Unsaturated Flow in Compressible Fiber Preforms

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SUMMARY:

In many cases of composite processing by liquid matrix infiltration, the reinforcement is compressed when it comes in contact with the liquid and relaxes as the matrix flows within its pores. In parallel, as the reinforcement is generally made of fiber tows, these become gradually saturated. Modeling of the process hence requires solving the coupled equations of multi-phase flow in a compressible medium. For isothermal infiltration, the physics of the process are similar to imbibition/drainage phenomena encountered in soil mechanics. Using this similarity, a finite-element code originally developed for soil mechanics is adapted to simulate the multiphase flow of polymer in a compressible porous preform. The dual scale of the porous medium is accounted for by introducing an additional sink term. The chosen case study is polypropylene transversally infiltrating glass fiber mats as used in the production of Glass Mat Thermoplastic blanks. The progression of the flow front, the fiber volume fraction and local preform stress profiles, as well as the saturation and local matrix pressure profiles are obtained. The influence of processing and materials parameters is discussed in light of the experimentally observed phenomena, pointing out the advantages and limi5n22

KEYWORDS: non-saturated flow, compressible preform, dual-scale, finite element.

INTRODUCTION

In many cases of composite processing by liquid matrix infiltration under externally applied pressure, the reinforcement is progressively compressed when it comes in contact with the liquid under increasing pressure and relaxes as the matrix flows within its pores. In parallel, as the reinforcement is generally made of fiber tows, hence presenting a two-level structure, the fiber tows become gradually saturated.

This coupled process is schematically represented in Figure 1:

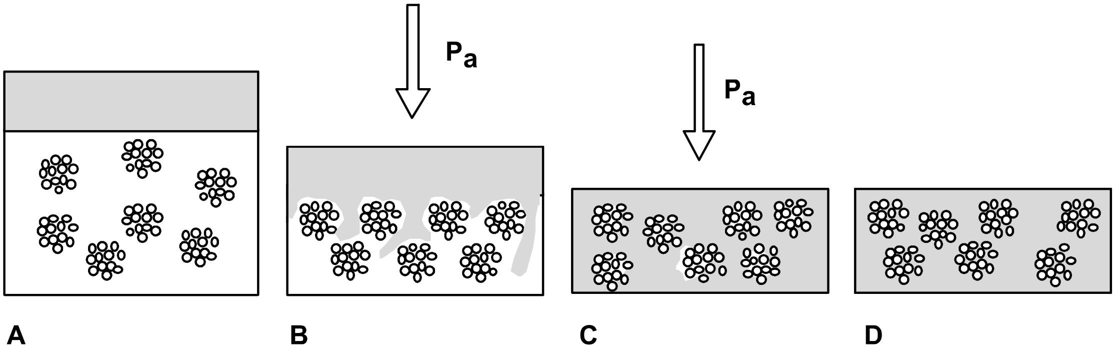


Figure 2: Infiltration of a compressible dual-scale preform by a fluid taking into account mutli-phase flow. A: intial state of a dry preform and separated fluid. B: pressure is applied, infiltration and compression of the preform start. C: macro-impregnation completed, micro-impregnation on the way. D: preform completely impregnated.

Modeling of the process hence requires solving the coupled equations of multi-phase flow and mechanical equilibrium. For isothermal infiltration, the physics of the process are similar to imbibition/drainage phenomena encountered in soil mechanics. Using this similarity, a finite-element code originally developed for soil mechanics is adapted to simulate the multiphase flow of polymer in a compressible porous preform. The case study presented here is polypropylene transversally infiltrating glass fiber mats as used in the production of Glass Mat Thermoplastic blanks. The dual scale of the porous medium is accounted for by introducing an additional sink term based on the solution of radial flow into an elliptical glass fiber tow, as experimentally observed [1].

THEORY

General equations & numerical solution

The governing equations are written in one dimension over a representative volume element ΔV, following reference [2]. These equations consist in Darcy's law, mass conservation in the liquid and solid phase and stress equilibrium, all equations accounting for the saturation S. This set of non linear differential equation is solved with the finite element code GEFDYN. The formulation applies a Galerkin procedure for space discretization and a modified Newton method for the iterative solution [3].

Macro-Saturation

The saturation S is defined as the local ratio of resin volume fraction V_m over $(1-V_f)$, where V_f is the fiber volume fraction. It is generally expressed in soil mechanics as a function of pressure. The relationship is given by the drainage or imbibition curve for the considered system. The obtained curves can be fitted to phenomenological equations introducing a threshold pressure (p_0), which must be overcome to initiate infiltration, and a shape parameter (α).

As long as the pressure remains below p_0, saturation is equal to zero. For $p \geq p_0$, S increases, and a potential law to describe this is the Van Genuchten law [4]:

$$S = 1 - \frac{1}{\sqrt{1+\alpha^2 (p-p_0)^2}} \quad \text{valid for } p>p_0. \tag{1}$$

The curve shape is described by α and varies with the pore size distribution, with the size and type of reinforcement and with the wetting behavior of the matrix on the reinforcement. This value is empirically estimated for a given system or obtained by fitting experimental drainage/imbibition curves [5]. The threshold pressure p_0 corresponds to the capillary pressure differential to infiltrate the largest of the accessible pores. It may be negative for a wetting system. In composite processing, however, contrary to soil science, the saturation, in addition to being a function of the pressure, is also a function of time owing to the dual-scale of the reinforcement, and the high viscosity of the infiltrant. Indeed, infiltration is often reported to take place in two steps [6], representing the macro-impregnation, in the large pores between the fiber bundles, and the micro-impregnation, within the fiber bundles. Depending on wetting properties and kinetics of the infiltration, the saturation of the macro-pores can be accomplished prior to the impregnation of individual fiber bundles.

Micro-Saturation

To account for this, a sink-term is added in the code, assuming that infiltration first takes place gradually in a macroscopic scale as represented by the Van Genuchten law. Then, as soon as the bundles are surrounded by matrix, the micro-impregnation consists in the radial infiltration of matrix in the bundles. The pressure differential driving the micro-impregnation is the difference between the local pressure in the preform around the bundle and the pressure in the entrapped gas within the bundle plus the capillary pressure. The cross section of a fiber bundle and its dimensions are represented in Figure 2:

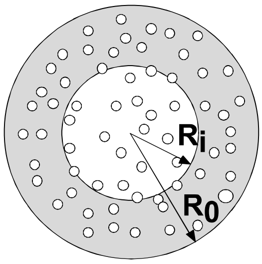


Figure 3: Schematic of a representative GMT bundle cross section. R_i is the internal and non-impregnated radius and R_0 is the intial radius of the bundle.

One fiber bundle contains an average of 100 fibers (N=100). The fiber radius r_f is about 5 µm. The fiber volume fraction in the compressed bundle is assumed to remain constant and equals 0.7 ($V_{f,b}$).

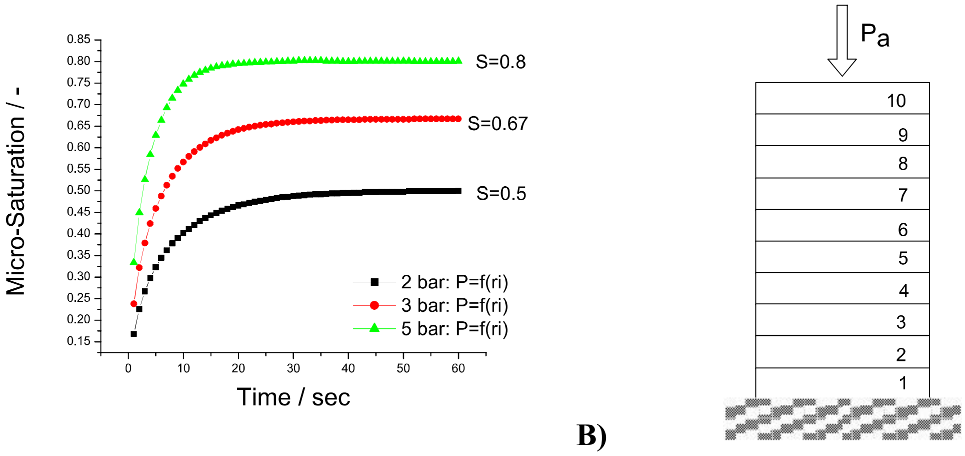
The micro-impregnation in the fiber bundle is carried out in the direction orthogonal to the fibers of an initially dry cylindrical fiber bundle, of initial radius r_0, under constant applied pressure P_a. The equations are written in cylindrical coordinates. We assume saturated flow and Newtonian behavior of the matrix.

Integration of Darcy's law and mass conservation equations over radial distance yields to [1]:

$$r_i \ln\left(\frac{r_i}{r_0}\right)\dot{r}_i = \frac{-K_p}{\eta(1-V_{f,b})}\left(P_g(r_i) - P_c - P_a\right) \qquad (2)$$

where r_i is the unimpregnated bundle radius, r_0 the initial bundle radius, $\dot{r}_i$ the derivative of r_i over time, K_p the fiber bundle permeability, η the matrix viscosity, $V_{f,b}$ the fiber volume fraction in the bundle, P_g the gas pressure, P_a the applied pressure and P_c the capillary pressure, which is the pressure difference existing across the air-liquid interface.

Furthermore, the fiber bundle transverse permeability tensor K_p is determined by Gebart's formulation [7] based on fiber arrangement parameters. If we consider air entrapment during impregnation in the bundle and no dissolution in the polymer matrix, this will lead to a void pressure increase within the reinforcement, which can be evaluated using the ideal gas law. The analytical calculation of the evolution of the micro-saturation with time, assuming gas entrappment for constant pressures of 2, 3 and 5 bars is given in Figure 3 A.



A) **B)**

Figure 4: A) Analytical micro-Saturation curve of a glass fiber bundle impregnated by polypropylene at a pressure of 2, 3 and 5 bars. Accounting for gas pressure function of r_1^2. B) Grid of 10 elements used for numerical model.

The void pressure increase leads to a decrease of the final saturation value: for an applied pressure of 2 bars and after 50 seconds of impregnation, the micro-saturation reaches 0.5 instead of 1 for the case of constant void pressure. These non-negligible micro-impregnation times, between 15 and 60 seconds, confirm the need to introduce this effect in the complete model.

RESULTS

Isothermal unidirectional transverse infiltration of polypropylene at 200°C into glass mats is modeled using the modified Gefdyn program. The compressive behavior of the fiber preform, as well as the variation of permeability with volume fraction fibers are experimentally determined [8], and bi-linear fit curves are introduced into the code.

The Van genuchten parameters values are $\alpha=2\cdot10^{-8}$ and p_0=1 bar. In this case study, a pressure of 2 bars is applied with a ramp of 1bar per second to an initially dry preform of 4mm thickness. The dry preform is represented by a grid of 10 elements and 63 nodes. The first element is placed at the bottom and the 10th element at the top of the preform, where the polymers enters under applied pressure (Figure 3B). In the following figure, the positions in the preform are referred to as 1, 5, 8, and 10, each value corresponding the referred element. Once the pressure applied, the evolution of the macro-saturation and micro-saturation are calculated and given in Figure 4A and B respectively. It is observed that the time necessary for the fluid to reach the bottom side of the mold is about 6.5 seconds since the macro-saturation of the element 1 is observed to increase suddenly after 6.5 seconds. Then, once the flow front has reached one given element, the impregnation of the bundle at this level can start (Figure 4A). It is to notice that the time to impregnate a bundle is about 30 seconds and is then much longer than the time to macroscopically fill the preform. This information is of interest because it shows that an apparently well-impregnated part may contain residual air entrapped in the fiber bundles. Furthermore, the micro-saturation reaches a plateau at S_{micro}=0.5, so a full impregnation of the bundle is not accomplished for an applied pressure of 2 bars,. This result is in accordance with the value obtained analytically (Figure 3A). It can then be concluded that for this material system, a higher pressure is necessary to complete bundles impregnation: 5 bars, for instance would provide a S_{micro}=0.8. Evolution of the preform height, local resin pressure and effective stress on the preform are also obtained, indicating a global preform compression followed by relaxation of the preform, as expected.

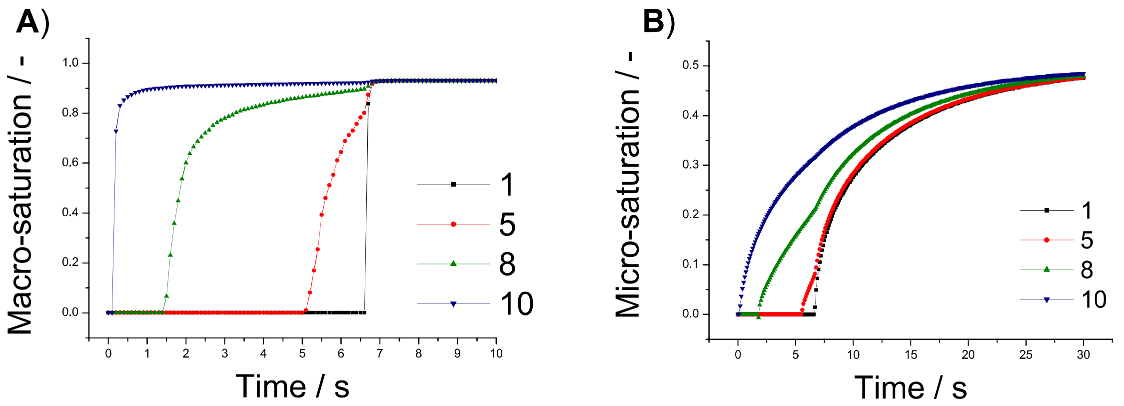


Figure 5: Evolution of the macro-saturation (A) and the micro-saturation (B) at different position in the mold: from element 1 (bottom) to element 10 (top).

CONCLUSIONS

This paper presented a Finite Element tool to model the unsaturated flow of polymer in a compressible dual-scale preform. Micro-impregnation is taken into account by the introduction of a sink term, based on the practical observation of delayed micro-impregnation in GMT materials. The progression of the flow front, the local pressure and stress values as well as the macro-saturation and micro-saturation profiles are predicted. The main issue remaining is the accurate description of the material and process parameters used in the model, such as the parameters of the Van Genuchten law, the amount of gas entrapped, the variation of permeability with saturation. Careful validation with model experiments are thus a remaining step.

ACKNOWLEDGEMENTS

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