Composites: Part A 93 (2017) 199–206

Contents lists available at ScienceDirect

Composites: Part A

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

# Effect of tool surface topography on friction with carbon fibre tows for composite fabric forming

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ARTICLE INFO

*Article history:*
Received 5 July 2016
Received in revised form 22 September 2016
Accepted 17 October 2016
Available online 29 October 2016

*Keywords:*
A. Carbon fibres
A. Tow
E. Forming
Friction

ABSTRACT

The effect of tool surface roughness topography on tow-on-tool friction relevant to the dry forming of composite fabrics is investigated. A comprehensive range of tool average surface roughness $R_a$ values from 0.005 to 3.2 μm was used in friction testing with carbon fibre tows. The measured slope of these surfaces, which is the critical surface topographical characteristic, increased significantly with increasing roughness amplitude. Friction was found to be sensitive to roughness topography for very smooth surfaces ($R_a < 0.1$ μm) and increased with decreasing roughness slope and amplitude. For rougher surfaces ($R_a > 0.1$ μm), friction was relatively insensitive to roughness slope and amplitude. A finite element idealisation of the tow-on-tool contact was used to explain these results in terms of the level of tow-tool conformance. Smooth surfaces have low slopes which allow good conformance, and hence high real contact area and friction. Rougher surfaces have high slopes, particularly at shorter wavelengths, which prevents good conformance. In this case, point contact between fibres and surface dominates, leaving the resulting friction less sensitive to roughness.

## 1. Introduction

Carbon fibre based composite parts are often produced by a dry fabric pre-forming stage whereby a metal tool presses carbon fabric layers into the required shape before subsequent resin infusion. Presently, the fabric forming step must be designed by an iterative process owing to the absence of a robust predictive modelling tool. Forming industry practitioners would like to be able to predict forming forces, part thicknesses, wrinkling, void formation and fabric deformation, etc., but achieving this requires a better understanding of the underlying physical phenomena in the forming process. A particular issue is the frictional behaviour both between tool and fabric and between fabric layers.

Since the carbon fibre tow is the basic building block for a fabric, recent work on friction in composites forming [1–5] has focused on tow-on-tool and tow-on-tow friction as a first step. Our own group investigated some of the fundamental mechanisms at play in Mulvihill et al. [5] (using techniques developed previously by Smerdova and Sutcliffe [6,7]). Here, it was shown for the tow-on-tool case that the 'real' fibre contact length at the tow frictional interface is not a constant following from an idealised assumption of parallel touching fibres, but increases in a characteristic repeatable manner with increasing normal load. Accounting for this evolving contact length in a Hertzian calculation of the real contact area (assuming cylindrical fibres) produced a contact area versus load variation which differed only by a constant factor compared with the measured friction force curves. The friction force curves took the form $F = kW^n$, where $W$ is the normal load and $k$ and $n$ are experimentally determined constants. The exponent $n$ was generally within the range 0.7–1. Such exponents come about due to the combination of an increasing real contact length and an increasing Hertzian contact width, in a manner analogous to the way that Greenwood and Williamson's theory [8] produces an exponent close to unity for elastically deforming rough surfaces. The constant factor between the area and friction force means that the tow behaviour agrees with the 'constant interface strength' model of friction developed by Bowden and Tabor [9], i.e. that friction force $F = \tau A$, where $\tau$ is the constant interface shear strength and $A$ is the real contact area under the fibres (interface strength $\tau$ will clearly be related to the strength and surface energy of the sizing on the fibres). In this model the real contact area has a key role in determining the frictional behaviour. This finding can be used to explain various experimental observations. For example, Mulvihill et al. [5] and Cornelissen et al. [1] explained the higher friction measurements found for tow-on-tow contact in the parallel arrangement, as compared with the perpendicular arrangement,

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http://dx.doi.org/10.1016/j.compositesa.2016.10.017
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by noting that the theory predicts a smaller real contact area in the case of perpendicularly contacting tows. Likewise, the higher friction noted in [5] for the more highly sized (i.e. coated) tow was ascribed to a correspondingly higher real contact area. The number of fibres per tow was found by Chakladar et al. [4] to have little effect on the friction coefficient; presumably changing from a 6 k to a 12 k tow does not change significantly the interfacial real contact area as a fraction of the nominal contact area.

In tow-on-tool contact, another parameter which might be expected to affect frictional behaviour is that of tool surface roughness topography; this is the subject of the present paper. Roselman and Tabor [10] investigated this effect by sliding an individual carbon fibre against stainless steel counterfaces having four different roughness values ($R_a$ = 0.01, 0.05, 0.26 and 0.95 μm). They found that friction decreases as the counterface roughness increases. The most significant decrease occurred in moving from an $R_a$ roughness of 0.01 μm to one of 0.05 μm, while the friction difference between the rougher surfaces (from 0.05 to 0.95 μm $R_a$) was smaller. Cornelissen et al. [3] carried out friction measurements with carbon, E-glass, and aramid tows in contact with two steel counterfaces having $R_q$ roughness values of 0.02 and 1.1 μm ($R_a$ of approximately 0.018 and 1 μm). For each tow type, the smoother counterface again gave higher friction. Both Roselman and Tabor [10] and Cornelissen et al. [2] have explained this behaviour by noting that smoother surfaces should allow greater real contact area under the fibres and, hence, higher friction. They each put forward a model based on a calculation of the real contact area assuming smooth cylindrical fibres undergoing Hertzian contact with spherically tipped asperities (with constant radius) arranged on the counterface. In Roselman and Tabor [10], the asperities were simply placed along the counterface at a constant height, while Cornelissen et al. [2] gave the asperities a Gaussian distribution of heights and used a Greenwood and Williamson type analysis [8] for calculating the contact area. For their rougher surface, Cornelisson et al. [2] introduced a second scale of larger sized asperities (again with constant radius): an effective nominal contact area was first calculated based on the fibres contacting the larger sized asperities (again spherically tipped), and the Greenwood and Williamson approach was then reverted to for calculation of the real contact areas within each of these nominal contact patches. Both groups were able to use their model to show a greater real contact area for the smoother surface and thus infer a higher level of friction.

The above contact mechanics models are based on approaches from contact mechanics [11] and from Greenwood and Williamson [8] which have been used successfully for contact between hard, rigid, rough surfaces such as for the titanium alloy metal-to-metal contacts occurring in Mulvihill et al. [12,13]. However, this type of model breaks down where the ratio of true to nominal contact area is large, as can occur with soft conformal contacts. This may indeed be relevant for contact between a soft fibrous tow and a hard rough tool surface. Moreover, at small length scales the bending resistance of the fibres may become important. The assumption of Cornelisson et al. [2], that the tow fibres remain as straight cylinders as they are pushed into the distribution of asperities on the tool, may not be appropriate. These issues are explored in the paper.To understand better the problem of compliant rough contacts, it is useful to consider Westergaard's analysis [14] for a two-dimensional contact between a smooth rigid surface and a deformable surface with sinusoidal roughness, where there is a large amount of contact between the surfaces (see Johnson [11]). In this case the contact pressure $\bar{p}$ is related to the amplitude $a$ and wavelength $\lambda$ of the sinusoidal roughness by the expression:

$$\bar{p} = \frac{\pi E^* a}{\lambda} \sin^2\left(\frac{\pi A}{\lambda}\right), \tag{1}$$

where $E^*$ is the effective contact modulus and $A$ is the half-width of each contact patch. This result illustrates how, for a given contact area ratio $2A/\lambda$ (i.e. the ratio of the true to the nominal contact areas), the contact pressure is proportional to the ratio $a/\lambda$ of the amplitude to the wavelength of the roughness. This ratio $a/\lambda$ is a characteristic slope of the roughness topography. Conversely increasing $a/\lambda$ results in a reduced contact area at a fixed pressure. There is a critical pressure $p^*$ given by

$$p^* = \frac{\pi E^* a}{\lambda} \tag{2}$$

above which there is complete conformance between the two surfaces, with $2A = \lambda$. More recently, Persson [15] has developed a theory for contact of soft surfaces such as rubber, to allow for different wavelengths of roughness that are present.

From this review of rough contacts it is possible to identify a number of gaps in the present understanding of the role of counterface roughness for contact of fibrous tows with rough surfaces. Firstly, only two surface roughness values were used in the only available work [3] where the effect of tool roughness in tow-on-tool friction was studied (Roselman and Tabor's work [10] was on single fibres). Therefore, there is a need for a more thorough experimental investigation. Secondly, although the models discussed above are helpful in broadly understanding the results, there are some areas of over-simplification that require improvement. One obvious (and only recently identified) over-simplification has already been mentioned: that the real fibre contact length is not a constant based on an idealised arrangement of parallel touching fibres as assumed for the model in Cornelisson et al. [2], but increases in a particular manner with normal load as described by Mulvihill et al. [5]. Another important point is that the models discussed above make no allowance for the conformance of the carbon fibres with the rough surface. The fibres are long slender cylinders which lie on a bed which is soft relative to the metal counterface, consisting of thousands of other loosely packed fibres. It is hypothesised that elastic deformation of the fibres and tows can significantly affect the conformance of the fibres with rough surfaces, hence altering the real contact area and friction. With this picture of the contact, the topographical parameter of the surface that is mostly likely to influence friction is not the roughness amplitude, but rather the characteristic slopes of the surface which will affect the conformance, as per the Westergaard model of contact. Moreover, it is likely that roughness at different length scales will have different slopes so will influence friction in different ways. The present paper undertakes a comprehensive experimental study of the effect of tool surface roughness on tow-on-tool contact by taking friction measurements with counterfaces having eight different $R_a$ roughness values over a very wide range varying from 0.005 to 3.2 μm. A spectral analysis of the surface roughness profiles, together with a finite element contact modelling approach based on a Westergaard [14] type analysis of an soft sinusoidal surface pressed against a rigid flat, is then used to explain the friction results in terms of the degree of tow conformance with the rough surface. The critical effect of roughness slope on the conformance and friction is explored.

## 2. Friction measurements

### 2.1. Materials and methods

Tests were performed on T700SC-12k-60E carbon fibre tows (Toray Industries, Tokyo, Japan [16]), where'T700S' is the fibre type (tensile strength of 4.9 GPa), 'C' denotes that the fibres were never twisted, 12k is the fibre count and '6' gives the sizing type (in this case compatibility with epoxy). The letter 'E' corresponds to a siz-