NUMERICAL PARAMETRIC STUDY OF A WAVY THIN CHANNEL THERMOPLASTIC MELT IMPREGNATOR FOR CARBON FIBRE REINFORCED PREPREG PRODUCTION

M. Pitto[1], P. Hubert[2,3], TD. Allen[1], CJR. Verbeek[1], S. Bickerton[1]

[1]Centre for Advanced Materials Manufacturing and Design, Department of Mechanical and Mechatronics Engineering, The University of Auckland, Newmarket, New Zealand
[2]Structures and Composite Materials Laboratory, Department of Mechanical Engineering, McGill University, Montreal, Quebec, Canada
[3]CREPEC – Research Center for High Performance Polymer and Composite Systems, Montreal, Quebec, Canada
Email: mpit768@aucklanduni.ac.nz
Email: pascal.hubert@mcgill.ca
Email: tom.allen@auckland.ac.nz
Email: johan.verbeek@auckland.ac.nz
Email: s.bickerton@auckland.ac.nz

Keywords: Thermoplastic, Tape, CFD, Carbon fibre, Resin flow, Optimisation.

Abstract

The objective of this research is to produce carbon fibre-reinforced prepreg tape manufactured with a waste polyamide 6 matrix for automated tape placement and filament winding. Excellent impregnation quality is necessary in the intermediate material to maximise the consolidated composite performance. Pin-assisted melt impregnation, where static pressure is negligible, has been effective for the production of glass fibre-reinforced thermoplastic composite prepreg due to a high transverse permeability compared to carbon fibre tows. Zhang et al. [1] recently adapted the pin-assisted melt impregnation process by manipulating the tow in a thin channel with a wavy geometry. The convergent, 'wedge' shaped zone leading to the tow-crest contact point raises pressure in the melt. Zhang et al. [1] focused on crest-driven impregnation without considering the static melt pressure in the thin channel.

In this work, a cross-head thermoplastic melt impregnator with a wavy channel was simulated in ANSYS Fluent. The polymer melt static pressure is in the order of 1×10^6 Pa due to the thin channel geometry and high melt viscosity (~200 Pa.s). It was of interest to model the static pressure-driven impregnation combined with the 'wedge' and 'crest' pressure-driven impregnation.

Figure 1a depicts a mechanical drawing of the impregnator, where the fibre tow is manipulated over a series of crests. Figures 1b and 1c illustrate the laminar computational fluid mechanics domain and boundary conditions of the wavy channel and the 'wedge', respectively. The moving carbon fibre tow was assumed to be impermeable to model the static pressure (Figure 1b) and 'wedge' pressure (Figure 1c). Pressure at the crest (P_{crest}) was computed from the tow tension, which increased at each consecutive crest due to contact friction. The melt film thickness (δ) was iteratively solved using the approach by Bates and Zou [2]. The total pressure was the sum of static, 'wedge', and 'crest' pressure. The impregnation flow rate was computed using Darcy's law with a transverse tape permeability governed by the Kozeny equation [2]. A fit between pressure and fibre volume fraction according to Gutowski's fibre bed compaction equation was used to estimate the permeability as a function of fibre volume fraction [3].

Figure 2 illustrates the predicted total pressure along the melt impregnator with seven crests. The pressure profile due to the 'wedge' zone initiates upstream from each crest and peaks at the point of the fibre-crest intersection. The profile then linearly approaches the crest pressure.

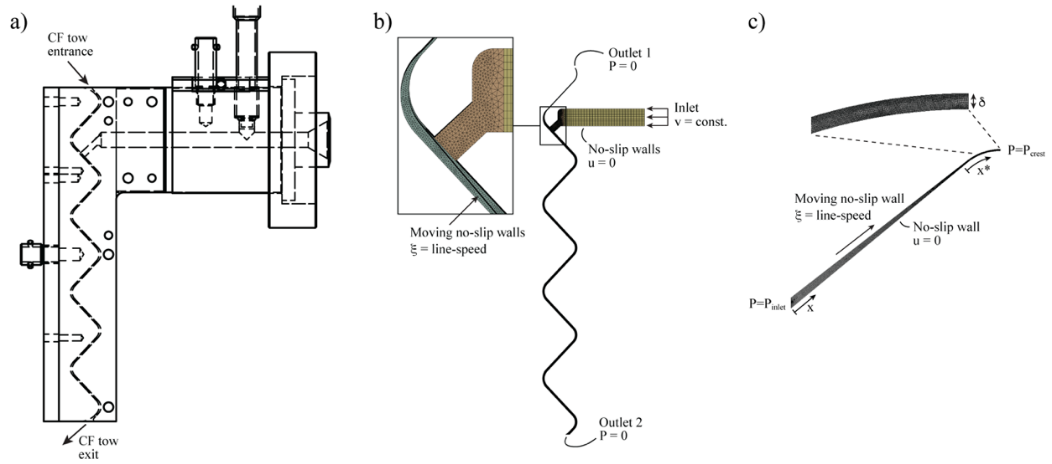

Figure 1: (a) mechanical drawing of the cross-head melt impregnator. (b) illustration of the global impregnator domain with a carbon fibre tow entering from the top and exiting through the bottom. (c) illustration of the 'wedge' domain. This represents the polymer which is between the moving carbon fibre tow and the crest, where the domain contracts to the melt film thickness (δ).

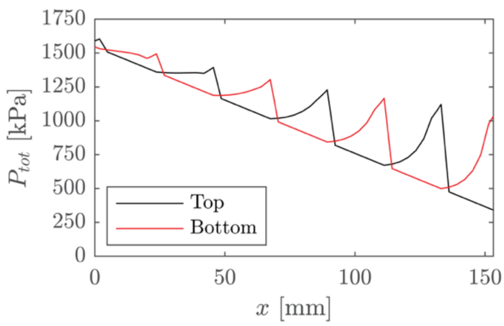

Figure 2: Combined static, 'wedge' and 'crest' pressure for a die with seven crests, a crest spacing of 20 mm, contact angle of 41°, $\mu = 200$ Pa.s, $v_f = 0.6$, and a line-speed of 0.2 m.min^{-1}. The pressure at each crest alternates between the top and bottom of the fibre tow. Crest pressure incrementally increases due to elevated tension by contact friction.

Static pressure reduces with increasing line speed due to drag flow in the impregnation channel. The maximum pressure that develops in the 'wedge' region prior to the crest contact is a function of line speed, melt viscosity and the tow pre-tension. Maximum static pressure at the die gate significantly affected the degree of impregnation. Parameters that increase the residence time, such as the number of crests and crest length, significantly affect the degree of impregnation. Compared to a straight slot die, the crest-assisted degree of impregnation was 5% greater at a line speed of 0.3 m.min^{-1}. This difference increases with increasing line speed as the static pressure significantly reduces. Additionally, the thin channel produces a higher static pressure than the pin-assisted process in a melt chamber. Finally, the 'wedge' zone extends between the crests, while pin-assisted impregnation only builds pressure close to the pin. Therefore, the residence time in the 'wedge' zone is longer, resulting in a higher degree of impregnation. In conclusion, the pressure profile alterations lead to a higher overall degree of impregnation in the wavy cross-head die.

[1] Z. Zhang, C. Xin, F. Ren, and Y. He, "A novel slot die and impregnation model for continuous fiber reinforced thermoplastic ud-tape," Applied Composite Materials, pp. 1–21, 2023.
[2] P. J. Bates and X. P. Zou, "Polymer melt impregnation of glass roving: modelling and experimental," International Polymer Processing, vol. 17, pp. 376-386, 2002.
[3] T. G. Gutowski, Z. Cai, S. Bauer, D. Boucher, J. Kingery, and S. Wineman, "Consolidation experiments for laminate composites," Journal of Composite Materials, vol. 21, no. 7, pp. 650–669, 1987.