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Frictional behaviour of high performance fibrous tows: A contact mechanics model of tow–metal friction

B. Cornelissen [a,*], M.B. de Rooij [b], B. Rietman [a], R. Akkerman [a]

[a] University of Twente, Faculty of Engineering Technology, Chair of Production Technology, P.O. box 217, 7500 AE Enschede, The Netherlands
[b] University of Twente, Faculty of Engineering Technology, Chair of Surface Technology and Tribology, P.O. box 217, 7500 AE Enschede, The Netherlands

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ABSTRACT

Composites forming processes involve mechanical interactions on the ply, tow, and filament level. 0The deformations that occur during forming processes are governed by friction between tows and tooling material on the mesoscopic level and consequently between filaments and a counterface on the microscopic level. A thorough understanding of the frictional properties on the level of individual filaments is important to understand and predict the macroscopic deformations of a fabric during forming. The contact mechanics based friction model in this work confirms an experimentally observed decrease of frictional forces with an increasing roughness of the counterface. The developed model provides a qualitative understanding of the frictional behaviour of filaments on a cylindrical metal counterface.

1. Introduction

The mechanical properties of continuous fibre reinforced polymers or composite parts are determined to a large extent during the forming phase. Such composite parts consist of a thermosetting or thermoplastic matrix, which is reinforced with continuous fibrous tows that typically consist of several thousands of filaments. The continuous fibrous tows deform during the forming phase of production processes. They conform to the local shape of the tool surface on which the composite part is being manufactured. Local cross-sectional changes occur in the tow due to the induced loads. The tow orientation and filament distribution determine the mechanical properties of the composite part to a large extent. Knowledge of the tow orientation and tow deformation behaviour is therefore essential to control the desired product quality in terms of e.g. mechanical performance, dimensional accuracy and visual appearance.

Composite materials can be represented in a hierarchical structure. A classification is generally made in three scales, as illustrated in Fig. 1: macro, meso and micro, to represent the composite laminate, tow and filament scale, respectively.

The hierarchical approach does not imply that deformation mechanisms are isolated on a single scale level. For example, filaments moving relatively to each other within a tow on the microscopic level will result in a change in cross-sectional properties of the tow on the mesoscopic level. Meso- and macroscale effects are interrelated as well. An example is the formation of macroscopic wrinkles in a doubly curved rubber-pressed composite product. These wrinkles develop due to tow orientation-dependent inter-ply friction and shear on the mesoscopic level [1].

The deformations that occur in composites forming processes mainly result in compaction and shear loads, which both depend on the frictional behaviour of fibrous tows [2,3]. The deformations of the individual tows influence their cross-sectional shape, which in turn has an effect on the formability of, for example, stacked plies of woven fabric. The macro-deformation behaviour of the composite part is thus determined by the individual tow properties.

The frictional behaviour of fibrous tows during processing typically involves intra-tow (on the microscopic filament scale), inter-tow, and tow–metal interactions. In the latter case, filaments are in sliding contact with the counterface of the metal tooling material during forming processes. This work deals with the dry frictional behaviour of the tow–metal system.

Capstan experiments on carbon, aramid and E-glass tows showed that the measured coefficient of friction between a fibrous tow specimen and a metal counterface varied strongly with the surface topography of the metal surface [4]. The experiment consisted of measuring forces in the ends of fibrous tow specimens while wrapped around a rotating friction drum, as illustrated in Fig. 2.

* Corresponding author. Tel.: +31 534 894 346.
E-mail address: b.cornelissen@utwente.nl (B. Cornelissen).

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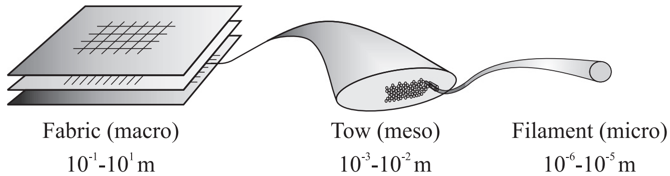

Fig. 1. Hierarchical structure of composite materials with characteristic length scales.

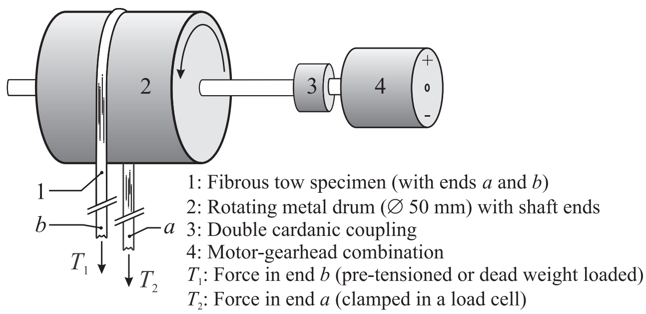

Fig. 2. Schematic description of the capstan experiment for friction characterisation of fibrous tows.

To date, little work has been done to provide an approach to relate the material behaviour on the microscale to that on the macroscale. Here, the frictional properties of fibrous tows are examined on the combined micro- and mesoscopic scale, with the aim of providing a relation between the micro-, meso- and macroscopic frictional behaviour. This relation is based on a theoretical understanding of the frictional behaviour of fibrous tows. With this modelling effort, we aim to support the experimental findings in a qualitative manner [4].

Section 2 presents a theoretical model to predict the frictional forces as a function of the applied normal load on the tows. The model results are presented in Section 3 and are subsequently discussed and compared with the outcome of the tow friction experiments in Section 4.

2. Contact mechanics model

Here, an analytical contact mechanics modelling approach is proposed to describe the frictional behaviour of fibrous tows in contact with a metal counterface. After the relevant contact loads in the system have been determined, the proposed model consists of a two-step process to determine the contact area between filaments and the counterface.

First, a nominal contact between a filament and the counterface is calculated with Hertzian contact assumptions. In this step of the process *nominal contact* refers to the contact for a counterface microgeometry that is assumed to be perfectly flat in this first step of the process.

Second, the real area of contact, i.e. now including the surface topography of the counterface microgeometry, is calculated with either a Hertzian or a Maugis–Dugdale (MD) approach [5,6]. The latter approach includes the effect of adhesion of filaments in contact with the metal counterface. The effect of adhesion on the real contact area depends on the surface energy of the contacting materials, their elastic properties and the geometry of the contacting bodies. The contribution of adhesion effects to the contact is expected to be significant, based on the small diameter of the filaments and their transverse elastic properties.

The proposed contact model assumes that there are no irregularities on the filament surfaces, but takes the characteristics of the surface topography of the metal counterface into account by means of a statistical multi-asperity approach [7–9]. The assumption regarding the filament surfaces is allowed, because the dimensions of the irregularities on the filament surface are at least an order of magnitude lower than those of the metal counterface topographies. In addition, the filaments are soft compared to the metal counterfaces, i.e. any irregularities are expected to conform easily to the hard metal counterface microgeometry.

2.1. Scope of the modelling approach

The contact mechanics approach of tow deformation behaviour is based on the relation between the developed friction and the applied pressure on a filament. The area of contact between the filament and the metal counterface is load dependent. This in turn results in a load dependency of the frictional force between the tow and the counterface represented by the empirical Howell relation [10]:

$$F_f = kN^n, \tag{1}$$

where N is the applied normal load on the contacting body (in this case a tow that consists of many filaments). Gupta and Mogahzy gave the empirical fitting parameters k and n a background [11,12] by stating that in the case of fibrous materials the index n is governed by the (visco)elastic properties of the junctions in the contacting asperities under compression, implying that n is not necessarily equal to 1, which corresponds to purely plastic deformation of the junctions in the contact locations. The value of k is determined by chemical, physical and morphological properties of the filament material and the filament-counterface contact dimensions. Another interpretation was presented by Adams et al. [13]. In their approach, the index n varies between 2/3 and 1 depending on the pressure dependency of the interfacial shear strength of the material combinations under consideration τ. In the case that τ is not pressure-dependent, $n=2/3$ [13].

Roselman and Tabor stated that the frictional force F_f is determined by the product of the interfacial shear strength τ of the contacting materials with the real contact area A_r between them and a ploughing term represented by P [14,15]:

$$F_f = A_r\tau + P. \tag{2}$$

The ploughing component P of adhesive friction in Eq. (2) is expected to play a minor role in the system under consideration and is therefore omitted in the current model. This is supported by the observation that after more than 100 measurements with carbon fibre tows of which the properties are stated in Table 2, the drum surface appeared unaffected [4]. No material transfer to the friction drum nor any damage to the filaments in the tows was observed. Therefore, it will be assumed that only shear at the interface between the filaments and the friction drum has taken place.

Furthermore, the slenderness of filaments leads to a relatively low bending stiffness, which leads to good conformation of filaments to the counterface asperities, thereby further minimising ploughing effects. Only the E-glass filaments showed mildly abrasive behaviour on the smooth counterface.

The strong dependence of the measured coefficient of friction on the surface topography was characterised for single carbon filaments by Roselman and Tabor [15]. More specifically, these authors found friction coefficients for carbon filaments on stainless steel (EN58B/1.4541) that showed up to three times higher values for a low surface roughness. The lowest surface roughness was 0.01 μm Ra (arithmetical mean deviation), the highest Ra roughness value was 0.95 μm. The authors explained this phenomenon from a surface topography perspective. The real contact area of a filament on the drum with a low roughness is larger than that of the drum with a high roughness at equal load.