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ScienceDirect
Wear 263 (2007) 992–999
WEAR
www.elsevier.com/locate/wear

Tribological investigation of thin polyester substrates for displays

K.A. Sierros, S.N. Kukureka [*]

University of Birmingham, School of Engineering, Department of Metallurgy and Materials, Edgbaston, Birmingham B15 2TT, UK

Received 15 August 2006; received in revised form 19 January 2007; accepted 20 January 2007
Available online 21 March 2007

Abstract

Thin polyester films are currently used as substrates in thin flexible displays, touch-screens and flat panel displays. The advantages of using such films in various display technologies include excellent optical transparency, mechanical flexibility and they are light weight and low cost.

However, little research has been reported to date on the tribological properties of such top-sheet display components. Nano-scale wear and friction experiments have been conducted in the past, mainly on polyethylene terepthalate (PET) in biaxially oriented thin solid films.

The aim of this paper is to investigate the unlubricated tribological response of biaxially oriented PET and polyethylene napthalate (PEN) films developed for use in display device assemblies. Tests were conducted under a relatively high normal load for up to a few thousand sliding cycles.

Counterformal contact under pure dry sliding conditions is used by means of a pin-on-disc wear testing apparatus, with a steel ball on thin polyester rotating flat. Wear track depths were measured, after testing, with a contact-mode stylus profilometer. Ex situ microscopical studies were performed on virgin and worn surfaces using scanning electron microscopy, SEM, optical microscopy and contact-mode atomic force microscopy (AFM).

The results such as values of friction coefficient and wear rates, can help the understanding of the tribological behaviour of the polymer film particularly in demanding display applications. Examples of such applications include electronic touch-drawing pads, where a stylus is repeatedly in contact, for at least a few hundred thousand cycles, with the polyester top-sheet surface, and flexible electronic touch-maps where top-surface handling conditions can be severe in some cases.

Keywords: Polymers; Polyester films; Displays; Pin-on-disc

1. Introduction

Polyethylene terepthalate (PET) and polyethylene napthalate (PEN) in the form of thin, 125 μm, polymer substrates have been given serious consideration as flexible display film materials in various display technologies such as organic light emitting displays and resistive touch-screens. The most important reasons are that they exhibit satisfactory optical properties with optical transmission higher than 85% in the visible range and also they are mechanically flexible under bending or buckling conditions [1].

Although PET and PEN thermoplastic semi-crystalline films belong to the same polyester family they possess different fundamental properties. For example, the glass transition temperature (T_g) of PET is 78 °C whereas the T_g for PEN is approximately 120 °C. Also, mechanical properties, such as Young's modulus and tensile strength, are observed to be better for PEN as compared with PET. Furthermore, the surface quality of PEN is better than that of PET. Finally, PEN display film exhibits better dimensional stability when exposed to temperatures of up to 180 °C, as compared with PET [2].

Both films are produced by the same sequential drawing method, which can be described as follows (i) melt extrusion through a slot die and quenching to form an amorphous precursor film, (ii) on-line drawing in the extrusion direction (machine direction, MD), (iii) on-line drawing in the transverse direction (TD) and (iv) on-line heat setting. The amorphous precursor film is then reheated above T_g as a prelude to the biaxial stretching process. The crystallinity of the final film product is between 25 and 40% and there is anisotropy in the thickness direction [3].

As polymer materials are used in demanding technological applications, such as displays, tailored mechanical and chemical properties have to be achieved. Polymer tribology also becomes increasingly important for such technological applications [4].

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[*] Corresponding author. Tel.: +44 121 414 5189.
E-mail address: s.n.kukureka@bham.ac.uk (S.N. Kukureka).

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doi:10.1016/j.wear.2007.01.073

In the specific case of thin polyester display films, appearance and transparency are critical and film damage or debris generation, due to friction and wear, are not desirable. Wear, due to scratching, occurs during polyester film processing, when the web is pulled over rolls and guides that are stationary [5]. During service conditions, the display substrate, which serves as the interface between the user and the machine, can be susceptible to repetitive scratching, intensive in the case of inexperienced users. Particular applications such as electronic touch drawing pads, where a ball-pen is used in order to make contact with the screen, must exhibit high mechanical and tribological reliability. It is therefore apparent that the tribological properties of such films need to be fully understood in order to minimize deficiencies during manufacturing and in service.

As far as PET film is concerned, previous research, mainly at the nano-scale using contact-mode atomic force microscopy (c-m AFM) has been reported. Beake et al. [6] reported on the nanotribology of additive-free, biaxially-oriented PET film. They explained that by using c-m AFM, in order to study tribological properties, it is possible to enable in situ nano-scale spatial resolution of wear features, which cannot be achieved by macroscopic tribological testing. They used silicon nitride and silicon spherical tips as a counterface. They observed that for the whole applied load range, 6–51 nN, well-defined wear ridges formed and that there is a tendency for material to be displaced to the periphery of the worn track. They also reported no dependence between the ridged structures and the film orientation.

Chalmers and Knox [5] investigated the abrasive wear of biaxially-oriented PET when reels of film were wound over 25.4 mm diameter metal pins, approximately 150 nm roughness, for two different speeds (3.8 and 10.2 m/s), and 150 passes. By using SEM they observed little wear at the higher speed and significant wear at the lower speed. Debris particles exhibited platelet form and the particles started as small white specks in the interface before growing in size as they adhered to the metal, and finally breaking loose from the metal surface. Also, Yang et al. [7] conducted friction and wear tests using a one-way reciprocating tester on unimplanted and ion-implanted PET, with a 25 μm thick film and a 3 mm diameter steel ball. The normal load applied was 2 N. They found, for the unimplanted PET film, that the initial friction coefficient was 0.31 and then decreased slightly as the number of passes increased, using a speed of 0.18 m/min. However, details of the film morphology are not given.

Yamada and Tanaka [8,9] studied the effect of degree of crystallinity on friction and wear of PET plates, 2 mm thick, and annealed PET film, 500 μm thick. Unlubricated and water-lubricated conditions were employed. The PET samples were used in the form of pins. They conducted experiments using a pin-on-disc wear and friction tester. The disc material was stainless steel with an average surface roughness of about 20 nm. The normal load used was 10 N for two different test speeds of 0.01 and 0.1 m/s. In unlubricated conditions, they found that the friction is little dependent on crystallinity whereas the wear rate increases with increase in crystallinity and is higher in the case of PET film as compared with PET plates. Wear of PET film seemed to be mainly due to surface fatigue during sliding. They also suggested that the difference of wear mechanisms, for low and high crystallinity PET, is due to the difference in morphological structures. As crystallinity increases, the wear rate increases remarkably in the range above 40%. In addition, Samyn et al. [10] investigated the sliding behaviour of bulk PET, with dimensions of 150 mm × 150 mm × 20 mm, against a steel counterface of size 410 mm × 200 mm × 20 mm. The test results presented were obtained using a large-scale tribotester under extremely high loads, 190–3380 kN. They concluded that PET shows high friction and unstable wear due to stick-slip.

For PEN there is little published tribological research, compared with that for PET. Some research has been done on PEN films used for magnetic tape applications [11]. PEN, 4.5 μm thick, was rubbed against itself or a Ni–Zn ferrite head or a metal particle tape. The apparatus was a reciprocating friction tester and operated at a velocity of 25 mm/s for a total experimental duration of 15 min. Higher friction coefficients were measured when PEN was rubbed against the ferrite surface than when it was rubbed against itself or the metal tape counterface.

However, little work has been done comparing PET and PEN in biaxially oriented films. These films are used in increasingly important technological applications, such as displays. Critical questions, such as the relationship between the wear and crystallinity of such semicrystalline polyester films and/or the effect of film surface and countersurface roughness on friction and wear, have to be addressed [12]. Also, it will be interesting to test and compare such films, in the form of rotating flat discs, against rigid counterfaces since most previous testing has been conducted using polymer pins [8,9].

The aim of this study is to investigate and compare the tribological properties of biaxially oriented PET and PEN films sliding against smooth stainless steel ball counterfaces using a commercial pin-on-disc tribotester.

2. Experimental technique

2.1. Test equipment

A commercial atomic force microscope operating in contact-mode (Digital Instruments 3100 series) was used in order to provide images and measure the surface roughness of the polymer films and the steel balls. Commercial silicon cantilever tips were employed. Three scan sizes were used: 2.5 μm × 2.5 μm, 2 μm × 2 μm and 5 μm × 5 μm. Root mean square (RMS) roughness, average roughness (R_a) and maximum roughness (R_{max}) were obtained for each material.

The uniaxial tensile properties, Young's modulus and yield stress, of PET and PEN films were investigated using a commercial mechanical tester (Instron 5520 series). Dumb-bell samples, 25 mm long and 4.8 mm wide, were cut from A4 sheets and tested, under uniaxial tension, using a cross head speed of 1 mm/min for different angles with respect to the *x*-axis of the A4 sheets.

The crystallinity of the polyester substrates, as well as T_g and T_m, were measured using differential scanning calorimetry, DSC