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Simulation of void formation in liquid composite molding processes

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ABSTRACT

Air entrapment within and between fiber tows during preform permeation in liquid composite molding (LCM) processes leads to undesirable quality in the resulting composite material with defects such as discontinuous material properties, failure zones, and visual flaws. Essential to designing processing conditions for void-free filling is the development of an accurate prediction of local air entrapment locations as the resin permeates the preform. To this end, the study presents a numerical simulation of the infiltrating dual-scale resin flow through the actual architecture of plain weave fibrous preforms accounting for the capillary effects within the fiber bundles. The numerical simulations consider two-dimensional cross sections and full three-dimensional representations of the preform to investigate the relative size and location of entrapped voids for a wide range of flow, preform geometry, and resin material properties. Based on the studies, a generalized paradigm is presented for predicting the void content as a function of the Capillary and Reynolds numbers governing the materials and processing. Optimum conditions for minimizing air entrapment during processing are also presented and discussed.

1. Introduction

It is well known that composite materials fabricated through liquid composite molding (LCM) processes and similar methods often exhibit defects from air entrapment during the resin infiltration process, leading to flaws in the resulting cured composite material such as potential failure locations and discontinuous material properties. These air voids undermine the property and performance benefits of fiber reinforced composites and are sought to be avoided during composites manufacturing. Air entrapment occurs during the preform infiltration step of LCM processes by virtue of the dual scale nature of the resin flow through and around the fiber tows in the preform. The resin flow is primarily influenced by the fiber preform geometry, mold complexity, and resin properties. In addition, the processing parameters imposed on the system, for example the vacuum pressure in vacuum assisted resin transfer molding (VARTM) and the injection flow rate in resin transfer molding (RTM), have a significant effect on the resin flow and consequently influence the relative size and location of the entrapped air voids in the resulting composite material.

The flow through fibrous preforms is effectively modeled as a porous medium and is fundamentally governed by the preform permeability, which is a measure of the resistance offered to the flow by the porous structure of the preform. Toward describing the flow in liquid molding processes, several studies are reported in the literature that relate the transverse and longitudinal permeability of the porous structure to the fiber bundle volume fraction and the fiber diameter for idealized rectangular and staggered packing arrangements of fibers within the tow bundles e.g. [1–5]. A detailed review of experiments and theoretical studies on low Reynolds number flow through fibrous porous media and the permeability relationships is presented in [6]. The infiltration of the resin into the fiber bundles is further affected by the capillary pressure at the resin flow front, which is fundamentally a function of the fiber bundle volume fraction, the individual fiber filament radius, and the surface tension and wetting angle of the infiltrating resin with respect to the fiber surface [7]. These effects are increasingly significant at the relatively high fiber bundle volume fractions generally found in the preform fabrics used as reinforcements in advanced composites [8].

A summary of the physics associated with modeling flow through porous media and a review of the advancements in numerical simulation tools used to model LCM processes in two- and three-dimensional geometries, including investigations concerned with micro- and macro-void prediction in fibrous preforms, are given in [9–11]. The formation of entrapped air locations is primarily the result of the dual-scale nature of the resin infiltration, consisting of flow through the macro-scale channels around the fiber bundles (the inter-tow regions) combined simultaneously with flow through the micro-scale pores within the fiber bundles (intra-tow regions) around the individual fibers [12]. Several techniques have been explored in the literature to model the resin infiltration and the consequent air entrapment in LCM and similar processes. Darcy's law was used in [13] to predict air entrapment within a

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Nomenclature

a	fiber bundle thickness (m)
b	fiber bundle height (m)
Ca	Capillary number
F_{cap}	capillary source term (N/m^3)
F_{por}	porous media source term (N/m^3)
l	unit cell length (m)
p	pressure (Pa)
r_f	fiber filament radius (m)
Re	Reynolds number
t	time (s)
u	velocity (m/s)
v_f	fiber volume fraction
W	unit cell width (m)
x	x-direction coordinate (m)
y	y-direction coordinate (m)
z	z-direction coordinate (m)

Greek symbols

α	fluid volume fraction
η	resin–air meniscus location
θ	contact angle (°)
κ	permeability (m^2)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
ϕ	void content

Superscripts/subscripts

–	dimensionless value
a	air phase
avg	average quantity
r	resin phase
∞	steady-state value

cylindrical fiber bundle by considering resin flow radially inward in the fiber bundle cross-section and using an ideal gas assumption to determine the entrapped air volume within the bundle. This model was further developed to study the effect of varying the individual fiber diameter and number of fibers in each bundle on the resulting size of the entrapped air void within a single fiber bundle [14]. A similar study utilizing Darcy's law was conducted to predict the void formation over time by using the finite element method to simulate resin flowing transversely over a fiber tow [15]. Darcy's law was also used in [16] to predict processing conditions that led to macro-void formation, and the results were presented as a function of the Capillary number. The model in [16] was extended to include the effects of injection pressure and distance from the mold inlet and the analytical predictions were validated experimentally [17]. Simplified cross-sections of various multi-layer woven fabrics were analyzed in [18] using a control volume to predict void formation. The Lattice Boltzmann Method was used to model air entrapment location and size considering transverse flow through arrays of square-packed fiber bundles when compared with similar experimental results [19]. Optimization of VARTM processing parameters based on dual-scale flow analysis was presented in [20] to minimize the void formation and mold fill time. In addition, a simulation of LCM processes was developed which considered the different permeabilities in the warp and weft directions as well as air bubble formation and migration, where the results were able to predict voids throughout the local zones of the flow domain as a function of the Capillary number [21].

The studies in the literature have focused primarily on simplified two-dimensional fiber preform geometries or three-dimensional geometries described by a bulk permeability, whereas the flow in actual processing is both fully three-dimensional and contains multi-scale flow. Towards a realistic prediction of void entrapment during liquid molding processes, the objective of the present study is to develop a numerical model to describe resin permeation through a preform comprised of multiple layers of the plain weave fabric architecture. Considering flow through a three-dimensional unit cell and representative two-dimensional slices of the plain weave geometry, the analysis accounts for the capillary forces at the resin–air interface, and additionally, the effects of nesting between adjacent layers of fabric. Simulations are performed for a wide range of the Capillary and Reynolds numbers in order to explore their individual effects on the location and relative size of air entrapment within the preform architecture. Based on the numerical simulation results, the effects of the resin flow conditions and preform parameters on the final void content and processing time are discussed along with an optimization of the flow conditions for void minimization.

This paper is organized as follows: Section 2 of the paper describes the numerical model formulation, the results of the study are presented and discussed in Section 3, and conclusions are drawn from the simulation results in Section 4.

2. Numerical model

The geometry considered in the current study consists of a unit cell of length l, containing multiple layers of plain weave fabric, with fiber bundle thickness a and height b, stacked in a nested configuration as illustrated in the isometric and side views in Fig. 1a and b, respectively. The weave of the fiber bundles is considered to be a sinusoidal function and the cross section of each bundle is defined as being lenticular in shape. In actuality, each fiber bundle consists of several thousand individual fiber filaments, which is modeled by describing the fiber bundle as a porous medium with a permeability defined as a function of the fiber bundle volume fraction and the individual filament radius, considering a staggered packing arrangement of the fiber filaments within the bundle.

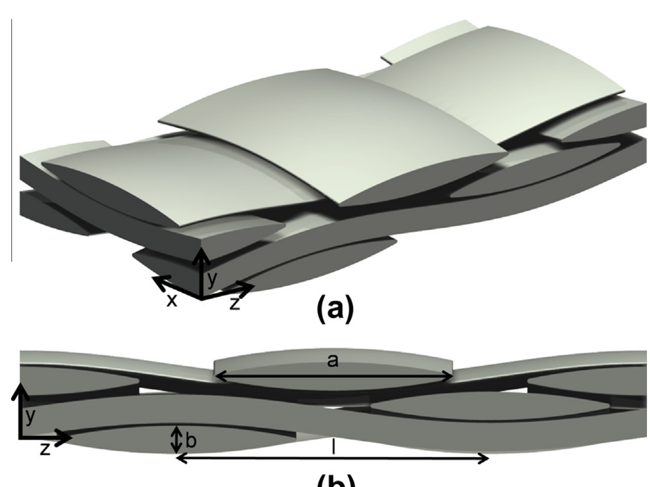

Fig. 1. Schematic illustration of the fiber preform architecture with two layers of nested plain weave preform shown from an (a) isometric and (b) side view, along with the fiber bundle width, a, thickness, b, and unit cell length, l.