Plastics Research Online
10.2417/spepro.006343

Predicting the extent of resin infiltration in pin-assisted pultrusion

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A simple explicit model is proposed, based on analysis of computational results that show the extent of resin infiltration in a pin-assisted pultrusion process scales with a novel dimensionless group.

The infusion of a polymeric resin into a fibrous network is the determining step in many processes for the manufacturing of composites (e.g., pultrusion and resin transfer). Poor resin infusion, however, is at the heart of most quality-control problems in manufactured composite components and the source of in-service failure. During pin-assisted pultrusion, a porous roving is pulled through a molding die and over an array of solid pins that are located inside a pool of resin. The objective of this process is to spread the fibers on the pin surfaces and force an adequate amount of resin into the roving, to ensure complete saturation.

Besides the mechanical action of the pin for spreading the fibers, the saturation process is facilitated by the formation of a small wedge-shaped region filled with resin, which forms between the pin surface and the roving (see Figure 1). Lubrication theory mandates a pressure rise occurs within this region, and this pressure forces the resin to infiltrate into the fibrous roving. This has been demonstrated clearly in previous studies that have also highlighted the influence of processing and material parameters.[1–3]

In our work,[4,5] we have conducted a large number of simulations for various combinations of material (i.e., with different substrate permeability, K, and resin viscosity, μ) and process parameters. Such process parameters include the pin radius (R), roving speed (V), gap size (δ), and saturated porous zone thickness (L_o). We have thus developed an extensive database in which the infiltration depth (h_f) is expressed as a function of these parameters. The dimensionless group that we propose can collapse all the parametric data into a master curve and thus be used for the formulation of a simple explicit expression of h_f. Our reasoning for this dimensionless group can be summarized as follows: the fluid entering the wedge (at flow rate Q_{in}) will either be pushed into the roving (at rate Q_p) or will exit the wedge through the gap (δ) at rate Q_d. Although Q_{in} is the result of drag flow, which is

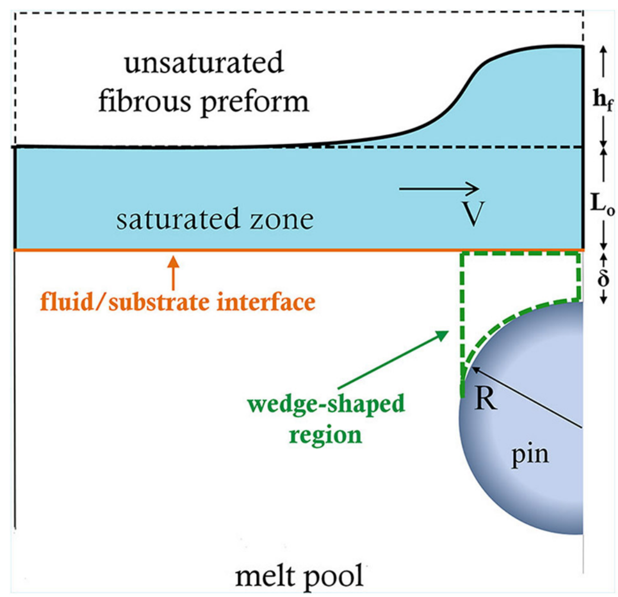

Figure 1. *Schematic illustration of the model geometry. A saturated porous zone (with thickness L_o) moves with speed (V) over a rigid pin of radius, R. The resin infiltration depth (h_f) and gap size (δ) are also indicated.*

resisted by the pressure developing in the wedge,[4] the ratio Q_d/Q_p is important. This is because it defines the limits inside which most of the resin infiltrates the web (i.e., a 'good' process) or is 'wasted' by exiting the wedge through the gap. If we assume an average pressure ($\overline{P}$) in the wedge, Darcy's law dictates that $Q_p \sim \frac{K\overline{P}R}{\mu L_o}$. Furthermore, if we assume simple shear conditions at the zero tangency point, $Q_d \sim V\delta$. The Q_d/Q_p ratio therefore defines the dimensionless group, $\Lambda = \mu V \delta L_o / \overline{P} K R$. By plotting our computational data for h_f in terms of Λ we thus reveal a master curve (see Figure 2).

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It is evident from our results that for $\Lambda < 0.1$, the infiltration depth during pin-assisted pultrusion reaches a plateau of maximum efficiency. For $\Lambda > 0.1$, however, the efficiency of the resin infiltration decreases exponentially with Λ. Overall, the data in Figure 2 can be described by the power law $h_f = h_{f,max}[1 + m\Lambda^n]^{-1}$, where $h_{f,max}$ is the maximum infiltration depth ($8.21 \times 10^{-4} \pm 0.0005$m), and m and n are constants (equal to 0.879 ± 0.011 and 1.2 ± 0.1, respectively).

The results shown in Figure 2 and the resultant power-law relationship offer a means for analyzing actual pultrusion data and for optimizing operations. By replacing the average pressure (which is difficult to measure) with the tensioning force (T), through $T \sim \overline{P}WL_o$ (where W is the width of the roving), we can obtain a new dimensionless group, $\Pi = \mu VWL_o^2\delta/TKR$. Since the action of each pin is additive, we can extend this model to a sequential arrangement of an arbitrary number (N) of pins. At the kth pin, the model will be $h_f^k = h_0^k + h_{f,\max} \cdot [1 + m\Pi^n]^{-1}$, for k=1...$N$.

We have reported parametric analyses based on this model,[5] and our results are in line with experimental evidence. For example, the extent of infiltration is predicted to increase with N and contact time, and to decrease with increasing V and μ. An example comparison between our model data and experimental data[2] is shown in Figure 3. Any direct comparison between model and experimental data sets, however, is hampered by lack of reliable data for K and δ. In addition, the extent of resin infiltration is usually determined indirectly in experiments by measuring a mechanical property of the pultruded tape or strip. We therefore regard any agreement between our model data and experimental results as semi-quantitative at best. Better material characterization is therefore required.

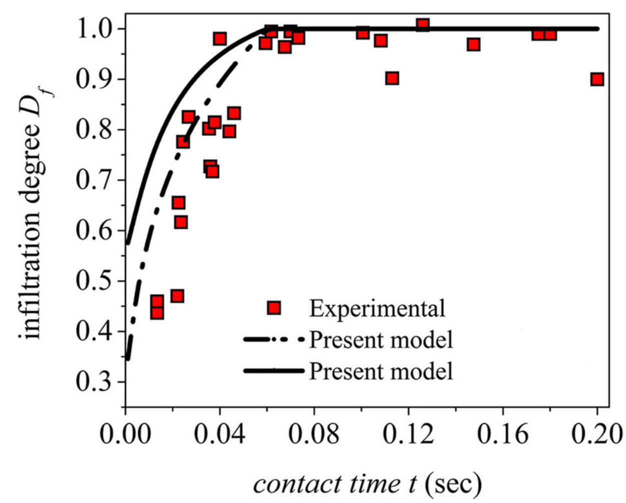

Figure 3. *Infiltration degree (equal to h_f/H, where H is the thickness of the roving) shown as a function of resin contact time (equal to R/V) with the pin. The continuous and dashed lines correspond to predictions for two and seven pins, respectively. The pulling speed range is about 0.034–0.5m/s and R is 2–7mm. In addition, $K = 10^{-9}m^2$, T = 20N, μ = 100Pas, and δ = 500μm.*

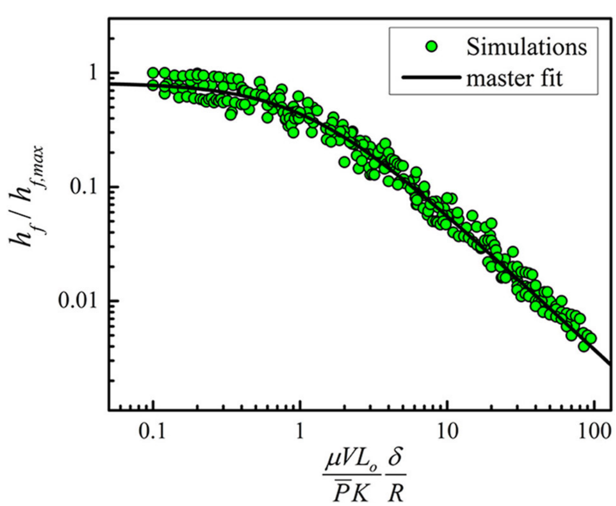

Figure 2. *Plot of computational h_f data. The master curve expresses the effect of the dimensionless group $\mu V\delta L_o/\overline{P}KR$ on h_f. μ: Resin viscosity. $\overline{P}$: Average pressure. K: Substrate permeability. $h_{f,max}$: Maximum resin infiltration depth.*

In summary, we have conducted a comprehensive numerical study of pin-assisted pultrusion, based on which we have proposed a simple explicit model that can be used to estimate the resin infiltration depth as a function of measurable parameters. In our work so far, the roving has been treated as non-deformable. In our current work, therefore, we are examining the effect of roving deformability. As a way to guide future theoretical work, we also wish to investigate the relationship between resin infiltration and the dimensionless group (Π) in actual pultrusion lines.

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