tribological properties of the epoxy-based composites efficiently [15].

Polyimide (PI) fibers as special engineering materials have enormous potentials based on the high elasticity modulus, high thermal stability and wear resistance [16,17]. PI fiber felt with distinct 3D elastic network structures can also be used as skeleton structure to reinforce EP composites. Moreover, in order to relieve the phenomena of the interfacial separation between fibers and EP composites, nanofibers or nanoparticles are usually added to fill the micro zone of composites owing to their unique properties such as small size effect, boundary effect and quantum effect [18,19]. Carbon nanofibers (CNFs) as a common nanofillers are

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suitable to reinforce polymeric materials due to their excellent electric conductivity, thermostability and self-lubricating properties [20,21]. The characteristics of small-size and high strength of CNFs can strengthen the small region within the materials, realizing micro-area increasing and microscopic wear resistance [22]. On the other hand, the synergistic effect between CNFs and PI can enhance structural strength and interface bonding force of nanocomposites. Accordingly, the EP nanocomposites with interpenetrating 3D networks which possess of outstanding mechanical and tribological properties can be hopefully achieved.

In this work, we fabricated robust EP-based nanocomposites with 3D network structures by means of vacuum assisted resin transfer molding (VARTM) method. The interpenetrating 3D network structures were designed by incorporating 3D PI fiber felt and CNFs. The friction and wear tests of pure epoxy, PI/EP and CNFs/PI/EP composites were carried out at different loads and sliding velocities under dry sliding condition. The worn and counterpart surfaces of composites were studied by a scanning electron microscopy (SEM). In order to analyze the structure and wear mechanism of composites, a series of mechanical properties were comparatively investigated.

2. Experimental

2.1. Materials

In this work, Araldite LY1564SP epoxy resin with low viscosity and corresponding XB3487 curing agent were provided by Huntsman Advanced Materials (Nanjing) Co., Ltd, China. Three-dimensional polyimide fiber felt was purchased by Changchun HipolyKing Co., Ltd., China. The dimensions of the PI fiber felt are 100 cm × 50 cm × 4 mm and the felt can be cut to any desired size as needed. The diameter of single fiber is approximately 8 μm. The mechanical properties of this PI fibers are as follows: Tensile strength >100 MPa; Impact strength >8 kJ/m^2; Bending strength >70 MPa; Breaking elongation(%) >0. Vapor grown carbon nanofibers (CNFs, grade PR-24-XT-LHT) with an average diameter of 150 nm and a length of 50–200 mm were obtained from Pyrograf Products, Inc. Vacuum bags applied in VARTM process were purchased from Beijing Inova Technology Co., Ltd., China.

2.2. Pre-treatment

Pristine CNFs were treated by immersing the CNFs in concentrated nitric acid (4 mol/L) via magnetic stirring at 60 °C for 3 h. After the acid treatment, the CNFs was filtered and washed with deionized water until the pH value was approximately 7. Then, the CNFs were dried in a vacuum drying oven at 100 °C overnight. Three-dimensional polyimide fiber felt was cut to the certain size according to the demand for different test and dried in a vacuum drying oven at 80 °C for 2 h.

2.3. Preparation of CNFs/PI/EP nanocomposites

Fig. 1 shows the fabricating process of CNFs/PI/EP nanocomposites. The prepared CNFs were incorporated to the epoxy resin at proper mass fractions (0.5, 1.0, and 1.5 wt%) via magnetic stirring at 40 °C for 1 h. The curing agent was added into the above prepared resin solution with an epoxy resin/curing agent weight ratio 100/34. Ultrasonic vibration was conducted at room temperature for 10 min to compound resin and curing agent sufficiently. Then the epoxy-based nanocomposites reinforced by polyimide fiber felt and CNFs were fabricated by the vacuum assisted resin transfer molding (VARTM) process [23] by transferring the prepared epoxy resin into polyimide fiber felt. The volume fraction of PI in the composite was about 23–24%. The whole process was conducted in vacuum conditions to remove bubbles in the composites. The unformed composites were cured by a plate vulcanizing machine, which were heated and pressurized at 80 °C over 1.5 h and followed by 5 h at 100 °C under an applied load of 1 MPa. For comparison, the pure EP and PI/EP composites were also prepared at the same curing procedure.

2.4. Characterization

2.4.1. Morphology of CNFs/PI/EP nanocomposites

The morphologies of PI fiber felt, fracture surfaces of PI/EP and CNFs/PI/EP composites were comparatively investigated by a ΣIGMA scanning electron microscope (SEM, ZEISS, Germany). Fracture surfaces of PI/EP and CNFs/PI/EP composites were prepared as following procedures: Composites was handled with liquid nitrogen frozen and conducted the process of brittle fracture. Fix a prepared sample and then exert a certain force to break the sample.

2.4.2. Mechanical properties

Tensile and bending properties of the composites were measured using a universal testing machine (HDW-20KN, Huayang Experimental Equipment, China). Tensile test was conducted according to the American Society for Testing and Materials (ASTM, 2010, standard D638-10). The specimens were prepared following the standard ASTM D638 requirement. Five samples were tested at the speed of 2 mm/min and the average value from five measurements was used. Bending test was carried out following the standard ASTM D790-10. Testing speed was 2 mm/min ruled according to the standard ASTM. At least five specimens were tested and the average value was presented. Shore D durometer (LD-J, Wenzhou Haibao Instruments, China) was used to investigate the hardness of composites.

2.4.3. Friction and wear test

In this section, the friction and wear tests of pure EP, PI /EP and CNFs/PI/EP composites were conducted by using a pin-on-disc friction and wear tester (MPX-2000, Xuanhua Testing factory, China). The schematic diagram of friction and wear tests is shown

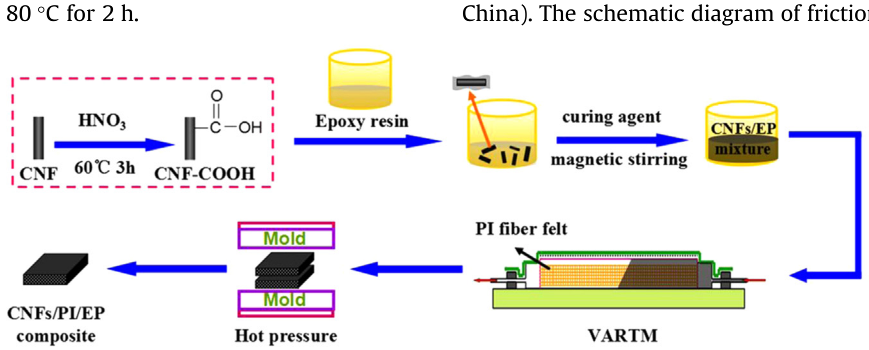

Fig. 1. Flowchart for the preparation of CNFs/PI/EP nanocomposites.