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Study of the friction mechanisms of pile surfaces: Measurement conditions and pile surface properties

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ABSTRACT

Pile can be found on different kinds of surfaces on textiles or carpet surfaces for example. This pile exhibits complex contact and friction behaviour. In this study, model surfaces of pile entities produced from PET fibres have been lab-made and their friction behaviour was investigated. The influence of the penetration depth of the slider into the pile, the sliding velocity, the pile density, and the surface tension of the fibre constituting the pile has been studied. The mechanisms involved during friction with a single pile entity—bending in front of the slider and then friction underneath the slider—have been identified and studied. In the first mechanism, pile entity deformation is predominant, and in the second, friction with the slider is significant. In the case of a pile entity assembly, friction also occurs between bristles/loops. The depth penetration into the pile increases the bending contribution. The surface tension of the fibre has a significant influence on fibre-to-fibre friction. The sliding velocity influence comes from both the friction with the slider and between fibres. The coefficient of friction due to the mechanisms underneath the slider is constant whatever the depth of penetration into the pile.

1. Introduction

Pile surfaces occur in different fields. In textiles, pile surfaces such as velvet, corduroy, polar fleece, carpet, terry towelling fabrics, and so on are commonly used for garments, upholstery (home furniture and transport), household linen, floor coverings, and so on. This kind of fabric consists of two parts: the main structure (which is due to woven fabric interlacing, knitted fabric stitches, etc.) and a superficial layer, that is, a pile.

Therefore, during use this pile is the component that is directly in contact with the counter-material (the skin, another textile fabric, a shoe, or another material).

Pile can be constituted of different kinds of entities: bristles (velvet, corduroy, some carpets, etc.), loops (terry towels, some sport socks, some carpets, etc.), or a mix of bristles and loops (polar fleece).

During the process of textile manufacturing or use, a textile surface can be in contact with another textile or with another kind of material. During spinning, weaving, braiding, or knitting processes or during use, the contact textile or other counterparts can occur with different machine pieces or environment objects. The textile–textile contact can be fibre against fibre in a yarn, yarn against yarn in a fabric, or fabric against fabric in wearing conditions or between garment and car or sofa upholstery for instance.

Surface fabric friction between two fibre assemblies or against another surface is commonly measured with a pin-plane tribometer. A well-known example is the Surface Tester of the Kawabata Evaluation System for Fabrics [1].

Since 1950s, the capstan method has been the most commonly used method for fibre friction measurements [2,3], even recently it has been used with the contact models developed by Cornelissen et al. [4–6] for carbon fibre tows.

For the fibre-to-fibre friction measurement, three kinds of methods are available and are detailed by Howell [2] and Hong [3]; the fibres can have a single contact point or a linear or multilinear contact. In most cases, the single contact-point methods consist in an orthogonal movement between the two fibres. The two fibres can be under tension during the measurement as for Howell's method or the hanging fibre methods [7]. A single fibre can be clamped on one side, like a cantilever, and the other fibre is clamped on both sides. This cantilever method is convenient for stiff fibres. In the cases of linear contact methods, the two fibres are twisted together and one fibre is pulled out. In another method, a

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single fibre is pulled out from a fibre assembly. For these two last methods, the pull-out force is measured [8]. Similar methods can also be used for yarn characterization.

Studies have been realized in order to estimate the influence of experimental conditions. These studies are summarized in detail by Hong et al. [3]. The normal load is the major experimental parameter. For textile materials, the coefficient of friction (COF) follows the commonly used empirical law established by Bowden and Young [9]; the COF $\mu \propto W^{n-1}$, where W is the normal force and n is a coefficient between 2/3 and 1 [2,10,11].

The influence of the sliding velocity is more complex insofar as it depends on the velocity range. When the sliding velocity varies over a large range of values, the evolution of the COF can follow a Stribeck curve, that is, firstly the COF increases with the velocity and then after a minimum value it increases slightly [2]. Moreover, the characteristic velocity which corresponds to the minimum value of the COF can differ according to the material [12] and the textile structure (filament or fibre, woven fabric, knitted fabric, etc.) [13–15] and whether the counterpart is a metallic or a textile material [13]. This Stribeck tendency has been observed in several studies but is not evident in all cases [2]. The limited range of speeds investigated might be a reason. Moreover, the method used for the measurement, that is, rolling (capstan method) or sliding friction, is important. In fact, in rolling friction, the COF is calculated from the capstan law, which includes the assumption of the non-extensibility of the material. But in most cases of textile materials it is not the case and the COFs obtained are not correct. Nevertheless, the COF values are in the same range with both methods [16].

Other studies have been realized in order to characterize the effect of surface treatments [2,17]. Such studies have been discussed by Hong [3]. It is obvious that the COF depends on the chosen treatment. For instance the anti-soiling finish applied to several pile yarns and tested by Cieslak et al. [18] was found to decrease the COF.

The studies described above have been conducted on textile materials, but few studies specifically concern pile fabrics. Nishimatsu et al. [19], whose pile was constituted of loops, also found the Stribeck tendency when rubbing such fabrics at varying sliding velocities. In addition, they studied the influence of the normal force on the tangential force during a friction test. The results obtained show that the COF follows Coulomb's law by remaining constant. This result is in contradiction with the results obtained with standard textile surfaces, discussed above, following Bowden and Young's law. Tanaka et al. [20] studied the behaviour of pile surfaces of furs. They indirectly studied the effect of the normal load by studying the influence of the vertical position of the slider compared to the textile base. The tangential force increases strongly when the slider brings it closer to the base. Moreover, the tangential force increases with the bristle length for a given vertical position of the slider.

While previous studies discussed influencing factors and experimental parameters, the friction mechanisms of pile surfaces were not analysed in detail.

The present study focuses on the friction behaviour of different pile surfaces composed of PET fibres with a defined fineness. The objective is to understand the phenomena occurring when a pile surface is rubbed. The influence of measurement conditions (sliding velocity and normal load), the pile density, and pile surface properties is investigated. In order to change the surface tension of pile entities, plasma treatments have been applied on polymer fibres.

2. Experimental method

2.1. Material investigated

In this study we used a pile surface model designed in our laboratory with monofilaments of polyester (polyethylene terephthalate, abbreviated to PET). PET filaments have been chosen because they are the most commonly used type of fibre all around the world [21]. In order to modify the adhesion properties of the polymer, two types of plasma treatments were applied to the monofilaments to change their surface tension. The two treatments have been performed in the presence of dioxygen and argon and mainly differed in duration. The morphological and mechanical properties of these monofilaments are unchanged, having a diameter of 0.205 mm and Young's modulus of 8.2 GPa. The surface tensions are modified by these treatments; the initial filament called NT (non-treated) is more hydrophobic than THI and THO, with a surface tension of 32 mJ m² and a contact angle with water of 85° versus 34 mJ m^2 and 79°.

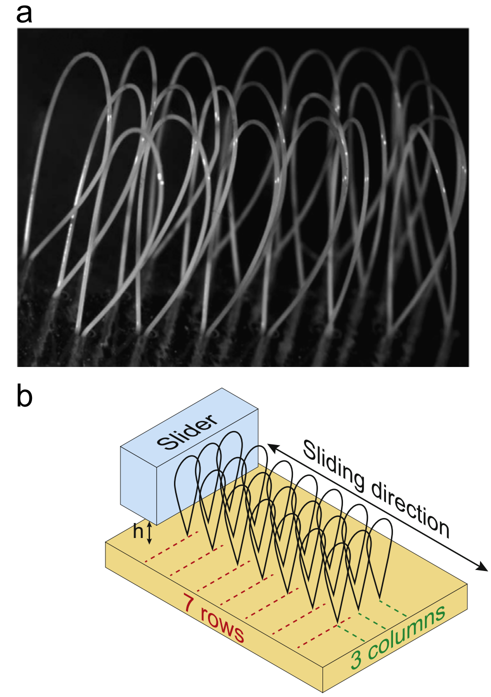

Fig. 1. Loop assemblies, example of a 3 × 7 sample: (a) photograph and (b) diagram.

Two configurations of pile entities have been used. The geometry of these pile entities corresponds to loops (as in terry towels, some sport socks, some carpets, etc.) or a single straight bristle (velvet, corduroy, some carpets, etc.) that is constituted of one set of PET filaments.

Loops or bristles are perpendicularly clamped on a plate by means of a rigid joint. The plate surface is parallel to the sliding direction. A surface of loops can be constituted from one or several loops (Fig. 1). For all these samples, the initial height of a loop is 10 mm and the radius of curvature is 2.5 mm. Different samples have been designed by varying the number of loops along the sliding direction (from one to three columns) and across the sliding direction (from one to seven rows). The distance between rows and the density of loops is also a chosen parameter (3 or 4.5 mm between each row). The distance between columns of loops either does or does not allow a lateral contact between loops. These samples are called i × j (for example 1 × 1 or 3 × 7, and so on), indicating first the number of columns and second the number of rows (Table 1).

The samples in the form of a straight single bristle have a free length of 6 mm.

2.2. Friction measurement

The principle of the experiments consists in rubbing the pile structure with a slider. The forces tangential and normal to the sliding direction, respectively $\mathbf{F_t}$ and $\mathbf{F_n}$, are measured in order to