A NON-NEWTONIAN FLOW MODEL FOR SIMULATING THE FABRIC COATING PROCESS

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ABSTRACT

The peak stress value (PSV) at the interface between a coating polymer solution and a fabric during coating has been calculated using generalised Navier-Stokes and Carreau models for non-Newtonian flow. The model suggested that knife gap is the most important machine parameter affecting the coating process. A 20% decrease in knife gap for example leads to 100% increase in PSV in the coating paste, which subsequently can lead to poor adhesion between the paste and the fabric during coating. Coating speed was found to have less effect on the PSV, a 50% increase in speed leading to only a 30% increase in PSV, implying that this factor is less significant. The validity of the rheological models was confirmed by experimental investigations.

Kew words: Modelling, simulation, non-Newtonian flow, fabrics, coating

1. INTRODUCTION

Manufacturers of advanced technical textiles are facing increasing pressure to improve product performance and quality while simultaneously reducing costs. In order to reduce production costs, mathematical modelling and numerical simulation are more and more extensively used in product development, process optimization and quality control, which can contribute significantly to meeting these challenges (1).

Previous studies (2) on the rheological behaviour of the paste formulations in coating indicated that the coating paste corresponds to a non-Newtonian, shear thinning fluid as the viscosity decreases with increasing shear rate. The Carreau model was fitted with measured data describing viscosity dependence of the paste formulations on shear rate, with coefficients varying at different solvent volume fraction.

Coating quality can be assessed by the penetration of paste into the fabrics, adhesion between the paste and fabrics, and the uniform spreading of the paste on the fabrics (1). Knowing the parameters of paste formulations, a computer simulation of the coating process can be carried out to relate the coating quality with coating material properties and coating process parameters by modelling the polymer paste flow during the coating process.

2. MODEL OF POLYMER SOLUTION DURING COATING

Most theoretical studies on the spreading of polymer solutions onto a solid surface have been focussed on shear-thinning behaviour (3–7), as attempts to account for other non-Newtonian properties concluded that normal stress effects are not important (7, 8). Based on this assumption, the property of coating materials can be characterized in a phenomenological way, yielding equations of motion that have the form of generalized Navier-Stokes equations 1, 2 (9, 10).

$$\rho\frac{\partial u}{\partial t}-\nabla\cdot\eta(\nabla u+(\nabla u)^{T})+\rho(u\cdot\nabla)u+\nabla p=F \quad (1)$$

$$\nabla\cdot u=0 \quad (2)$$

where η is the dynamic viscosity, ρ is the density, u the velocity field, p the pressure, and F a volume force field such as gravity.

To characterise the dynamic viscosity during coating, the Carreau model (Equations 3 and 4) was employed based on the rheometric analyses of coating materials (2).

$$\eta=\eta_{\infty}+(\eta_0-\eta_{\infty})\left[1+\left(\lambda\dot{\gamma}\right)^{2}\right]^{\frac{(n-1)}{2}} \quad (3)$$

Where

$$\dot{\gamma} = \sqrt{\frac{1}{2}((2u_x)^2 + (u_y + v_x)^2 + (2v_y)^2)} \qquad (4)$$

where η_0 represents the zero shear rate viscosity, η_∞ is the infinite shear rate viscosity, λ is a parameter with units of time, and n represents the shear rate sensitivity ($0 < n < 1$).

The rheological behaviour of the polymer paste during coating can be defined by equations 1, 2, 3, and 4, together with a set of appropriate boundary conditions. The formulated mathematical model was then solved via a computer based numerical technique.

3. SYSTEM GEOMETRY

For the knife-over-roll coating, a solvent borne, aromatic, one-component polyurethane fabric coating, (Clear Durane® Basecoat 51144, Raffi and Swanson Inc., Wilmington, MA) was used to coat a number of woven fabric substrates. The fabric was placed between the coating knife and the roller (Figure 1), and the coating material was applied uniformly along the coating knife. The gap distance was adjusted by moving the blade up or down, and the fabric pull-through speed was also adjusted.

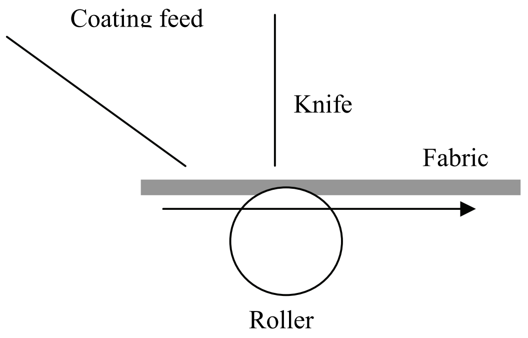

Figure 1: A simplified knife over roller coating mechanism

Coating machines which use knife coating are in general simple to operate and can be used for a wide variety of coating thicknesses. Experimental wok was carried out using a Coatema base coater, which is a pilot scale knife coating machine. A simple sketch of the knife position is shown in Figure 1.

The model equations in this study were used in the finite element method (FEM) to simulate the behaviour of the polymer solution (coating materials) during the coating process. FEM is used because of its ability to efficiently resolve the non-linear phenomena with a non-uniform grid mesh, the ease with which it handles variable boundary conditions and its firm theoretical foundation. The equations were solved using the MATLAB software package under selected conditions. The geometry and Finite Element mesh of the system can be illustrated in Figure 2.

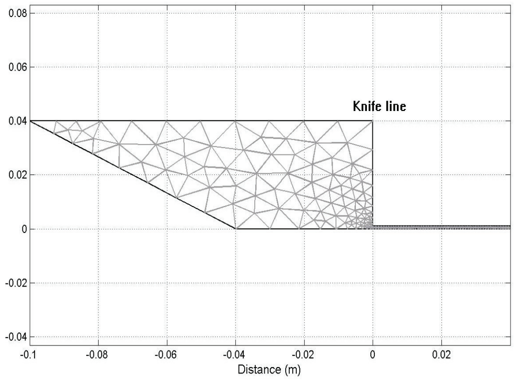

Figure 2: Geometry and Finite Element mesh of the system

4. SIMULATION RESULTS

Based on the model equations 1, 2, 3 and 4, and the system geometry, the results of computer simulation of the properties of the polymer paste within the defined system were presented. These results are mainly presented in graphical forms.

Figure 3 shows the velocity and pressure distribution of the polymer paste before knife (within paste tray) and after knife (on fabric). The colour expresses the pressure distribution. Hotter colours indicate higher pressures. Arrows represent the velocity of polymer paste within the system. The length of the arrow denotes the magnitude of the velocity, and the arrow heads indicate the direction. This figure demonstrates the flow behaviour of the paste during coating. For example, there is a peak value of both velocity and pressure just near the knife.

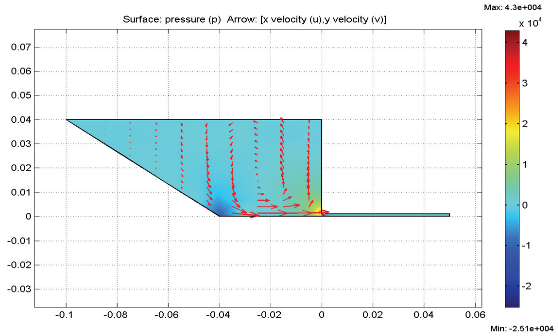

Figure 3: Velocity and pressure distribution of polymer paste within the coating system

To evaluate the quality of coating, the stress values at the interface between a coating polymer solution and a fabric during coating were calculated. They subsequently affect the degree of the penetration of paste into the fabric, the adhesion between the paste and the fabric, and the uniform spreading of the paste on the fabric during coating.

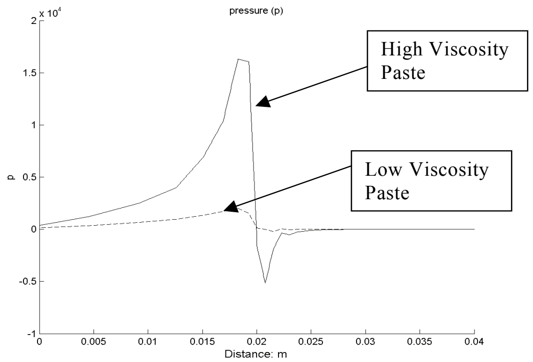

Figure 4: Stress profiles for two polymer pastes

Figure 4 provides stress profiles of two polymer paste samples (dashed curve for sample with solvent concentration of 20/1000, and solid curve for a thicker paste sample of 10/1000) before and after the knife along the interface of the paste on the fabric (x = 0.02 line is the knife position). It can be seen that for both samples there is a steady increase of the stress when the fabric approaches the knife line and a sharp decease when paste and fabric just pass the knife.

This is an expected property due to the chain nature of polymers. Their molecular structure tends to align when subjected to a shear field. After the knife position, the relaxation of the molecular chain causes a spring-back illustrated by the peak. Higher peak stress value (PSV) after the knife position should be avoided during the coating process since it will cause a poorer adhesion between the paste and the fabric. This has been observed from experimental work.

It can also be seen from Figure 4 that a thicker paste leads to a higher PSV. The simulation result indicates that a decrease of viscosity of coating paste by adding small amount of solvent will remarkably decrease the PSV, hence improving adhesion and penetration in the system resulting in a better quality product.

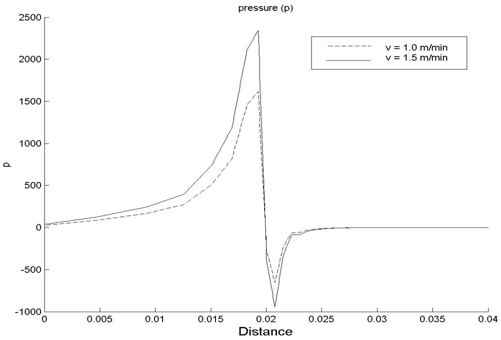

Figure 5: The effect of coating speed on the stress profile of the polymer paste

Figure 5 shows stress profiles of the polymer paste of different coating speeds before and after the knife along the surface of the paste on the fabric (x = 0.02 line is the knife position). It can be seen that a higher coating speed will lead to a higher PSV. A 50% increase (from1.0 to 1.5 m/min) in coating speed caused a 30% increase for PVS. This result implies that keeping other factors constant, the coating quality is affected by changing the coating speed, but not significantly.

Figure 6 illustrates the effect of knife gap on coating. It is remarkable that only a 20% decrease (from 1000 to 800 micron) in knife gap leads to a 100% increase for PSV (from -600 to -1200) indicating that knife gap is the most important processing parameter which need to be carefully controlled during the coating process.

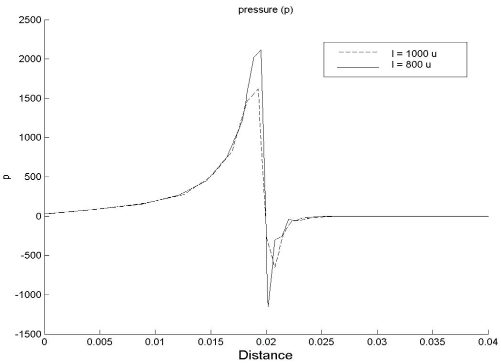

Figure 6: The effect coating knife gap on the stress profile of the polymer paste during coating

Figure 7 presents the viscosity distribution of the polymer paste before the knife (within the paste tray) and after the knife (on the fabric). Hotter colours indicate higher values of viscosity. This result clearly shows the non-Newtonian behaviour of the polymer paste. Viscosity decreases significantly with the increase of the shear rate.

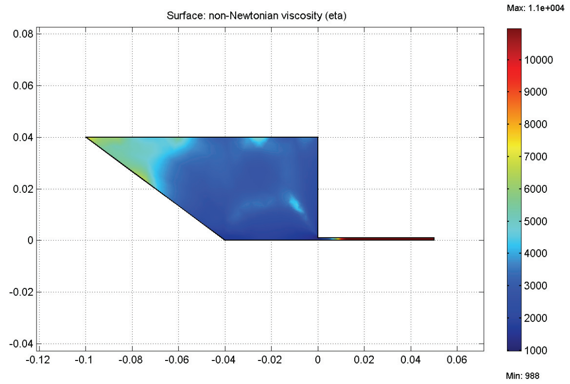

Figure 7: Viscosity distribution of the polymer paste within the system

5. VALIDATION OF RHEOLOGICAL MODELS

To verify the numerical prediction of coating quality from rheological modelling, seven commercial nylon and polyester fabrics of various woven structures were used as base fabrics for the experimental investigation. Factorial experimental designs were used to produce over 50 samples of coated fabrics by altering 5 variables (knife gap, curing temperature, fabric speed, solution viscosity and fabric structure).

The mechanical and physical properties of the coated and uncoated fabrics where characterised and their tensile, tear, compression and surface properties were measured using the Kawabata Evaluation System for Fabrics (KESF) and the Instron tensile machine. Water vapour permeability and water resistance were measured to evaluate the performance of the samples. Other characteristics were also observed or measured, e.g. through Scanning Electron Microscope (SEM), Differential Scanning Calorimetry (DSC), and chemical tests. Online visual images during coating were also collected and analysed. Using this pool of experimental data, the relationships between coating parameters and textile properties were established and the validity of the rheological models was confirmed.

The strong influence of knife gap, as identified from the rheological models, was confirmed. Increasing this parameter led to improved hydrostatic head resistance, lower water vapour permeability, tear resistance and improve surface uniformity. The viscosity of the solution paste was also found to have an effect on several properties of the coated fabric, including tear resistance and adhesion, as validated with tests and observed by SEM (Figure 8). This is also in agreement with the rheological predictions.

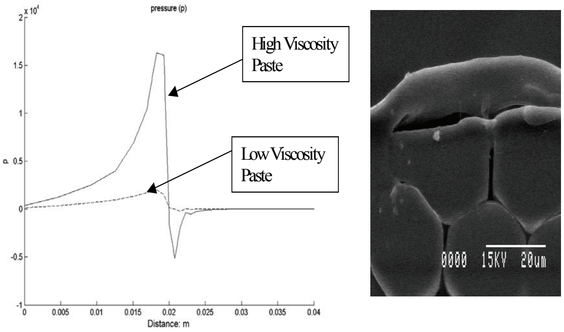

Figure 8: Stress profiles during coating and corresponding SEM images of poor adhesion for low knife gap height (400 nm) and thicker polymer paste (10/1000)

6. CONCLUSIONS

A comprehensive Finite Element model for polymer pastes under given coating conditions opens up possibilities for process optimization and prediction of coating qualities using different polymers and different coating variables such as knife gap, knife angle, fabric speed, etc. Simulation results, which are based on non-Newtonian theories, combined with experimental results provide a clear understanding of the coating process.

The interrelationships between coating materials and coating process conditions have been established for obtaining different coating penetration depths and adhesion, which was verified by user performance measurements. A narrow width continuous base coater has been modified and the findings have been implemented as a test bed for new product development and/or pre-industrial runs for industrial and academic uses.

This model can also be used to improve the design of new and existing coating machinery. For example, the type of knife, the knife blade geometry, the knife introducing angle, the roller diameter, and the dimension of the polymer paste tray, can be simulated and optimized. The selection of suitable materials for the construction of the equipment parts based on the pressure predictions under different coating conditions can also be carried out.

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