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Mechanical and abrasive wear performance of woven flax fabric/polyoxymethylene composites

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ABSTRACT

We report an investigation on the abrasive wear behaviors of flax fabric-reinforced polyoxymethylene (POM) composites. The effect of weave structure on the friction coefficient and wear rate of the composites varied according to the level of applied load and sliding speed. Incorporation of the flax fabrics could reduce the wear rate by as much as 4-fold at high load and high sliding speed conditions and could improve the mechanical properties of POM significantly. By careful choice of the weave structure, this low wear rate could be achieved without increasing the friction coefficient. The wear mechanisms of the composites were discussed in detail based on evidences from scanning electron microscopy. It was concluded that the formation of transfer film and the weave structure of flax fabric had an important impact on the wear performances of the composites.

1. Introduction

Polyoxymethylene (POM) is considered to be the most suitable rubbing pair material among engineering plastics for its good wear resistance, low friction coefficient, high stiffness and high value of pressure and sliding velocity (PV), which is widely used in the automotive and aeronautic industry [1,2]. However, the wear performance of POM in highly loaded applications is still poor [3,4], especially in abrasive wear conditions [5]. In order to improve the mechanical and tribological properties of POM for tribo-engineering applications such as bearings and bushings, various reinforcements, including synthetic fibers [2,6–11] and inorganic particles [2,7,12] are often added. Recently, some natural fibers such as flax, hemp and sisal fiber have shown great potentials to replace synthetic fibers for their excellent mechanical properties, biodegradability, recyclability and weight-lighting [13,14].

An increasing number of natural fibers have been used as reinforcements in POM based composites to improve their specific mechanical properties and to reduce their weight and cost [15–20]. Yakubu et al. investigated the mechanical properties of different types of kenaf fiber-reinforced POM using short and long fibers [15], twisted yarns [17] and woven fabrics [16]. They found that the impact strength of long kenaf fiber reinforced POM was higher than that reinforced with short kenaf fibers. The tensile, flexural and impact properties of twisted yarns reinforced POM composites were superior to the short fiber composites. The tensile strength and elastic modulus of woven kenaf/PET/POM hybrid composite were higher than that of the neat POM. Bledzki et al. [19] investigated the mechanical and thermo-mechanical properties of cellulose and abaca fiber reinforced POM composites and found that the incorporation of both fibers improved the properties of POM such as modulus, flexural strength, impact strength, storage modulus and heat deflection temperature. Espinach et al. [20] found that chemical interaction between eucalyptus bleached fiber and POM was low and the load transmission from matrix to fiber was mainly through interfacial interlocking and friction, which resulted in only slight improvement on the tensile strength of eucalyptus bleached fiber-reinforced POM composites over the neat POM. Although many studies have been done on the mechanical properties of natural fiber reinforced POM composites, there have been no openly published reports on abrasive wear performances of natural fiber-reinforced POM

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composites.

In the last decade or so, researches on the wear performance of natural fiber-reinforced composites have increased significantly [14]. Many factors, such as volume fraction, orientations, treatments, and mechanical and thermal properties of the natural fibers can influence the mechanical and tribological properties of natural fiber-reinforced composites [14,21]. In addition, tribological operating conditions (applied load, sliding velocity, temperature and sliding distance) also have a great impact on the friction and wear performance of natural fiber polymeric composites [21,22]. Abrasive wear as one most severe form of wear is observed in various industrial applications like vanes, gears, bearings and pumps, which are made of fiber-reinforced composites [23,24]. Natural fiber woven fabric-reinforced polymer composite, as one important type of natural fiber composites, has shown great potentials for applications in structural components such as automotive hoods, turbine blades and rotorcraft interiors and cowlings in the automotive and aeronautic industry [25–28]. So far, most researches focused on the adhesive wear performance of composites reinforced with short, long and unidirectional natural fibers [22,29–32] and the mechanical properties of natural fiber woven fabric-reinforced composites [25–28]. However, we have not found any studies on the abrasive wear performance of natural fiber woven fabric-reinforced polymer composites.

In present work, we report our investigation on the effect of weave structure on the mechanical properties of flax fiber woven fabric-reinforced POM composites and their abrasive wear performance under different applied loads and sliding velocities. In addition, the relationship between the mechanical properties and abrasive wear resistance of the composites has been studied.

2. Experiment

2.1. Materials

POM (POM:M90-44) resin with a density of 1.41 g/cm^3 was supplied by Polyplastics Corp. The mechanical properties of the POM resin as provided by the supplier is presented in the Table 1.

Three plain-weave flax fabrics were provided by a textile mill in China. These fabrics are denoted as Fabric A, Fabric B and Fabric C, and their characteristics are given in Table 2. Their SEM images are shown in Fig. 1.

2.2. Composite fabrication

POM pellets were dried in convection oven at 80 °C for 4 h before being used. POM sheets were fabricated using a hot press at 190 °C for 20 min under the pressure of 10 MPa, and then cooled down to room temperature under the same pressure. An open-ended two-part leaky mould was used to produce composites, as illustrated in Fig. 2.

The woven flax fabrics and POM sheets were cut into and stacked in alternation in the leaky mould. Both top and bottom plates of the mould were heated to 190 °C and a constant force (50 kN) was applied to the leaky mound while hot pressing. The total duration of the hot pressing process was approximately 40 min. The top plate of the press was lifted up to release trapped moisture in the composite during the first 20 mins. At the last 20 min, the heating elements were switched off to allow the specimen to cool down to about 150 °C. Then the leaky mould including the specimen were moved to a cold press for quick cooling to the room temperature under the pressure of 10 MPa. The number of layers of flax fabrics and POM sheets were decided so that an approximately constant fiber volume fraction was achieved in all the composites. The final dimensions of the manufactured composites were 260 mm × 32 mm × 3 mm. Composite A, Composite B and Composite C were denoted to composites made from Fabric A, Fabric B and Fabric C, respectively. The characteristics of Composite A, Composite B and Composite C are listed in the Table 3. The specimens were cut into preset sizes for mechanical and tribological tests using a diamond tip cutter.

Table 1
Mechanical properties of POM resin.

Material	Tensile modulus (GPa)	Tensile strength (MPa)	Flexural modulus (GPa)	Flexural strength (MPa)
POM	2.6	60	2.8	89

Table 2
Characters of woven flax fabric materials.

Material	Fiber diameter ($\bar{d}_0/\sigma_{d_0}$) (μm)	Yarn width ($\bar{d}_1/\sigma_{d_1}$) (μm)	Weft threads/cm	Warp threads/cm	Fabric density (g/m^2)	Fabric thickness (μm)
Fabric A	21.3/5.8	413/84	17	17	300	420
Fabric B	21.3/5.8	336/67	18	18	186	270
Fabric C	21.3/5.8	261/86	23	23	138	200

2.3. Mechanical properties testing

Tensile testing of the final composites was performed on an Instron 5567 testing machine according to ASTM D3039-00. Flexural properties of the composites were determined using the three-point bending test according to ASTM D790-03 on an Instron 5500 R machine. The specimen sizes of tensile tests and flexural tests were 150 mm × 10 mm × 3 mm and 70 mm × 10 mm × 3 mm, respectively. Six specimens from each composite sample were tested in each test.

2.4. Wear properties testing

A pin-on-disc apparatus [5,14,34] (as per ASTM G-99 standard) was used to test the abrasive wear properties of the composites, as shown schematically in Fig. 3. The circular composite slice with a diameter of 6 mm and a thickness of 3 mm cut from the composite sheet was glued to a steel pin. To ensure uniform contact between the specimen and the counter surface, the specimens were polished against a 1600 grade SiC paper before each wear test. The specimen surfaces were then cleaned with acetone and dried completely before carrying out wear test. The wear loss of composite specimens was measured using an analytical balance with an accuracy of 10^{-4} g.

All wear tests were conducted at the room temperature of 20 ± 2 °C and relative humidity of 60%. The specimens were abraded against a waterproof 1200 grade SiC paper (grit size ≈ 6 μm) supported by Buehler Company [34]. As shown in Fig. 3, the 1200 grade SiC paper was adhered to a disc (ϕ80 mm × 10 mm) with an average roughness of $R_a = 0.4\,\mu m$, which was made of AISI 1045 carbon steel. During the abrasive wear tests, warp yarns of the samples were parallel to the abrading direction while weft yarns were perpendicular to it. Wear tests were conducted at two normal loads (25 N and 50 N) and three sliding velocities (0.2, 0.5 and 1 m/s). The total sliding distance in a test was 100 m. The wear test for each sample at the same conditions was repeated three times. The specific wear rate k was calculated using the following Equation [22]:

$$k = \frac{\Delta m}{\rho F_N S} \tag{1}$$

where Δm is the wear mass loss (g), ρ is the density of test composite (kg/m^3), F_N is the normal load (N) and S is the sliding distance (m).

2.5. Microstructure examination

A scanning electron microscope (HITACHI TM3030Plus, working