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Tribological properties of woven para-aramid fabrics and their constituent yarns

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The tribological behaviours of woven fabrics made from Kevlar® (DuPont's registered trademark) yarns of different linear densities were compared with the friction properties of their constituent yarns with different surface treatments. The latter were examined with a traditional friction meter, and the woven fabrics were studied with a pin-on-disc tribometer in alternate and continuous sliding mode. Scoured fabrics, a poly(tetrafluoroethylene)-coated fabric, and fabrics made of surface-treated yarns (polysiloxane oil, hydrophobic paraffin or ester oil lubricant) were compared. These treatments are not representative of commercial Kevlar® yarn finishes but are suitable models for simulating various tribological situations. Both the yarn texture and the surface treatment have an influence on friction coefficient values. Relative humidity affects the friction coefficient only in the case of hydrophilic surfaces, whereas hydrophobic surfaces exhibit fairly constant tribological characteristics. The largest impact on friction seems to be evidenced by the linear density factor. This comparative tribological analysis could lead the way to correlations between yarn friction, weaving performance and woven structure tribological characteristics. © *1998 Kluwer Academic Publishers*

1. Introduction

Para-aramid woven fabrics are known for their remarkable performance, in ballistic protection vests and helmets for example. The heat resistance and strength of the Kevlar® (DuPont's registered trademark) fibres as well as the design and the engineering of energy-dissipating woven patterns have especially contributed to this exceptional success [1]. Briscoe and Motamedi [1] have produced one of the most exhaustive reviews and a modelling approach of the deformation behaviour and the ballistic capture performance of para-aramid fabrics, with special attention to polysiloxane treatments of the woven material.

Para-aramid fibres also replaced asbestos as phenolic resin reinforcement, e.g., in brake pads [2]. In this case, the fibre size, orientation and percentage play important roles in the wear process. Good know-how of the engineering merits of these parameters combined with the tensile strength, the toughness and the breaking strain of the Kevlar® fibres yield better wear resistance. Indeed, scientists [2–4] have confirmed the advantages of these fibres compared with glass and carbon fibre structures.

The advent of the nanotechnologies such as atomic force microscopy (AFM) and scanning tunnelling microscopy have opened up new avenues for a better understanding of the morphological surface attributes of the advanced fibres [5]. Their surface was for a long time described as especially smooth; in fact the surface macromolecular arrangements are complementary attributes which may be confirmed as part of the friction and wear characteristics of the Kevlar® fibres which are beneficial to the brake and clutch end uses.

The dynamic mechanical performance in the matrices of advanced Kevlar® fibres also plays a key role in the interface properties. The dynamic approach [6] may also enhance the scientific understanding of the wear and friction phenomena evolution in the environment of use. Nonetheless, most published work seems to continue to favour the static approach.

With this latter inclination, the friction behaviour of aramid fibres is examined in a few published studies focussing on yarns [1], fabrics [1, 7] and composites [2, 3]. In the present work, special attention is devoted to the para-aramid woven fabrics compared with the Kevlar® yarn properties which they are made of. An especially careful selection of the materials tested as well as of the conditions of measurement has been made in order to obtain meaningful end-use-translatable conclusions without sacrifying the fundamental comprehension of the complex tribological phenomena. This has not been always the case in the previously mentioned studies where sometimes the selected materials are understandably described with commercial criteria lacking precision in terms of their properties and surface characteristics. It is therefore difficult for end users to apply these findings. Although the performance of the ballistic or the friction products is largely affected by its wear and friction characteristics, more attention should be paid to the processing of the base materials which during the manufacturing may lose from 20 to 30% of their core strength if the processing tribological parameters are wrongly appreciated. Unfortunately a literature survey [1–3, 7] tends to demonstrate that the end-use final performance has been to the scientists a more appealing subject than has intermediate material processing. Moreover, in these studies, the test conditions have been oriented towards rather high stresses and strains, while rather low and well distributed forces and deformations are recommended for the processing of high-technology fibres. Therefore a considerable lack of data is to be compensated for in order to predict the processing performance of the high-technology fibre structures.

In the present study, friction properties of different Kevlar® 29 yarns and woven fabrics are determined for different types of weaving construction, model surface treatment and wear mode. Measurements were performed with a pin-on-disc tribometer working either by alternating or by continuous sliding. Results are compared with the fabric constituent yarn properties and discussed. No attempt is made to consider the fairly broad surface-finishing aspects of high-performance yarns since the surface treatments considered here are only model compounds used to simulate various tribological situations.

2. Experimental procedures

2.1. Samples

Various samples of fabric were tested. They were all made of the Kevlar® 29 aramid yarns described in Table I, i.e., a medium-linear-density yarn and a yarn approximately three and a half times heavier. The samples woven from the lighter yarns (0.093 $\mathrm{g\,m^{-1}}$) are plain constructions of 12 × 12 yarns $\mathrm{cm^{-1}}$ in each of the warp and the weft directions of the fabric (referred to in Table II as the yarn count). The heavier fabrics made of 0.33 $\mathrm{g\,m^{-1}}$ Kevlar® 29 yarns correspond to a plain construction with a yarn count of 7 × 7.

The coated yarns (hereafter coded with the prefix Y-; see Table I) used to weave the fabrics, PD3, PD9, PW3 and PW9 (Table II), were obtained by surface treatment with low-viscosity (20 mPa s at 20 °C) aqueous emulsions of a commercial polysiloxane oil and for PW3 and PW9 with a commercial paraffin wax with a melting point of 52 °C. After the coating operation, the yarn surface treatment involved a drying step at 170 °C for few seconds to yield yarns with an approximately active material dry pick-up of 1 wt% fibre. The materials described as EO3 and EO9 (Table II) were simply coated with 1% of a neat commercial ester oil lubricant of a viscosity of 200 mPa s at 20 °C; no further drying step took place in this case.

The sample FC9 is a coated fabric, prepared by exhaustion of a commercial aqueous formulation of fluoropolymers and polymethacrylate. This sample is referred to in Table II as a poly(tetrafluoroethylene) (PTFE)-coated fabric. The fabric was then dried at 130 °C and cured for about 2 min at 170 °C. The scoured fabrics, FF3 and FF9 in Table II, were obtained by extraction of the processing oil in boiling 1,1,1-trichloroethane.

The hydrophobic fabrics, FC9, PD3-9 and PW3-9 were tested against their water repellency properties according to the AATCC 22-1977 spray test procedure developed by E.I. DuPont & Co. This method is widely used to simulate in a simple manner the exposure to rain. Before testing, the wovens were conditioned in an atmosphere of 65 ± 2% relative humidity (RH) at 20 ± 2 °C for at least 24 h. With distilled water at 20 °C all the hydrophobic samples gave a rating above 80, on a scale ranging form 0 to 100. For comparison the hydrophilic samples, such as EO3-9

TABLE I Characteristics of the Kevlar® 29 yarn samples

Sample	Linear density ($\mathrm{g\,m^{-1}}$)	Filaments per yarn	Filament diameter (μm)	Yarn diameter (mm)	Strength (GPa)	Modulus (GPa)
Y-EO9, Y-FC9, Y-FF9, Y-PW9	0.093	570	12	0.31	3.345	93.65
Y-EO3, Y-FF3, Y-PD3, Y-PW3	0.330	1333	15	0.61	2.915	69.92

TABLE II Composition and friction coefficients of the Kevlar® 29 woven fabric samples

Sliding mode	Sample	Yarn surface treatment	Fibre linear density $\mathrm{g\,m^{-1}}$ ($\times 10^4$)	Yarn count per cm of fabric	Fabric friction coefficient[a] ± 0.03 at 96 mm $\mathrm{min^{-1}}$
ASM	PD3	Polysiloxane	3300	7 × 7	0.23
ASM	PW3	Hydrophobic paraffin wax	3300	7 × 7	0.35 (1), 0.38 (2)
ASM	EO3	Ester oil lubricant	3300	7 × 7	0.36
ASM	FF3	Scoured *fabric*	3300	7 × 7	0.38
ASM	FF9	Scoured *fabric*	930	12 × 12	0.55
ASM	EO9	Ester oil lubricant	930	12 × 12	0.27 (1)
ASM	PW9	Hydrophobic paraffin wax	930	12 × 12	0.46
ASM	FC9	PTFE-coated *fabric*	930	12 × 12	0.41
CSM	EO9	Ester oil lubricant	930	13 × 13	0.21 (1), 0.24 (2), 0.28 (3)

[a] (1), (2), and (3) corresponds to independent repeats.

and FF3-9, rate 0, which corresponds to a complete wetting of the upper and the lower surfaces.

All the samples were examined under friction on a poly(vinyl chloride) (PVC) surface.

2.2. Apparatus

Experiments were carried out with a classical pin-on-disc tribometer shown in Fig. 1. Two different equipment configurations have been used: alternate sliding mode (ASM) and continuous sliding mode (CSM).

2.2.1. Alternate sliding mode

The first set of experiments were performed with a pin-on-disc tribometer programmed for an alternate movement of a quarter of a rotation, i.e., a back-and-forth sliding movement with an angular amplitude of 90° on the disc. Compared with a unidirectional displacement, the alternate mode has the advantage of amplifying any anisotropy in the friction coefficient which therewith can be detected. It is presumably a more recommended set-up for fabrics. A poly(methyl methacrylate) (PMMA) pin having a square section of 6 mm × 6 mm is used. The sample, 5 cm × 5 cm, is firmly clamped to the holder over the pin as shown in Fig. 1. In this configuration, the frictional force is measured under either traction or compression.

The rotating disc is a rigid PVC (supplied by Simona) disc 45 mm in diameter and 8 mm thick. The apparatus set-up and the test conditions are as follows: rotation speed, 96 mm min^{-1}, or as otherwise mentioned; applied load, 2.2 N; recording time, 15 min; RH, $50 \pm 5\%$; temperature, $20 \pm 1.5\,^{\circ}$C. From the above settings the speed was also gradually increased to the following values: 262, 480 and 600 mm min^{-1}. Some experiments with the selected samples FF9, PW9, EO9 and EO3 were also conducted at 20% and 90% RH under this alternate mode.

2.2.2. Continuous sliding mode

A second set of experiments has also been run with the pin-on-disc tribometer according to a continuous unidirectional movement. As for previous studies on polymer films [8], the sample, cut into a strip shape and fastened onto the pin holder, is brought into contact with the PVC rotating disc. The disc rotates at a constant speed of 1 rev min^{-1}, corresponding to a linear speed of 96 mm min^{-1}, for a recording time of 50 min. Friction is measured as a function of time with a pair of strain gauges.

The kinetic friction coefficient is the ratio of the tangential force resulting from sliding to the normal applied load, maintained for this set of experiments at 2.2 N (equivalent to a pressure of 0.06 MPa). The experiments are conducted at room temperature and at 50% RH.

For both configurations, ASM and CSM, the coplanar positioning of the pin versus the disc was adjusted using a dummy fabric sample. Prior to this preliminary levelling, which ensures good contact between the specimen and the counterface, the PVC disc as well as the supporting pin were cleaned with ethanol. This operation followed by air drying had no interference on the results.

The standard deviation for the coefficient of friction data, both ASM and CSM modes, is ± 0.03. Results are given as a function of the woven density, the surface treatment, the friction speed and the relative humidity.

2.2.3. Yarn friction measurement

In the case of the yarns the friction coefficients were determined according to the following method.

A package of yarn is threaded through a tensioning device, between a guide roll and two strain gauges, and onto a take-up roll driven by a variable-speed motor. The two strain gauges record the input tension, T_1, and the output tension, T_2. The coefficient of friction is computed according to the formula

$$T_1/T_2 = \exp(\alpha f)$$

where α is the friction angle and f the friction coefficient (fibre to fibre, fibre to metal, fibre to ceramic or fibre to PVC, depending on whether the pin was

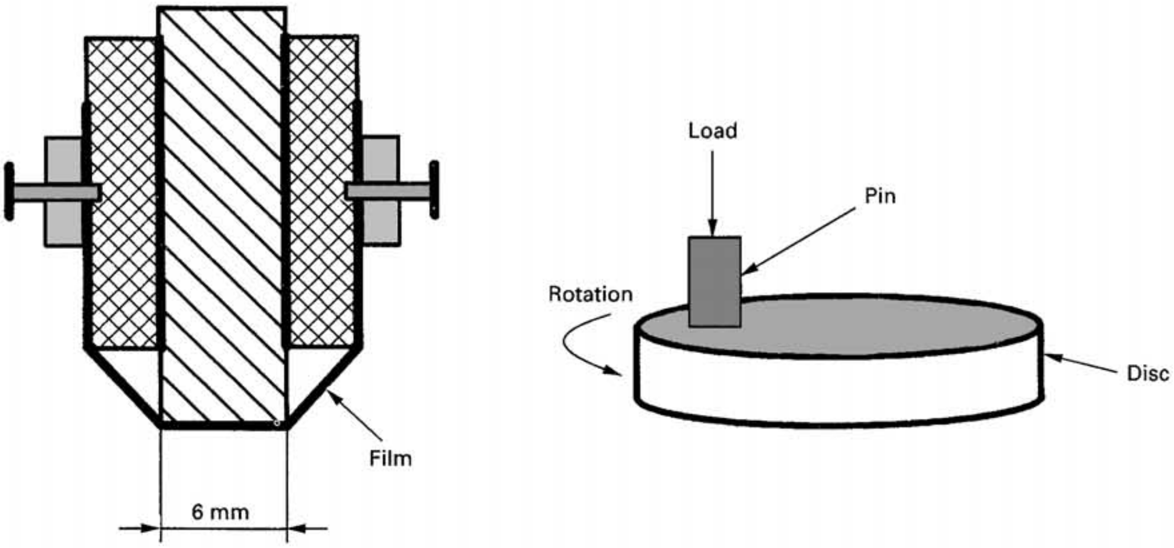

Figure 1 Pin-on-disc tribometer.

covered with fibre or whether a polished or a matt chrome, a ceramic or a PVC pin was used). The Rothschild® friction meter R-1182 was used according to the standard procedure. Yarn friction measurement was also conducted at 20 °C and 50% RH. The input tension was set at 0.3 N. Under these conditions the variability in the results in terms of the 95% confidence limit interval did not exceed 0.03 in the value of the friction coefficient.

3. Results

3.1. Linear density and surface treatment

Table II gives the friction coefficient, as per the ASM described before, for the different samples at the basic sliding speed of 96 mm min^{-1}. Kevlar® wovens having the same density or yarn count, identified respectively with the code termination 3 for the heavier structure or 9 for the lighter structure, give different friction coefficients depending on their surface treatment.

In terms of the latter, fabrics PD3, made of polysiloxane-treated yarns, give lower friction properties than those made of the yarns treated with paraffin, ester oil or fluoropolymers. Scoured wovens, FF3-9, have the highest friction coefficients, up to 0.55; samples PW3-9, made of paraffin-finished fibres, lead also to a high fabric friction coefficient (up to 0.46).

Then, considering only the samples made of the higher-linear-density yarn (0.33 g m^{-1}; code termination 3), one can identify an increase of the coefficient from 0.23 for PD3 (polysiloxane) to 0.38 for PW3 (paraffin wax) and FF3 scoured specimen.

Among the lighter samples, EO9 (ester-oil-treated-yarn) woven has the lowest friction coefficient. This is confirmed under the CSM conditions. In Table II the "independent repeats", made from new samples of the same characteristics and a different operator, are identified by a number in parentheses which represents the rank of these independent duplicated measurements. The reproducibility of the technique under either ASM or CSM is excellent, as shown in Table II.

3.2. Sliding speeds

Table III provides a summary of the results obtained at gradually increased sliding speeds. Samples are renewed for each data point, i.e., for each speed or repeat. The polysiloxane-treated yarn, sample PD3, presents the best friction characteristics over this range of speeds. The poorest friction performance is that of the cleaned sample FF9. The friction coefficient is almost constant as a function of the speed for samples PW3, PW9, FF3, FF9 and EO9. However, an increase in the average stick–slip amplitude (average value $F_{\max} - F_{\min}$ of the frictional forces) at high speeds was observed for samples PW3, FF3 and FF9. The decrease in the friction coefficient between 480 and 600 mm min^{-1}, especially for samples PW9 and EO3, might be attributed to some heat built up at high speeds. In Fig. 2 are shown the recordings of the friction coefficient as a function of time at the different speeds for the PD3 specimen. One can see that constant steady-state values are obtained reproducibly after sliding for 2–3 min.

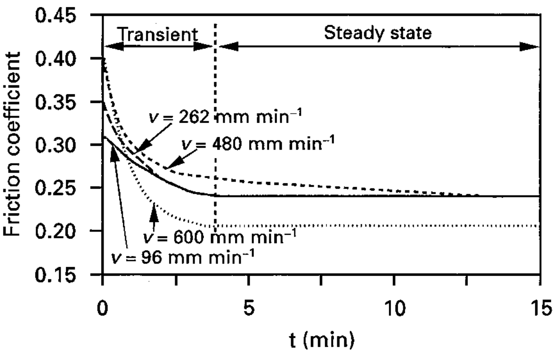

Figure 2 Friction coefficient as a function of time at different speeds, for sample PD3 (ASM; PVC disc; $F_N = 2.2$ N; RH, 50 ± 5%; temperature, 20 ± 1.5 °C).

3.3. Sliding modes

In order to compare the results under the two sliding modes, experiments have been performed with a continuous pin movement; no significant difference, within the experimental error, has been observed, as illustrated in Table IV.

3.4. Relative humidity

Under the ASM, the samples EO9, FF9, PW9 and EO3 are tested at three different RHs, as shown in Table V.

TABLE III Friction coefficients of the Kevlar® 29 woven fabrics at different alternate sliding speeds (ASM)

Fabric sample	Yarn surface treatment	Friction coefficient[a] (± 0.03) at the following speeds			
		96 mm min^{-1}	262 mm min^{-1}	480 mm min^{-1}	600 mm min^{-1}
PD3	Polysiloxane	0.25 (1), 0.22 (2)	0.25	0.25 (1), 0.20 (2)	0.21
PW3	Hydrophobic paraffin wax	0.34 (1), 0.37 (2), 0.38 (3)	0.38 (1), 0.37 (2)	0.33 (1), 0.32 (2), 0.36 (3)	0.52 (1), 0.51 (2), 0.42 (3)
EO3	Ester oil lubricant	0.35 (1), 0.37 (2),	0.52	0.49 (1), 0.51 (2)	0.36
FF3	Scoured *fabric*	0.38	0.38	0.43	0.36
FF9	Scoured *fabric*	0.55	0.51	0.60	0.57
EO9	Ester oil lubricant	0.27	0.28	0.26	0.32
FC9	PTFE-coated *fabric*	0.41	0.42	0.48	0.53
PW9	Hydrophobic paraffin wax	0.46	0.48	0.51	0.43

[a] (1), (2), and (3) correspond to independent repeats.

TABLE IV Friction coefficients of the Kevlar® 29 woven fabrics under CSM ASM at the speed of 96 mm min^{-1}

Fabric sample[a]	Friction coefficient (± 0.03)	
	ASM	CSM
PD3	0.25	0.25
PW3 (1)	0.34	0.34
PW3 (2)	0.38	0.41
EO3	0.35	0.36
FF3	0.38	0.39
FF9	0.55	0.49
EO9	0.27	0.30
FC9	0.41	0.42

[a] (1) and (2) correspond to independent repeats.

TABLE V Friction coefficients of Kevlar® woven fabrics as a function of RH at a speed of 96 mm min^{-1}

Fabric sample	Friction coefficient (±0.03) at the following RH		
	20%	50%	90%
FF9	0.55	0.54	0.40
PW9	0.46	0.46	0.40
EO9	0.34	0.29	0.53
EO3	0.36	0.35	0.22

The result obtained at 50% RH is in agreement with the previous results at the same RH, which, once more, validate the reproducibility of the methods. It appears that this parameter has a strong influence, especially at 90% RH for some wovens.

3.5. Yarn friction characteristics

Yarns sliding on a PVC cylinder lead to values of the friction coefficient given in Table VI. Finish-free (Y-FF3-9)-, ester oil (Y-EO3-9)-, polysiloxane (Y-PD3-9)- and paraffin (Y-PW3-9)-treated yarns of the two linear densities (0.0930 and 0.330 g m^{-1}) have been studied as per the procedure presented previously. At the 96 mm min^{-1} sliding speed, the finish-free yarns, Y-FF3-9, have a friction coefficient of 0.25 regardless of the density. The ester oil samples, Y-EO3-9, have a value of 0.28, the paraffin-treated Kevlar® yarns, Y-PW3-9, lead to a value of 0.24 for the lighter product and to a value of 0.36 for the 0.330 g m^{-1} product. The polysiloxane sample corresponding to this heavier density has a friction coefficient of 0.26, which is constant with speed. Although the variation range for the yarn friction analysis looks narrower than that observed for the fabrics, there are still interesting aspects to be considered.

4. Discussion

4.1. Preliminary considerations

The laws of friction on *dry surfaces* are well established and can be briefly summarized as follows.

1. Friction is proportional to the pressure, and the coefficient of friction is constant versus pressure.
2. The magnitude of the friction for a given pressure is independent of the surface area in contact; this is also valid for the coefficient of friction.
3. The friction coefficient does not vary with relative velocity except that one should distinguish static from kinetic friction in this case.

Of course, as for most laws, they are only valid within some boundaries; for example, friction may differ in the extreme case of a small pressure over a large area versus a high pressure upon a reduced surface area.

These principles and related boundaries become more difficult to define when the surface is *lubricated.* In this case a further simplification is commonly introduced by distinguishing the thickness of the lubricating layer. Generally, thick lubricating films are associated with the hydrodynamic friction while thin films correspond to boundary friction.

Nonetheless, this simplified transfer layer concept and the deduced friction variation principles are insufficient to cover some cases. For example, the same thickness of two oil compositions of the same viscosity provides different levels of friction. The physical, chemical and mechanical interpretations of such phenomena, called the oiliness, are rather complex and remain generally empirically described. The advent of rheology has partially helped to fill the gap although this domain also requires interdisciplinary interpretation skills.

Therefore, prior to the detailed discussion of the specific results obtained in this work, it might be useful to select an organized path structured around simple physical, chemical, and rheological classifications characteristic of the tested materials; the samples studied can be classified as follows.

4.1.1. Chemically: hydrophobes and "hydrophilics"

The hydrophobic surface agents used to weave PD3, PW3-9, FC9 are typical models for water repellents

TABLE VI Friction coefficients of the Kevlar® 29 yarns at different linear speeds

Yarn sample	Yarn surface treatment	Friction coefficient (± 0.03) at the following speeds			
		96 mm min^{-1}	262 mm min^{-1}	480 mm min^{-1}	600 mm min^{-1}
Y-PD3	Polysiloxane	0.26	0.25	0.24	0.23
Y-PW3	Hydrophobic paraffin wax	0.36	0.37	0.37	0.35
Y-FF3	Finish free	0.26	0.27	0.26	0.27
Y-FF9	Finish free	0.25	0.26	0.26	0.26
Y-FF9t	Finish free twisted 100 tpm	0.24	0.21	0.21	0.22
Y-EO9	Ester oil lubricant	0.28	0.27	0.27	0.28
Y-PW9	Hydrophobic paraffin wax	0.24	0.21	0.21	0.22

used for the ballistic vests and outdoor garment water "proofing". These wovens will be later called the hydrophobes.

The hydrophilic surface agents are EO3-9 and FF3-9. The first is made of yarns coated with a processing aid to facilitate, for example, the twisting, the weaving, the knitting or the braiding processes. These manufacturing steps yield intermediate products to engineer end-use parts such as ballistic helmets, hoses and other composite materials. The second category, FF3-9, corresponds to the scoured materials entering the final phases of the manufacturing. It is not surprising that the hydrophilic nature of the EOx class of fibres and fabrics is important to ensure ultraclean FFx fabrics for further treatment during the conversion into the final products. These scoured samples will also be considered as hydrophilic materials owing to the affinity of the base fibre for water.

4.1.2. Physically: porosity and contact area

The samples which are made of treated yarn have the highest porosity, i.e., all except the FC9. Among those can be distinguished the medium-linear-density products corresponding to the yarn linear density of 0.093 g m^{-1} and the 12 × 12 construction versus the rather heavy-density specimens woven from the 0.330 g m^{-1} yarn. These latter samples with a 7 × 7 construction have a higher porosity. Considering a simplified alignment geometry of parallel fibres positioned as cotangent cylinders of the approximated fibre diameters given in Table I, the pore volume per unit area of the woven structure for the higher-linear-density fabrics is about twice that for the lower-linear-density fabrics.

The coated fabric surface can be assimilated to a thin polymeric film owing to the film-forming step to which it is submitted. This is typically the case of the fluorinated fabric FC9, whose surface porosity is much lower than that of any other material tested in this work.

This porosity characteristic translates into surface roughness levels and consequently different localized pressures for a given load.

4.1.3 Rheologically: melting point and viscosity

The samples coated with liquid lubricants and/or hydrophobes such as the ester oil and the polysiloxane-coated fibres yield fabrics (PD3 and EO3-9) with a thin liquid interfacial film. In this category may be included, to a certain extent, the scoured samples (FF3-9) owing to regaining the water equilibrium of the base material, which varies from 6 to 9 wt % depending on the RH. At this stage it seems that the viscosity and temperature stability of these liquid films may be important considerations for further discussion. For example, the ester oil used as lubricant exhibits a viscosity change of 110 mPa s between 20 and 35 °C and starts to degrade partially around 200 °C. The polysiloxane on the other hand has an extreme temperature resistance (above 280 °C) and a fairly moderate viscosity change with temperature.

For the samples with a solid hydrophobic and/or lubricating film, such as the paraffin wax specimens, PW3-9, and the fluorinated polymeric-coated material FC9, two further distinctions might lay the ground for further reflections, i.e., the first has typically a molecular-like structure with a low melting point of about 52 °C, while the second is a polymeric structure cured at about 180 °C with a generally considered higher tear resistance.

The above considerations should lead to a "reader-friendlier" analysis of the results which follow.

4.2. Tribological behaviour of Kevlar®

In view of the complexity of the tribological behaviour of para-aramid fabrics and fibres [1–3,7] it appeared essential at the start of this study not only to complement the data already available but also to define a clear and reachable industrial objective. Therefore an experiment plan and a set of testing parameters in accordance with the real manufacturing world had to be designed. Deliberately an attempt to simulate the wear and friction, which occurred during weaving of ballistic fabrics, quickly became a target meeting the two criteria mentioned above.

Weaving and the preliminary warping operations involve controlled tensions ranging from 1.5 to 12 N depending on the yarn linear density and the particular processing steps. The experimental results here discussed were obtained under a tension of 0.3 N for the yarn friction analysis and a normal force of 2.2 N for the fabric tribological characterization. Another important parameter is the weaving speed, which generally ranges between 150 and 300 mm min^{-1} depending on fabric construction and density. The speed for this study was set between 100 and 600 mm min^{-1}, which covers fairly well industrial practice.

Considering the above, interesting points can be discussed on the basis of the results given in Tables II–VI and Figs 3–5.

4.2.1. Linear density and surface treatment (Tables II and VI and Fig. 3)

Table II and Fig. 3 clearly outline at 96 mm min^{-1} the excellent performance in terms of friction of the polysiloxane and ester oil treatment to yield yarn and

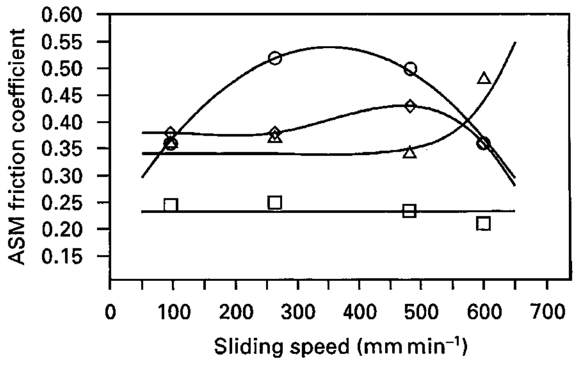

Figure 3 Frictional properties of various fabrics made of surface-treated Kevlar® yarns as a function of the sliding speed. (□), PD3 Polydimethylsiloxane (PDMS); (△), PW3 (paraffin wax); (◇), FF3 (scoured); (○), EO3 (ester oil).

fabric of extremely comparable friction coefficients close to 0.25 (see PD3, YPD3, EO9-ASM, EO9-CSM and Y-EO9 in Tables II and VI). These two liquid-state lubricants at this speed, although one is hydrophobic and the other hydrophilic, are equivalent. Furthermore the yarn friction predicts well the fabric surface friction.

At the other extreme and at the same speed the low-density scoured fabric FF9 gives a high coefficient of friction of 0.55. The equivalent yarn Y-FF9 does not reflect this situation with a coefficient of friction of 0.25 which is as low as the well-lubricated yarns given above. Furthermore the higher-density fabric FF3 made of the Y-FF3 equivalent yarn, which also has a low coefficient of friction of 0.26 (Table VI), exhibits at 96 mm min^{-1} a moderate friction coefficient of 0.38. A possible explanation for this observation may be in accordance with the fact that fibrillation occurs at the surface of the lower-density fabric which has more cross-over contact points where this phenomenon is favoured. In this latter case a key conclusion is that the finish free yarn friction levels misrepresent the corresponding wovens.

For the solid-state hydrophobes, either the coated fabric FC9 or the paraffin-waxed surfaces PW3-9, still at 96 mm min^{-1}, the friction levels correspond to medium to high coefficients ranking from 0.35 to 0.46 (Table II). Once more the higher-density fabric PW3 presents a slight advantage versus PW9 and also shows a slightly better friction performance versus the lowest surface porosity "PTFE-like"-coated fabric FC9. Therefore this may suggest that the wax material is favoured in terms of lubricating performance under the conditions of the measurements. Only the Y-PW3 friction level seems to correlate well with its fabric counterpart while the lower-linear-density Y-PW9 shows much better properties (0.24 in Table VI) than its corresponding fabric.

4.2.2. Sliding speeds (Table III and VI and Fig. 3)

A striking observation is that none of the yarn coefficient of friction varies significantly with the speed range studied (Table VI) while significant variations are observed for the wovens (Table III and Fig. 3). Nonetheless, Kevlar® yarns are known to exhibit friction variation with the speeds as shown in Table VII for a wider range of speed. Assuming as shown in other work [8] that the PVC counterface disc represents well the behaviour of steel, one can make the interesting remark that the ester oil-treated yarn exhibits a constant friction coefficient over a thousandfold speed increase, i.e., a coefficient of friction of 0.28 at 96 mm min^{-1} (Table III for EO9) versus 0.27 at 77×10^3 mm min^{-1} in Table VII. Then a significant increase occurs during the following three folds increase (Table VII). This situation would be more typical of a hydrodynamic friction pattern where the frictional resistance is proportional to the contact area and the relative velocity and inversely proportional to the lubricating film thickness. In view of the above, a direct interpretation of the bell-shaped curve for the samples EO3 in Fig. 3 might be provided as follows.

The initial speed increases for 100–500 mm min^{-1} associated with an eventual heat build-up may reduce the local moisture content of the lubricant, leading to a higher viscosity, and possibly a stick–slip type of local rheology yielding higher frictional resistance. A further increase in the speed may provoke a favourable heating which would have a significant effect on the oil film viscosity since, as mentioned before, a substantial viscosity change occurs for this product between 20 and 35 °C. A second explanation can be linked to a mass transfer, leading to a finish-free-like contact which therefore explains the reason for the comparable friction level of EO3 and FF3 at 600 mm min^{-1} as shown in Fig. 3. This is supported by the fact that, assuming a cocylindrical uniform distribution of the ester oil around the fibre, the oil film thickness would not exceed a few microns while the surface fabric irregularities could be several hundreds time deeper. In this case a mass transfer of the oil is plausible at a certain speed, although this is not in agreement with the idea of a plentiful supply of oil generally assumed for the hydrodynamic friction pattern mentioned above. In this case, one should not be surprised at the difference observed between the rather smooth yarn and the higher-porosity fabric.

The performance of the polysiloxane lubricant is once more confirmed in the analysis of the speed effect (Fig. 3). On the other hand the paraffin treatment may suffer from a potential heat build-up at high speed causing a stick–slip effect due to the relatively low softening temperature and shear resistance of the wax (PW3 in Fig. 3). This factor would be more obvious for the higher localized pressure occurring for PW3 versus PW9 (Table III).

TABLE VII Reference friction coefficients

Samples	Friction coefficient (± 0.03)		
	9.6 mm min^{-1}	77×10^3 mm min^{-1}	2×10^5 mm min^{-1}
Kevlar® (0.167 g m^{-1})[a], fibre to fibre	0.22	0.27	
Kevlar® (0.167 g m^{-1})[a], fibre to metal	0.05	0.27	0.55
Dry oak [9]	Static		Kinetic
Perpendicular fibres	0.43		0.19
Parallel fibres	0.63		0.49

[a] Yarn of this study was treated with 1% ester oil as for Y-EO9.

The fibrillation propensity of the scoured woven, FF3 in Fig. 3, may reach a peak at 400–500 mm min^{-1} although this tendency is not very clearly exhibited in the results. A second explanation of the FF3 behaviour might be linked to a water mass or heat transfer which would reveal that the dry polymer is moderate-friction type of product. The solid polymeric hydrophobe FC9 sample may be peeled off at higher speed, leading the observed friction increase given in Table III.

4.2.3. Relative humidity (Table IV and Fig. 4)

For the scoured hydrophilic FF9 sample it appears quite clearly that the unfavourable electrostatic effect on the friction at low RH (20%) disappears at higher RH (Fig. 4), while for the other hydrophilic material EO9 an increase in the RH leads to a deterioration in the friction probably associated with local plasticization. This observation is not validated in the case of the higher-density material (Table V), possibly because of a higher mass transfer of the finish at the contact point which is well compensated by the lubricating properties of water at higher residual humidity. In the case of the hydrophobic PW9 specimen the water barrier effect contributes to an accumulation of water as a boundary layer on the fabric surface, reducing the friction resistance as shown in Fig. 4.

4.2.4. Sliding Modes (Table V and Fig. 5)

Friction properties of most of the material tested are not affected by the sliding mode except for the scoured material FF9, confirming the earlier hypothesis associated with the fibrillation of the material which is apparently aggravated by the alternate movement.

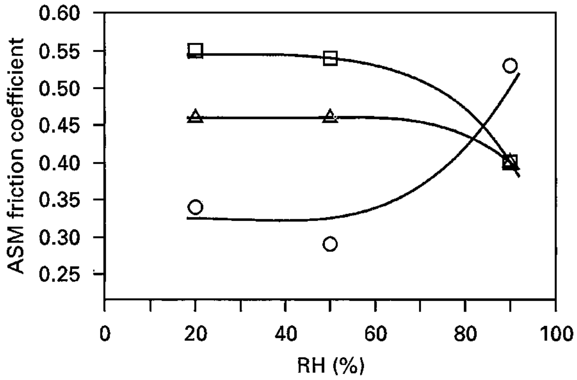

Figure 4 Friction coefficient variation of various Kevlar® fabrics as a function of the RH. (□), FF9 (scoured); (△), PW9 (paraffin wax); (○), EO9 (ester oil).

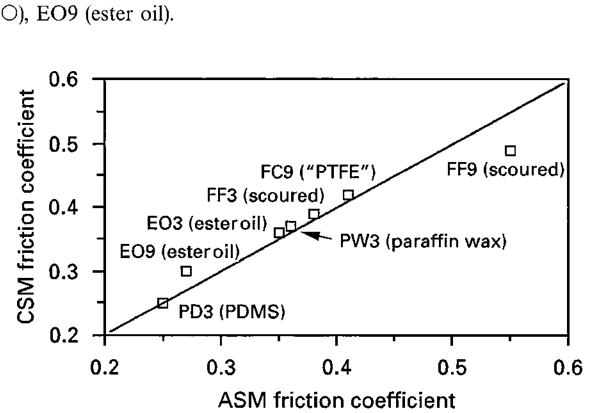

Figure 5 The sliding mode effect on the coefficient of friction of Kevlar® fabrics made of various surface-treated yarns.

5. Conclusion

The friction properties of Kevlar® woven fabrics have been characterized with a pin-on-disc tribometer, as a function of yarn surface treatment, fabric texture, yarn linear density, sliding speed and mode, and RH. Results were compared with the fabric constituent yarn tribological properties measured with a traditional friction meter. The polysiloxane and the ester oil treatments showed relatively low friction, whereas the yarn or the fabric treatment with a hydrophobic "solid" coating generally increased the friction coefficient. The worst situation occurred when the fabrics were scoured. In contrast, the ester oil treatment led to good friction properties, especially for lighter fabrics. In a very general way, the results are in agreement with those obtained in the study of biphasic polymeric materials containing polysiloxane, paraffin or fluorinated oil inclusions [10] which showed a better sliding with the polysiloxane inclusions.

The texture of the wovens is an important factor, in comparison with those of the yarns whose friction properties generally misrepresent the fabric performance. In general, the friction coefficient is lower for the woven fabrics made of the higher-linear-density yarn and therefore the lower yarn count. It seems that the number of contact points, being higher with the lighter fabric, is especially detrimental to the friction when there is a tendency for fibrillation or peeling. The reverse is observed when the surface treatment is a lubricating liquid film which can be partially removed by mass transfer under higher localized pressure. Recent tribological investigations of textile fabrics [7–11] show that textile roughness also has an influence on the frictional behaviour. This was confirmed in some cases of the present work where we observed a discrepancy between frictional characteristics of the yarn and the corresponding fabric under the same testing conditions.

The sliding speed does not have a great influence on the friction coefficient value, except for the materials woven from paraffin- or fluorine-treated fibres which are sensitive to shear. RH, in particular at 90%, increases noticeably the friction coefficient of the hydrophilic lighter fabric only, while it becomes a favourable environment for hydrophobic and scoured surfaces.

Paraffin-treated and fluorinated surfaces did not result in a great improvement in the tribological performance. The polysiloxane surface treatment seems more efficient but should be examined with a larger range of textures. The surface treatment and the texture are definitely the two main factors in Kevlar® woven fabric friction properties. Since none of the yarn surface treatments represents commercial surface finishes of high-performance yarns, no attempt should be made to use this study as a finish selection guide. This work should merely indicates a way to correlate yarn and fabric properties towards enhanced processing flexibility and predictability.

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