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Tribological properties and thermomechanical analysis of unsaturated polyester fabric composite in oscillating line-contact sliding

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ABSTRACT

The friction and wear properties of a composite containing unsaturated polyester resin with polyester fiber fabric reinforcement and internal PTFE lubricants are described under reciprocating dry sliding in a cylinder-on-plate contact against steel. By taking into account the deformation, creep, thermal expansion and strain recovery, on-line measurements for diameter reduction by wear are in agreement with post-mortem weight loss measurements. However, it is most important to consider the effects of the maximum polymer surface temperatures. The sliding properties are controlled by mechanical shear and plasticization of the PTFE lubricants under mild sliding conditions with a transition into instable sliding at 75 °C correlating with curing of the matrix, and stable sliding at temperatures of 120 °C corresponding to thermally-controlled sliding of PTFE.

1. Introduction

Thermoset polyester composites are nowadays used under dry running in bearings, bushes, seals, gears, guiding liners, cams, shafts or brake pads for automotive and aircraft industry. Under high load/high sliding velocity, thermoplastics such as polyamide, polyoxymethylene or polyethylene are efficiently replaced by thermoset polyesters to bring higher temperature and fatigue resistance because of the stiffening action of the aromatic phenylene group in the polymer backbone together with more flexible aliphatic segments. Previous studies on thermoplastic polyester such as polyethylene-terephthalate and PTFE-filled polyesters indicate frequent overload and plasticization [1]. The thermoset or unsaturated polyester is an economic alternative that can be conveniently processed into complex shapes with better thermal stability, chemical resistance, rigidity, dimensional stability and lower moisture absorption than thermoplastics. Therefore, thermoset polymers can favourably operate under higher stress [2]. As an ecological advantage, bio-based oils can be used for the synthesis of various polyester resins [3].

The sliding properties of thermoset polyester are significantly different than thermoplastics due to lack of thermal softening or melting and low surface plasticity [4], which both can be favourable mechanisms for energy dissipation and reduction in friction. Thermal heating of unsaturated polyester causes cross-linking that may predominate the thermochemical and thermomechanical sliding mechanisms: therefore, its wear properties are characterized by the formation of a brittle layer under high surface temperatures that fractures into abrasive debris in the sliding interface [5]. The thermoset polyester composites should be altered by fiber reinforcements to improve the mechanical loading capacity. Especially, glass-fiber reinforced polyesters received attention but synthetic fibers show a highly abrasive nature [6], therefore providing mainly erosive wear resistance [7]. Alternatively, treated and untreated natural fibers [8,9] and especially betelnut fibers [10] reduce wear of unsaturated polyesters due to plastic deformability [11]. Limited work has been reported by adding organic fibers into polyester composites, such as polyamide and PTFE fibers [12]. Furthermore, internal fillers should be added to improve the self-lubricating ability of thermoset polyesters. The addition of graphite powder up to 2% reduces friction and wear for unsaturated polyesters, in parallel with an increase in elasticity modulus and decrease in flexural stress and strain at failure [13]. Other lubricants such as vegetable oils have been used for impregnation of polyesters [12], and up to 5% clay fillers have been added [14] to reduce friction and wear of thermoset polyesters under mild conditions. In order to benefit from both tribological advantages of thermoset and thermoplastic polymers, new processing methods by hot pressing blends of aromatic thermosetting polyester with PTFE powders have been developed to withstand contact pressures up to 7 MPa with low friction and wear [15,16]. Other blends of thermosetting polyester with UHMWPE and appropriate compatibilizer display good thermal stability and low wear rates, attributed to the dominating effect of lamellar orientation of the thermoplast [17].

Compared to fiber reinforcement, the textile fabrics provide higher structural ordering and tightness in addition to the intrinsic

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properties of the matrix and fibers, depending on the fabric structure (e.g., woven, braided, knitted) and weave style (e.g., plain, twill or satin) [18]. Therefore, fabric composites provide higher structural stability, specific strength, loading capacity and wear resistance. However, many tribological studies on polymer composites considered only unidirectional fiber orientations [19] or short fiber-reinforcement [20], while a 3D-braided carbon fiber structure could provide significant improvement in wear resistance [21]. The woven fabrics especially provide high shear strength in the plane of the reinforcing sheet, while unidirectional weaves generally have lower shear strength [22]. Therefore, fabric self-lubricating liners can be extensively applied in plain bearings. The directionally oriented warp knitted structures of glass fibers arranged in different textile preforms have gained importance due to their isotropic properties and good tribological performance in combination with polyester [23]. The enhancements of wear resistance for different matrixes with fabrics of glass fiber [24,25], or carbon fiber [26] have been documented, often presenting abrasive wear [27]. The reinforcing mechanism of inorganic fabrics is liable to brittle fracture while the polymeric fabrics should be more ductile. The tribological properties of composites with polymer fabrics mainly focused on the use of carbon and aramid [28,29], Nomex [30], PTFE [31], hybrid Kevlar/PTFE [32], cotton/PTFE [33] or aramid/PTFE [34], natural coconut [35], heat-resistant polyoxadiazole [36], and occasionally polyester fibers [37]. The polyester fabric played a main role in the wear-resistant properties of epoxy composites, but once fillers were added, the matrix started to play a more important role. The role of PTFE fillers in fabric composites was proven to decrease coefficients of friction and increase wear resistance [38]. Advantageously, the use of polyester fabrics may enhance the tribological characteristics by artificial surface microstructures leading to entrapment of debris or solid lubricants. In a case study, the polyester thermoset with polyester fabric has reduced stick-slip effects in presence of internal lubricants [39].

At present, knowledge on tribological properties of thermoset polyester fabric composites is limited and has not been extensively studied in combination with a solid lubricant. While existing literature mainly focused on the optimization of matrix and fiber compositions, an in-depth thermomechanical characterization on the intrinsic role of solid lubricants is lacking. The role and physical meaning of fictional heating and temperature rise at the surface should therefore be considered: interestingly, it will be demonstrated how the properties of the thermoplastic fillers dominate under thermally-controlled sliding. In parallel, the deformation of thermoset polyester fabric composites should be analyzed under high loads, which is different than previously observed plasticization effects for thermoplastics. With the aim of using fabric composites in highly loaded bearing applications, a cylinder-on-plate testing (initial line contact) configuration has been intentionally selected in this study to simulate the influences of deformation under high Hertzian contact pressures and detect eventual mechanical overloads. The formation of a polymer transfer film during running-in may be enhanced under high contact pressures and accelerate the establishment of a steady-state sliding regime in parallel with the formation of a more conformal contact.

2. Experimental

2.1. Material

The sliding material includes a laminated thermoset polyester composite, containing plain weave polyester fabric with fiber diameter 15 μm that is impregnated with unsaturated polyester resin and 15 wt-% PTFE internal lubricant with powder size of about 30 μm homogeneously distributed in the bulk. The materials were commercially delivered (Luytex, Busak and Shamban) and further details on composition and processing of the material can be found in manufacturing data [40], together with the basic material properties reported in Table 1. The composite plates of 15 mm thickness were delivered with fabric layers oriented parallel to the machined surface. The composite cylinders were fabricated by turning and finishing with abrasive paper to a surface roughness Ra = 0.1 μm. As a reference material, polyester fabric composite without PTFE was used in only few sliding tests due to frequent overload.

The counterfaces of high-alloy 40 CrMnNiMo8-4-6 steel (DIN 1.2738) were used, after polishing with a GRID 600 abrasive paper to an average surface roughness Ra = 0.05 μm with grooves oriented perpendicular to the sliding direction. The steel hardness is 330 HV with yield strength 765 N/mm^2, tensile strength 1000 N/mm^2 and thermal conductivity 33 W/mK.

2.2. Thermal characterization

The thermal stability of the composite was evaluated by thermogravimetric analysis (TGA, Perkin Elmer Pyris 1). A sample weight of 5 mg was heated from 30 to 700 °C at a rate of 10 °C/min in an atmosphere of either flowing nitrogen or air. The transitions with either endotherm or exotherm reactions (convention Endo Up) were monitored by differential scanning calorimetry (DSC, Perkin Elmer 8500). A sample weight of 10 mg was heated from 0 to 350 °C at a rate of 10 °C/min in nitrogen atmosphere.

2.3. Tribological testing

Composite cylinders with a diameter of 5 mm (perpendicular to fabric) and length of 15 mm (parallel to fabric) were sliding in a reciprocating motion against a fixed steel counterface, using a PLINT TE 77 (cylinder-on-plate) configuration, as shown in Fig. 1. The cylinders were mounted with the fabric layers parallel to the sliding surface and weft fibers oriented along the sliding direction (0°), and sliding surfaces were rinsed with acetone prior to testing. Sliding tests were done under normal loads of 50, 100, 150 and 200 N and sliding velocities of 0.3, 0.6, 0.9 and 1.2 m/s over a total sliding distance of 15 km in case of no premature failure. The testing environment was surrounded by a climate box with controlled temperature (T_{env} = 23 °C) and humidity (RH = 60%). The coefficient of friction $\mu = F_f/F_n$ was calculated from the friction force F_f exerted by the composite cylinder on the counterface (measured by a piezo-electrical transducer in contact with the counterface), and the normal force F_n^* applied to the sample. The on-line vertical displacement of the sample was measured by a contactless inductive displacement transducer as the combined effect of wear and deformation of the polymer samples during sliding.

Table 1
Basic material properties for thermoset polyester fabric composites [40].

Property	Polyester fabric composite
Tensile strength	55 MPa
Static compressive strength perpendicular to fabric	345 MPa
Static compressive strength parallel to fabric	97 MPa
Charpy impact strength	122 kJ/m^2
Density	1.25 g/cm^3
Hardness	100 Rockwell M
Coefficient of linear thermal expansion perpendicular to fabric	$9 \cdot 10^{-5}$/°C
Coefficient of linear thermal expansion parallel to fabric	$5 \cdot 10^{-5}$/°C
Thermal conductivity	0.293 W/mK