Composites: Part A 80 (2016) 228–236

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Experimental simulation of friction and wear of carbon yarns during the weaving process

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ARTICLE INFO

Article history:
Received 6 May 2015
Received in revised form 17 July 2015
Accepted 18 July 2015
Available online 26 October 2015

Keywords:
A. Carbon fibre
B. Wear
E. Weaving
Friction

ABSTRACT

Nowadays many mechanical composite parts are reinforced by carbon weaving material. During the weaving process some damage to the carbon yarns appears that decreases the final mechanical properties of the part. This study focused on the friction interactions that occurred between warp yarns. A specific kinematic experiment has been done in order to simulate the weaving movement of these yarns, which induces friction. By varying experimental parameters, initial normal load, oscillation frequency and oscillation angle, it is possible to understand their influence on friction phenomena and fibre damage. The energies induced during friction have also been studied. The results obtained show that the coefficient of friction decreases with the increase of normal load, but is not influenced by the oscillation frequency. Yarn wear, i.e. filament breaks, appears beyond a certain normal load. The friction energy increases with normal load and oscillating angle but does not depend on oscillation frequency.

1. Introduction

Nowadays, carbon is often used in mechanical industries for reinforcement of composite materials. Most of the time, this carbon is in the form of yarns. These yarns, made of multifilaments, are woven. According to the application, the interlacement of the yarns, i.e. the kind of weave, can change. The main goal of these materials is to assure the required mechanical properties in specific directions whilst minimising the global mass of the mechanical part. The most important domains for use of these materials are transportation (automotive, airplane, rail) and space.

During the weaving of these carbon yarns, friction phenomena occur, breaking fibres and affecting the production process [1]. There is friction between yarns and metallic parts of the weaving machine but also friction between only yarns. This damage decreases the mechanical properties of these carbon woven fabrics, and are more particularly common in 3D-weaving [2], for interlocking woven fabrics. The final composite part then shows some defects [3]. Mechanical properties of yarns after each step of the weaving process can be evaluated [4]. Studies have been conducted for different types of yarns (carbon, polyester, glass, etc.) and for different weaving parameters. For instance, the effect of the tensioning step [5] or the shedding parameters [6,7] have been studied in order to reduce the yarn damage during the weaving process.

This study concerns only the friction phenomena between yarns and more particularly between warp yarns (Fig. 1). Friction between warp and weft, which occurs during the weft insertion, is not considered in this paper, because it occurs once for each yarn portion during the process and is therefore not considered to be crucial.

Several studies have been done to quantify friction between fibres or yarns. Most of them are summarised by Hong and Jayaraman [8]. For these methods, the contact can be punctual or linear. In Howell's method [9,10] the contact is punctual between two fibres. The first fibre part is hung and the tension is given by a dead mass. The other fibre is taut on a horizontal bow with a lateral movement, which drags a displacement of the hung fibre. This displacement is linked to the static coefficient of friction (COF) between these fibres. The hanging fibre method [11–13] is close to the previous one. The horizontal fibre is fixed with a tension and the hung fibre has a vertical movement. The apparent load of the vertical fibre changes according to the coefficient of friction between these fibres obtained from the capstan equation. This method is also applied to estimate the coefficient of friction of yarns [14]. Mercer and Makinson [15] and Gralen and Olofsson [16] have measured friction between two fibres taut by two perpendicular bows. They studied the friction evolution relative to the sliding distance and the stick–slip.

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http://dx.doi.org/10.1016/j.compositesa.2015.07.024
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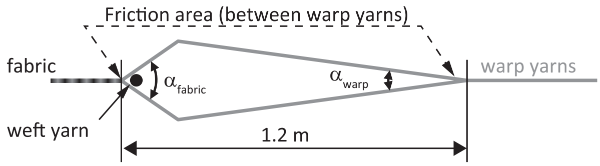

Fig. 1. Schematic of the weaving area with the crossing movement area between warp yarns.

Others methods have a linear contact. The fibre twist method [17] consists of twisting two yarns or fibres together. The force to extract a fibre is used to calculate the COF from the capstan equation. Another method used is based on the capstan method by covering a roller with the tested yarn or fibre [18]. The measurement can be done by measuring the force for moving the yarn against this roller. This method is used for the measurement of yarn to yarn friction for carbon by Cornelissen et al. [19,20] and Chakladar et al. [21] by wrapping friction pulleys with carbon tows. The influence of the experimental conditions, and more particularly fibre orientation and tow size, is evaluated. These two methods (i.e. fibre twist and the capstan method) are used in ASTM D3412-01 [22].

However, no method proposes to study the friction between yarns with respect to the particular kinematic of warp yarns with an angular movement occurring during weaving process. The experiment developed in this study consists of reproducing this movement and analysing the influence of the experimental parameters: the oscillation angle, the oscillation frequency and the normal force between yarns.

2. Experiment

2.1. Carbon yarn investigated

The study is carried out on 3 K carbon yarn (HTA40) manufactured by Toho Tenax Europe GmbH. That means that there are 3000 filaments of carbon per yarn section, whose diameter is 7 μm. The tensile modulus is 240 GPa and the tensile strength is 4100 MPa (datum from the producer).

2.2. Friction experiment

The objective is to simulate the weaving process in terms of friction stress. Friction measurements are performed by means of a NTR2 nanotribometer (CSM Instrument Company, Peseux, Switzerland). This device is originally a pin-on-disk tribometer with reciprocating movement allowed (Fig. 2). Specific yarn carriers have been designed for this experiment to affix the carbon yarn (Fig. 3). An upper yarn carrier is fixed to a cantilever, which allows measuring the normal and friction forces during the experiment by means of capacitive sensors whose force range in each direction is 1 N. The second and lower piece of carbon yarn is located on a similar yarn carrier that is fixed to the rotation stage and allows the relative alternative movement. In this study, the altitude of the upper yarn carrier is chosen and fixed during the whole measurement. The normal force is adjusted at the beginning of the experiment and is recorded during the whole test.

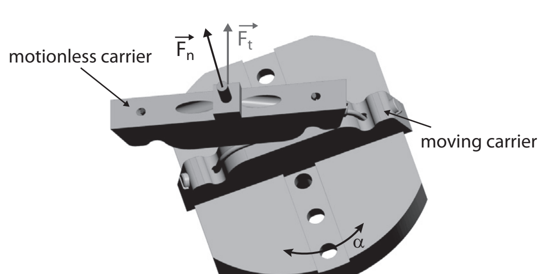

Fig. 2. Schematic of the principle of the friction measurement with F_t the friction force and F_n the normal force.

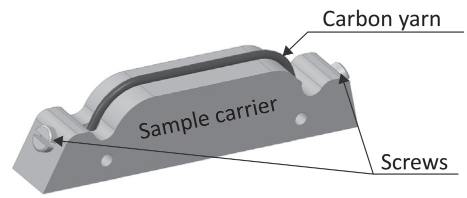

Fig. 3. Yarn sample fixed on the sample carrier.

Table 1
Analogies between experimental conditions and real weaving conditions.

	Weaving	Friction test
Angular amplitude	Up to 34°	34° (±17°) 68° (±34°)
Number of cycles in the friction area	120 cm (length of the friction area) × 10 (number of weft yarns/cm) = 1200 cycles	1200 cycles
Number of cycles per second	3–5 cycles s^{-1}	1.5 Hz (i.e. 22 mm s^{-1} for ±17° or 45 mm s^{-1} for ±34°) 3 Hz (i.e. 45 mm s^{-1} for ±17°) 4 Hz (i.e. 60 mm s^{-1} for ±17°)
Initial yarn pretension	From 2 to 3.5 N per 24 K yarn →0.08–0.15 mN/filament	35 cN per 3 K yarn →0.12 mN/filament
Initial normal load	The normal load is linked to the warp yarn density	200 mN 500 mN 800 mN

The friction and normal forces are acquired during friction tests and the ratio between these forces called the coefficient of friction (COF) is obtained. The COF is not a specific material criterion but depends on the shape of each first body in contact, the speed, the normal force... It characterises a movement resistance and takes into account the adhesion and deformation mechanisms occurring between the bodies in friction [23]. Moreover, in this experiment the instantaneous friction force is computed from the acquired force by taking into account the instantaneous oscillation angle.

The experimental conditions in terms of angular amplitude, number of cycles, and normal load, have been chosen in order to get close to real weaving conditions, and are summarised in Table 1.

During the weaving process, the maximum angle α_{warp} between the two webs of warp yarns before the frame is about 6° and α_{fabric} between the frame, and the beam roll is higher with 34° (Fig. 1).

A piece of yarn is subjected to weaving cycles during the time needed to cross about 1.2 m from the beam roll to the fabric, which corresponds to about 1200 cycles for a standard woven fabric with 10 weft yarns per centimetre.

The weaving speed is from 3 to 5 beatings, i.e. cycles, per second. Because of the nanotribometer limits, 1.5–4 cycles per second have been considered for the experiments. The velocity follows a sinusoidal profile, and these test frequencies correspond to maximum velocity range from 22 mm s^{-1} to 60 mm s^{-1} depending on the oscillating angle. This sliding velocity is the maximum linear velocity at the extremity of the rotating yarn (Fig. 4).