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Flow control by progressive forecasting using numerical simulation during vacuum-assisted resin transfer molding

Ryosuke Matsuzaki [a,*], Seiji Kobayashi [b], Akira Todoroki [b], Yoshihiro Mizutani [b]

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

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ABSTRACT

Because slight differences in the wrinkle of a vacuum bag and other inherent variations in the preforms may cause unexpected resin flow in vacuum-assisted resin transfer molding (VaRTM), flow control is strongly required to prevent dry spots. We propose an active flow control scheme by forecasting resin flow from the monitored time to the filling ends using numerical flow simulation and taking corrective action using dielectric heating at a specific targeted location to decrease the viscosity of the resin. Because dry-spot configuration can be forecasted early, the flow can be actively controlled before the occurrence of an adverse flow front. This method can be extended to forecasting load-bearing performance as the critical dry spot can be selectively prevented based on applied stress distribution information. We demonstrate the validity of the proposed method to improve uniaxial compressive buckling of plate structures by conducting virtual experiments based on a multifunctional interdigital electrode array film.

1. Introduction

Resin flow control is required to prevent dry spots or micro voids during the vacuum-assisted resin transfer molding (VaRTM) process, because these defects may significantly deteriorate the mechanical properties of a structure [1–3]. In general, the flow control is classified into passive (or off-line) and active (or on-line) control. Passive flow control is performed before the actual molding process by optimizing mold design or gate location using numerical flow simulation and an optimization scheme such as a genetic or gradient-based algorithm [4], a branch-and-bound search and map-based exhaustive search [5,6], or a neural network [7] to minimize the fill time, resin waste, or dry regions. However, any slight differences in the wrinkle of the vacuum bag or misalignment of the fabric preform may cause unexpected resin flow. Since passive control is conducted prior to manufacturing, it does not react to these unexpected flows, which results in defects. Active flow control, on the other hand, is employed to monitor the impregnation state and can react to unexpected resin flow. In recent years, structures with complex shapes have been integrally molded by VaRTM to reduce the number of parts and time required. Since these structures will have multiple preform alignment, warped preform, part-to-part joints, and vacuum bag wrinkling, the resin flow is often unpredictable. Thus, active flow control is essential for manufacturing such complex structures by VaRTM with high quality.

In studying active control, Modi et al. [8] controlled resin injection using solenoid valves by minimizing the distance between the centroid of an unfilled region and the vent as this distance indirectly reflects the fill-time and wasted resin volume. Furthermore, active control based on decision trees has been proposed [9–11]. This method distinguishes between scenarios simulated prior to experiments. In these systems, pressure regulators are installed near the injection gate for adjusting the pressure distribution to control resin flow [12,13]. This method, however, usually requires many injection gates or outlet vents, and it is difficult to control flow at a distance from the gates or vents. Johnson et al. proposed a coil induction heating method [14,15], which decreased the resin viscosity via heating and thereby controlled the resin flow at a specific targeted location. Matsuzaki et al. [16–18] developed active flow control using multifunctional interdigital electrode array (MIEA), which raises the resin temperature at the targeted location and thus decreases the viscosity and increases the resin flow velocity. The heated locations were selected on the basis of the monitored flow front configuration or detection of the delay of flow. Although these methods are low-cost and facilitate real-time interfacing, the effectiveness of the impregnation of complex structures is unclear since the prediction of dry-spot location is difficult in the first place. The system assumes that the experimental flow is within the scenario calculated by simulations because they require a pre-defined tree diagram or void location.

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

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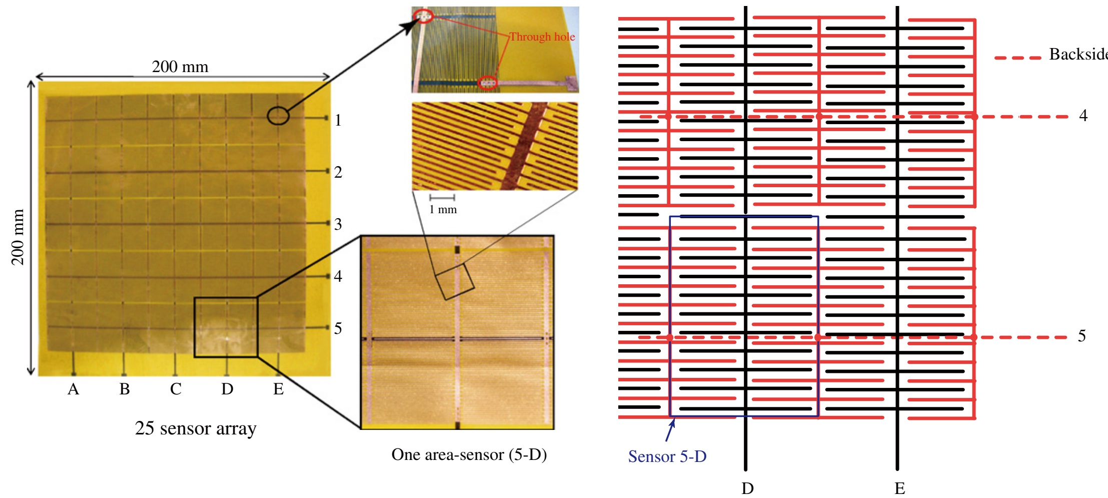

Fig. 1. Multifunctional interdigital electrode array (MIEA) film for monitoring full field of resin flow/temperature and actuating resin flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To address this issue, Nielsen and Pitchumani developed real-time flow control based on numerical prediction of resin flow in the impregnation state while it is being monitored [19–21]. However, employing this method, flow simulation combined with an artificial neural network was conducted in only one small-time step, and flow was controlled only to match the desired flow scheme prescribed prior to experiment. This makes it difficult for the control to react to unanticipated dry-spot occurrence or flow that is located at a distance from the pre-defined flow. Alms et al. [22] proposed an adaptive controller using Vacuum Induced Preform Relaxation (VIPR) and Liquid Injection Molding Simulation (LIMS) to manipulate the resin flow by influencing the permeability of the reinforcing fabric during infusion. However, they controlled resin flow as straight across the width as possible in each control step; thus, the flow reacted only after the occurrence of an adverse flow front line.

In the present paper, we propose an active flow control by forecasting resin flow from the monitored time to the end of filling using numerical flow simulation during the VaRTM process. Since the method does not require a desired flow pattern, decision tree, or prescribed dry-spot configuration, it can deal with unanticipated situations. Because the dry-spot configuration can be forecasted at an early stage, the flow can be actively controlled before the occurrence of an adverse flow front line. Moreover, this method can be extended to forecast the characteristics of molded products, such as load-bearing performance. The mechanical performance can be predicted by finite element simulation following resin flow simulation. The system can detect critical dry spots that have a significant effect on load-bearing performance using numerical simulation while the process is taking place; the critical dry spots can then be selectively prevented. Our study adopts the uniaxial compressive buckling problem of plate structures; it investigates the validity of the proposed active flow control by progressive forecast using numerical simulation by conducting virtual experiments based on the use of MIEA film for resin monitoring and actuating.

2. Flow control using multifunctional interdigital electrode array

2.1. Multifunctional interdigital electrode array

Resin flow monitoring/actuating can be performed using MIEA [16]. A pattern of electrodes and wirings of MIEA made by photolithography is shown in Fig. 1. The thickness of the film including copper for the electrode and polyimide base was 13 μm. Because of the thickness of the film, the MIEA was very flexible and could be easily attached to complex or curved molds [23]. Moreover, the film was stacked between the composite laminates and the mold; flow interference and decreased strength did not occur in the cured composites. The electrodes were aligned in a matrix or grid, and the wiring of the electrodes was divided into rows and columns. The sensors/actuators had capacitive interdigital electrodes with input voltage V+ and ground. Each sensor/actuator had a square sensing/actuating area. Since the electrode lines were shared with the adjacent sensors (see Fig. 1), the entire film surface was covered with these square interdigital electrodes without non-sensing/actuating space. The developed method controls the specific targeted location of the flow front to prevent dry spots forming.

2.2. Flow control by monitoring/actuating resin flow

For flow monitoring, an area-sensor array on MIEA could be used during the VaRTM process. Each squared sensor was aligned without any non-sensing space; thus, the film measured the full field flow monitoring area and missed none of the dry spots that occurred anywhere on the film, unlike conventional sensors such as optical fibers [24–28], permittivity or conductivity sensors [29–32], or grid sensors [33,34]. Each area sensor measured the impregnated area ratio for the corresponding sensor area, and the sensor array enabled us to determine the distribution of the impregnated area ratios. Since there is a linear relationship between the impedance change ratio and the impregnated area ratio in MIEA, the impregnated area could be estimated at each sensing area. By approximating the measured impregnated area ratio using the cubic spline approximation, we drew the provisional flow front according to the threshold parameter. By determining the threshold via minimizing the residual sum of squares between the measured and estimated impregnated area, the precise flow front or dry-spot configuration could be estimated. MIEA can also monitor the cross sectional impregnated region through measurements of electrical resistance and capacitance [18]. The details of the flow front drawing procedures can be found in [17].

The flow velocity of resin inside the mold through the fiber preform during the VaRTM process can be assumed to follow Darcy's law: