Composites: Part A 73 (2015) 1–10

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Three-dimensional reconstruction of resin flow using capacitance sensor data assimilation during a liquid composite molding process: A numerical study

Masayuki Murata [a], Ryosuke Matsuzaki [b,*], Akira Todoroki [a], Yoshihiro Mizutani [a], Yoshiro Suzuki [a]

[a] Department of Mechanical Sciences and Engineering, Tokyo Institute of Technology, 2-12-1, O-okayama, Meguro-ku, Tokyo 152-8552, Japan
[b] Department of Mechanical Engineering, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan

A R T I C L E I N F O

Article history:
Received 16 April 2014
Received in revised form 5 September 2014
Accepted 31 January 2015
Available online 17 February 2015

Keywords:
B. Electrical properties
C. Computational modeling
D. Process monitoring
E. Resin flow

A B S T R A C T

Liquid composite molding (LCM) is a method to manufacture fiber-reinforced composites, where dry fabric reinforcement is impregnated with a resin in a molding apparatus. However, the inherent process variability changes resin flow patterns during mold filling, which in turn may cause void formation. We propose a method to reconstruct three-dimensional resin flow in LCM, without embedding sensors into the composite structure. Capacitance measured from pairs of electrodes on molding tools and the stochastic simulation of resin flow during an LCM process are integrated by a sequential data assimilation method based on the ensemble Kalman filter; then, three-dimensional resin flow and permeability distribution are estimated simultaneously. The applicability of this method is investigated by numerical experiments, characterized by different spatial distributions of permeability. We confirmed that changes in resin flow caused by spatial permeability variations could be captured and the spatial distribution of permeability could be estimated by the proposed method.

1. Introduction

Liquid composite molding (LCM), such as resin transfer molding (RTM) and vacuum assisted resin transfer molding (VaRTM), is a method for manufacturing fiber-reinforced plastics (FRPs) used for wind turbine blades, marine vessels, airplanes and other industrial products. In an LCM process, dry fabric reinforcement is impregnated with liquid resin in a molding apparatus. However, inherent process variabilities, such as spatial variations in permeability caused by variability in the fabric architecture, can change the resin flow patterns during mold filling, which in turn may result in the formation of voids, including large dry spots or micro voids that significantly degrade the mechanical properties of the composite structure. The application of LCM is currently limited because of its poor quality.

Recent studies proposed optimization of resin injection gates and vents based on resin flow simulation [1–4] to address quality issues in LCM. Statistical modeling of permeability variations [5] or stochastic simulation of resin flow [6] has also been studied to further improve optimization of the processing conditions. However, it is almost impossible to control and optimize many factors involved in an LCM process prior to manufacturing. Therefore, monitoring of resin flow patterns during an LCM process and implementing control systems are preferable to reliably predict and prevent formation of voids.

This paper focuses on flow monitoring methods in an LCM process. In previous studies, various methods for monitoring of resin flow have been proposed. Optical fiber sensors [7–9], including fiber Bragg grating (FBG) sensors [10,11], are used for monitoring of resin arrival to the sensor location on the basis of changes in the refractive index or strength of the reflected light. Electric time-domain reflectometry (E-TDR) [12–14], is also used to monitor resin flow by measuring reflected waves on a transmission line embedded in composites or molding tools. Although the optical fiber and E-TDR methods can monitor resin flow with high accuracy, they only measure resin flow along sensor lines. Further, the possible degradation of the mechanical properties of parts and interference with the smooth resin flow due to embedded sensor lines may pose problems. Permittivity [15] or conductivity [16–18] methods have been proposed for monitoring resin flow by measuring the relative permittivity or conductivity of the polymer resin at the sensor location. However, these sensors are point or linear sensors on molding tools and only measure the resin flow close to the sensors. Although grid sensor [19], area array sensor

* Corresponding author. Tel./fax: +81 4 7124 1501.
E-mail address: rmatsuza@rs.tus.ac.jp (R. Matsuzaki).

http://dx.doi.org/10.1016/j.compositesa.2015.01.031
1359-835X/

[20], or pressure sensor-based methods [21] enable monitoring of an arbitrary resin flow process, the resin flow was assumed to be two-dimensional and flow in the thickness, or out-of-plane direction, has not been considered.

This paper presents a method to reconstruct three-dimensional resin flow in an LCM process without embedding sensors into composite parts. Electrical capacitance measured from pairs of electrodes on molding tools and stochastic simulation of resin flow during an LCM process are integrated by a sequential data assimilation method based on the ensemble Kalman filter (EnKF), and then, three-dimensional resin flow and permeability distribution are estimated simultaneously. This improves the accuracy of the flow front prediction by simulation and can provide valuable information for formulating a strategy to control resin flow and reduce the formation of voids during an LCM process.

2. Flow reconstruction method

Several types of sensors based on different physical phenomena have been used to capture resin flow during LCM processes in previous studies, as summarized in the preceding section. In this study, an electrode array sensor was employed for flow monitoring because of its ability to obtain information unobtrusively on resin flow away from the sensor. In fact, it has been reported that an electrode array sensor can detect both in-plane and out-of-plane resin impregnation [22]. However, the monitoring of three-dimensional resin flow, in which in-plane and out-of-plane flow exist simultaneously during the molding of a thick part, has not been addressed. To address this problem, we propose in this paper a method to reconstruct three-dimensional resin flow using values measured with an electrode array sensor, complemented by simulation modeling. The details of the method are presented in this section.

2.1. Electrical capacitance measurement

2.1.1. Electrical capacitance sensor and measurement

Plate electrodes are arrayed on the molding tool and used as sensors to obtain information on resin flow in the mold cavity, as shown in Fig. 1. Sensors of this type can be fabricated by embedding copper electrodes in a molding tool [19] or by making a pattern of electrodes on a flexible substrate that can be attached to a molding tool [20,23]. Capacitances are measured by pairs of electrodes, and the measured values $(c_1, c_2, \cdots, c_i, \cdots, c_M)$ are organized in an electrical capacitance vector defined as

$$\mathbf{c}_t = (c_1, c_2, \cdots, c_i, \cdots, c_M)^T, \tag{1}$$

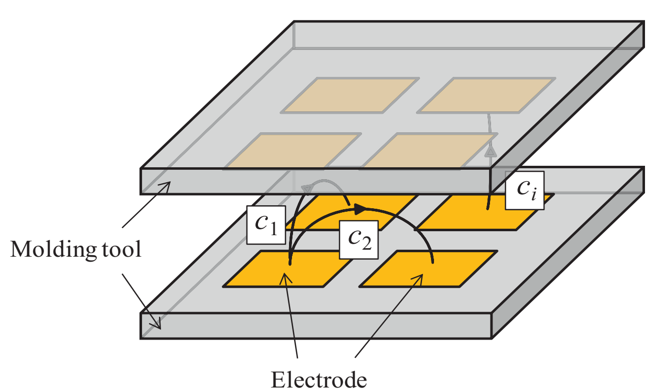

Fig. 1. Schematic of electrical capacitance measurements. Capacitance is measured from a pair of electrodes on molding tools. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where M is the number of measurements, and t is an index of the discrete time. The capacitance c_i between a pair of electrodes is the ratio of the charge on electrode Q_i to the potential difference between the electrode pair ΔV_i, i.e., $c_i = Q_i/\Delta V_i$.

Fiber reinforcements placed in the mold cavity are impregnated with polymer resin during an LCM process. When the electric field excited by the measurement electrodes is applied to a polar polymer such as polyester or epoxy resin, the dipoles in the resin are aligned to the direction of the electric field, which causes dielectric polarization. Thus, polymer resin acts as a dielectric material. The electrical capacitance vector changes with resin impregnation during an LCM process because the dielectric constant in the space between a pair of electrodes increases as the resin impregnates into fiber reinforcements in the mold cavity. Therefore, the capacitance vector provides the information about the resin-filled region.

2.1.2. Governing equations of electric field and sensitivity calculation

To reconstruct resin flow from measured capacitance, the relationship between resin distribution and capacitance must be established. Here, we consider this relationship in a manner similar to electrical capacitance tomography [24,25], which is the methodology used to reconstruct the permittivity distribution of an object from electric capacitance measurements. Because the wavelength of the electromagnetic field substantially exceeds the dimensions of the sensors in typical measurement systems for ECT, the electric field distribution obeys the electrostatic field theory. The governing equation of the electric field can be derived as the electrostatic approximation of the Maxwell equations in the absence of internal charges, i.e., $\nabla \cdot \mathbf{D} = 0$, where $\mathbf{D}$ is the electric displacement. The electric displacement $\mathbf{D}$ is related to the electric field intensity vector $\mathbf{E}$ via the permittivity of a material $\boldsymbol{\varepsilon}$, i.e., $\mathbf{D} = \boldsymbol{\varepsilon}\mathbf{E}$. The permittivity $\boldsymbol{\varepsilon}$ reflects the ability of a material to store electrical energy under the influence of an electric field and is a second-order tensor when the material is anisotropic. We can then assume $\mathbf{E} = -\nabla V$ for electric potential V and finally the governing equation of the electric field can be written as

$$\nabla \cdot \boldsymbol{\varepsilon} \nabla V = 0 \quad \text{in } \Omega, \tag{2}$$

where Ω is the region inside the mold cavity. Once the electrical potential distribution is obtained by solving Eq. (2) with boundary conditions for the electrical potential V at the measurement electrodes, the capacitance between the electrodes can be calculated using the electric potential distribution. Because the induced charge on the electrode can be obtained from a volume integral,

$$Q_i = \frac{1}{\Delta V_i} \int_{\Omega} (\nabla V)^T \boldsymbol{\varepsilon} (\nabla V) d\Omega, \tag{3}$$

the capacitance can be obtained from its definition,

$$c_i = \frac{Q_i}{\Delta V_i} = \frac{1}{\Delta V_i^2} \int_{\Omega} (\nabla V)^T \boldsymbol{\varepsilon} (\nabla V) d\Omega. \tag{4}$$

Let Ω_j be a small region in Ω, and let f_j be the fill fraction f of that region, which ranges from 0 to 1 such that the limits $f = 0$ and $f = 1$ signify the region being completely unfilled and completely filled with resin, respectively. The sensitivity of f_j to c_i, i.e., the change in the capacitance c_i induced by a change in fill fraction f_j in a small volume Ω_j, is obtained from the following equation:

$$s_{ij} = \frac{\partial c_i}{\partial f_j} = \frac{1}{\Delta V_i^2} \int_{\Omega_j} (\nabla V)^T \left(\frac{\partial \boldsymbol{\varepsilon}_j}{\partial f_j} \right) (\nabla V) d\Omega_j, \tag{5}$$

where $\boldsymbol{\varepsilon}_j$ is the permittivity tensor in Ω_j. By exploiting the sensitivity, the relationship between small changes in the resin distribution and small changes in the capacitance vector can be described quantitatively. However, the information obtained by the