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Periodically micro-patterned viscose fiber-reinforced polypropylene composites with low surface friction

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ABSTRACT

Polypropylene/viscose fiber (PP/VF) composite with a surface pattern consisting of periodic, micro-scale cylindrical pillars were manufactured and the effect of fiber loading and micro-patterning on the friction and wear properties of the composites was studied. The micro-patterned viscose fiber composite surfaces were prepared via melt compounding and injection molding. SEM studies showed that the fiber dispersion within the micro-bumps was influenced by the fiber loading and high aspect ratio (300–1200) of viscose fibers. With higher fiber loadings the fiber content of the micro-bumps was prominently higher than with lower fiber loadings of the composites. The wear and friction behavior of the patterned composite series were evaluated by sliding the fabricated surfaces against rough and smooth steel surfaces with a pin-on-disc type tribometer. It was noted especially in the case of a smooth counter surface that while both high fiber content and sparse micro-bump coverage individually decreased the sliding friction, their synergetic effect produced a dramatic drop in friction coefficient.

1. Introduction

There are economical and environmental advantages in using natural polymers such as cellulose [1–4] and starch [5–8] as reinforcing material in plastic composites. The cellulose and its processed product, viscose fiber, are both cheap and effective filler materials for thermoplastics materials such as polypropylene and polyethylene [9,10,11], which decreases the raw material cost and enhances the physical properties of the material. With a good coupling agent some of the properties of natural fiber/thermoplastic composites are better than those of carbon fiber or glass fiber reinforced composites. These include low density, high toughness, biodegradability and reduced machinery abrasion [12].

Different kinds of micro-structures and their effect on anti-wetting, optical, friction and wear properties have been studied for a multitude of different materials, such as ceramics [13], metals [14,15] and polymeric materials [16]. A micro-scale surface pattern can drastically decrease the friction of the surface which is a desired property in many applications. By combining the increased physical properties of a thermoplastic reinforced with natural fiber and the benefits of micro-patterning, it could be possible to create durable surfaces with desired frictional and wear properties.

In our previous study [17] we found out that periodic micro-scale surface structures have a stabilizing effect on the sliding friction of polypropylene. Our main focus in this study was to find out if viscose fiber reinforced polypropylene (PP/VF) surfaces could be furnished with the same stabilizing effect by combining the mechanical strength of the composite with the surface structure controlled friction. The research was carried out by injection molding of PP/VF composites with different fiber loadings using micro-structured aluminum mold inserts. The composite samples were examined by determining the fiber content, distribution and orientation of the fibers within the micro-bumps in comparison to the bulk material. The effect of the fiber loading and surface micro-patterning on the friction and wear properties of the composites was studied against smooth and rough steel surfaces in order to discern the differences in friction caused by different wear mechanisms.

A modified pin-on-disc method was chosen for testing because it provides long-term, uninterrupted sliding conditions under which the polymers are usually in technical applications. A slow sliding speed and low load were used to monitor the adhesive behavior of the micro-patterned samples under mild wear conditions. The same test conditions were used in our previous study [17] allowing comparison between the results, and permitting us to find out influence of cellulose fibers on the dynamic friction of micro-structured PP.

2. Experimental

2.1. Materials

The polypropylene (PP) used in this study was obtained as pellets from Borealis Polymers AB (HD120 MO: density 908 kg/m³;

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melt flow rate 8 g/10 min at 230 °C/2.16 kg). The aluminum foil (Puratronic, 0.25 mm, 99.997%) used as mold insert material was obtained from Alfa Aesar. The viscose fiber (VF) used in the study was Danufil®KS (6 mm in length, 5–20 μm in diameter, 1.7 dtex) and was obtained from Kelheim Fibres, Germany. Maleic anhydride grafted polypropylene (MAPP) used as a coupling agent was obtained from Crompton Uniroyal Chemicals, USA (Polybond 3200).

2.2. Manufacturing of the patterned composite samples

Polypropylene composites with different amounts of added viscose fiber and surface structures were prepared by using melt compounding and injection molding. Four different patterns were manufactured on the surfaces of each composite and PP discs. The surface patterns were prepared by injection molding using aluminum foils with periodic micro-scale depressions as mold inserts to achieve surfaces with patterns consisting of periodically arranged micro-bumps. Fabricated aluminum mold inserts have been previously used successfully to produce patterned plastic surfaces with controlled surface coverage [18]. An un-patterned mold was used to fabricate smooth reference surfaces for the patterned samples.

2.2.1. Manufacturing of the patterned aluminum molds

The aluminum foil was cut into pieces of 3.5 cm × 3.0 cm in size and degreased in acetone with an ultrasonic bath. The foils were then patterned with periodic depressions using a tungsten carbide needle approx. 100 μm wide using a working speed of 500 mm/s and an impact depth of 50 μm. The patterning process was performed with a micro-working robot RP-1AH from Mitsubishi Electric, equipped with a CR1 controller and a feedback unit from Delta Enterprise Ltd. After the patterning, the foils were fixed onto a steel prop disc (15 mm in diameter) with a technical two-component adhesive (Loctite® Hysol® 9492 A & B) and was allowed to dry for 24 h at room temperature. The foils were then cut to match the shape of the steel prop. The scheme of one of the molds, alongside a graphical presentation of the parameters of the molded surface pattern, is presented in Fig. 1.

Four different micro-pattern molds were manufactured. The pitch p (Fig. 1) for the patterns was chosen so that the approximate surface area covered by the micro-bumps (SC value) would range from 15% to 45%. The pattern series fabricated were SC15 (SC 15.0%; *pitch* 129 μm), SC25 (SC 25.1%; *pitch* 77 μm), SC35 (SC 34.9%; *pitch* 50 μm) and SC45 (SC 45.1%; *pitch* 32 μm). The surface coverage (SC) is calculated from the diameter of a micro-bump (t; 100 μm) and the distance between micro-bumps ($t+p$) (Fig. 1) with the following equation:

$$SC(\%) = [pt^2/4(t+p)^2]\% \quad (1)$$

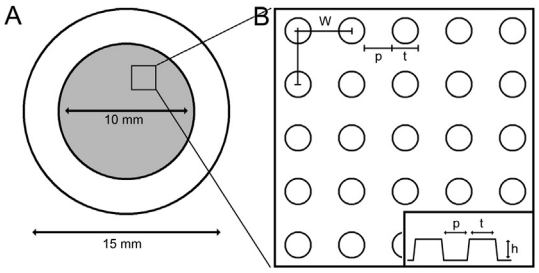

Fig. 1. (A) Scheme of a composite disc portraying the size of patterned area (gray) on un-patterned (white) surface. (B) Overhead and side view of the pattern after molding. ***p***=pitch between micro-bumps, ***t***=top diameter of micro-bump, ***W***=***p***+***t*** e.g. distance between micro-bumps. The actual height of the micro-bumps ***h*** is dependent on the working parameter *F*.

A smooth, un-patterned mold (SC100) was manufactured as a reference surface.

2.2.2. Manufacturing of the composite samples

Four composite series were used in this study, with viscose fiber contents ranging from 10 wt% to 40 wt%. To promote adhesion between the viscose fibers and the PP matrix, an optimum amount of coupling agent (6 w-% of fiber's mass) was added to the PP matrix. The fiber contents used in this study were 10 wt% (series PP/VF 10), 20 wt% (PP/VF 20), 30 wt% (PP/VF 30) and 40 wt % (PP/VF 40). The maximum fiber content chosen (40 wt%) and the amount of added coupling agent (6 wt% of the fiber mass portion) were based on our earlier studies on viscose fiber composites of PP [19]. A pure polypropylene (PP) series was used in the experimental studies for the reference.

The micro-structured composite samples were fabricated by injection molding with a DSM Midi 2000 melt compounder and a DSM micro-injection molding machine. The parameters used in the molding process were obtained from previous studies [9] on the viscose fiber composite. A screw temperature of 190 °C, a screw rotation speed of 80 rpm and mold temperature of 125 °C were used with the melt compounder. A piston pressure of 7–8 bars was used with the injection molding. The viscose fiber, coupling agent and polypropylene were fed to the melt compounder in patches of 5 g. The composition of a single patch was weighed to match the material proportions mentioned above. The composite was allowed to homogenize within the compounder for 5 min before molding. The same process parameters were used for the polypropylene reference samples. Ten parallel composite and PP discs with different surface patterns were molded for friction measurements. Ten specimens for the tensile measurements were molded for each different composite composition. Pure PP samples were manufactured for reference.

2.3. Tensile strength measurements

The tensile tests were carried out with material testing equipment Zwick Z010/TH2A model 2001, Ulm, Germany. The PP and composite samples were stored at room temperature (23–26 °C) for 5 days before the measurements. The speed of the crosshead was 50 mm/min. At least 10 parallel measurements were made for each series. Young's modulus (at a strain value of 0.1%), tensile strength (maximum stress) and elongation at break were measured by standard methods. Measurements were carried out at room temperature, normal pressure, and relative humidity of 30–40%.

2.4. Thermogravimetric analysis

Thermogravimetric analysis (TGA) [20,21] measurements were carried out with a Mettler-Toledo DSC821^e device (Greifensee, Switzerland) to determine the fiber content of the composites as in Ref. [9]. The composite samples were heated from 40 °C to 600 °C with a heating rate of 20 °C/min under a nitrogen flow (50 ml/min). The device was calibrated with an aluminum standard.

2.5. Surface studies

Surface structures, fiber distribution and wear deformation of the composite samples were examined with a Hitachi S4800 FE-SEM scanning electron microscope (SEM). Cross-sections of the patterned area (thickness 200 μm) were cut from each composite disc with a microtome. Samples were mounted on a stub with a carbon adhesive tape and coated with 3 nm of Au. An accelerating voltage of 3 kV and current of 5 μA were used with a working distance of 8 mm.