Characterisation and modelling friction at the tool-ply interface for thermoplastic woven composites

P. Harrison[1], Rene ten Thije[2], Remko Akkerman[2], Andrew C. Long[3]

[1]*University of Glasgow, UK, p.harrison@mech.gla.ac.uk*
[2]*University of Twente, The Netherlands*
[3]*University of Nottingham, UK*

Introduction

Press forming of thermoplastic textile composites is a fast and efficient method of production. Friction occurring between the composite material and pressure blank-holder during forming imparts tensile stresses in the sheet which help counteract compressive stresses generated by material deformation; stresses that can result in unwanted wrinkling of the forming sheet. In order to model the press forming process and optimise boundary conditions, this friction behaviour must be characterised and modelled. Two different test methods are employed to characterise the friction and two complementary modelling strategies, an empirical and a predictive approach, are presented.

Material

Two types of 2x2 twill weave pre-consolidated thermoplastic textile composite, Vetrotex Twintex®, consisting of commingled E-glass and polypropylene (PP) yarns have been tested. Type 1 has an areal density of 710gm^{-2} and a yarn width of 5mm. Type 2 has an areal density of 1485 gm^{-2} and yarn widths of 2.65 in the warp direction and 5.92 mm in the weft direction.

Pull-through and Pull-out Test Set-up

Traditional methods of characterising friction use large scale test rigs fitted in universal test machines. Three alternative variations on a similar experimental design set-up have been employed [1-3]. The basic method involves pulling pre-consolidated Twintex sheet (Type 1 or 2) from between 2 platens that apply a controlled normal pressure on the sheet. By measuring traction force, the friction coefficient can be determined under different experimental conditions (normal pressure, draw velocity and temperature).

Rheometer

An alternative method of measuring friction has been employed by adapting a Bohlin CVOR200 Rheometer with Extended Temperature Cell (ETC) oven. The rheometer was fitted with a custom designed rig that allows the textile sheet (Type 1) to be held firmly in place during testing. The rig consists of a pair of parallel stainless steel platens, the lower platen was a truncated cone with a diameter of 25 mm. The upper platen was a flat disk with diameter 40 mm. The advantage of using the rheometer lies in the higher rate at which test results can be produced when compared to the more traditional pull-though and pull-out methods. The disadvantage is that the experimental conditions (normal pressure, p, and velocity, v) are lower than can be expected in typical forming situations (p up to ~ 1000KPa and v up to ~ 5000 mm/min [4]) and so any results have to be extrapolated to the relevant processing conditions.

Shifting Procedure

A general process of shifting data to determine parameters in an empirical model for friction has been demonstrated using data generated by rheometer experiments. The process consists of several steps:

1. Choose a reference condition (i.e. a specified shear stress, τ, temperature, T, and normal pressure, p, to which all other data will be shifted)
2. Determine the average gradient of the p vs v data under various constant T and constant shear stress, τ, conditions.
3. Determine the shift factor required to collapse the p vs v data produced at various τ onto a single curve at a given T.
4. Determine a second shift factor to collapse several shifted p vs v data, obtained using various constant stress conditions and at different T, onto a single master curve.

The final form of the master equation obtained using this method on Type 2 Twintex is:

$$\mu = 565\times10^{-6}\sqrt[3]{\frac{v^{1.37}}{4\times10^{-6}\cdot p^2\cdot a_T}} \qquad (1)$$

where μ is the coefficient of friction, v is the velocity in mm/s, p is the normal pressure in MPa and T is the temperature in °C. The numerical constants are determined through the choice of reference conditions, and the shifting behaviour. a_T is determined from the temperature shift behaviour.

Meso-scale modelling

A meso-scale model has been developed based on a geometrical description of the tows within the fabric.

Hydrodyamic lubrication is assumed between the bundles and the tool surface. Reynolds' equation, Eq (2), is used to describe the relation between the pressure and thickness distributions in the thin fluid film separating tool and material:

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\eta}\frac{\partial p}{\partial x}\right)=6U\frac{\partial h}{\partial x}. \qquad (2)$$

where η is the fluid viscosity, x is position, h is the film thickness and U is the velocity in the x direction. The viscosity of the matrix fluid was modelled using a Cross/WLF model for PP. The model was selected due to the excellent comparison it provides when comparing the meso-scale model friction predictions with experimental measurements. An important advantage of the meso-scale model is that the film thickness can be predicted rather than determined from microscopy measurements.

Results: Comparison 1

Comparison between master curve and meso-scale model predictions is given in Fig 1. Conditions used to generate Fig. 1 correspond to experimental conditions within the working range of the rheometer. Fabric geometry used in the meso-scale model predictions correspond to Type 1 Twintex. The average relative error in the comparison is 7.0%.

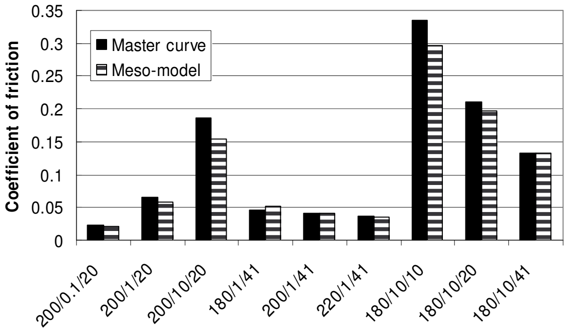

Figure 1. Meso-scale model predictions compared against master curve predictions, Eq (1). Experimental conditions are given in the format of (T in °C / v in mmmin^{-1} / p in KPa to 2 significant figures)

Results: Comparison 2

A comparison between the meso-scale model, the master curve and pull-through and pull-out tests has also been made. As it stands Eq (1) is unable to give a good comparison. The reason for this is believed to be that velocities used in collecting the rheometer data are much lower than those used in conducting pull-though and pull-out tests which tend to be closer to actual forming conditions. Thus, any error involved in the shifting process used to determine Eq (1) is magnified in extrapolating predictions of Eq (1) to experimental conditions beyond the rheometer's working range. For this reason a modified version of Eq (1) is proposed which has been found to give good results. An extra fitting parameter, b, is included and can be determined using a least squares fitting algorithm:

$$\mu=\frac{565\times10^{-6}}{b}\sqrt[3]{\frac{v^{1.37}}{4\times10^{-6}\cdot p^{2}\cdot a_T}} \qquad (3)$$

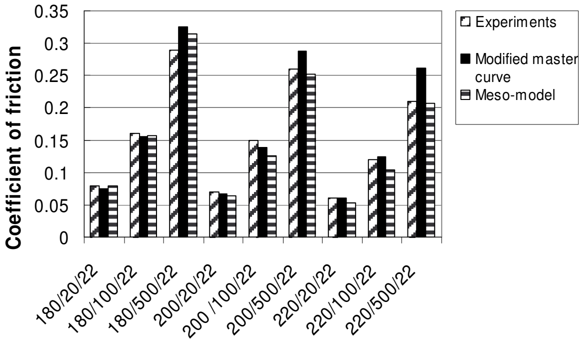

Figure 2. Experimental measurements compared against modified master curve predictions with b=3.66. Experimental conditions are given in the format of (T in °C / v in mmmin^{-1} / p in KPa to 2 significant figures)

The average relative error in the comparison between meso-scale model predictions and experimental results is 7.2% a similar comparison between modified master curve predictions and experimental results is 8.2%.

Conclusions

Both the meso-scale model and master curve provide close comparison with experimental data. An extra parameter was introduced into the master curve that allowing it to be used over an extended range of experimental conditions.

References

1. Ubbink, M., *Tool ply friction of woven fabric composites*, in *Mechanical Engineering*. 2006, University of Twente: Twente. MEng Thesis.
2. Wilks, C.E., *Processing technologies for woven glass polypropylene composites*. 1999, University of Nottingham. PhD Thesis.
3. Wilks, C.E., Rudd, C.D., Long, A.C. & Johnson, C.F., *Tool/Ply Friction and Consolidation during Processing of Glass/Thermoplastic Composites*, in *6th International Conference on Automated Composites*. 1999: Bristol, UK
4. Gorczyca, J.L., Sherwood, J.A., Liu, L. & Chen, J., *Modeling of Friction and Shear in Thermostamping of Composites - Part I*. Journal of Composite Materials, 2004. **38**(21): p. 1911-1929.