INVESTIGATION OF TOOL-PLY FRICTION OF VISCOUS TEXTILE COMPOSITES

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ABSTRACT

Dynamic tool-ply friction for a thermoplastic viscous textile composite has been measured using a commercial rotational rheometer as a function of rate, temperature and normal pressure. Results of this novel experimental technique have enabled a general empirical equation to be determined relating the dynamic friction force to experimental conditions. The method has been corroborated using an alternative experimental technique. Advantages of using the rheometer include significantly faster production of data and more precise measurement of experimental conditions.

INTRODUCTION

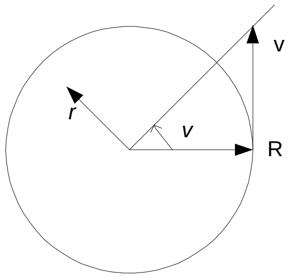
With the proliferation of fibres, resins and manufacturing processes, composites materials enable designers and product engineers to create tailored products for a broad range of application areas. The manufacture of fibre composites involves a forming stage in which dry or impregnated reinforcement takes the required shape under the combined action of holding pressure and forces due to contact with flexible or rigid tooling. The friction that occurs as the material slides relative to the tooling imparts a tensile stress on the material which helps to counteract any compressive stresses in the material during forming that may cause ply buckling. Investigation of the tool-ply friction of viscous textile composites is relatively new. Existing methods for determining friction coefficients of fabric sheets consider effects of normal pressure, temperature and pull-out speed on friction (Murtagh et al 1995, Maldonado 1994, Wilks 1999, and Groczyca et al, 2004). In these methods, either a thin composite sheet is pulled through two horizontal tools or a metal shim is pulled from between two composite sheets. The applied normal load and pull-out speed are predetermined and the pull-out forces are recorded. Friction coefficients are calculated using Coulomb's equation. There are some limitations of this method. One is that it is time consuming, typically requiring 40-60 minutes for one sample; the second is that the required force to pull out the ply from between two metal platens is a combination of the friction force and fabric deformation force (the deformation of fabric is clearly visible after testing). Furthermore, test repeatability is rather poor. To overcome these limitations, a novel experimental technique, involving in the use of a commercial rheometer, is proposed and evaluated. A master curve is derived based on the data produced by the experimental programme, predicting the shear forces at the interface of heated composites and tool surface as a function of rate, temperature and normal pressure.

EXPERIMETNAL METHOD

Test equipment and procedure

Experiments were performed on a Bohlin CVOR200 Rheometer with Extended Temperature Cell (ETC, oven) (Fig.1a). The rig consists of a pair of parallel stainless steel plates, with the lower plate a truncated cone with diameter 25 mm, and the upper plate a flat disk with diameter 40 mm (Fig.1c). A specimen is put onto the upper plate and a ring (outer diameter of 40mm and inner diameter of 30mm) with four bolts is put onto the specimen. The four bolts secure the specimen through the ring onto the upper plate. The specimen is then placed in the

ETC (oven) and heated. After the specimen reaches the required temperature, the upper plate with the specimen is positioned in the rheometer parallel with the lower plate. A normal force is set on the specimen by lowering the upper plate against the lower plate. The value of the normal force is monitored by a computer.


(a)


(b)

(c)

Figure 1 (a) Bohlin Rheometer with ETC, (b) geometry of testing disk, (c) truncated cone and flat disk inside of the rig

Material

The material tested was 1-layer of pre-consolidated 2 x 2 twill weave of Vetrotex Twintex® commingled E-glass and Polypropylene yarn with fibre volume fraction of 0.35.

Specimens were cut at 40 x40 mm (Fig. 2) with squares of 7 x 7mm removed from the corners to leave crosses for the attachment bolts.

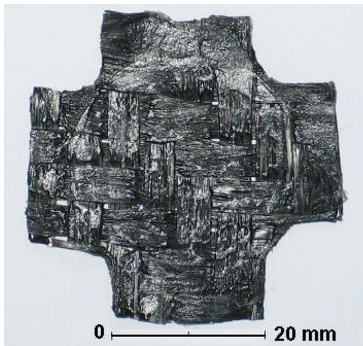


Figure 2 Test sample

DEVELOPMENT OF MASTER CURVE

Input and output of the rheometer

The input data in the rheometer are normal force, N (N), shear stress (Pa) and temperature (°C). Experiments were performed for a range of normal forces 2.5%, 10%, 20%, 50% or 90% of 19.6 N, for a range of shear stresses 500Pa, 1100Pa, 2000Pa, and 5000Pa, and for a range of temperatures 160, 180, 200, and 220°C. Each test was repeated three times and average results were used for data processing.

The output of the rheometer is normal force, n, (normal force is also as an input) and rotation angle (rad) versus time (sec). The data from the rheometer needs to be adjusted in order to compare the data with results from the pull out method.

The normal force can be transferred to normal pressure (MPa) by

$$N = \frac{n}{A} \qquad (1)$$

where N is normal pressure, and A is the testing area ($\pi x 12.5^2$).

The angular velocity can be transferred to linear velocity (mm/sec) by

$$v = \omega r \qquad (2)$$

where ω is the angular velocity, r is an arbitrary radius.

The linear velocity varies from 0 (r = 0) to maximum (r = R) as shown in Fig. 1b. The linear velocity at a radius of 2/3 of the maximum radius (R) is used to process the rheometer data.

Output plot and curve shifting

Transferred outputs from the rheometer, namely normal pressure, N, versus linear velocity for different shear stresses at temperature 180°C are plotted in Fig.3. Similar graphs were also produced at temperature 160°C, 200°C and 220°C. Trend lines have been fitted through the data for the different curves. All trend lines have a constant slope of $v^{-1.37}$.

There are several empirical techniques to shift several data curves to one master curve. Here, the ‘method of reduced variables’ (Macosko 1994) was used for shifting the curves to a master curve. It is possible to shift the curves horizontally and/or vertically as indicated by the arrows in Fig.3. Since the fitted curves are linear on a log-log graph, horizontal or vertical shifting could be used. Here the vertical shifting method was used.

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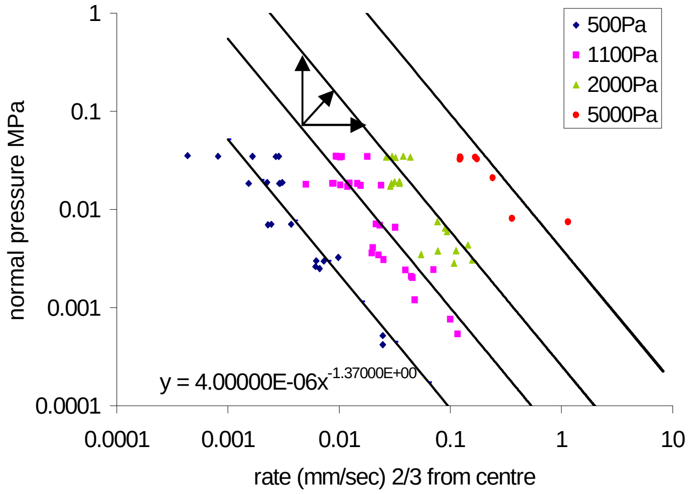

Figure 3 Trend lines for different shear stresses at 180°C

An equation, relating shear stress with rate, temperature and normal pressure, for the master curve can be derived by setting reference parameters and calculating shift factors between the different trend lines. Here, a temperature of 180°C and a shear stress of 500 Pa were set as the reference shifting parameters and shear stress and temperature were shift factors.

From the reference curve fitting (shear stress 500Pa) (Fig. 3), we have

$$N = (4.0 \times 10^{6}) v^{-1.37} \qquad (3)$$

Hence, a general function for normal pressure and velocity is

$$N = c_1 b a_T v^{-c_2} \qquad (4)$$

Where N"is the normal pressure (MPa), v the velocity (mm/sec), b the shift factor for shear stress, a_T the shift factor for temperature, c_1 is a curve fitting coefficient and c_2 = -1.37.

Therefore, the development of an equation for the master curve involves derivations of the shift factors, i.e., b and a_T .

Shear stress shift factor

The shear stress shift factor b in Eq. 4 can be obtained by (van de Haar 2005). Assuming:

$$b = \left(\frac{\tau}{\tau_{ref}}\right)^m \tag{5}$$

Then m in Eq.5 can be obtained by

$$m = \frac{\log b}{\log \frac{\tau}{\tau_{ref}}} \tag{6}$$

Also $b = \dfrac{c_1}{c_{1ref}}$ or $c_1 = bc_{1ref}$ (7)

where, τ_{ref} is the reference shear stress and c_{1ref} is a curve fitting coefficient for the reference shear stress (Fig.3).

Substituting Eqs.5 and 7 in Eq.4, we have

$$N = c_{1ref}\, a_T \left(\frac{\tau}{\tau_{ref}}\right)^m v^{-c_2} \tag{8}$$

where $c_{1ref} = 4.0\text{x}10^{-6}$, $c_2 = 1.37$, $m = 3$ and $\tau_{ref} = 500\text{x}10^{-6}$ MPa

Fig.4 presents plots for normal pressure versus velocity for different shear stresses. Analysing the data in Fig.4 gives the required shifting factors c_1 and b for different shear stresses as shown in Table 1.

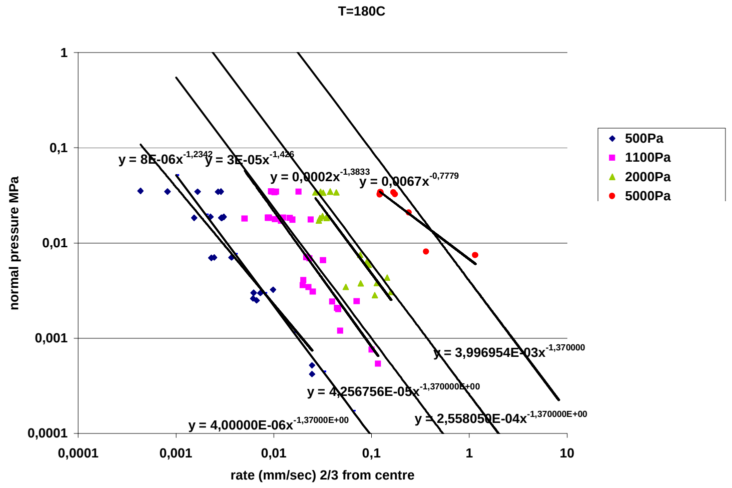

Figure 4 Trend lines for different shear stresses at temperature 180°C,

Table 1 Shear stress shift factors

Shear stress (Pa)	c_1	$\frac{\tau}{\tau_{ref}}$	b	m
500	$4.0\text{x}10^{-6}$	1	1	-
1100	$4.25\text{x}10^{-5}$	2.2	11	3
2000	$2.56\text{x}10^{-4}$	4	64	3
5000	$4.0\text{x}10^{-3}$	10	1000	3

Temperature shift factor

The temperature shift factor a_T was calculated based on the following procedure (Harrison et al. 2001):

$$N = c \exp\left(\frac{A}{T}\right) \qquad (9)$$

where c and A are constants. Hence, the temperature shift factor is

$$a_T = \frac{N(T)}{N(T_{ref})} \qquad (10)$$

where $N(T_{ref})$ is normal pressure at reference temperature.
Combining Eq.10 with 9 and rewriting, we have

$$\log(a_T) = A\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \qquad (11)$$

The constant A in Eq.9 is estimated using the least squares method, resulting in, A = -282.85.

Hence $a_T = 10^{-282.85\left(\frac{1}{T} - \frac{1}{180}\right)}$ (12)

Substituting Eq.12 in Eq.8, the master curve can be expressed by:

$$N = c_{1ref} 10^{-282.85\left(\frac{1}{T} - \frac{1}{180}\right)} \left(\frac{\tau}{\tau_{ref}}\right)^m v^{-c_2} \qquad (13)$$

Substituting the constants c_{1ref} = 4.0x10^{-6}, c_2 = 1.37, m = 3 and τ_{ref} = 500x10^{-6} in Eq. 13 and rearranging, shear stress can be expressed by

$$\tau = \left(500 \times 10^{-6}\right) \times \sqrt[3]{\frac{v^{1..37} N}{4.0E - 06 a_T}} \text{ with } a_T = 10^{-282.85\left(\frac{1}{T} - \frac{1}{180}\right)} \qquad (14)$$

in which shear stress τ is a function of normal pressure N, temperature T and velocity v.

Fig. 5 gives a plot of the shifted data points and the master curve.

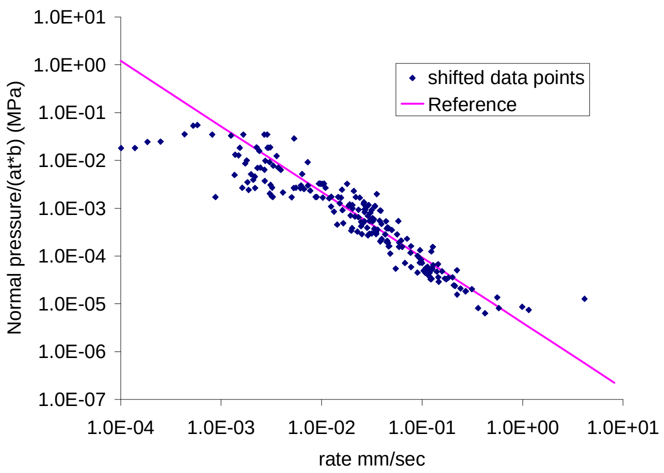

Figure 5 All data from the rheometer is normalised using the shift factors a_T and b.

COMPARISON BETWEEN THE MASTER CURVE AND RESULTS FROM PULL OUT METHOD

To evaluate the master curve, experiments were carried out on the same material at a temperature of 180°C and a velocity of 0.8 mm/sec, using the pull-out and pull-through methods described by Wilks (Wilks 1999). For the results at low pressure, a sheet of Twintex® is pulled from between two steel shim platens; high pressure measurements involve a steel shim being pulled from between two layers of the composite. Fig.6 shows that overall the master curve predict a higher shear stress than that the pull-out and pull-through method. The discrepancy could be caused by deformation of the material sample during the pull-out/pull-through tests, ie. data measured by the rheometer may actually be more accurate.

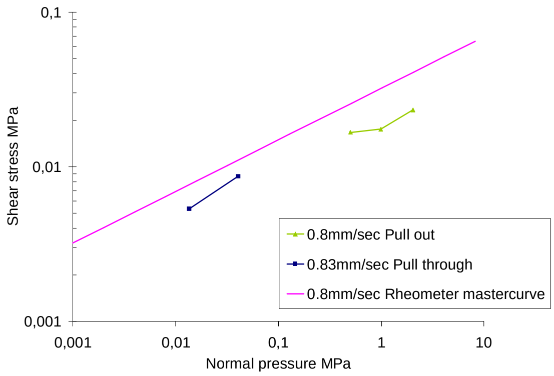

Figure 6 Master curve from rheometer and Pull-through and pull-out test

CONCLUSION

A novel experimental programme dealing with the friction between the heated composite and tool surface during forming has been presented. The data from the new testing technique has been used to derive a master curve for prediction of the shear stress as a function of rate, temperature and normal pressure. The comparison of the master curve with the results from a pull out method shows a similar trend between the two. The advantages in using the rheometer include significantly faster production of data (2-3 minutes against 40-60 minutes per cycle) and more precise measurement of experimental conditions as normal pressures and temperatures are controlled more accurately.

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