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Michel Tournalonias, Catherine Jordan, Marie-Ange Bueno, and Dominique Poquillon

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Friction of Carbon Fibre and Influence of Sizing Treatment

Michel Tournalonias^{1, a)}, Catherine Jordan¹, Marie-Ange Bueno¹ and Dominique Poquillon²

¹*Laboratoire de Physique et Mécanique Textiles, Ecole Nationale Supérieure d'Ingénieurs Sud Alsace, University of Haute-Alsace, 11 rue Alfred Werner, 68093 Mulhouse, France*

²*CIRIMAT, University of Toulouse, 4 allée Emile Monso - BP 44362, 31030 TOULOUSE Cedex 4, France*

^{a)}Corresponding author: michel.tournalonias@uha.fr

Abstract.

Friction between carbon fibres or tows often occurs during the implementation of Carbon Fibres Reinforced Polymer. Defects are due to these friction phenomena that can reduce the mechanical properties and the lifetime of the final parts. This study has been conducted to study the friction behaviour between carbon fibres or carbon tows with an angle of 90°. The coefficient of friction (COF) of 3 types of carbon fibres differentiated by their Young's Modulus is determined thanks to an experimental device dedicated to this study. It consists in rubbing 2 tows or 2 yarns together with an angle of 90°. A particularity of this study is a work conducted on single fibres whose diameter is small up to 4.9 µm. For single fibre as for tow, there is no influence of friction velocity and normal load. It has been shown the COF is higher at tow scale because of fibrous rearrangement. As the Young's Modulus increases, the COF between single fibres decreases. At tow scale, no influence is highlighted. Moreover, this study highlights the sizing treatment is damaged during a friction test and can participate to the evolution of the COF.

INTRODUCTION

Nowadays, carbon is often used as reinforcement for composite materials. Most of the time, this carbon is in the form of tows, made of filaments. During the implementation of the composite, defects due to friction between carbon tows or carbon fibres can occur, for instance during weaving process [1, 2]. In order to improve the cohesion of the tow and to facilitate their handling a sizing treatment is applied on the fibres [3, 4]. This sizing influences the friction properties of the carbon fibres. Therefore the present study consists in studying the friction of such carbon fibres.

Two types of friction measurements linked to the kind of contacts are proposed in the literature: 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 [5] and was used as a normalised method for yarn in [6]. The coefficient of friction (COF) is obtained from a modified capstan method. There are few methods where the contact between fibres or the tows is punctual. For rigid fibres, it is possible to use the cantilever method proposed by Pascoe and Tabor [7, 8] and by Briscoe and Kremnitzer [9]. A fibre is clamped under tension on both ends and the other fibre is clamped-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 [10]. 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 moves along its axis direction. The two fibres are perpendicular to each other and are in contact. The COF is deduced from the maximal displacement of the suspended fibre during the displacement of the clamped fibre, during friction. Next, the capstan method makes it possible to determine the friction between tows insofar as the cylinder is recovered by glued tows [6]. 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 [11]. The pull-out method used by Mulvihill can be classified in point contact or linear contact method depending on the orientation of the rubbed tows. The study shows the influence of the sizing on the friction by altering the real contact area [12].

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 [4, 13]. Chakladar et al., using the capstan method, studied the influence of the friction angle between counterpart tows [14]. 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 [15].

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 consisting 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.

EXPERIMENT

Carbon tows and fibres investigated

The study was carried out on carbon tows manufactured by Toho Tenax Europe GmbH. Three kinds of tows with closed 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. It can be noted that the fibre diameter also differs according to the filament type. The fibre diameters are 7, 5, and 4.9 μm for the SM, IM, and HM samples, respectively.

TABLE 1. Mechanical properties of tested carbon tows

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

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. 1a).

FIGURE 1. Experimental device: overview of the device with fibre samples (a), tow sample (b) and fibre sample (c)

Specific sample carriers have been designed for this experiment to affix the carbon tow or the single carbon fibres (fig. 1b and c) [15]. The 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 lower one in its central location (fig. 2), so the device leads to a 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.

FIGURE 2. Schematic of friction experiment

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 (around 0.2 mN) at the other end. Then, this end is also glued (fig. 1b). The same steps are done for the upper and lower fibre carriers. Sample preparation with tows (fig. 1c) follows the same steps but the handling is much easier (pre-tension of 0.35 N). 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 normal force is a parameter adjusted at the beginning of one experiment and is recorded during the test. All the experimental conditions in terms of angular amplitude, number of cycles, and normal load are summarized in table 2.

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 (F_t), the normal force (F_n), 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. Summary of experimental conditions

Friction test conditions	Fibres	Tows
Angular amplitude	20° ($\pm 10^\circ$)	
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

RESULTS AND DISCUSSION

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. 4 (for fibre and for tow friction tests), 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 shape of the curve obtained is also similar and is in concordance with the simulation of Durville [16].

Measurement reproducibility

These graphs also make it possible to highlight the good reproducibility of the measurements for single fibres as well as for tows.

FIGURE 3. COF cycle and the average curve for single fibre friction (a) test and tow friction test (b), 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.

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. For the single fibres study, the initial normal load is 5 mN and for tows the initial normal load is 600 mN.

The average cycle relative to the angular position corresponding to the 100 cycles is considered for both fibre and tow friction (fig. 4a and 4b). These curves are symmetrical between each friction direction. When the steady state is reached, the COF is constant whatever the sliding velocity. But if we consider the friction direction change, small differences appear. The steady state is longer to be reached at higher friction velocity. That can be explained by viscous behaviour of the whole system composed by the sample, the glue and the sample carrier.

FIGURE 4. Influence on the velocity of the coefficient (a) of friction fibre to fibre and (b) of friction tow to tow.

Influence of the initial normal load

For studying the influence of the initial normal load, tests have been also performed with fibres and tows. The friction frequency is 0.5 Hz and the normal load values are 5, 7.5 and 10 mN for fibres and 300, 600 and 900 mN for tows. The number of cycles is the same as for the previous study (fig. 5).

When the steady state is reached no difference appear according to the initial normal load. In the range of the normal loads tested, the COF is constant. The sliding direction change is faster at low normal load. That can be explained by viscous behaviour of the whole system composed by the sample, the glue and the sample carrier.

FIGURE 5. Influence of the normal load on the coefficient (a) of friction fibre to fibre and (b) of friction tow to tow

Influence of the number of cycles

It has been shown the COF decreases with the sliding distance, i.e. the number of cycles. For tows it is due to the fibre rearrangement proved by the decrease of F_n . For fibres the influence of sizing must be significant (see §Influence of sizing).

Coefficient of friction for tow and fibre

The results obtained give a COF between fibres lower than the COF between tows, whatever the type of fibres. Except the scale, a main difference can be noticed between the fibre and the tow: the fibrous arrangement, because a tow is composed from 12000 fibres which can moved in the section in different ways during friction. It has been observed, the fibrous rearrangement modifies the friction forces. Even if the interaction forces tend to decrease during a friction test thanks to the fibrous rearrangement within the tow, the friction force is higher at the tow scale because of these fibre interactions within each tow.

Influence of sizing

In order to better understand the decrease of COF during a friction test, SEM picture have been acquired and compared to fibre before friction (fig. 6a). The fibre before friction presents the usual aspect of carbon fibres with some longitudinal ribs due to the manufacturing process. The rubbed fibre shows a worn zone and some fragment of sizing layer (fig. 6b). That wear can explain the decrease of COF during the friction test.

FIGURE 6. Picture of SM carbon fibre (a) before friction test and (b) after friction test showing the wear of the sizing.

CONCLUSION AND PERSPECTIVES

In this study, friction tests have been successfully performed between two single carbon fibres, whose diameter is as small as $4.9 \mu\text{m}$. 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 ranges.

However, at the fibre scale, the COF decreases when the fibre's Young's modulus increases. The wear of the sizing layer is assumed to be responsible for the decrease of the COF during the friction test carried out on single carbon fibres.

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 highlighted in 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.

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