Surface Friction Effects in Pressforming of Continous Fibre Thermoplastic Composites

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Abstract

In the pressforming of thermoplastic composite sheet, the heated laminate is rapidly formed into a mould. The moulding force is transmitted using either matched metal dies or by a rubber pad/metal mould combination. Friction must occur between the metal or rubber mould surface and the heated composite as the laminate moves across the tool surface until it is fully formed. This paper describes work carried out to characterise and measure these frictional forces. Composites such as unidirectional CF/PEEK and GF-fabric reinforced PA-12 have been tested, with rubber and tool steel as the mould materials. Two methods of testing were utilised, one comprising of two fixed heated platens, between which the surfaces to be tested were placed while the composite was sheared from between the platens. Pulling out force was achieved by using a variable velocity shearing rig and also using dead-weight loading. A heated friction sled was also built which allows various samples of metal and rubber material to be dragged across a heated composite sheet. The effects of varying surface temperature, normal pressure, surface fibre orientation and mould release agent was investigated. An adhesive bond was found to occur if the surfaces were left in contact during heating. By varying the shearing velocity, the friction between the molten composite and tool surface was found to be hydrodynamic in nature at forming temperature.

1. Introduction

Thermoplastic composites offer many potential advantages over more traditional thermoset materials due to their ease of formability, potential lower cost of manufacture, higher impact properties and indefinite shelf life. Available in preimpregnated sheet or tape form, parts may be formed by heating the material until it softens, then applying pressure to reshape it into the desired structure. Although materials such as ICI's APC-2 have been available for almost 10 years now, there still seems to be a reluctance on behalf of industry in general to gain full use of these materials. This is mainly due to a lack of viable fabrication technologies. Methods such as diaphragm forming [1] are available, but long cycle times and high cost of consumables mean that only low volume, high cost parts for such industries as the aerospace sector are truly cost competitive. Thus there is a strong need for a rapid production technique akin to thermoforming of conventional plastic sheet or sheetforming of metal, that will allow thermoplastic composites to be used to their full advantage and help bring material costs down.

One such possible technique is pressforming, whereby the composite sheet or laminate is heated (usually externally), then transferred between two dies, which come together rapidly to form a part in a matter of seconds. Both dies may be made of metal, usually tool steel, however one may be fabricated from a rubber material which allows a more even distribution of pressure to the part being formed, allowing better part quality. Traditionally, parts have been pressformed successfully, but this has involved largely a process of trial and error whereby the part, mould and process cycle require constant modification and re-manufacture before consistent quality in the finished article is achievable. A project involving partners from four countries has been initiated under Brite/EuRaM funding [2] to develop a numerical simulation of pressforming, the final result of which will be a software package allowing the user to simulate all aspects of pressforming, including laminate properties, mould geometry, heating conditions, actual forming processes, cool-down and removal of parts. This would remove the necessity of expensive experimentation and prototyping and allow a successful process to be attained much more quickly. In developing this numerical simulation, basic characterisation work must be carried out on the pressforming process cycle and this paper deals with one such aspect, which occurs during forming, namely the friction that must occur between the heated composite and tool surface during forming.

The actual forming step for a typical top-hat section part is shown in Figure 1. Initially, the composite sheet is pre-heated, usually using a system of infrared heating. A blankholder is normally used to hold the sheet in position during this stage. After transferring the sheet between the dies, forming is initiated (Stage 1). Due to the anisothermal nature of the process (the dies may be up to 200°C below the temperature of the molten laminate), forming needs to be achieved as quickly as possible, often in a matter of 1-2 seconds. Friction must occur wherever the molten laminate makes contact with another surface, either the mould or the blankholder. The friction that occurs as the laminate slides from beneath the blankholder may actually aid the forming process so as to counteract any compressive stresses in the laminate that may cause ply buckling. Elsewhere, the laminate must slide along the edges of the die, which are usually rounded (Stage 2). The actual area of contact is determined by the matrix viscosity and fibre stiffness. As the punch progresses, more and more of the laminate comes into contact with the tool surface (Stage 3) and the frictional forces developed depend on the normal force exerted by the die. Finally, the part is fully formed (Stage 4) and friction has no further part to play.

There are two main types of friction - Coulomb friction and hydrodynamic friction. Coulomb friction occurs between 'dry' surfaces and in general the frictional force is proportional to the applied normal force and independent of sliding velocity. hydrodynamic friction is a form of lubrication whereby a thin film of fluid exists between the two surfaces and viscous shearing can occur in this region. In this case, sliding velocity may affect the frictional force. For polymeric friction, especially at high temperatures, hydrodynamic friction is dominant, although a certain element of Coulomb friction may occur wherever fibres are in direct contact with the mould surface. Two further theories have been proposed regarding the actual mechanism of friction on a microscopic scale. Deformation theory suggests that asperities ploughing through an adjoining surface feed energy into the surface ahead of the asperity, some energy is restored at the rear, and the net loss in energy is related to the bulk viscoelastic properties of the material, which in turn are dependent on temperature, normal pressure and rate of deformation [3]. Adhesion theory suggests that asperities from adjoining surfaces which make contact bond together and are continually being broken and reformed as sliding occurs. With plastics, adhesion is thought to be a more realistic theory, especially at high temperatures, where the polymer has softened sufficiently to allow for a larger contact area and more contact between the pliable polymer and the hard metal surface.

When pressforming composites, the main factors affecting friction are :

- Temperature
- Normal pressure
- Fibre orientation
- Mould release agent
- Surface texture

All processing occurs above T_m, the melt temperature of the matrix, even though the tool may be at a much lower temperature. Assuming a constant surface and through-laminate temperature before pressforming occurs, the fibres are relatively free to flow in the molten matrix, allowing such mechanisms as interply slip, intraply shear and transverse flow [4] to occur. These mechanisms are strongly dependent on the matrix viscosity, which in turn depends on temperature. Temperature drop during forming also has an effect on frictional force as matrix properties vary.

Normal pressure also has an effect on friction, indeed the frictional force is proportional to the applied normal force. This force need not be uniform over the surface of the laminate - in some regions it may be zero where no contact occurs, in others high localised normal forces may develop as the part is formed. If rubber is used as the forming material, then normal forces would tend to equilibrate.

It is not really known how surface fibre orientation may affect the frictional performance of composites. Some researchers [5] have shown outer ply orientation to have little effect on friction at room temperature. At higher temperatures, however, fibres may come to the surface of the ply and interact with the tool surface. For hydrodynamic friction to occur however, a thin resin layer is thought to develop between composite and tool. Other research [6] has shown the flow of resin at the interface to be influenced by the fibre orientation, especially for unidirectional fibre composites.

Tool surface finish was not fully investigated for this project. In any event, pressforming in involved in forming parts with a smooth, glossy finish and thus the tool itself is made to a ground, polished finish. All tests carried out were done with samples machined to this criteria. Release agents have traditionally been used in order to aid part removal after forming. However, they may also assist in allowing sliding to occur during forming and help avoid a sick-slip motion. For this program, a number of commercially available release agents were investigated to see their effect on friction:

- Frekote FRP-NC
- Wurtz PAT 807B/808
- ChemTrend E274

For rubber pad assisted pressforming, a PTFE spray was investigated to see how it affected the slippage of the rubber across a composite specimen.

2. Experimental

Two methods for friction testing were utilised. One method consisted of drawing a central specimen (composite or tool material) from between two sheets of the other material, all three being clamped between two heatable platens contained in the jaws of a hydraulic press (Figure 2). This apparatus has been used previously for investigating interply slip of thermoplastic composites [7]. Using this set-up, isothermal conditions were easily achievable and normal forces of between 0.1 kN and 100 kN could be applied. A shim placed at the rear of the specimen maintained a constant gap between the platens. The other test method to be used more accurately simulated actual friction conditions during pressforming. It concerned the development of a 'friction sled', based on an ASTM standard [8], for obtaining coefficients of friction for plastic film and sheeting. It consists of two heating cartridges embedded in an aluminium block to which various test plates can be attached. The composite sheet is separately clamped on the surface of a heated platen and is heated to temperature by conduction from below. The sled is heated separately using it's own heaters and testing begins when the sled is lowered onto the composite surface (Figure 3). A photograph of the sled is shown in Figure 4. The pullout mechanism used was either a dead-weight system, consisting of a steel wire, pulley and weights, or a motor driven leadscrew, with variable linear velocity between 0.25-4 mm/s. To measure the frictional force, a 500 N load cell was mounted in line with the steel wire connected either to the pullout sample or friction sled. All data was monitored and recorded using a custom-built data acquisition/PC based system.

For the mounting of the specimens, unidirectional plies of APC-2 were simply clamped at the rear of the apparatus when testing in line with the fibres. For testing of transversely oriented APC-2 plies, the specimen had to be mounted sideways across the bottom platen and clamped beneath two side flanges. In order to prevent the fibres from slipping from beneath these flanges when above the melt temperature of the matrix, the PEEK resin was removed using a oxy/acytelyne torch prior to testing. Other materials were mounted in a similar fashion.

3. Results

Initial heat-up of the specimen took approximately 25 minutes to heat to 400°C for testing of APC-2. Figure 5 shows how a normal load of 0.2 kN (20 kPa) applied to the sample (0° ply APC-2 sheared from between two sheets of steel foil) during this period had a marked effect on the pullout behaviour of the specimen i.e. an adhesive bond at point A tended to develop between composite and tool surface which had to be broken before sliding could occur. Typical shear strengths for a APC-2 ply held at 20 kPa normal pressure for 30 minutes was 15 kPa. Following the breaking of this bond, the ply tended to slip in a viscous manner, maintaining a steady level of frictional force while velocity was kept constant (indicated by '——'), then showing an increase to a higher steady level as the velocity was incremented. This would indicate the presence of a resin layer existing between metal and composite surface, in which the shearing action was taking place. To avoid this adhesive load being developed, only a contact force was applied during heat-up of the specimen, with a normal force being applied only for a short period before, and during actual pullout.

The effect of temperature has been shown to have a strong effect on the friction of materials, especially polymeric materials since the frictional behaviour tends to be be a function of the material's bulk viscoelastic properties, which have a strong dependence on temperature [9]. Figure 6 shows the effect of temperature on the sliding friction of a 0° APC-2 ply sheared from between two sheets of stainless steel foil. The set point temperature of the platens varied for each test and an applied load of ~0.2 kN (40 kPa) was applied over the sample. Sliding velocity varied between 0.2 mm/s and 2.0 mm/s. The coefficient of friction was determined by dividing the measured frictional force by the normal load, taking into account reduction in area as the ply was sheared. For tests performed at room temperature (25°C), frictional coefficient did not vary significantly with velocity and remained at a low value, approximately 0.16. As the temperature was raised towards the melt temperature of the PEEK resin (343°C), the coefficient of friction began to increase, although not significantly and again, not strongly proportional to the velocity. However, further tests carried out at higher temperatures (365°C, 385°C, 405°C), showed a large increase in frictional coefficient, from a common value of approximately 0.4 at low velocities to a value of 1.2 at a velocity of approximately 2.0 mm/s, indicating a very strong adhesive component. This increase in friction may be attributed to the softening of the PEEK resin which allowed the real area of contact between composite and metal surface to increase substantially as temperature increased. It might be expected that once a resin layer was established between the surfaces that friction would be due totally to the shearing of the viscous fluid at the interface, and that an increase in temperature would cause the viscosity of the resin to decrease, thus causing a reduction in shear force and consequently a decrease in frictional coefficient. This was found not to be the case.

Figure 7 shows the influence of normal pressure on friction of a unidirectional 0° orientated APC-2 specimen drawn across a stainless steel foil surface coated with release agent (Frekote). Temperature was kept constant at 385°C for this series of tests. As shown, the coefficient of friction decreases as normal load is increased, a trend observed by other researchers [10] for polymeric materials. The coefficent of friction varies from approximately 0.1 at low speeds (<0.25 mm/s) and a normal load of 750N (150 kPa normal pressure) to 0.6 at high speeds (2 mm/s) and a low normal load of 0.1 kN (20 kPa). It is to be observed that as speed increases, the coefficient of friction tends to level off at a relatively constant value, for each increase in shear velocity. One explanation for this phenomenon is that as speed and displacement of the sample is increased, the lubricating resin layer gets thicker, due to build-up of a transferred polymer layer to the steel foil surface. This is also evidenced by visual inspection of the steel foil specimen after pullout, where a thick, polymer layer was seen to exist. Figure 8 shows further proof of this. A typical steel foil specimen was sheared from between two sheets of APC-2 at high shearing velocity of 2 mm/s. Once again, the shearing load increases rapidly to a peak value of 215 N, then levels off and begins to decrease, as would normally be expected to take account for area reduction. However, if shearing is stopped for a period of time (point A), to allow any excess polymer layer to re-percolate back into the composite, then when shearing is re-commenced (point B), the load recovers to a higher value than at which the shearing motion had ceased previously (point C). This would seem to indicate that the resin layer at the interface had once again returned to its original thickness. This phenomenon may be of assistance in the actual pressforming process, where high shearing speeds are to be expected when the part is formed, as it reduces the frictional forces. Once the part is formed, any transferred polymer is re-consolidated.

As mentioned previously, it is expected that fibre orientation has an effect on the friction of composites, despite the fact the a resin layer may exist in the interface between mould surface and composite. Figure 9 shows the result of tests carried out with APC-2 using the friction sled, under standard temperature and normal load conditions (385° and 50 N respectively). Its shows that friction occurs more easily for fibres lying in the 90° direction i.e. perpendicular to the direction of sliding, than for fibres in the 0° direction. Monaghan et al. [6] has proposed that this may be due to the higher apparent viscosity of the resin in the fibre direction, compared with the transverse direction, where the rolling motion of the fibres allows easier resin flow for lubrication of the sliding motion.

Various release agents were investigated to determine their effect on the friction of unidirectional APC-2 against stainless steel. It should be noted that not all these agents were regarded as suitable for giving optimum results at such high temperatures (385°C) or that surface quality is not a more important quality when selecting the appropriate agent. For all these tests, two coats of each agent were applied to the steel foil and allowed to dry. For the E274 agent, the foil had to be pre-heated to 400°C before the agent was applied using an aerosol. Figure 10 indicates that the highest friction was obtained for the sample with no release agent applied. Frekote FRP NC and E274 gave similar results. PAT-808, due to the fact that it dries to a thicker coat gave the lowest friction results. PAT-807B gave slightly higher results, but it was noted that it also gave a better surface finish compared with PAT-808.

Tests were carried out to determine the frictional characteristics of a silicon rubber pad sheared across a sheet of unconsolidated GF-PA12 material. This material is a cross-woven continous glass fibre-reinforced fabric reinforced with a nylon matrix, with a processing temperature of approximately 240°C. For this test, the rubber was pre-heated to a temperature of 120°C, as at higher temperatures, the silicon rubber material degraded rapidly. Two tests were carried out, with and without a PTFE coating, with a normal load of 50N. As shown in Figure 11, the coefficient of friction was quite high in both cases (0.75-0.25), with the presence of the release agent reducing the frictional force by a slight amount. This high coefficient of friction indicates a strong adhesive attraction between rubber and composite, due to the compliant nature of the rubber, especially at elevated temperatures.

4. Conclusions

An apparatus has being adapted and built to measure the frictional characteristics of various moulding materials against thermoplastic composite materials. Various tests were carried out, primarily using unidirectional APC-2, with a ground, polished steel foil representing the mould material. A resin layer was deemed to exist at the interface between composite and tool surface, which resulted in friction of a hydrodynamic, viscous nature. An adhesive bond was found to develop if the materials remained in contact during heat-up. An increase in processing temperature from 345°, just above the melt temperature of the matrix, to 385°, resulted in large, two-fold increase in coefficient of friction at low shear velocities, and an even greater, five-fold increase at higher velocities (2 mm/s). An increase in normal load caused a decrease in coefficient of friction, a phenomenon observed with other polymeric materials. At higher shear velocities, shearing force tended to decrease rapidly, indicating a possible thickening of the resin interface during sliding, causing a transfer of molten material to the mould surface. It was also shown that friction was less for sliding across a sample with fibres orientated at 90° to the direction of sliding, compared with a 0°-orientated sample. The presence of a release agent may substantially reduce the coefficient of friction. Tests carried out with a silicon rubber material has shown the presence of a large coefficient of friction, indicating a very strong adhesive component of friction with the composite.

5. Acknowledgements

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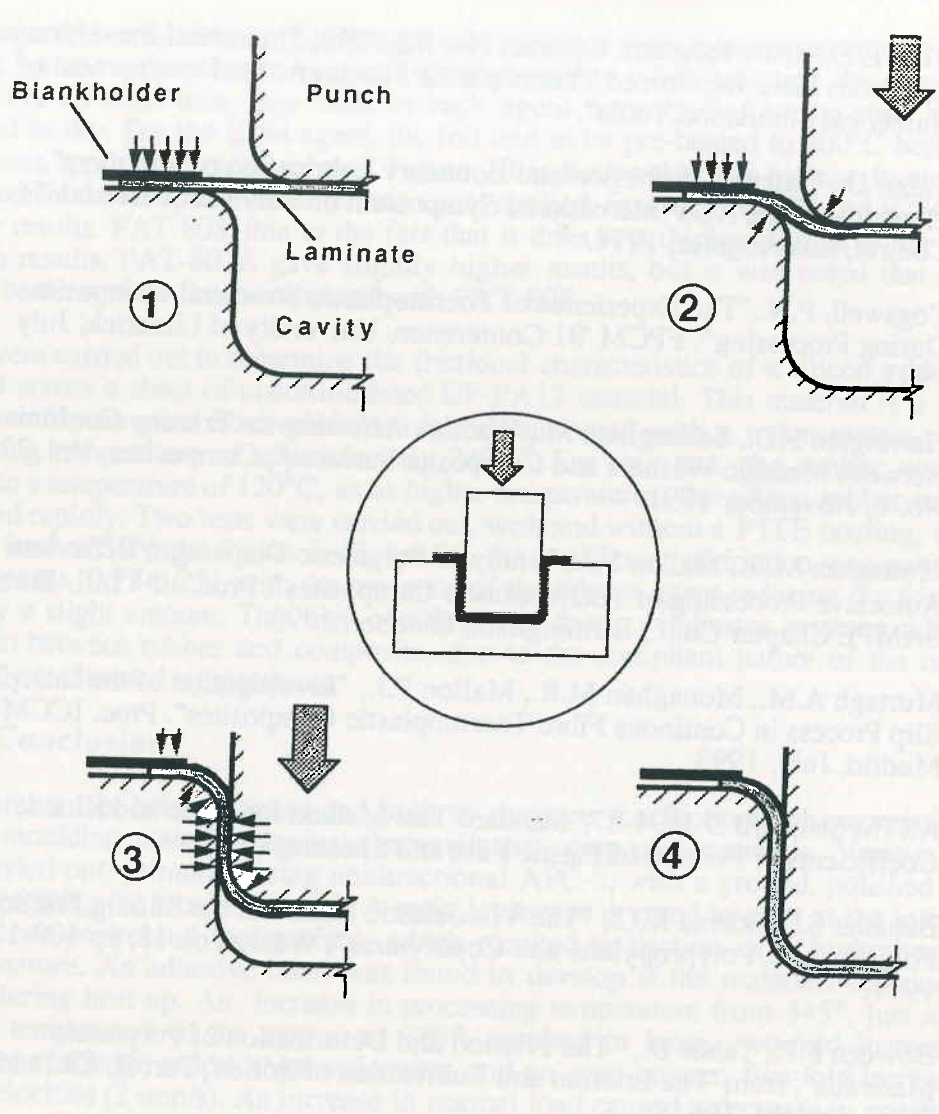

Figure 1 Stages in pressforming of a typical top-hat section

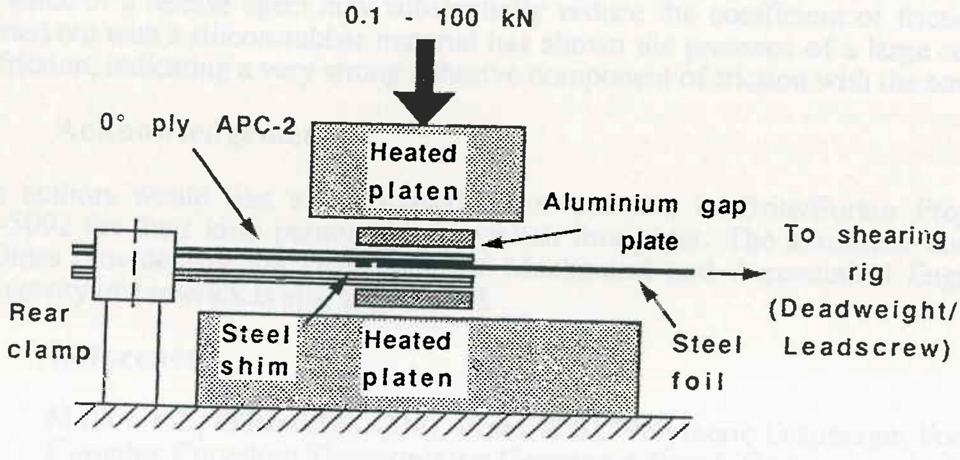

Figure 2 Twin platen arrangment for friction testing

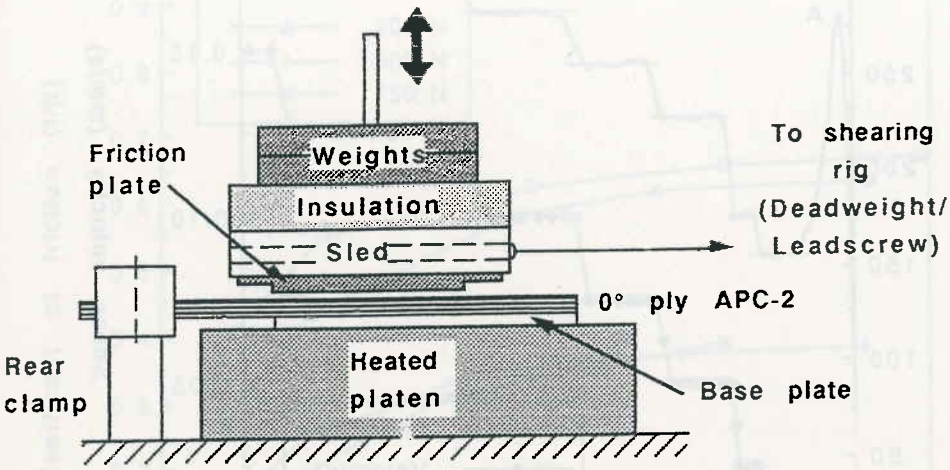

Figure 3 Schematic of friction sled

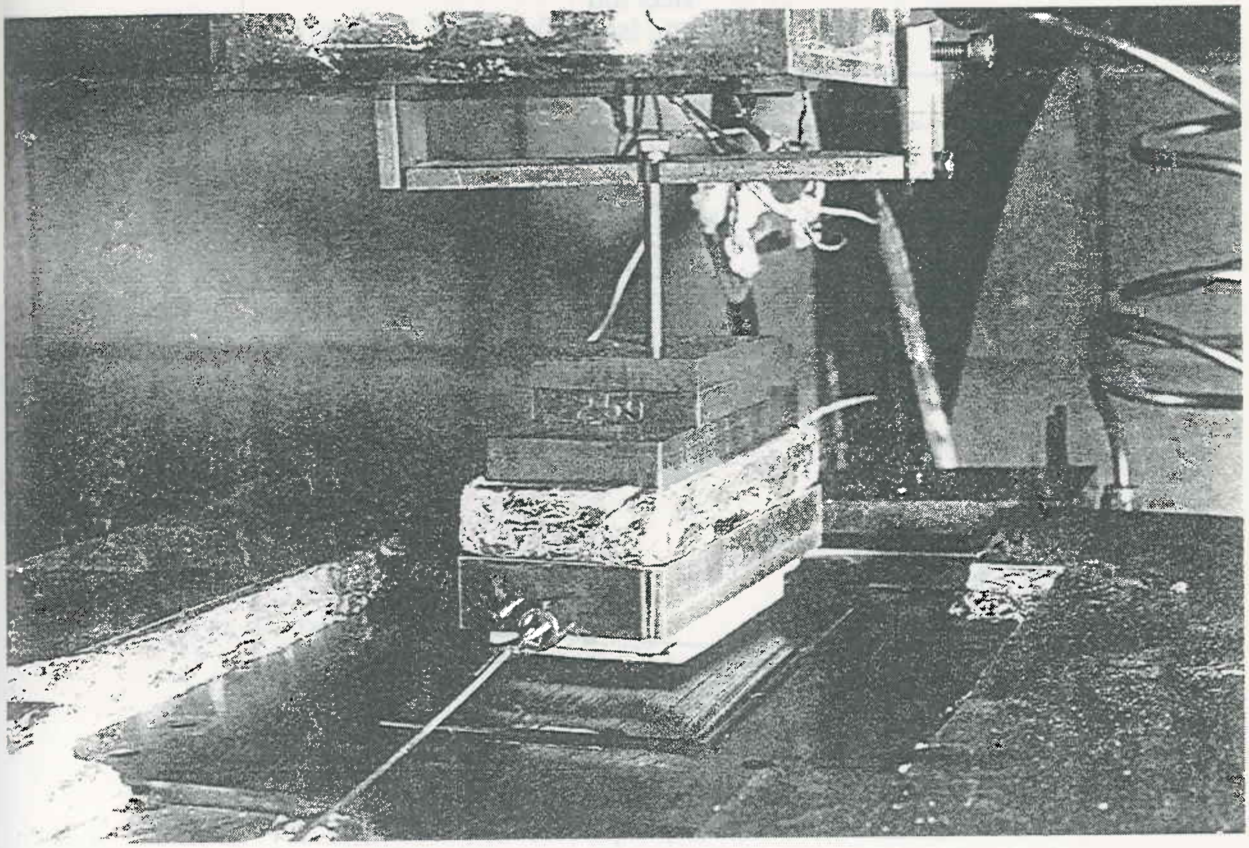

Figure 4 Photograph of friction sled
(insulation omitted)

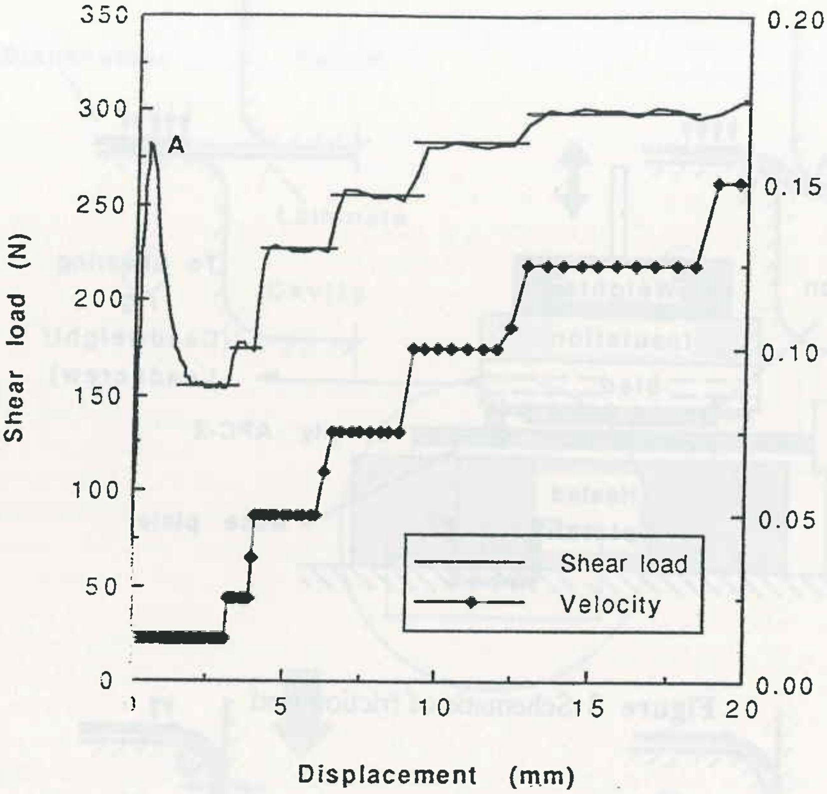

Figure 5 Pullout of 0° APC-2 from between two sheets steel foil

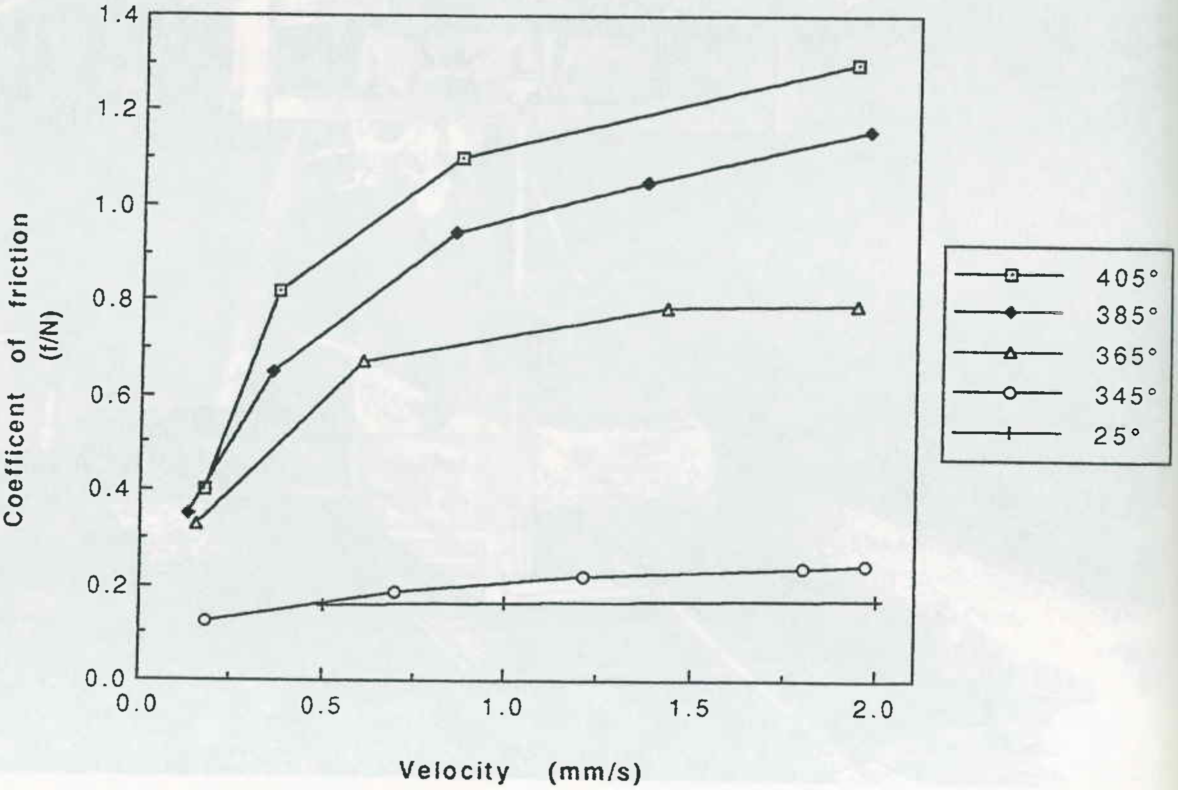

Figure 6 Effect of temperature on friction

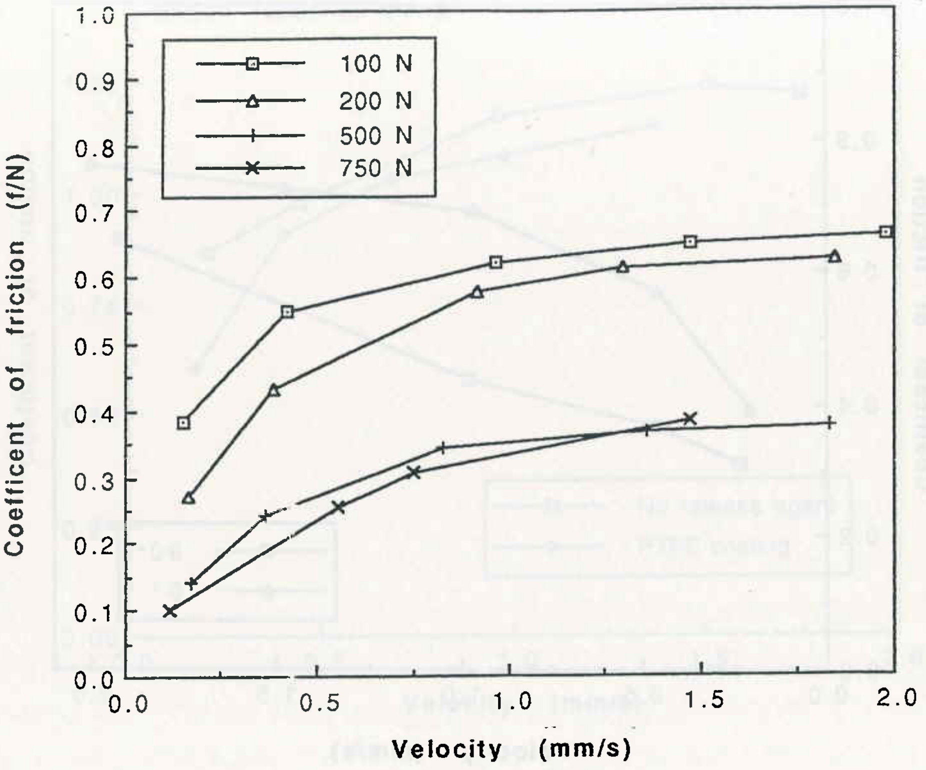

Figure 7 Effect of normal pressure on friction

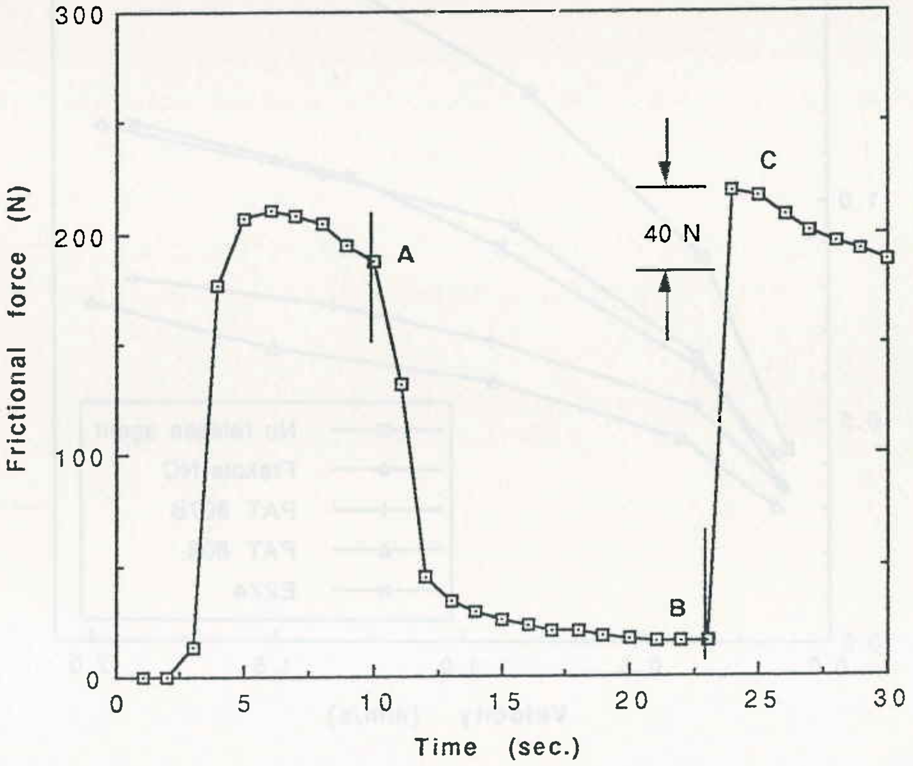

Figure 8 Frictional force reduction at high velocity

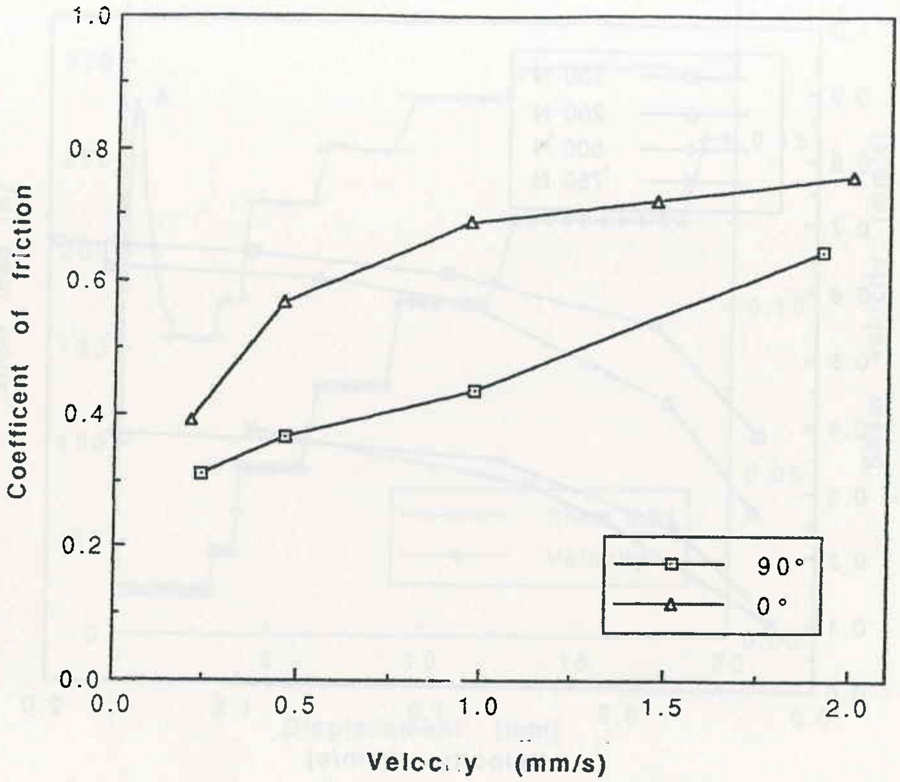

Figure 9 Effect of fibre orientation on friction

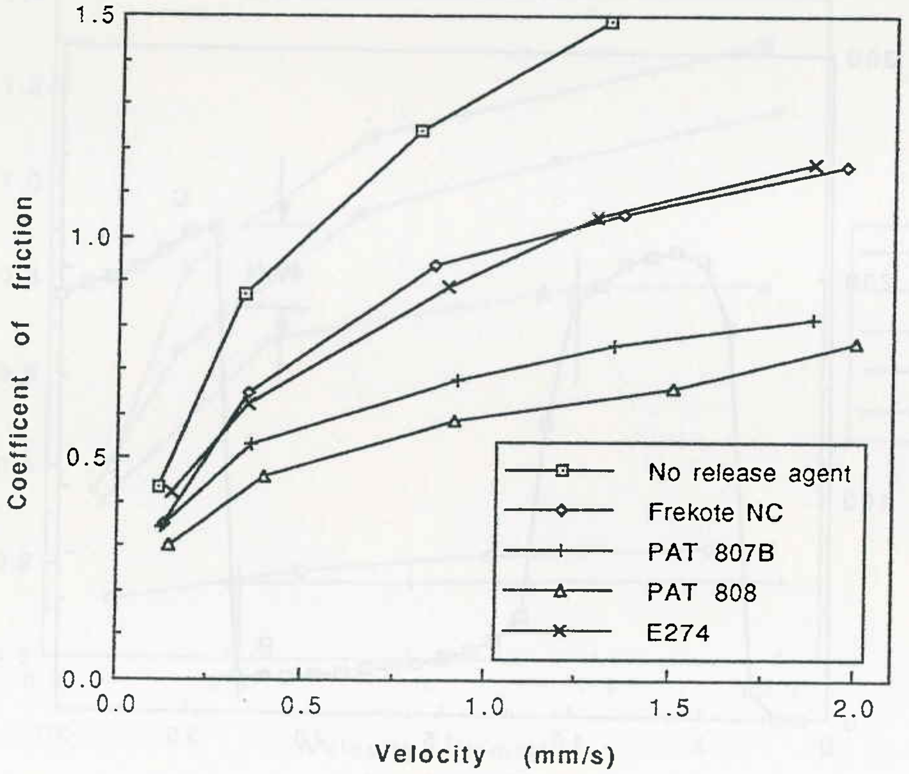

Figure 10 Effect of release agent application

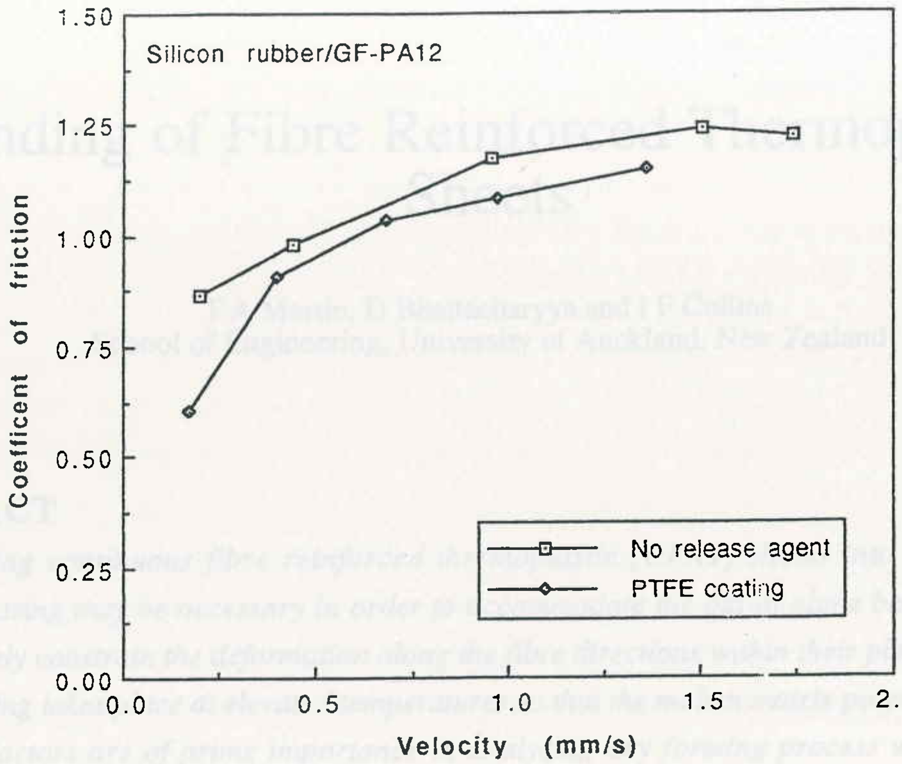

Figure 11 Silicon rubber/GF-PA12 friction