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Friction of carbon tows and fine single fibres

Michel Tourlonias [a,*], Marie-Ange Bueno [a], Dominique Poquillon [b]

[a] *Laboratoire de Physique et Mécanique Textiles, Ecole Nationale Supérieure d'Ingénieurs Sud Alsace, University of Haute-Alsace, 11 rue Alfred Werner, 68093 Mulhouse, France*
[b] *CIRIMAT, Université de Toulouse, 4 allée Emile Monso – BP 44362, 31030 Toulouse Cedex 4, France*

A B S T R A C T

The aim of this study conducted on carbon tows and single fibres is to highlight some friction behaviours to help better understand the friction mechanisms that occur during the manufacture of carbon composites. These mechanisms are responsible for damage that reduces the specifications and lifetime of mechanical parts. An experiment has been developed in order to rub together two carbon tows, or two single carbon fibres (with a diameter down to 5 μm), at an angle of 90°. The influences of friction velocity, normal load, and type of carbon fibre have been studied. For both tows and fibres the friction follows the Coulomb's law because there is no influence of the velocity and the normal load in the tested range. The rearrangement of fibres within the tow has been shown to be fundamental. For the single fibre, the role of the Young's modulus and the sizing treatment is important.

Keywords:
A. Carbon fibres
A. Tow
B. Wear
Friction

1. Introduction

Nowadays, carbon is often used as reinforcement of composite materials. Most of the time, this carbon is in the form of tows. These tows, made of multifilaments, are woven in most cases. According to the application, the interlacement of the tows, that is, the kind of weave, can change. The main goal of these materials is to assure the required mechanical properties in specific directions while minimising the global mass of the mechanical part. The most important domains for use of these materials are transportation (automotive, aeronautics, rail) and aerospace.

During the process from the manufacture of the carbon tows to the implementation of the composite reinforcement, carbon tows are handled and have to undergo several mechanical stresses. Besides tension, torsion, and shear, for instance, friction mechanisms occur, which can damage the carbon tows by defibrillation and even lead to breaking of the fibre. This damage occurs during the process from spinning of the carbon filament to weaving [1–4], and can take place between tows and certain parts of the machine (especially metallic parts) or between tows. For these reasons, study of the friction phenomena and wear of the carbon fibres is very important because defects created during the manufacturing process of the composite material will induce defects in the final composite component. These defects can reduce the mechanical properties and the lifetime of structural components. By considering the weaving process, friction can occur during the reed beating-up between warp and weft tows. At the moment of the process, motion between the tows is orthogonal and can be considered as a contact point friction.

Two types of friction measurements of tows or fibres are proposed in the literature [5–7]: tow or fibre against tow or fibre, respectively, or tow or fibre against another material. The method used in the case of the friction between a single fibre or tow and another material is the capstan method (from Jean Bernoulli, eighteenth century) [8–10]. For fibre–fibre or tow–tow friction measurement, two kinds of contacts are proposed: (i) point contact, where the tows (yarns) or fibres are crossed together, and (ii) linear contact, where the tows or fibres are twisted together. The second method proposed by Lindberg and Gralen [11] was used as a standard test method detailed by the ASTM Committee [12]. The coefficient of friction (COF) is obtained from a modified capstan method. There are few methods where the contact between fibres or tows is a point contact. For rigid fibres, it is possible to use the cantilever method proposed by Pascoe and Tabor [6,13] and by Briscoe and Kremnitzer [14]. A fibre is clamped under tension on both ends and the other fibre is clamped-free, i.e. an end is clamped and the other is free. The clamped-free fibre is pressed against the clamped fibre, which is clamped under tension. The COF is deduced from the lateral and normal deflections of the clamped-free fibre. This method can also be applied to tows. Another device has been developed for fibres by Howell [15]. A fibre is suspended under a fixed tension given by a weight and is in perpendicular contact with a second fibre. This fibre clamped at both ends under stress has movement in the direction along its axis. The COF is deduced from the maximal displacement of

* Corresponding author.
E-mail address: michel.tourlonias@uha.fr (M. Tourlonias).

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the first fibre during the displacement of the second fibre, which rubs against it. Next, the capstan method makes it possible to determine the friction between tows insofar as the cylinder is recovered by glued tows [12]. The cantilever, capstan, and Howell methods are all suitable for static friction measurement. El Mogahzy and Gupta's method is derived from the capstan and the Howell's method, where the suspended fibre has continuous movement that makes it possible to obtain the kinetic COF [16].

Cornelissen et al. also used the capstan method. It consists of evaluating the friction between one tow and a bundle of parallel tows. It has also recently been used in order to determine the friction behaviour between carbon tows and carbon woven fabrics [17,18]. Chakladar et al., using the capstan method, studied the influence of the friction angle between counterpart tows [19]. A previous study by the authors of the present paper was dedicated to the simulation of the friction between warp tows during the weaving process [20].

However, no method has yet been proposed to study the friction between single carbon fibres with static and kinetic friction measurements.

The aim of the present paper is, first, to simulate the friction phenomena between warp and weft tows with an experimental set-up, which consists of an orthogonal motion similar to the movement occurring next to the reed. Moreover, an experiment developed in this study made it possible to rub single fibres together with an orthogonal movement. This study at the fibre scale is linked to the global behaviour of carbon tows in the same kinematic conditions.

2. Experiment

2.1. Carbon tows and fibres investigated

The study was carried out on carbon tows manufactured by Toho Tenax Europe GmbH. Three kinds of tows with similar fineness are used. The main difference between these tows arises from the Young's moduli of the constitutive carbon fibres, called SM (standard modulus), IM (intermediate modulus), and HM (high modulus), which are 240, 290, and 390 GPa, respectively. The main tow characteristics are summarized in Table 1. One can note that the fibre diameter, whose cross-sections are considered as circular, also differs according to the filament type. The diameters are 7, 5, and 4.9 μm for the SM, IM, and HM samples, respectively.

2.2. Friction experiment

The objective is to rub together two perpendicular samples of tows or single fibres and to measure the friction forces. Measurements are performed by means of an NTR2 nanotribometer (CSM Instrument Company, Peseux, Switzerland). This device was originally a pin-on-disk tribometer with reciprocating movement allowed (Fig. 1). Specific sample carriers have been designed for this experiment to affix the carbon tow or the single carbon fibres (Fig. 2a and b). The first (and lower) sample is fixed onto the rotation stage. It follows a circular motion, allowing relative alternative movement. The upper sample does not move and is orthogonal to the first one in its central location (Fig. 3), so the device leads to a

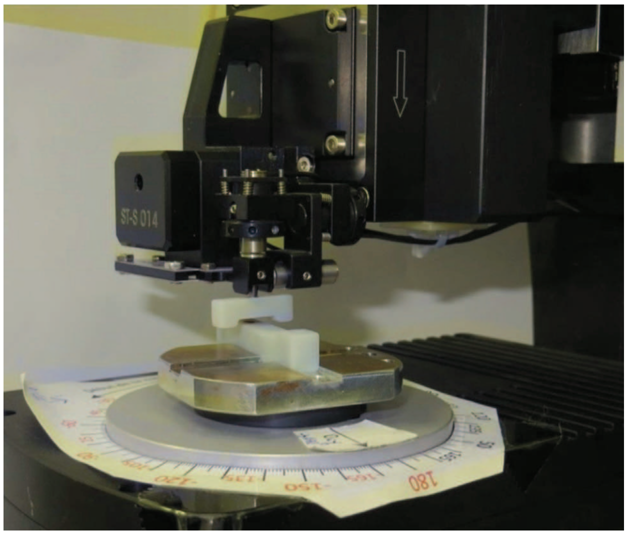

Fig. 1. Picture of the nanotribometer in the specific fibre carrier developed in the laboratory. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

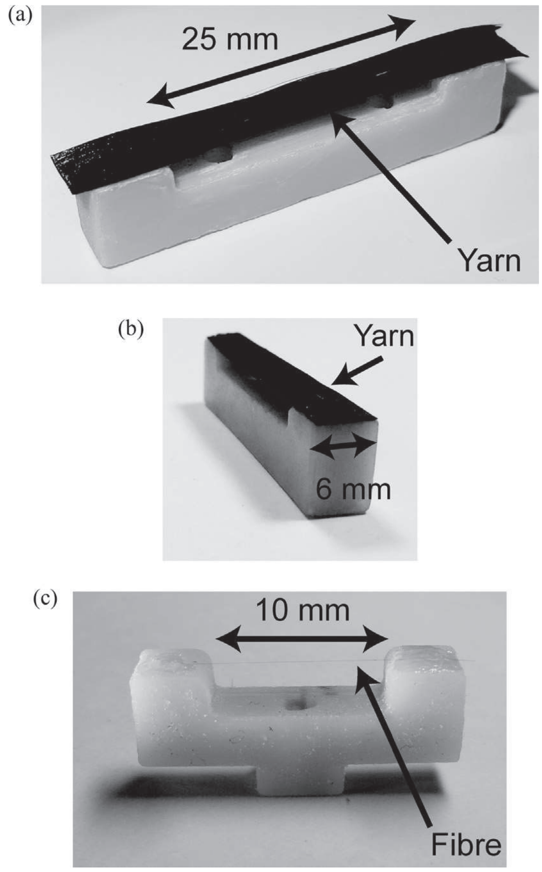

Fig. 2. (a) Tow and (b) fibre samples on their specific sample carriers.

Table 1
Mechanical properties of tested carbon tows.

Yarn sample	Fibre diameter (μm)	Young's modulus E (GPa)	Number of filaments per section (K)	Nominal linear density (tex)
SM	7	240	12	800
IM	5	290	24	830
HM	4.9	390	24	800

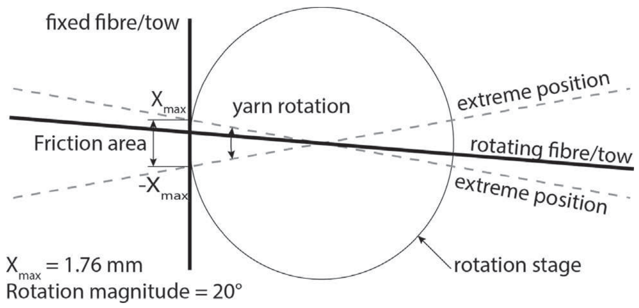

Fig. 3. Schematic of friction experiment.

perpendicular friction of the lower fibre onto the upper one. This second sample carrier is fixed to a cantilever, which allows the normal and friction forces to be measured during the experiment by means of capacitive sensors whose force range in each direction is 1 N or 100 mN, respectively, for tow or single fibres.

In this study, the distance between the upper sample and the lower sample is chosen at the beginning of the test and remains unchanged during the whole test. The normal force is a parameter adjusted at the beginning of one experiment and is recorded during the test. In the case of tow friction experiments, normal load has been estimated from the weaving conditions [20]. For single fibre experiments, normal load is between 5 and 10 mN, which is probably overestimated in comparison to the tow friction conditions. It is chosen to obtain a favourable signal-to-noise ratio.

The oscillation motion is limited to ±10° and the friction occurs 10 mm from the rotation centre. Due to this small angular amplitude, the motion between the samples can be assumed to be orthogonal even if the specific kinematics of the device induces a small lateral displacement (Fig. 3). This displacement is estimated to have a value of 0.15 mm and can therefore be neglected. The sliding distance is about 3.4 mm in length for half of the cycle.

During the friction test, the normal and friction forces are recorded and the COF is computed from these two signals. The data acquisition frequency is 400 Hz for both forces.

The experimental conditions in terms of angular amplitude, number of cycles, and normal load are summarized in Table 2.

The number of friction cycles is chosen as 100 for single fibres (if the fibre does not break during the friction test) and 300 for carbon tow. For information a yarn piece is submitted to more than a thousand cycles during the weaving process [20]. After a maximum of 40 cycles, an asymptote is reached for all the configurations tested in this study.

The oscillation frequency of the rotation stage is 0.5, 1.5, or 3 Hz. These frequencies are close to the weaving speed, i.e. three to five beatings per second. The velocity follows a sinusoidal profile, and these test frequencies correspond to the maximum velocity range of 5.5–33 mm s^{-1} depending on the oscillation frequency. This sliding velocity is the maximum linear velocity at the contact of the two samples that corresponds to the central location (Fig. 3).

Each sample is glued to the dedicated sample carrier under an initial longitudinal tension. This tension, given by the mass of a small piece of adhesive tape, is around 0.2 mN for single fibres. For carbon tow, it is given from a clamped suspended mass and is 0.35 N. It is obvious that all the fibres cannot have the same tension in the tows after being fixated in the sample carrier, however it is similar during the weaving process.

The most delicate operation is gluing the fibres on the sample carrier without breaking them, and with the target pre-tension. Because of the small diameter, the handling of a carbon fibre remains a difficult task. During the setting up of the sample, one end of the fibre is glued and the pre-tension is given by suspending the desired mass at the other end. Then, this end is also glued (Fig. 2). The same steps are done for the upper and lower fibre carriers. Sample preparation with tows follows the same steps but the handling is much easier. Friction tests are realized after the glue is dry, that is, after approximately 2 h at room temperature, as the glue used is Loctite Super Glue-3.

The lengths of the fibre samples are 10 and 14 mm for the upper and lower samples, respectively. For the tows, the lengths are 20 and 25 mm for the upper and lower samples, respectively.

The friction test begins as the rotating tow is located at an extreme angular position, and the rotation direction of every test starts in the same direction.

The dimensions of the samples and the experimental conditions have been chosen to be close to the weaving conditions and are adapted to the experimental device and the possibility to set up the samples.

Results are expressed by the instantaneous evolution of the friction force, the normal force, or the COF versus the angular position during a friction cycle. The average cycle relative to the angular position is also computed and studied. The average of the friction force (Ft), the normal force (Fn), and the COF can be computed for each cycle. The evolutions, during cycles, of these average values can also be followed during a friction test.

Table.2
Chosen experimental conditions for fibre and tow carbon samples.

Friction test conditions	Fibres	Tows
Angular amplitude	20°	
Reciprocating frequency	0.5/1.5/3 Hz	
Sliding velocity	Max speed 5.5/16.4/32.9 mm s^{-1}	
Friction duration	100 cycles (if possible)	300 cycles
Sample longitudinal tension	0.2 mN	0.35 N
Initial normal load	5/7.5/10 mN (if possible)	300/600/900 mN
Sample length	Upper sample: 10 mm Lower sample: 14 mm	Upper sample: 20 mm Lower sample: 25 mm

3. Results

3.1. Evolution of the coefficient of friction relative to the number of cycles

To study the evolution of the COF during friction, the analysis of the experimental data can be divided into two parts. The first part concerns the average friction cycle according to the angular position. In Fig. 4a, five average curves have been plotted and the curve shown as a bold black line corresponds to the average of these five different tests.

The general form of these cyclic graphs is symmetrical, which means the behaviour is the same in the two friction directions. This tendency is the same whatever the experimental conditions. If the whole tow is studied, the parallelogram shape of the curve obtained is also similar and is in concordance with the simulation of Durville [21]. In this simulation the COF and the normal force are fixed and the friction force is computed relative to the displacement of the fibre.

The same friction cycle curves have been plotted for tows in Fig. 4b. These graphs also make it possible to highlight the good reproducibility of the measurements for single fibres as well as for tows.

In the second part, the evolution of Fn, Ft, and COF during the friction test can be studied. Fig. 5a presents the results obtained

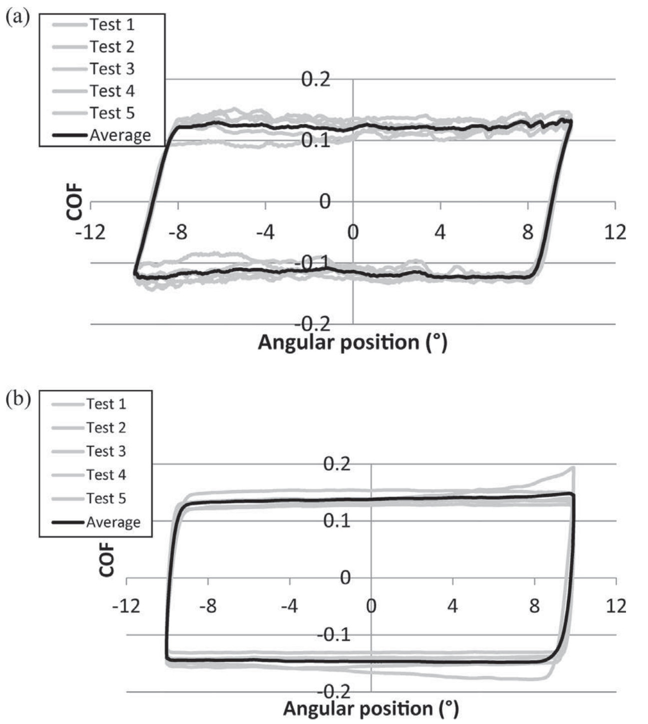

Fig. 4. COF cycle and the average curve for (a) single fibre friction test and (b) tow friction test, for the case of an oscillation frequency of 0.5 Hz, SM fibres, and initial normal loads of 5 and 600 mN for single fibres and tows respectively.

for single fibre friction. During the test, Fn remains constant but the COF decreases because of the decrease in Ft. That means there is no modification of the geometrical configuration of the system constituted by the fibre and the sample carrier but the evolution of the COF comes from the interface between fibres and their contact.

If we consider the same study for tows, the curves obtained for Ft and the COF have similar shapes to those obtained for the single fibre but there is a significant decrease of Fn (Fig. 5b).

Whatever the experimental conditions in terms of sliding velocity, normal force, or type of carbon fibre, the following two behaviours are observed: first, a decrease of the friction force for the fibres with a normal force remaining constant and second, a decrease of both the friction and the normal force for the tows. In consequence, the COF decreases with the number of cycles during the beginning of the test, before reaching stability, for both single fibre and tow friction tests.

3.2. Influence of the velocity

The influence of the velocity on the friction behaviour is studied through the results obtained for the three values of friction reciprocating frequency: 0.5, 1.5, and 3 Hz (Table 2). For the study of single fibres, the initial normal load is 5 mN, while for tows the initial normal load is 600 mN. Tests have been performed with the SM tows and fibres. The average cycle relative to the angular position corresponding to 100 cycles is considered for single fibres (Fig. 6a). As explained previously, no change is recorded due to the direction of friction, and the cycle always remains symmetrical. When the steady state is reached, the COF remains constant and does not depend on the sliding velocity. However, if we focus on the changes in the friction direction, small differences appear as it takes longer to reach the steady state for the higher friction velocity. This can be explained by the viscous behaviour of the whole system composed of the sample, the glue, and the sample carrier and/or a adhesion mechanism between the two fibres [21].

The evolution of the COF is studied during friction tests (Fig. 6b) for both tows and carbon fibres. In the range of velocities tested, the COF limit value is independent of the test velocity. However, it takes longer to reach the asymptote for tows than for single fibres.

3.3. Influence of the initial normal load

In order to study the influence of the initial normal load, specific tests have also been performed with SM fibres and tows. The friction frequency is set to 0.5 Hz and the normal load values tested are 5, 7.5, and 10 mN for fibres and 300, 600, and 900 mN for tows. The number of cycles remains the same as for the previous tests but some tests with carbon fibres are shortened due to premature rupture of the single fibres.

The shape of the COF cycles is similar to those previously plotted, as illustrated in Fig. 7a. When the steady state is reached, no difference appears due to the initial normal load. The change in the sliding direction is faster at low normal load. This can be explained by the viscous behaviour of the whole system composed of the sample, the glue, and the sample carrier and/or adhesion mechanism.

For both tows and single fibres (Fig. 7b), the COF does not depend on the initial normal load in the range of normal load used. As for the influence of the sliding velocity, the asymptote is reached more quickly for single fibres.

3.4. Influence of the fibre material

The third part of the study is devoted to the influence of the material of the fibre. Friction tests have been performed with three different types of carbon fibres as described in Section 2.1. In this part, the oscillation frequency is 0.5 Hz while the initial normal loads are 5 and 600 mN for single fibres and tows, respectively.

When the asymptote is reached, a difference appears between the friction behaviour of the different fibres tested. The COF increases with the Young's modulus (Fig. 8a and b). In fact, with a similar diameter, the IM- and HM-type fibres have Young's moduli of 290 and 390 GPa, respectively (Table 1). In contrast, the COF of the tows does not seem to depend on the fibre type (Fig. 8b).

4. Discussion

4.1. Influence of the fibre material: single fibre friction measurements

In order to analyse the influence of the fibre material, in a first approach it has be assumed the Hertz's theory [22] can be used to the contact between two fibres that are orthogonal. Each fibre can be modelled as a cylinder and the contact between two crossed cylinders whose diameters are equal is similar to the contact between a sphere and a plane (Fig. 9a and b). Thus it is possible to compute the theoretical contact area during the friction. For this study, carbon fibres have been considered to be isotropic, and therefore the axial Young's modulus indicated in Table 1 is used for the calculus. In fact, it has been established [23–26] that carbon fibres are not isotropic. However it is assumed the higher the axial modulus, the higher is the transverse modulus. In the light of these considerations, it has been established that:

$$a = \sqrt{Rd} \tag{1}$$

with

$$d = \left(\frac{3F_n}{4E^* R^{\frac{1}{2}}}\right)^{\frac{2}{3}} \tag{2}$$

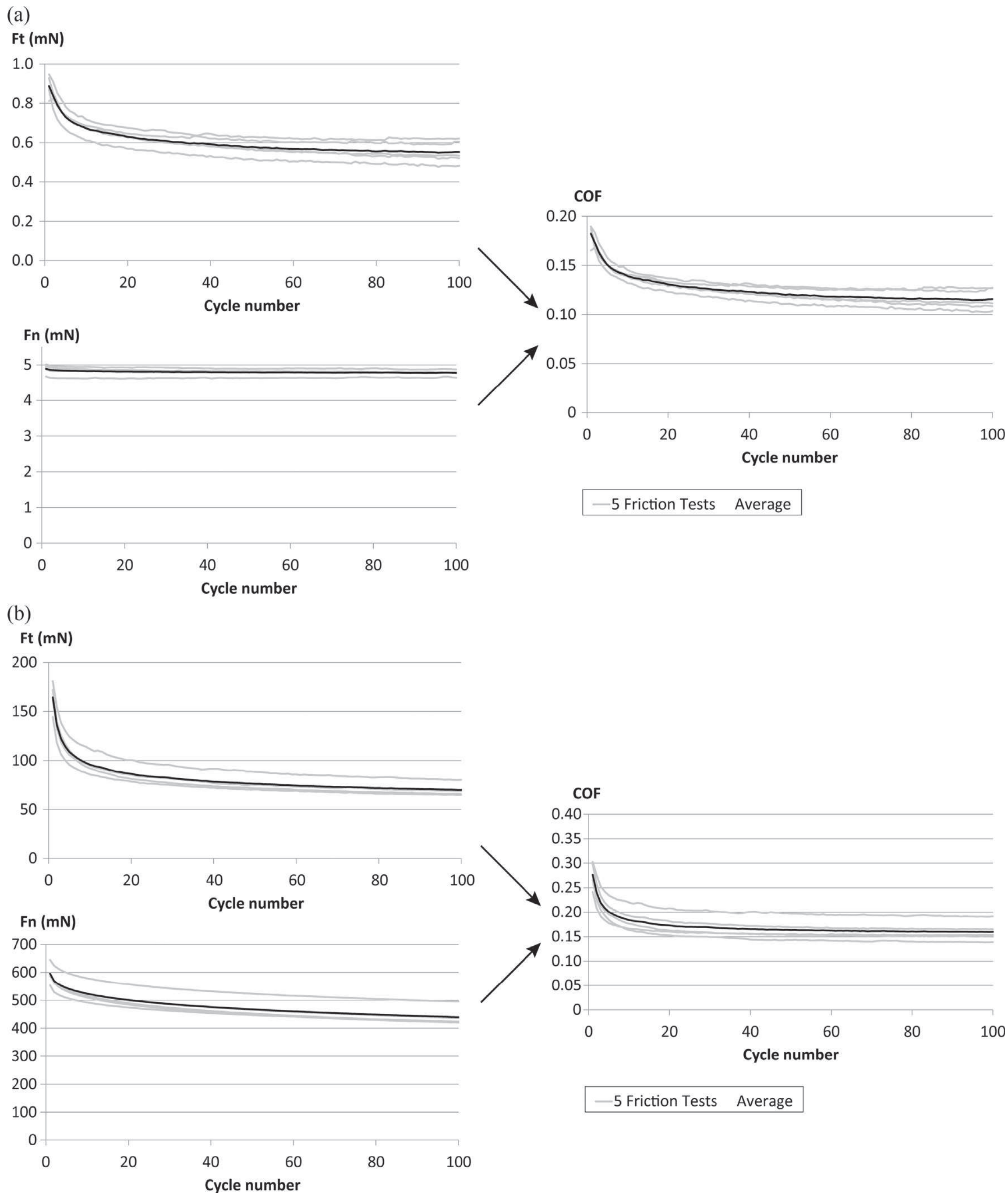

Fig. 5. Ft, Fn, and COF evolution curves during the friction test for (a) single fibre friction and (b) tow friction. Five experimental tests and the average curve for the SM sample at an oscillation frequency of 0.5 Hz and an initial normal load of 5 mN for single fibres and 600 mN for tows.

and

$$\frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} = \frac{2 \times (1-v^2)}{E} \tag{3}$$

Then

$$A = \pi a^2 \tag{4}$$

where

$E = E_1 = E_2$ is the Young's modulus of the carbon fibre,
$\upsilon = \upsilon_1 = \upsilon_2$ is the Poisson's ratio of the carbon fibre,
F_n is the normal force,
R is the radius of the carbon fibre,
d is the approach of centres,
a is the radius of the contact area, and
A is the contact area.

Thus it is possible to evaluate the approach of centres and the contact area for each kind of carbon fibre for the initial normal force of 5 mN. These values have been computed with the real experimental normal force and the data are summarized in Table 3.

The SM fibre, which is most commonly used as composite reinforcement, is assumed to be the reference. The IM and HM fibres present very similar diameters (a small difference in diameter of 1% differentiates these two fibres from the reference fibre). Hertz's theory makes it possible to estimate the approach of centres and the contact area. Compared to the reference fibre, a gap of 12%

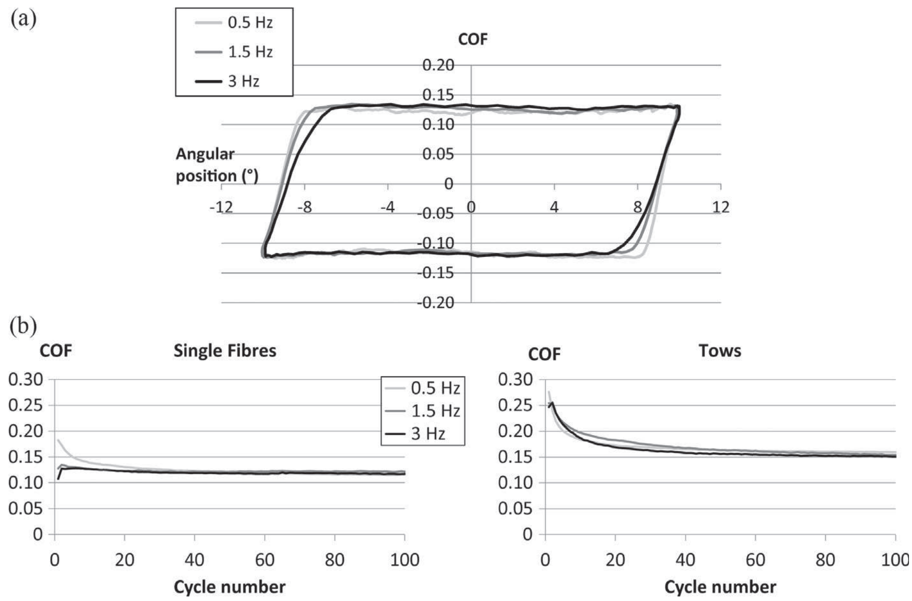

Fig. 6. (a) Average cyclic curve of COF versus angular position for SM single fibre friction with an initial normal load of 5 mN and oscillation frequencies of 0.5, 1.5, and 3 Hz, (b) Average curve of evolution of the COF during an SM single fibre friction test (on the left) and tow test (on the right) with an initial normal load of 5 mN and oscillation frequencies of 0.5, 1.5, and 3 Hz.

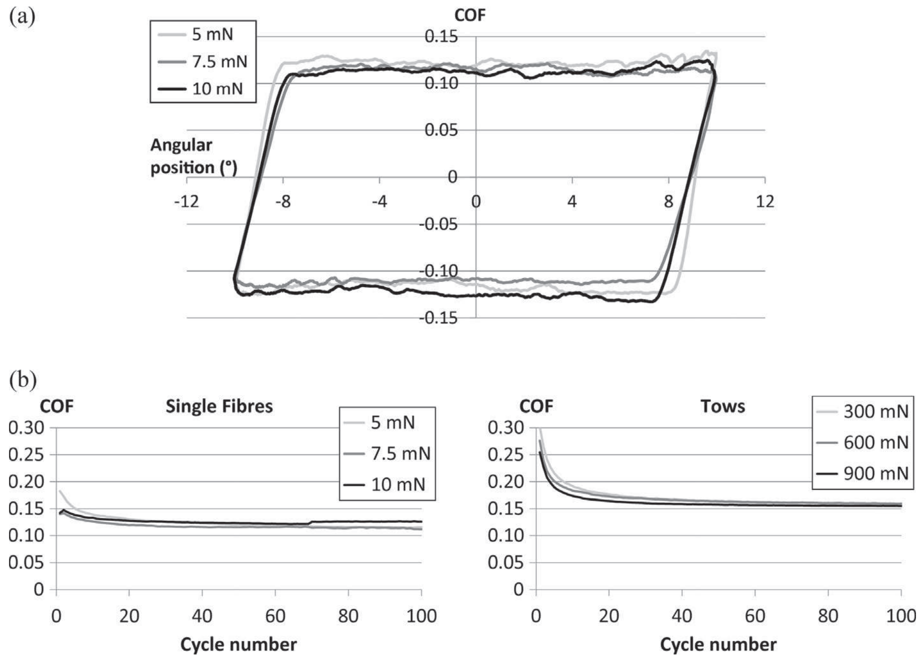

Fig. 7. (a) Average cyclic curve of COF versus angular position for SM single fibre friction at an oscillation frequency of 0.5 Hz and initial normal loads of 5, 7.5, and 10 mN, (b) Average curve of evolution of the COF during an SM single fibre friction test (on the left) and tow test (on the right) at an oscillation frequency of 0.5 Hz and initial normal loads of 5, 7.5, and 10 mN.

differentiates these two fibres in term of real contact area. The difference comes from the Young's modulus. It is obvious that the fibre with the highest Young's modulus induces the smallest strain and a smaller contact area. Experimentally, the COFs of these two fibres are found to differ by 21%.

4.2. Influence of the fibrous rearrangement

Five tests have been carried out for each experimental condition. An average curve is then obtained for each condition. The COF is then deduced from these curves and is plotted in Fig. 8b. It is interesting to note that no difference exists at the tow scale between the three kinds of fibres, whereas a difference, explained in the previous paragraph, exists for the single fibres.

Firstly, it is possible to detail the reason for the lack of a noticeable difference between the COF measured on the tows made of different types of fibres. The friction phenomenon can be decomposed into an adhesion part and a deformation part [27]. In the present case, deformation is a change in the fibre or yarn cross-section. For single fibre friction, it is obvious that the deformation part is negligible insofar as the normal force stays constant throughout the friction test (Fig. 5a). That means there no

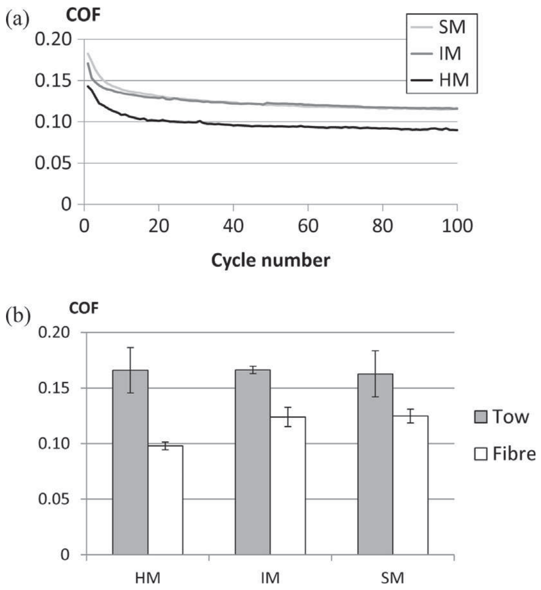

Fig. 8. (a) Average curve of evolution of the COF during a single fibre friction test according to the kind of fibre (oscillation frequency of 0.5 Hz and initial normal load of 5 mN), (b) COF values for single fibre and tow friction tests for each kind of fibre.

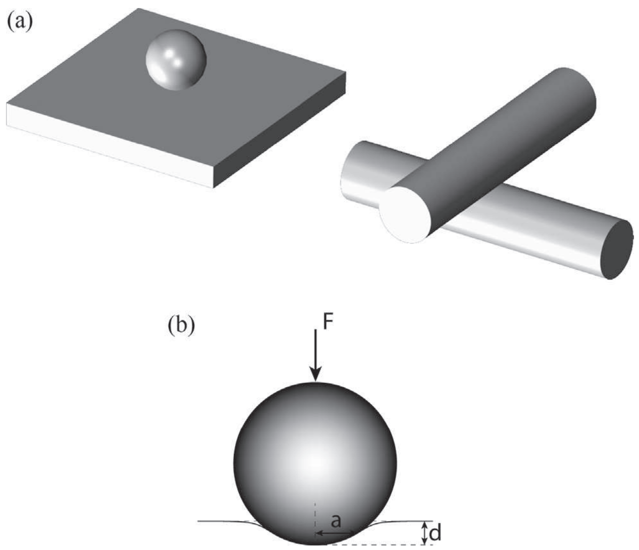

Fig. 9. (a) Analogies between two cylinders in orthogonal contact and sphere-to-plane contact for the application of Hertz's contact theory, (b) Schematic of sphere-to-plane contact for Hertz's contact theory.

Table 3
Theoretical fibre-to-fibre contact parameters obtained thanks to Hertz's theory.

Fibre	SM	IM	HM
E^* (GPa)(from Eq. (3))	132	159	214
Poisson's ratio	0.3	0.3	0.3
Experimental normal force (mN)	4.8	4.86	4.99
d (μm)	$5.0 \cdot 10^{-2}$	$6.0 \cdot 10^{-2}$	$5.9 \cdot 10^{-2}$
a (μm)	0.46	0.39	0.35
A contact area (μm²)	0.66	0.47	0.38

modification of the geometrical configuration of the fibre. The evolution of the friction force and the COF can only be explained by a modification of the contact between the counterpart fibres. Observations by SEM before and after the friction test show a modification of the surface of the single fibre through the breakage of the sizing layer in the area where friction occurred (Fig. 10).

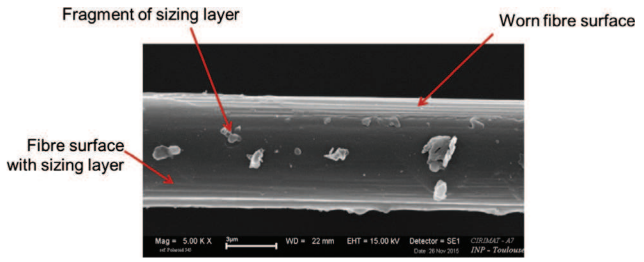

Fig. 10. Picture of SM sample after friction test showing the wear of the sizing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For the friction tests on the tow samples, the normal force decreases during the test (Fig. 5b). Indeed, as the carbon fibres cannot really elongate, the decrease in Fn according to the number of cycles can only be due to a modification of the contact between tows. Therefore a fibrous rearrangement occurs, leading to a deformation of the yarn cross-section and a change of the number of fibres in contact. This evolution of the number of fibres in contact has also been highlighted from experiments as bias extension test [28]. Thus the contribution of the deformation is probably important compared to the contribution of adhesion even if it is not possible at present to estimate the ratio of each part. This rearrangement of the fibres in the tow corresponds to a tendency of the fibres to change their location according to the minimum total potential energy principle. After several cycles the cross-section tow configuration is almost constant leading to constant normal and tangential forces. The effect of the sizing layer in that motion is important, and it seems to be dominant as the COFs determined for these tows are very similar among the three types of fibres, while the COF at the fibre scale depends on the fibre type. This fibrous rearrangement can also explain the shape of the COF curves (Figs. 6b and 7b) by comparing them to those obtained for the single fibre. Indeed, the fibrous rearrangement can cause the limit of the COF to be reached more quickly for single fibres, for which wear is the major concern, than for tows, where fibre rearrangement requires time.

It is also possible to compare the difference in the COF between tows and fibres. The fibrous rearrangement modifies the friction forces. Even if the interaction forces tend to decrease during the friction test, thanks to the fibrous rearrangement, the friction force is larger at the tow scale because of these fibre interactions within each tow. The decrease of the tangential force is smaller than the decrease of the normal force. This behaviour induces an increase of the COF compared to the COF of the single fibre.

5. Conclusions and future work

In this study, friction tests have been successfully performed between two single carbon fibres, whose diameter is as small as 4.9 μm. Their friction behaviour has been compared to the behaviour of the carbon tow tested using the same experimental device. This device, using a pin-on-disk nanotribometer, has been set up in the laboratory to allow a friction motion between rubbed samples positioned at an angle of 90° to one another.

Both friction velocity and normal load have negligible influences on the COF values for single fibres as well as for tows. Thus, for both tows and fibres the friction follows the Coulomb's law in the tested range.

However, at the fibre scale, the COF decreases when the fibre's Young's modulus increases. The wear of the sizing layer is responsible for the decrease of the COF during the friction test carried out on single carbon fibres. It will be interesting to devote future studies to testing the friction properties of fibres whose sizing treatments have been removed.

At the tow scale, the effect of the fibrous rearrangement during the friction tests of tows has also been highlighted through the decrease of the normal and then the tangential forces.

The COF values are larger for tows than for single fibres. The explanation for this tendency may be the fibrous rearrangement during tow friction. At the tow scale, no difference in COF is observed between each kind of fibre tested because of the predominance of the previous phenomenon compared to the adhesion part of the COF studied with the single fibre friction.

The influence of the angle between the two counterpart fibres also needs to be analysed to study the fibre interactions between and within the tows.

Acknowledgments

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