Tribology International 92 (2015) 222–232

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Mechanical and tribological properties of self-lubricating bio-based carbon-fabric epoxy composites made using liquid composite molding

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ARTICLE INFO

Article history:
Received 11 February 2015
Received in revised form
26 May 2015
Accepted 10 June 2015
Available online 22 June 2015

Keywords:
LCM
Mechanical properties
Carbon-reinforced composite
Tribological properties

ABSTRACT

Polymer composites reinforced with fibrous materials are used in several tribological and mechanical applications. In this study, the effect of carbon fiber as a reinforcement on the mechanical and tribological properties of a bio-based epoxy composite was investigated. The level of cure was investigated using DSC and the tribo-surfaces were studied using SEM micrographs. Use of carbon fibers with epoxy composites expectedly enhanced the bending strength and modulus of the composite. More importantly, the use of carbon fibers improved the tribological properties. Taguchi technique was employed in order to extract the data in a controlled situation in the experiments. Through the regression analysis equations, it was possible to predict the COF and volume loss as a function of these parameters.

1. Introduction

Polymer matrix fiber reinforced composites are being extensively used in numerous mechanical and tribological applications such as gears, bearings, seals, breaks, etc. [1–6] because of lightweight, high strength and stiffness [7], corrosion resistance [8], and low friction coefficient [9]. Growing world demand for using more environment friendly materials has resulted in a push for using bio-based materials in polymer composites. Although there has been considerable research to improve the understanding of mechanical and tribological properties of polymer composites, such a field of knowledge for bio-based composites with plant-sourced resins as matrix is still relatively new [10–14].

Carbon fibers have been employed as reinforcement with different polymeric matrices to fabricate carbon-fiber reinforced composites [15]. In particular, embedding of carbonous materials to enhance the physical and mechanical properties of metals and polymers has been a topic of interest over the last few years in industries, such as the automotive and aerospace industries [16–20]. This family of materials are widely studied and used in industrial high-performance applications due to its superior mechanical and tribological properties compared to unreinforced resins. Different parameters such as type [21], shape, direction [22,23], content [23], and size [24] of the reinforcement as well as matrix composition, matrix/fiber interface, and fabrication technique can influence the final mechanical and tribological properties of the composites. It has been reported that addition of carbon fibers in forms of long fibers [25], short fibers [26], and woven fabrics [27–32] as reinforcement in thermoplastic polymers imparts better tribological properties such that parallel and anti-parallel fibers increase wear resistance in carbon-reinforced composites. Xian and Zhang [26] reported that adding around 20% short carbon fibers in polyetherimide could greatly reduce friction coefficient and significantly improve wear resistance. Grove and Budinski [33] incorporated the fabric form of fiber reinforcement to fabricate a self-lubricated bearing. The layered-lattice structure of graphite in carbon fibers, which leads to a reduced coefficient of friction, provides additional lubricity in the composite [32]. Friedrich studied the influence of fiber volume fraction and fiber orientations on friction coefficient and wear rate of the carbon-fiber composites using both thermoplastic and thermoset matrices [34].

Although epoxy has been increasingly used in diverse engineering applications due to its great processing characteristics, superior strength, excellent performance at elevated temperatures, and high solvent resistance, it often cannot be used in tribological applications due to its three-dimensional cross-linked bond structure as compared with the thermoplastics. In order to functionalize epoxy for severe wear-prone working conditions, fillers need to be added to create wear resistant composite materials [35].

There is a worldwide interest among industries and academia in replacing common fossil fuel-based epoxies with natural bio-based resins due to the environmental concerns. However, the bio-based polymers still form a very small share of the total global

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http://dx.doi.org/10.1016/j.triboint.2015.06.007
0301-679X/

polymer market due to their poor performance and properties. Thus, enhancing the properties of the partially or full bio-based epoxy cross-linked polymers by addition of appropriate reinforcements is currently a challenge for both the academic and industrial researchers. Yet, not many careful studies have been undertaken to investigate the mechanical and tribological properties of bio-based epoxy composites reinforced with woven carbon fibers.

In this study, carbon fibers were used as a reinforcement with a bio-based epoxy matrix for making a carbon-reinforced composite using the resin transfer molding (RTM) process [36,37]. In our experiment, a bio-based epoxy made up of 37% bio-content was used. The effects of carbon fiber reinforcement content on the mechanical and tribological properties of the carbon/bio-epoxy composite were investigated. Three point bending test was used to compare the bending strengths and moduli under different fiber volume fractions. Friction coefficient and wear behavior were investigated under different sliding speeds and loads for three different fiber volume fractions. Tribo-surfaces were studied using SEM micrographs. Finally, Taguchi method was used to optimize the results and find optimum process parameters and predict the COF and wear loss for other fiber volume fractions and wear-test parameters.

2. Experiments

2.1. Fabrication method

The carbon-reinforced composites were made by an RTM process where carbon fiber was used as the reinforcement and a bio-based epoxy as the matrix. In our fabrication method, a positive pressure was used for resin injection in the RTM method to push the resin through the aligned carbon-fiber fabrics. The small RTM mold (to be called a 'micro-mold') used in the experiments was made from aluminum and plexi-glass which was previously used by the authors in fabricating carbon, glass and cellulose nano-composites [38]. The mold consisted of an aluminum base block and a plexi-glass top-plate; the latter was used as an air seal and also as a window to detect the resin movement between aligned carbon fibers. The micro-mold was designed with resin inlet at the center of the specimen and two vents at the opposite ends. In this configuration, the infusion of resin into packed carbon fibers was perfect where the resin was allowed in from middle point and traveled horizontally along the carbon fibers and came out from the vents. The epoxy used in all these experiments was a low viscosity resin called Super Sap Entropy (by Entropy Resins, Hayward, CA). The epoxy is made up of 37% bio-content that was derived from the byproducts of green industries including those involving wood pulp and bio-fuels [39]. The resin is classified as a USDA Bio Preferred SM Product using ASTM D638 [40] and has a total calculated biomass of 50%.

To avoid race tracking which is caused by racing of the resin along the side edges and corners, the positions of fabric layers with respect to each other were considered carefully since nesting[1] seemed to play a role in the appearance of race tracking. The carbon fabric layers were cut carefully in order to fit the mold cavity. The dimensions of the fiber layers were crucial because, if the in-plane dimensions were shorter than the mold cavity, the race tracking occurred along the preform-mold wall gap which caused a significant change in the resin/fiber infusion pattern in the composites. On the other hand, if the carbon fabric was larger than the mold cavity, closing of the mold and attaining a good sealing was difficult. After polishing the mold with a mold release agent, the carbon-fabric layers were placed inside the mold cavity and the plexi-glass top plate was closed in order to seal the mold. (The mold cavity was closed using bolts and clamps.) The resin entered the mold from the inlet and flowed through the stack of carbon fabrics, and thus filled the mold cavity, and then came out from the vents. For completing the curing process, specimens were left in the mold for 24 h at the room temperature. The specimens were then removed from the mold and smoothened further to obtain a suitable surface finish. Likewise, the edges were machined using a low-impact grinding machine and high-grit sand paper. Properties of carbon fabric used as a preform is presented in Table 1.

[1] Nesting happens when bumps created by tows of the upper fabric layer 'mesh' with the grooves of lower fabric layer.

2.2. Characterization and testing

The curing of the epoxy composites was studied using a Q1000 Differential Scanning Calorimeter (DSC) from TA Instruments. The procedure involved ramping 10 mg of uncured sample from room temperature to 260 °C at a heating rate of 5 °C/min. To study the glass transition temperature of the cured composites, the curing process was followed by another cooling–heating DSC ramp in the range of −20 °C to 180 °C. All DSC tests used T-Zero aluminum pans and 50 mL/min of Nitrogen purge gas. For all the DSC thermos-grams reported, upward peaks were exothermic.

The three-point bending tests on the carbon/epoxy composite specimens were performed in the displacement-controlled mode at a rate of 1.3 mm/min (0.05 in/min). During the test progress, the cross-head displacement and load values were simultaneously recorded. The load was applied using an electro-mechanical test system with a 97.8 kN (22 kip) capacity. A load cell, having a capacity of 2.2 kN (0.5 kip) was used in order to attain more accurate results. The maximum error of the recorded load was within 22 N (5.0 lb.). Three carbon/epoxy samples with fiber volume fractions ranging from 10% to 30% were tested. A bar of rectangular cross section rested on two supports and was loaded by means of a loading nose midway between the supports. A support span-to-depth ratio of 16:1 was used unless there was reason to suspect that a larger span-to-depth ratio was required. The specimen was deflected until rupture occurred in the outer surface of the test specimen. The parts were tested for ultimate bending strength, maximum load before failure, bending modulus of elasticity, and bending strain.

When a homogeneous elastic material is tested in flexure as a simple beam supported at two points and loaded at the midpoint, the maximum stress in the outer surface of the test specimen occurs at the midpoint. The tangent modulus of elasticity, often called the "modulus of elasticity," is the ratio, within the elastic limit, of stress to the corresponding strain. It is calculated by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve.

The flexural stress was calculated using the correlation

$$\sigma = (3PL/2bd^2) \quad (1)$$

The flexural strain was also obtained through the relation

$$\varepsilon = 6Dd/L^2 \quad (2)$$

where σ represents flexural stress, P is load, $\varepsilon$is flexural strain, D is deflection at the centerline of the specimen in the middle of the support span, L is the length of the specimen, b is the width of the specimen, and d is the thickness of the specimen.

2.3. Tribology test

The dry pin-on-disk test (ASTM G99) was employed to investigate tribological behavior at room temperature. During the wear test, a stationary pin was forced into a rotating disk. Samples as pins were cut from the fabricated composite specimen, with a contact surface of the rounded, 3 mm diameter shape. The disks were of hardened 440C stainless steel. The applied load varied from 10 N to 20 N and the