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Inter-ply Friction of Unidirectional Tape and Woven Fabric Out-of-autoclave Prepregs

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Abstract This paper describes experimental measurements and modelling of friction between two plies of out-of-autoclave thermoset prepregs with different fiber structures including unidirectional, 8-Harness and 5-Harness satin prepregs. Effects of four parameters including temperature, pressure, forming rate and fabric orientation were studied. Results show that the temperature is the most influencing processing parameter due to resin viscosity reduction. For the same processing conditions, unidirectional prepreg has the maximum friction followed by 8-Harness and 5-Harness prepregs. Fabric orientation has effect on interply friction. For fabrics, friction is symmetric with respect to the fabric orientation 45° due to fiber architecture symmetry. For unidirectional prepreg, the friction decrease from fabric orientation 0° to 90°. A friction model was developed based on the linear relationship between friction coefficient and Hersey number which could be used to predict coefficient of friction for any set of processing conditions (temperature, pulling rate, normal pressure) at any fabric orientation.

Keywords Forming, Prepreg, Out of autoclave processing, Inter-ply Friction, Hersey Number

1. Introduction

With the advancement in the technology, composite materials are replacing metals in more and more sectors of aerospace and automobile industries. Their superior properties like high specific stiffness, high strength to weight ratio, low thermal expansion, and corrosion resistance make them more versatile. Composite materials basically consist of fibre reinforcements bonded together with a matrix material. Composite structures allow the strength and stiffness of the material to be controlled with the direction of loading.

The increasing demand of composite materials in aerospace industry has resulted in great developments in the field of composites with the improvement in automated manufacturing technologies and materials used. It has become a necessity for aerospace industries to improve their manufacturing methods to achieve less manufacturing time and less cost to meet the present needs. From traditional way of hand lay-up to advanced manufacturing techniques like Automated Tape Laying (ATL) or Automated Fiber Placement (AFP), a wide range of fabrication methods are available for making composite components. Traditional hand lay-up technique is very time consuming and labor intensive. Advanced techniques like ATL or AFP are more efficient way of laying-up for larger structures. For making smaller parts, AFP will lose its advantages because of the head size and speed reduction. One way to handle this deficiency is to use automated manufacturing techniques (ATL and AFP) to make flat preforms relatively fast. Then preforms are transferred to the forming units such as double-diaphragm forming machine to turn the flat stack of material to the final shape.

Additionally, overall manufacturing cost can be reduced by avoiding autoclave based curing process. This need is satisfied by the use of Out-of-Autoclave (OOA) prepregs manufacturing technology. The use of out-of-autoclave (OOA) prepregs can reduce cost as well as production time. The OOA prepregs can be formed by the application of temperature and vacuum only, without the need of high pressure and thus, saving the expenses for costly autoclave. Void contents can be reduced in OOA prepregs by the use of tooling of appropriate type and identifying a maximum corner angle for a laminate of given thickness and a desired thickness uniformity [1].

In thermoforming of composites many deformation mechanisms take place, such as intra-ply shear, inter-ply slippage, ply-bending, and intra-ply tensile loading [2-7]. Inter-ply slippage plays the most important role in forming of prepreg plies and deciding the quality of the final product [8-9]. Friction between different layers of prepreg plies is dominated by processing parameters like temperature, forming rate, and normal pressure. In addition, material properties such as fiber structure, resin viscosity and fiber tow thickness influence inter-ply friction.

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Forming of stack of prepregs needs all the plies to deform according to the shape of tool without causing any defect in the final component. Intraply shear deformation mechanism and interply slippage deformation mechanism dominate the process of forming, but this paper focuses only on slippage mechanism between adjacent plies.

Various test methods were adopted by researchers to measure interply frictional forces and shear stresses [8-14]. Murtagh et al. used friction sled method in which composite specimen was sandwiched between two sheets of steel shim [12]. Scherer and Friedrich used pull-out test method in which individual ply was pulled out of the stack of plies [14]. Friction between prepregs can be considered as a combination of both Coulomb friction and hydrodynamic friction. Coulomb friction is governed according to the equation 1 in which f is the frictional force, μ is the coefficient of friction and N is the normal force to the friction interface.

$$f = \mu N \tag{1}$$

When the two surfaces are separated completely by a fluid, friction mechanism is completely hydrodynamic in nature. As shown in equation 2, shear stress is governed by rate of movement of one surface over other, fluid viscosity and thickness of the fluid film [15], where τ is the shear stress, η is the viscosity of fluid, d is the thickness of fluid film and v is the velocity of one surface over other.

$$\tau = \frac{\eta}{d} v \tag{2}$$

Chow [16] proposed the use of Stribeck curve to explain experimental results. This curve includes the effects of Coulomb and hydrodynamic friction models to predict the coefficient of friction for different values of processing parameters. In the Stribeck curve the key parameter, against which the coefficient of friction is plotted, is called the Hersey number. The Hersey number is the dimensionless number obtained from the velocity v (m/s) times the dynamic viscosity η (Pa·s = N·s/m^2), divided by the load per unit length of sliding plate s (N/m) [8]:

$$H = \frac{\eta v}{s} \tag{3}$$

In this study, based on the set-up configuration, the load per unit length can be calculated as

$$s = P.W \tag{4}$$

where P is the normal pressure and W is the sliding plate width.

2. Material and Test Methods

2.1. Material Selection and Specimen

The composite material selected for this research was Cytec engineered material. This prepreg material is called CYCOM 5320-1 system. It is an out-of-autoclave curing prepreg material. CYCOM 5320-1 is a newly developed out-of-autoclave material for automated manufacturing in aerospace industry [18, 19]. Due to the low temperature curing ability of this material, it can be used for prototyping where low cost and vacuum-bag-only curing is needed [19]. This composites material is suitable to be used in the primary structure of the aircrafts as it has the mechanical properties equivalent to the autoclave cured epoxy systems. Three different forms of this composite material were used which are unidirectional, 8-Harness satin, and 5-Harness satin carbon/epoxy prepreg materials. Table 1 shows the properties of the three different forms of CYCOM 5320-1 carbon/epoxy system.

Table 1. Material properties of the composite materials used in this study

Materials	8-Harness (8HS)	5-Harness (5HS)	Unidirectional (UD)
Manufacturer	Cytec Engineering Materials Inc.	Cytec Engineering Materials Inc.	Cytec Engineering Materials Inc.
Resin	CYCOM 5320-1	CYCOM 5320-1	CYCOM 5320-1
Fabric	T650-3K 8HS	T650-6K 5HS	T650-UD
Resin Content (wt %)	36	36	36
Areal Density (g/m^2)	569.10	574.90	218.60
Thickness (mm)	0.55	0.60	0.18

A pair of two samples was used in each test, i.e. inner and outer ply. The inner ply used was 610 mm (24 inch) long and 140 mm (5.5 inch) wide and the outer ply used was 685 mm (27 inch) long and 140 mm (5.5 inch) wide. The sizes of specimens were chosen according to the dimensions of the test-rig.

2.2. Friction Test Rig

To perform the interply friction tests, a test rig was designed and manufactured as shown in Figure 1. Test rig consists of a steel middle plate and two steel platens for applying normal pressure to prepreg plies. Six cartridge heaters and a thermocouple were inserted in the middle plate. Three cartridge heaters and a thermocouple were inserted in each platen. Temperature was controlled by using three controllers through feedback system. Four springs were used to apply normal pressure to prepreg plies. Springs were calibrated according to their force-displacement curves. Inner prepreg ply was clamped on the middle plate with the help of clamping plates. C-clamps were used to help clamping plates hold the prepreg material firmly. The middle plate was held in between two platens.

Outer prepreg ply was mounted over a wide spar at the bottom of test rig and was clamped between two platens on the inner ply. The contact area between two prepreg plies is 140 x 76 mm (area = 10640 mm^2). Test rig was installed on a tensile testing machine which can perform tests at different pulling rates. The middle plate effectively pulls the clamped prepreg sample between the two steel platens which apply pressure to the front and back surfaces of the prepreg ply. A load cell attached to the top of middle plate was used to measure the frictional resistance between two prepreg plies. As there are two slippage interfaces between inner and outer plies, so the relationship between tensile load F recorded by load cell and frictional force f is given by equation 5.

$$F = 2f \quad (5)$$

Combining equations 1 and 5, we get

$$\mu = f/N = F/2N \quad (6)$$

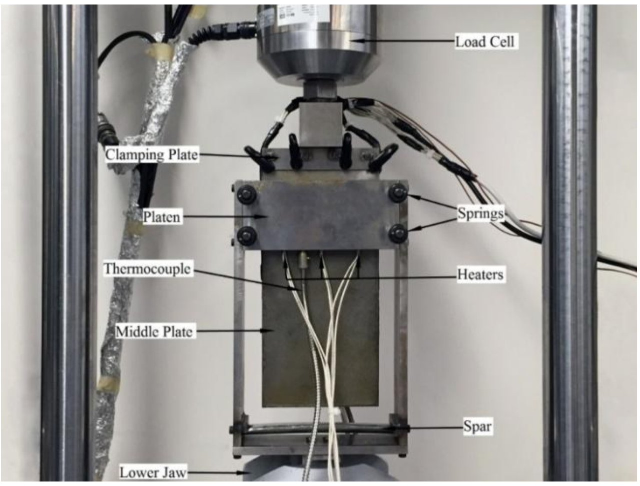


Figure 1. Friction Test Rig

3. Experiments

3.1. Processing Parameters and Their Ranges

Determination of the processing parameters and their range depends on the forming technique. The forming process under investigation is the double diaphragm forming. In this process the laminate will be placed between two plastic or silicon rubbers bagging under vacuum which hold and compact the laminate for the forming process. Then heat applied to the material and under the controlled vacuum inside the tool, the material deforms and takes the final shape. The processing parameters will be heat (temperature), compaction force (level of vacuum between the plastic bags) and forming rate (controlled vacuum inside the tool).

Next step is to determine the range of each processing parameters. Effect of temperature is to reduce the resin viscosity to decrease the friction. However, higher temperature makes the reaction get faster and curing accelerates. To find the processing window for temperature, DSC tests were performed. The dynamic runs were performed at rate of 2℃/min to monitor the difference in heat flow. The result is shown in Figure 2. The onset of reaction is about 100℃ and therefore any forming operation has to be done at temperature lower that 100℃. Considering the manufacturer recommended cure cycle which propose the temperature of 93℃ for 12 hours, it was decided to limit the forming temperature to maximum 90℃. To investigate further the temperature effect, rheometer was used to monitor the viscosity development during isothermal conditions. Three different temperatures 70℃, 90℃ and 100℃ were selected for this study. The results are shown in Figure 3. The results indicate that there is enough time for forming operation without having significant reaction. At 90℃, we have about two hours. Based on these observations, three temperatures 50℃, 70℃ and 90℃ were selected for the rest of the investigation.

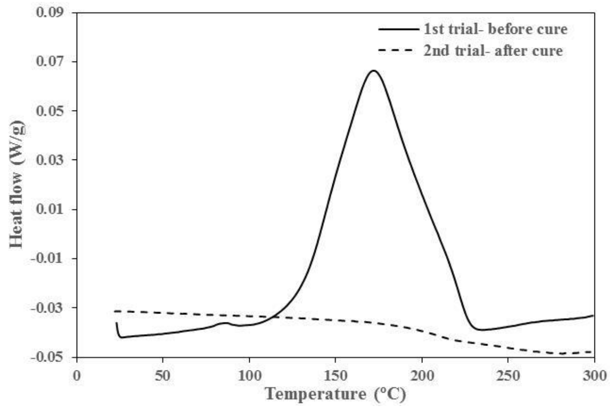


Figure 2. Heat flow for prepreg at 2℃/min

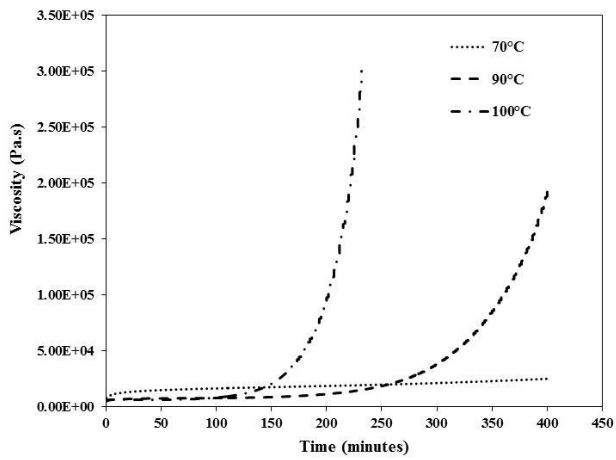
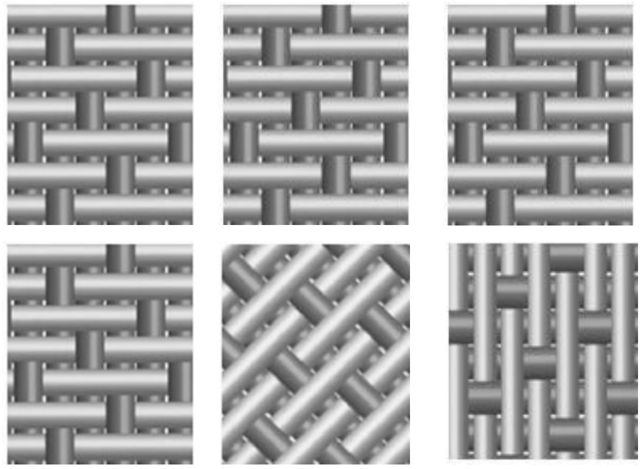


Figure 3. Viscosity development at different temperatures

For double-diaphragm forming, the level of vacuum between the plastic bags determines the compaction force. Therefore compaction force can be adjusted from zero (no vacuum) to maximum one atmosphere (very low vacuum inside the bag). Three levels of vacuum 0.5 atm, 0.2 atm and full vacuum were selected for the experiment. These translate to the compaction pressure of 0.5 atm, 0.8 atm and 1 atm, respectively. The force on the fixture adjusted to simulate these conditions.

Based on our experience and other reported data, the forming rate of 0.2, 0.5, 1, and 2 mm/sec were selected. The last parameter is the fabric orientation. The fabric zero orientation means that the two fabrics are aligned and slide in the weft direction as shown in Figure 4(a). Other angles were studied where one fabric is rotated with respect to the other one and there is an angle between their weft directions (Figure 4(b), (c)).

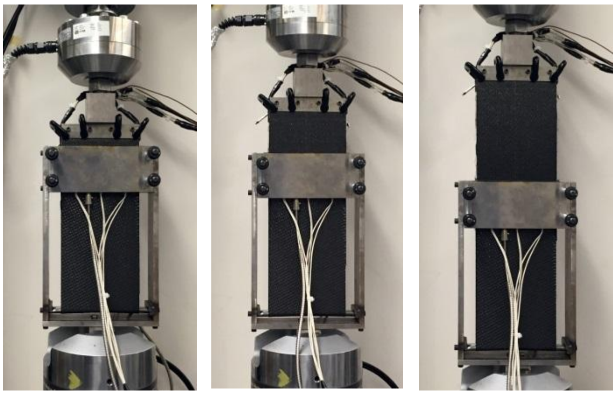


(a) (b) (c)

Figure 4. Friction test between two 5-harnerss satin fabric at (a) 0° fabric orientation (b) 45° fabric orientation (c) 90° fabric orientation

3.2. Experimental Method

A pair of two samples was used in each test, i.e. inner and outer ply. Samples from 8-harness, 5-harness and unidirectional material were cut rectangular in shape. The inner prepreg ply was clamped on the middle plate with the help of clamping plates. The outer prepreg ply was placed over the inner ply between the two platens. The outer ply was mounted over a wide spar at the bottom of the test rig to ensure that it would not move when inner ply is pulled upwards. Figure 5 shows the start, mid and end of the friction test.



(a) (b) (c)

Figure 5. (a) Start, (b) Mid and (c) End of the test

4. Results and Discussion

4.1. Temperature Effect

In order to facilitate the forming operation, these processes usually take place at high temperatures. To investigate the influence of operating temperature, tests were performed at a constant pulling rate of 0.5 mm/sec, a constant normal pressure of 0.5 atmosphere and fabric orientation at 0° to the pulling direction at different temperatures. All the three kinds of composite prepregs, 8HS, 5HS and UD, were analysed in the tests. Results are based on load-displacement graphs that were obtained from tensile testing machine at different conditions of test parameters. Figure 6 shows load-displacement graphs for 8HS at 50, 70 and 90℃ to analyse the effect of processing temperature on inter-ply friction. The graphs show that frictional load measured by load cell reduces as the temperature increases from 50℃ to 90℃. This is in agreement with the fact that the viscosity of resin decreases with the increase in temperature and resin changes from rubbery state to liquid state. According to the equation 2, shear stress is directly proportional to the viscosity of fluid. Therefore, force of friction is reduced at higher temperatures. The rheological tests show that with the rise in temperature resin viscosity reduces at initial stages while later it increases drastically [20]. The later rise in viscosity is due to the increase in degree of cure of the resin. In this study we are interested only in the initial stage as actual forming operation takes place during this period. As stated earlier, load-displacement graphs show high peak in the frictional load at the start of test and steady state afterwards.

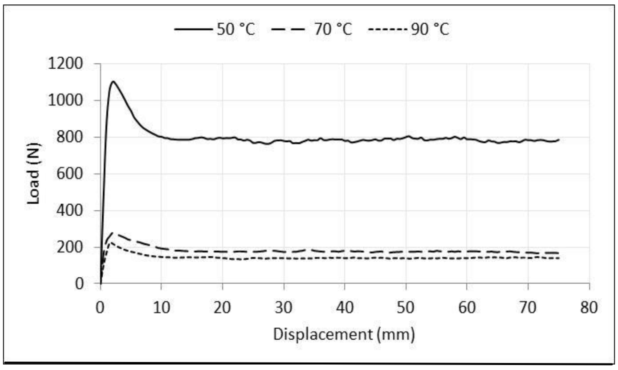


Figure 6. Influence of temperature on Inter-Ply friction at 0.5 mm/sec, 0.5 atm and 0° fiber orientation for 8HS prepregs

Friction coefficients are very important in the modelling of the inter-ply friction mechanism. Equation 6 was used to calculate the coefficient of friction at different temperatures. As shown in Figure 6, the load-displacement graphs show the initial rise in friction and then gradually decrease to a steady state, coefficients of friction for both these values were calculated. Table 2 shows the comparison between coefficient of friction at maximum value and steady state coefficient of friction at 50, 70 and 90℃ for UD, 8-harness and 5-harness fabrics. For example the maximum value of friction coefficient decreases from 1.02 to 0.2 for 8-harness prepregs as the temperature rises from 50℃ to 90℃.

Figure 7 shows the comparison of peak value coefficients of friction for unidirectional, 8-harness satin, and 5-harness satin carbon/epoxy prepregs at different temperatures, 0.5 mm/sec pulling speed, 0.5 atmosphere normal pressure and 0° fiber orientation. Similar trend in the behaviour of friction coefficients for UDs was observed as it was observed for 8HS and 5HS. Peak value of friction coefficients decreases from 1.25 to 0.22 for unidirectional prepregs as the temperature rises from 50℃ to 90℃. Coefficients of friction came out as the highest for UD, followed by the 8-harness and then 5-harness satin. It could be explained from the phenomenon of penetration of fibers from one prepreg layer to other. As there are fibers in one direction only in UDs, so fiber penetration will be more as compared to fabrics in which fibers in the transverse direction resist interference of one fiber layer into other. Also for 8-harness satin, there are more straight fibers compared to the 5-harness (less crimp) which cause higher coefficient of friction for 8-harness satin.

Table 2. Coefficient of friction at different temperature for constant pulling rate of 0.5 mm/sec, a constant normal pressure of 0.5 atmosphere and fabric orientation at 0°

	Unidirectional		8-Harness		5-harness	
Temp ℃	Max value	Steady State	Max value	Steady State	Max value	Steady State
50	1.25	0.87	1.02	0.72	0.72	0.48
70	0.27	0.17	0.28	0.18	0.21	0.14
90	0.22	0.13	0.2	0.16	0.18	0.11

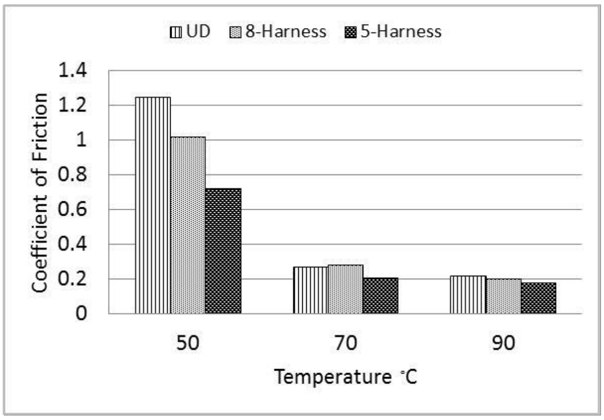


Figure 7. Influence of temperature on coefficients of friction for UD, 8HS, and 5HS at 0.5 mm/sec, 0.5 atm and 0° fiber orientation

4.2. Influence of Pulling Rate

Pulling rate during experiments represents the slippage speed of one prepreg ply over other. Tests were performed at a constant temperature of 50℃ and a constant normal pressure of 0.5 atmosphere at different pulling rates. The tensile testing machine provided the different pulling rates. Fabric orientation was 0° in these experiments. Results were recorded from tensile testing machine at various conditions of test parameters. Figure 8 shows load-displacement graphs at 0.2, 0.5, 1 and 2 mm/sec, for 5HS, to investigate the influence of pulling rate on inter-ply friction. It could be noticed that these graphs have similar stick-slip peaks of dry-coulomb as they were in the graphs for elevated temperatures. The graphs show that frictional load increases as pulling velocity increases from 0.2 mm/sec to 2 mm/sec. This is in agreement with the fact that the shear stress between prepreg plies is directly proportional to the velocity of one ply with respect to other.

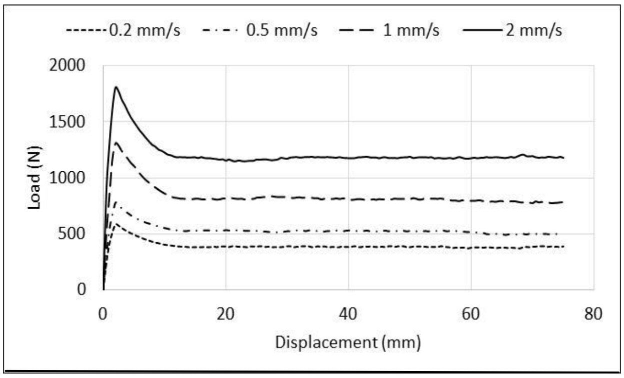


Figure 8. Influence of pulling rate on inter-ply friction at 50℃, 0.5 atm and 0° fabric orientation for 5HS prepregs

To calculate the coefficients of friction at different pulling rates, equation 6 was used. As load-displacement graphs show peak and steady states of friction, coefficient of friction for both these values were calculated. Table 3 shows the comparison between maximum value coefficient of friction and steady state coefficient of friction at 0.2, 0.5, 1 and 2 mm/sec. Friction coefficient increases for all composites as the pulling rate increases from 0.2 mm/sec to 2 mm/sec.

Table 3. Coefficient of friction at different pulling rate for constant temperature of 50℃, a constant normal pressure of 0.5 atmosphere and fabric orientation at 0°

	Unidirectional		8-Harness		5-harness	
Rate mm/s	Max value	Steady State	Max value	Steady State	Max value	Steady State
0.2	0.88	0.65	0.7	0.47	0.54	0.38
0.5	1.25	0.87	1.02	0.72	0.72	0.48
1	2.08	1.3	1.75	1.1	1.2	0.75
2	3.00	1.6	2.78	1.48	1.67	1.1

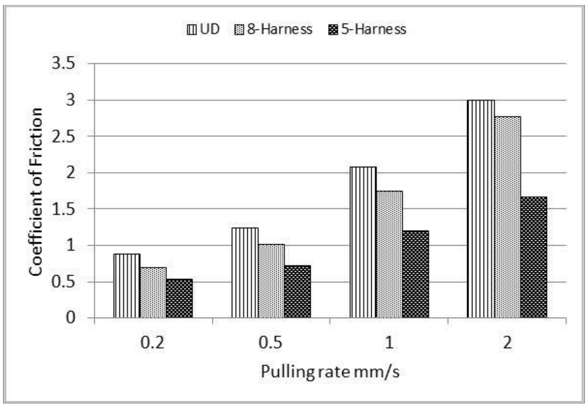


Figure 9. Influence of pulling rate on coefficients of friction for UD, 8HS, and 5HS at 50℃, 0.5 atm and 0° fiber orientation

Figure 9 shows the influence of pulling rate on coefficients of friction for UD, 8HS, and 5HS at 50℃, 0.5 atm and 0° fiber orientation. Only peak value of friction coefficients has been plotted. It was observed that friction coefficient increases with the increase in pulling velocity and depends on the prepreg fiber architectures. Maximum coefficient of friction happens at pulling rate of 2 mm/s and is related to UD prepreg followed by 8-harness and then 5-harness fabric. Having more crimp in the fabric create more separate contact points and reduce the coefficient of friction.

4.3. Effect of Normal Pressure (Compaction Force)

Normal pressure in the thermoforming operations is essential to consolidate the prepreg plies with each other. To study the influence of normal pressure on Inter-Ply friction, tests were performed at a constant pulling rate of 0.5 mm/sec and a constant processing temperature of 50°C at different pressures on 8-harness satin, 5-harness satin and unidirectional carbon/epoxy prepregs. Plies were oriented at 0° to the direction of movement. Figure 10 shows load-displacement graphs at 0.5, 0.8 and 1 atmosphere for UD prepregs. The results show that frictional load increases as the pressure increases from 0.5 to 1 atm.

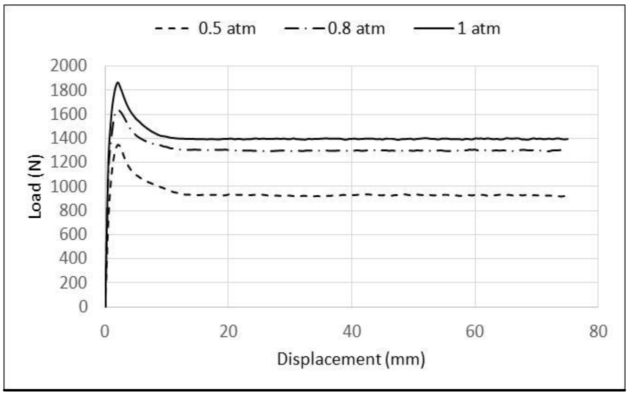


Figure 10. Influence of normal pressure on inter-ply friction at 50°C, 0.5 mm/sec and 0° fiber orientation for UD prepregs

The results could be explained by the deformation of the fiber geometry under different loading magnitudes. The fibers are assumed to have circular cross-section before the application of normal pressue. The width of the contact area between single yarn and the pressure plate increases as it gets compressed. With the increase in contact area, the force of friction increases accordingly. Also the fibers are not completely straight inside the prepreg and have some waviness. So the contact between them is through some points. Under the pressure, the fibers get closer and there are more contact area which cause higher frictional load.

Table 4. Coefficient of friction at different normal pressure for constant temperature 50°C, pulling rate of 0.5 mm/sec, and fabric orientation at 0°

	Unidirectional		8-Harness		5-harness	
Press atm	Max value	Steady State	Max value	Steady State	Max value	Steady State
0.5	1.25	0.85	1.02	0.72	0.72	0.49
0.8	0.95	0.75	0.81	0.58	0.59	0.43
1	0.85	0.65	0.74	0.50	0.53	0.38

Table 4 shows the comparison between maximum value coefficient of friction and steady state coefficient of friction at 0.5, 0.8 and 1 atm for all three fabrics. It is observed from the graphs, friction coefficients decrease as the normal pressure increases.

An increase of 100% in normal pressure gives a 45% increase in frictional load for UD. The reason for decrease in coefficients of friction with increasing normal pressure is that as coefficient of friction is the ratio of force of friction to the normal force and increase of normal force gives percentagewise less increase in force of friction. Relationship of frictional load, normal pressure and coefficient for 8-harness carbon/epoxy prepreg is shown in Figure 11.

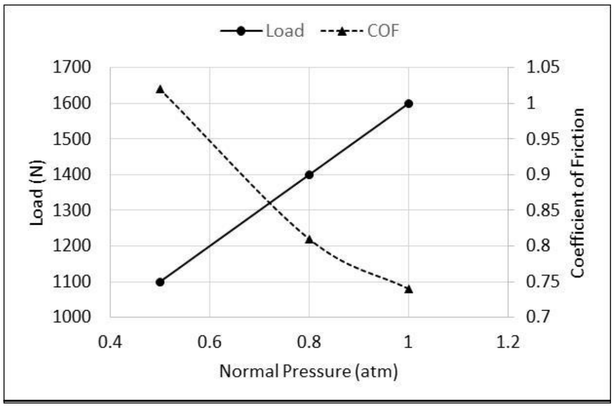


Figure 11. Relationship between Load, Normal Pressure and Friction Coefficient for 8HS

4.4. Fabric Orientation

For a stack of laminate, the orientation of the fibers in each prepreg ply is very important to obtain desired mechanical properties. During forming operations, fiber orientation could affect the occurrence of wrinkles and other defects in the final product. To analyse the influence of fabric orientation, friction tests were performed at a constant normal pressure of 0.5 atmosphere, a constant temperature of 50°C and a varying pulling rate of 0.2 mm/sec, 0.5 mm/sec, 1 mm/sec and 2 mm/sec. The orientation of the fibers to the pulling direction was changed to study its influence on inter-ply friction. 8-harness, 5-harness and unidirectional carbon/epoxy prepreg composites were analysed in the tests. Results are based on load vs. pulling rate graphs that were obtained from tensile testing machine at different conditions of test parameters. Figure 12 shows load vs. pulling rate graphs for 8HS at 0°, 15°, 30° and 45° fabric angle to the direction of ply movement to analyse its effect on inter-ply friction (See Figure 4). The graphs show that frictional resistance decreases as fiber angle changes from 0° to some angle to the pulling direction. Force of friction decreases as the angle changes from 15° to 30° to 45°.

The coefficient of friction (load) vs fabric orientation for two types of fabrics and unidirectional ply are shown in Figure 13. The testing were performed at a constant normal pressure of 0.5 atmosphere, a constant temperature of 50°C and a constant pulling rate of 0.5 mm/sec. For both 5-harness and 8-harness satin, the frictional force is reduced by increasing the fabric angles from 0 to 45°. By increasing the angle from 45 to 90°, the frictional force increases again. It has symmetrical behaviour. The reason is that the fiber structure is symmetric with respect to the 45° axis (see Figure 4). For unidirectional prepreg, there is no such symmetry. The contact between the fibers will change from a line at 0 degree to a point at 90 degree (See Figure 14). The frictional force decreases as the angle increases from 0 to 90 degree.

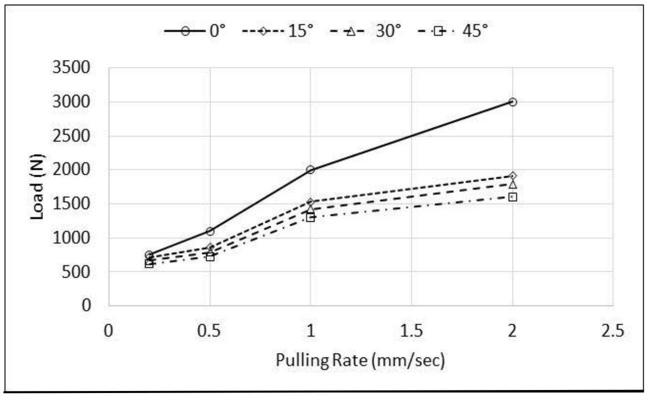


Figure 12. Plot of load versus pulling rate for 8HS at different fiber orientations

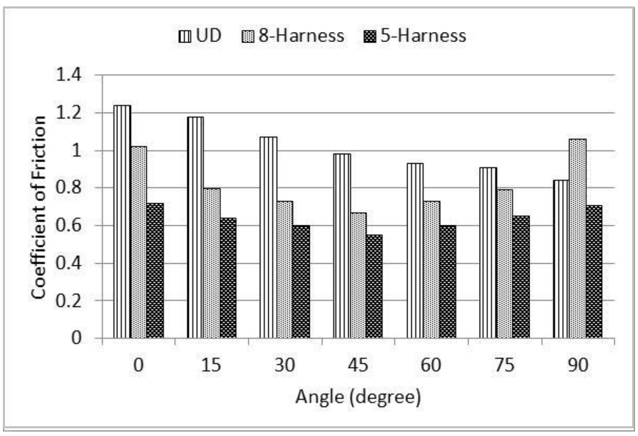


Figure 13. Influence of fabric orientation on coefficients of friction for UD, 8HS, and 5HS at temperature 50℃, pulling rate 0.5 mm/s, and pressure 0.5 atm

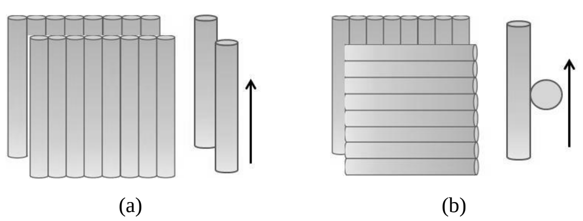


Figure 14. Friction test between two unidirectional prepreg at (a) 0° fiber orientation with line contact between fibers (b) 90° fiber orientation with point contact between the fibers

4.5. Stribeck Analysis

The coefficient of friction is a function of various parameters including temperature, pressure, rate, and fabric orientation. For each set of processing conditions, experiment has to be performed to obtain the frictional force and subsequently the coefficient of friction. Having a model that can predict the coefficient of friction based on different processing condition and fabric orientation is useful, particularly for the forming simulation. To develop the analytical model for frictional behavior of prepreg plies, Hersey number can be calculated for each set of processing parameters [21-25]. Hersey number combines three processing parameters including viscosity (temperature), pressure, and forming rate into one characteristic number. Resin viscosity at different temperatures calculated using equation provided in [26]. Hersey numbers were plotted against coefficients of friction for 5HS as shown in Figure 15. The curves were fitted to the intersecting points of friction coefficients and Hersey numbers. It is observed from the Stribeck curves that coefficients of friction increases with the increase in Hersey numbers. The curve show that inter-ply friction of carbon/epoxy prepregs are hydrodynamic in nature as the slope of the curves are positive.

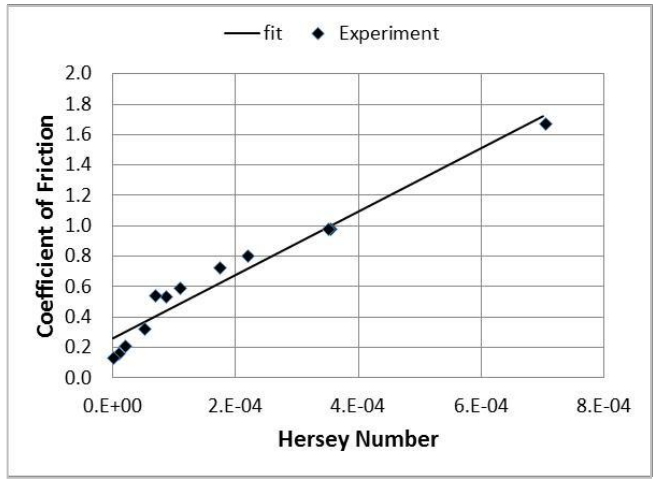


Figure 15. Experimental Stribeck curve for 5-harness satin carbon/epoxy prepreg oriented at 0° to the direction of slippage

The linear relationship was found between Hersey numbers and coefficients of friction as:

$$\mu = 2089\, H + 0.2 \quad (6)$$

The above linear equation could be used to find out friction coefficient at any particular set of processing conditions. As Hersey number (H) is the function of viscosity of resin, normal pressure and pulling rate, so using the viscosity values at any given temperature and using other processing conditions, coefficient of friction could be easily calculated with help of the linear equation 6. To include the fabric orientation into the model, experiments were performed under the different fabric orientations and experimental results were analyzed. The linear equations obtained at different fiber orientations for 5HS are shown in Table 5.

It is noticed that linear equations obtained from the Stribeck curves are in the form

$$\mu = a\, H + b \quad (7)$$

where variables *a* and *b* have different values for each set of fabric orientation. Figure 16 shows the variable *a* plotted against fabric angle θ. The variable *b* can be considered as a constant number *b*=0.26. For slop of the line *a* for different angles, a quadratic equation can be fitted to the data and the final equation is given as:

$$a = 0.3\,\theta^2 - 27\,\theta + 2150 \tag{8}$$

A general equation was developed which could be used to predict coefficient of friction for any set of processing conditions for 5HS at any fabric orientation, as given by equation 9.

$$\mu = (0.3\,\theta^2 - 27\,\theta + 2150)\,H + 0.26 \tag{9}$$

where θ is the fabric orientation angle in degrees. Similarly, general equation for 8HS was developed by using Stribeck curves (Figure 16) which is given below:

$$\mu = (0.84\,\theta^2 - 75\,\theta + 3620).H + 0.33 \tag{10}$$

The general equation for 8HS shows the similar trend of change in friction coefficient as shown by equation for 5HS.

Table 5. Linear equations for 5HS at 0°, 15°, 30°, 45°, 60°, 75° and 90° fabric orientation

Fabric Orientations	Linear Equations
5HS at 0°	μ = 2089 H + 0.26
5HS at 15°	μ = 1774 H + 0.27
5HS at 30°	μ = 1662 H + 0.26
5HS at 45°	μ = 1550 H + 0.26
5HS at 60°	μ = 1677 H + 0.26
5HS at 75°	μ = 1790 H + 0.26
5HS at 90°	μ = 2204 H + 0.25

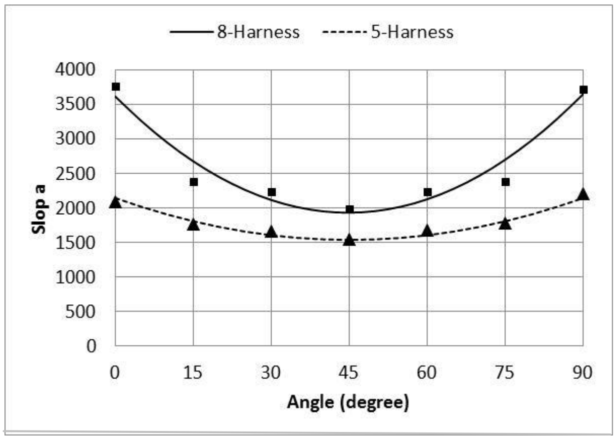


Figure 16. Relationship between "a" and fabric angle "θ" for 8HS and 5HS

As mentioned before, the unidirectional behaviour under different fabric orientations will be different in all fabric angles from 0 to 90 degree. Stribeck curves for unidirectional prepregs were made and linear equations were calculated from the fitted lines. Table 6 shows the linear relations for UD at 0°, 15°, 30°, 45°, 60°, 75° and 90° fiber orientation.

Table 6. Linear equations for UD at 0°, 15°, 30°, 45°, 60°, 75° and 90° fiber orientation

Fiber Orientations	Linear Equations
UD at 0°	μ = 4016 H + 0.37
UD at 15°	μ = 3484 H + 0.35
UD at 30°	μ = 3356 H + 0.29
UD at 45°	μ = 3244 H + 0.27
UD at 60°	μ = 3182 H + 0.25
UD at 75°	μ = 3107 H + 0.24
UD at 90°	μ = 2973 H + 0.22

Similar to 5HS and 8HS, it is noticed that linear equations from the Stribeck curves can be used for UD. Figures 17 and 18 show the variables *a* and *b* plotted against fabric angle θ. Quadratic equations can be fitted to the data and the final equation is given as:

$$a = 0.13\,\theta^2 - 21\theta + 3913$$
$$b = 1E\text{-}05\,\theta^2 - 0.0026\,\theta + 0.37 \tag{11}$$

A general equation was developed which could be used to predict coefficient of friction for any set of processing conditions for UD at any fabric orientation.

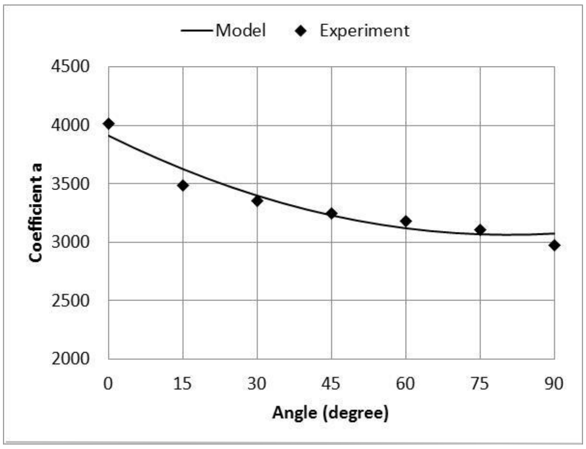


Figure 17. Relationship between "a" and fiber angle "θ" for UD

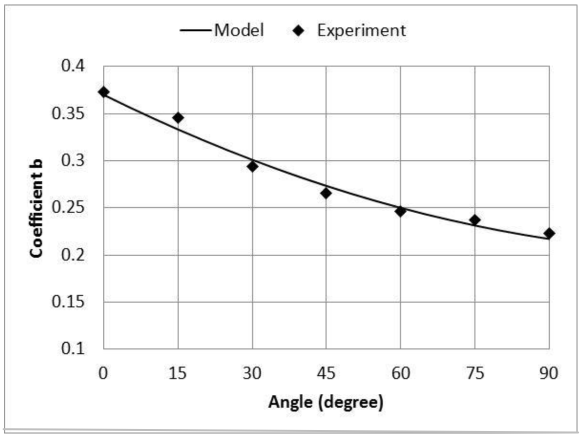


Figure 18. Relationship between "b" and fiber angle "θ" for UD

It is interesting to note that the trend in change of coefficient of friction of fabrics with the change of fabric angle is different than the trend in change of coefficient of friction with the change of fiber angle for UD. For fabric, friction coefficient decreases as the fabric angle increases from 0° to 45° and increases as the angle changes from 45° to 90°. This may be due to the fact that 5HS has fibers aligned in weft and warp directions and as the fabric angle exceeds from 45° the weft fibers start playing the role of warp fibers. For UD, the friction coefficient decreases as the fiber angle increases from 0° to 90°. This is due to the decrease in contact area of fibers as fiber angle increases.

5. Conclusions

The inter-ply friction behavior of 8-harness satin, 5-harness satin and unidirectional carbon/epoxy prepreg was investigated at different processing conditions using a friction test-rig developed for this study. Results show that temperature, pulling rate and normal pressure have different impacts on inter-ply friction. Increase in temperature and decrease in the pulling rate can enhance slipping between prepreg plies. Decrease in normal pressure is helpful in inter-ply slippage. The change in fiber orientation of the prepreg plies has influence on the frictional resistance between layers of the composite laminate. For woven fabric, the frictional resistance was found maximum at 0° fabric orientation and it decreases when orientation of fiber was changed to 15°, 30° and 45°. As the angle of warp yarn increases, the force of friction decreases and reached the minimum value as the warp fiber angle reaches 45°. From 45° to 90° the coefficient of friction increases again due to the fabric architecture symmetry. For UD, the coefficient of friction decreases from 0° to 90°. Stribeck curve analysis was used to predict the coefficient of friction using linear relationship between friction coefficient and Hersey number. Equations were developed that could be used to predict coefficient of friction for any set of processing conditions (temperature, pulling rate, normal pressure) at any fabric orientation.

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