Investigation of interply shear in composite forming

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ABSTRACT: This paper describes work carried out on investigating the interply slip phenomenon. First, rheological measurements on the PP resin have been performed, indicating a shear thinning behaviour of the resin. An Ellis model was used to describe the flow behaviour of the resin. Second, the influence of the process conditions on the interply shear properties of a glass/PP woven fabric are assessed by changing the temperature, speed and normal pressure. A peak shear stress, similar to a yield, was observed. A mild increase of the yield shear stress is observed for increasing normal pressure. The influence of both the temperature and velocity on this peak stress is related to the viscous nature of the interply shear.

Key words: thermoplastic, woven fabric, interply slip, viscosity

1 INTRODUCTION

During the forming of a single or doubly curved shape multiple fiber reinforced laminate, the individual plies slide over each other to avoid kinking. This interply slip will depend on the material properties of the fibres and the resin, the fibre distribution, the reinforcement architecture and the process conditions.

To support process optimization and reduce the cost for designing a composite product numerical models are currently under development [1]. The behaviour of the laminates under interply slip needs to be determined to assure the reliability of these predictions. Previous studies investigated the interply slip in unidirectional fiber reinforced thermoplastics [2, 3]. Temperature, slip velocity and lay-up configuration are the major influences on the slipping behaviour. Murtagh et al [3] observed a resin rich layer existed between different plies and showed that the viscosity of this interlayer dominates the slip behaviour at elevated temperatures. Nino et al. [4] measured the intraply shear of a multiply woven lay-up after forming through the composite. The internal layers are subject to viscous-friction interactions that affect the way in which the fabric accommodates to the mould. Tam and Gutowski [5] developed a linear viscoelastic model of the interply slip process using the resin interlayer as a viscous layer. The stress evolution through the thickness of a laminate during forming is highly depended on the temperature profile, confirming the importance of the forming temperature.

This study presents interply shear experiments performed on a custom-made pull-out system. Different process conditions are considered and their influence on the interply shear behaviour is determined.

2 MATERIAL AND METHOD

2.1 Material

The material used in this research is a glass fiber reinforced polypropylene fabric; known as Twintex®. Table 1 summarizes the properties of the weave. Note that it is a highly unbalanced twill weave, with a very high crimp height in warp direction.

Table 1. Twintex® TPEET44

Areal density [g/m²]	1485
Linear density [tex]	1870/2*1870
Crimp [%]	10.3/0.1

2.2 Method

2.2.a Test set-up

Figure 1 depicts the set-up for testing the interply shear behaviour of the composite laminate. It consists out of two metal plates that are attached to a frame, which is mounted onto a tensile testing machine.

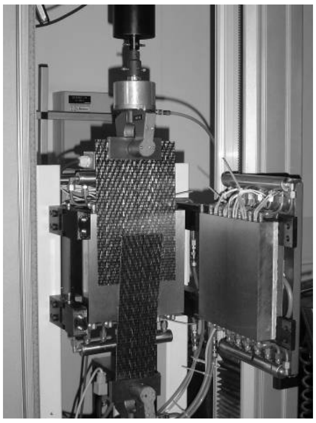

Fig. 1. Set-up for interply shear tests

One plate is fixed on the frame while the other plate can be translated horizontally by using a pneumatic cylinder. Electrical heaters inside the steel plates are used to heat both plates to the desired temperature. Cooling channels are foreseen in the plates, but not yet used in this study.

2.2.b Interply Shear Tests

A specimen of three layers of preconsolidated fabric is positioned between the metal plates. The middle ply is pulled out from the specimen by attaching it to the moving clamp of the tensile testing machine. Both outer plies are held in place by the stationary grip of the machine. Before testing, the preconsolidated fabric is cut to the appropriate size. The area of overlap between the middle ply and outer plies is 80x80mm². The middle ply is cut slightly larger than the outer plies, to prevent the yarns from deforming during the pull-out test.

Figure 2 shows a typical force-displacement curve. A rapid increase to a kind of yield point is followed by a decrease that tends towards a plateau value. This is in agreement with previous studies [2,6].

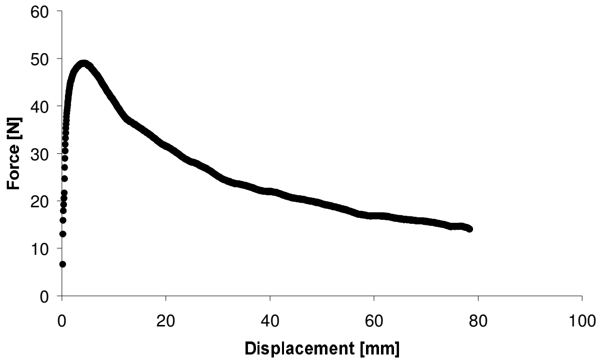

Fig. 2. Typical force-displacement curve

The yield force is associated with a yield shear stress, which is calculated according to equation (1).

$$\tau = \frac{F}{A} \qquad (1)$$

Where τ is the yield shear stress, F the recorded yield force and A the instantaneous surface over which the shear occurs.

The influence of different process conditions on the interply shear behaviour is assessed by changing the temperature, normal pressure and pull-out velocity. Table 2 gives an overview of the different values that are considered. Note that the normal pressure is not constant during the pull-out test. The values in table 2 are the initial normal pressures.

Table 2. Process values

Velocity [mm/min]	12.5, 25, 50, 100, 200, 400
Temperature [°C]	175,185,195,205
Normal pressure [bar]	0.63, 0.55, 0.47, 0.39, 0.31, 0.23, 0.16

2.2.c Viscosity tests

The viscosity of the polypropylene (PP) used in Twintex® is determined by using a rotational rheometer with a plate-plate set-up. The Cox-Merz rule, which is based on the similarity between the shear rate dependence of steady flow apparent viscosity and frequency dependence of dynamic viscosity, is applied. The polymer is already processed by Saint-Gobain into a fibrous form, but not yet commingled with glass fibers. Before testing, the PP-fibers are pressed at 185°C in thin round plates in order to eliminate the influence of air bubbles during testing. Tests are performed at different temperatures. For temperatures below the melting point of PP (165°C), the polymer was first heated to 175°C and then cooled to the appropriate temperature.

3 RESULTS AND DISCUSSION

3.1 Viscosity

Figure 2 depicts the flow curves for PP at different temperatures.

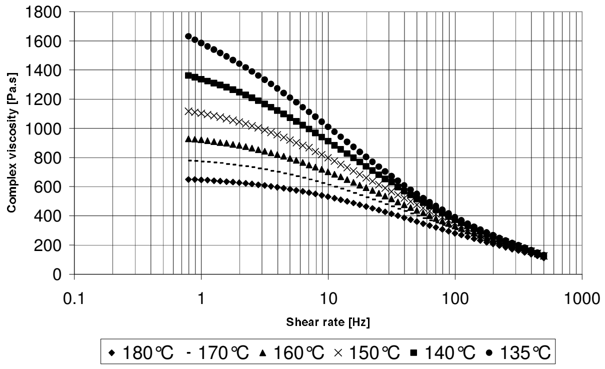

Fig. 3. Flow curves for PP at different temperatures

At low shear rates the viscosity tends toward a plateau level, which is commonly referred to as the Newtonian plateau. When the shear rate increases, the flow behaviour can be described by a power-law. An Ellis model, shown in equation (2), describes the combination of both behaviours and is fitted to the data.

$$\eta(\dot{\gamma},T)=\frac{\eta_0(T)}{1+(\frac{\dot{\gamma}}{C(T)})^{n-1}} \quad (2)$$

An Arrhenius equation (3) has been used to represent the temperature dependence of η_0 and C.

$$A(T)=A_0\times\exp(B/T) \quad (3)$$

Table 3 lists the values of the different parameters.

Table 3. Ellis/Arrhenius model parameters

A(T)	A_0	B
η_0(T)	exp(-1,36)	3576
C(T)	exp(14,82)	-4861

3.2 Interply shear

3.2.a Influence of velocity

Figure 3 indicates the influence of the pull-out velocity on the yield shear stress. An increase in velocity results in an increasing yield stress. Two regions can be identified, (a) a linear region and (b) a region where the yield stress behaves as a power law as function of the velocity. This is an indication of the hydrodynamic nature of the friction.

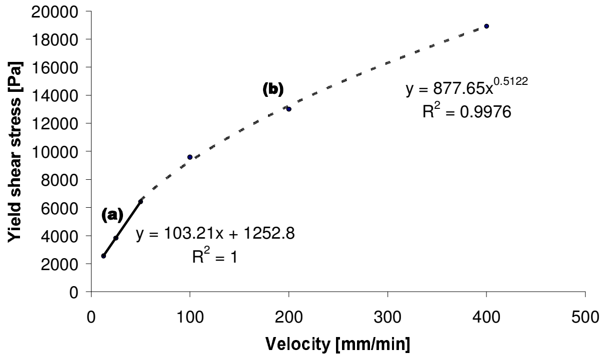

Fig. 4. Yield shear stress versus velocity at a temperature of 195°C and a normal pressure of 0.16 bar

However, for hydrodynamic friction to occur, a thin resin layer needs to develop between the laminates. Murtagh et al. [3] measured the resin layer thickness for a unidirectional fiber reinforced thermoplastic, it was found to be 7μm. Using this value to calculate the shear rate, the power-law region that starts from 50 mm/min agrees with a shear rate of 119 Hz. A power-law model is fitted to the viscosity data at 180°C between the range of 100 and 500 Hz. The power law coefficient is 0.451, which agrees reasonably well with the power-law coefficient indicated in figure 4 namely 0.512.

3.2.b Influence of temperature

Figure 4 shows the influence of temperature on the yield shear stress. An increase in temperature results in a decreasing yield stress. This effect is attributed to the increased viscosity of the matrix at lower temperatures. The exponential decay of the yield stress is related to an Arrhenius model, indicated in equation (3), which has been shown to describe the temperature dependence of the viscosity of the PP resin.

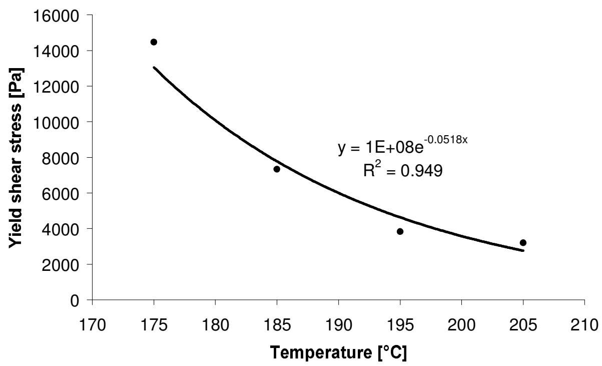

Fig. 5. Temperature dependence of the yield shear stress at a velocity of 25 mm/min and a normal pressure of 0.16 bar

3.2.c Influence of normal pressure

Figure 5 illustrates the influence of the normal pressure on the yield shear stress.

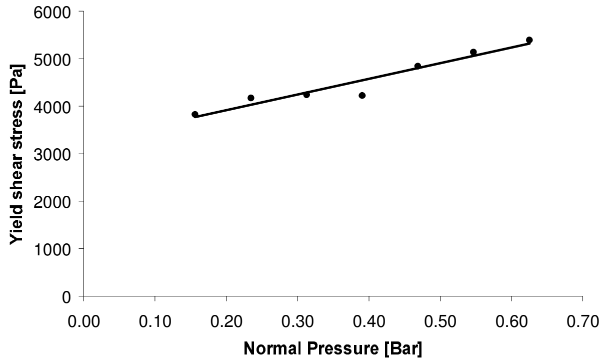

Fig. 6. Influence of the normal pressure on the yield shear stress at a temperature of 195°C and a velocity of 25 mm/min

The yield stress is more pronounced at higher normal pressure. Though, an increase of 300% in normal pressure only gives a 40% increase in yield shear stress. Hence, the friction coefficient, calculated as the ratio between shear and normal force, decreases with increasing normal pressure, as shown in figure 6.

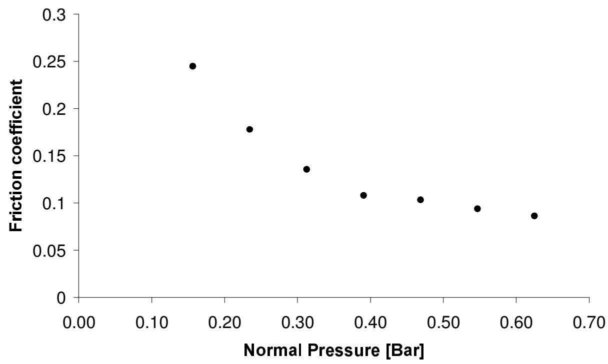

Fig. 7. Influence of the normal pressure on the friction coefficient

This trend is in agreement with a previous study [6] and explained by a shift from inter- to intralaminar shear deformation at higher normal pressures, due to a reduction of the thickness of the resin interlayer. Though, visual proof for intralaminar shear has not been observed.

4 CONCLUSIONS

Rheological measurements on the polypropylene resin used in Twintex® have been performed and indicated a shear thinning behaviour of the resin. An Ellis model in combination with an Arrhenius law was successfully used to describe the flow behaviour of the resin.

An interply shear slip apparatus has been developed and used to investigate the influence of processing conditions on the interply slip behaviour. For all tests performed, a peak shear stress, similar to a yield, was observed. This yield stress was more pronounced at lower temperatures and a reduction of the yield stress is noticed for decreasing pullout velocity. Both phenomena are considered a consequence of the hydrodynamic nature of the interply slip. A mild increase of the yield shear stress is observed for increasing normal pressure, which can be attributed to a reduction in the thickness of the resin interlayer.

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