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Dry friction characterisation of carbon fibre tow and satin weave fabric for composite applications

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ABSTRACT

Composites forming processes such as resin transfer moulding (RTM) typically involve a preforming step in which dry fabric material is deformed. Frictional forces in tool–fabric and fabric–fabric contacts determine the fabric deformation behaviour to a large extent. Previous investigations of the frictional behaviour of fibrous materials were mostly performed on a particular scale, i.e. microscopic (filament), mesoscopic (tow), or macroscopic (fabric). This study aims to provide a coupling between these scales by means of friction experiments on both carbon tows and carbon fabric in contact with metal counterfaces. The frictional behaviour of both materials on metal was measured on a capstan and a flat plate-friction setup. The frictional behaviour of fabric was comparable to that of single tows for matching pressures based on the mesoscopic contact area with the metal counterface. Furthermore, the agreement of the results forms a validation of both friction characterisation methods.

1. Introduction

Preforming processes like resin transfer moulding (RTM) are often performed with dry reinforcement material. Friction plays an important role in these preforming processes. In the past several studies related to frictional behaviour of fibrous materials were performed on different geometrical scales, from the microscopic single filament level studied by Roselman and Tabor [1] to the macroscopic level in which the deformation behaviour of entire multiaxial, multiply stitched preforms was investigated by Lomov et al. [2]. Hivet et al. focused on the mesoscopic effect of fabric interlocking on the frictional behaviour of fabric–fabric contact and presented tow–tow friction experiments as well [3].

This work aims to provide a coupling between the micro-mesoscopic frictional behaviour of tows and the behaviour of fabric material on the meso-macroscopic level. With this purpose in mind and the micro-mesoscopic frictional behaviour of tows covered in earlier work [4,5], the focus lies on the frictional behaviour of tow and fabric material in contact with a metal counterface. Tow–tow and fabric–fabric contact measurements are possible as well, although these measurements are not addressed in this work. Fig. 1 illustrates the multi-scale nature of composite materials in a three-level decomposition with the associated length scale for each level. Additionally, the associated contact areas and pressures addressed in subsequent sections are included.

Carbon fibre tow and fabric specimens made from the same tow material were used in friction experiments. The friction between 5 Harness Satin (5HS) carbon fabric and mild steel was determined on two different experimental setups in order to validate the employed capstan setup. In the capstan setup approach, a ribbon of dry carbon fabric was wrapped around a rotating metal drum, measurements on tows extracted from the fabric were performed in the same manner. In the second setup a fabric specimen was pulled through two metal clamping blocks with plane surfaces. Both experimental setups have different sliding velocity and loading capabilities with some overlap. Measurements in this overlap region were compared and were used as a validation for both friction measurement setups. A straightforward relation between the friction of fibrous tows and 5HS fabric on the capstan setup is proposed, based on contact area measurements. Section 2 provides detailed information on the specimen materials and the experimental setups. The two different experimental setups are described and the relevant material properties are listed in this section. In Section 3 a relation is proposed between the frictional forces and the contact area, for both tow and fabric materials in contact with a metal counterface. The presented approach is based on experimental observations and modelling work of the frictional behaviour of fibrous tows [4,5]. The results of the performed friction measurements on tow and fabric material for the current work, including a summary of the observations, are presented in Section 4. Subsequently, the relation between tow and fabric friction and the relevant mechanisms is discussed in Section 5, together with a comparison of both experimental methods. Finally, Section 6 presents the general conclusions from this study.

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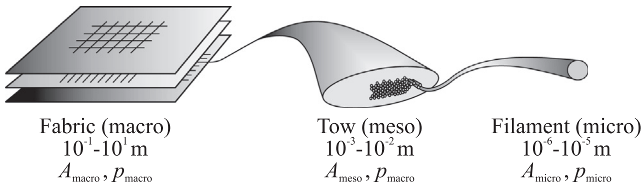

Fig. 1. Hierarchical structure of a typical composite product and its constituents with their characteristic length scales. The associated contact areas *A* and pressures *p* are addressed in the following sections.

2. Materials and methods

Tow and fabric friction measurements were performed on a capstan setup for two different metal counterfaces. Additionally, fabric friction measurements were performed on a plate-friction setup on one of the metal counterfaces. This section describes the properties of the fibrous tow and fabric material, as well as the properties of the metal counterface materials. The measurement methods that were applied in the capstan and plate-friction setup are explained.

2.1. Tow and fabric material

The fabric material for the experiments was provided by Ten Cate Advanced Composites. The fabric was woven in a weight balanced 5HS pattern, as shown in Fig. 2. However, this weave is not balanced geometrically, due to a difference in crimp ratio between the warp and weft direction, originated by the nature of the weaving process. A surface finish to protect and facilitate handling was applied on the carbon fibre tows by the tow manufacturer, Torayca. This finish was removed after weaving by Ten Cate by means of a thermal treatment.

The tow specimens were extracted from the fabric material to ensure identical material and surface properties. Friction experiments on the capstan setup, which is described in Section 2.3, were performed on tow as well as fabric specimens on two different counterfaces. Validation measurements were performed with fabric specimens on a plate-friction setup, which is described in Section 2.4. The properties of the tow and fabric material are summarised in Table 1.

2.2. Friction in textile materials

This work deals with the friction of dry tow and fabric material. The term *dry* in this context refers to the absence of a lubricating film between the two interacting materials, such as the surface finish applied by the tow manufacturer.

The well-known Coulomb friction law is the most straightforward approach to characterise the dry friction between two sliding materials. The frictional force F_f is considered to be directly proportional to the applied normal load N through the coefficient of friction μ:

$$F_f = \mu N. \tag{1}$$

However, the coefficient of friction has been observed to vary with the applied normal load on the tow, whereas the Coulomb friction implies a constant value [6,7]. This load dependency is included in Howell's equation, a widely accepted relation between the normal load and the resulting frictional force, given as [8]:

$$F_f = kN^n, \tag{2}$$

where k is an experimentally determined proportionality constant, which relates the normal load N to the frictional force F_f. The load index n is a fitting parameter that relates to the deformation mechanism in the real contact between asperities of the contacting surfaces. The value of n ranges from $n = \frac{2}{3}$ for fully elastic deformation to $n = 1$ for fully plastic deformation of the contacting asperities. The Howell approach of friction can be expressed in terms of Coulomb friction by substitution of F_f in (1) with (2):

$$\mu_{equ} = kN^{n-1}, \tag{3}$$

where μ is in this case the Coulomb-type coefficient of friction that would be measured at the given normal load N. It is now clear that the calculated μ in (1) would not remain constant with a variation of the normal load in the case of load-dependent material behaviour.

2.3. Capstan friction setup

The capstan measuring method has been widely applied since the beginning of the twentieth century. The first experiments were performed on cotton, wool, viscose, and nylon tow material [9–11]. Other synthetic materials like polyester were studied later as well [12–14]. The frictional behaviour of high modulus and strength materials like carbon and aramid has been studied on capstan

Table 1
Properties of the 5HS carbon fibre fabric used in the friction experiments (manufactured by Ten Cate Advanced Composites, type: CD 0286). The fabric was woven with Torayca T300JB tow material.

Description	Symbol	Unit	Value
Areal weight	W_{area}	g/m^2	285
Warp count (fabric)	C_{warp}	tows/m	700
Weft count (fabric)	C_{weft}	tows/m	700
Filaments count (tow)	n_{fil}		3000
Filament diameter	d_{fil}	µm	7.0
Linear density (tow)	D	tex	198
Axial E-modulus (tow)	E_{axial}	GPa	230
Transverse E-modulus (tow)	E_{trans}	GPa	15

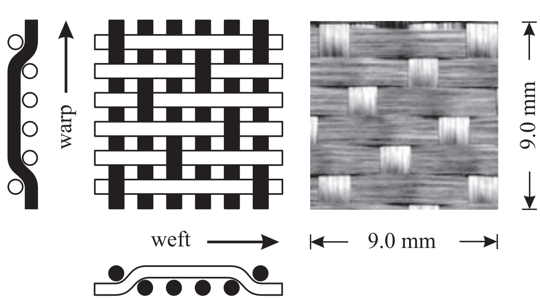

Fig. 2. Schematic overview and photographic detail of the 5HS weave used for the fabric friction measurements.

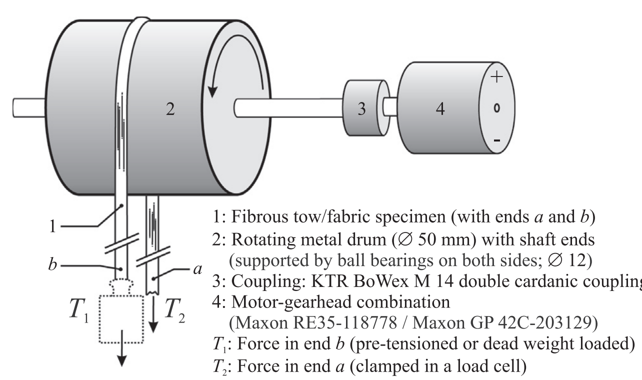

Fig. 3. Schematic description of the capstan experiment for friction characterisation of fibrous tows.