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IN-PLANE AND TRANSVERSE DETECTION OF THE FLUID FLOW FRONT DURING THE LRI MANUFACTURING PROCESS

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SUMMARY: This paper deals with the problem of fluid front detection in order to validate and improve a numerical model of resin infusion during LRI (Liquid Resin Infusion) manufacturing processes. Recently, this finite element model has been developed by Celle et al. [1,2] for studying the manufacturing process of composite materials by infusion. In this infusion model, it is postulated that resin first fills in a distribution layer, and then infuses gradually in the direction transverse to the perform plane. This numerical model makes it possible to predict the position of the resin flow front during the infusion process. The fluid front detection will permit us to both verify the two-stage infusion postulated and more generally to correlate the numerical and experimental flow front positions. The experimental method for detecting the flow front position is based on an array of in-situ temperature micro-sensors [3]. The principle is to detect the arrival of the resin front by the resulting temperature change in each sensor. The micro-sensor arrangement permits us to improve the knowledge about the resin flow front in the preform mid-plane and across the preform thickness. The article presents details of the technique as well as preliminary results.

KEYWORDS: fluid flow front, micro-thermocouple, Liquid Resin Infusion (LRI)

INTRODUCTION

In the recent years, the liquid resin infusion processes (LRI) have become popular for the manufacturing of structural polymer-based composites for aerospace, automotive and other civil and military applications. LRI has been identified as a cost-effective alternative to conventional autoclave manufacturing technique. With LRI it is possible, for example, to produce complex and thick parts with very good mechanical properties and with less expense than in traditional methods [4]. However, the process is difficult to control because of the complex mechanisms involved, and its industrial use relies very often on trial and errors optimization.

In LRI-like processes, resin infusion is performed through a highly permeable draining fabric placed on top of the preform of fibres (Fig. 1). A pressure differential is created by a vacuum at the vent of the system. As can be observed in some experiments, one can figure out that the resin first fills in the draining fabric and then permeates across the thickness of the dry preforms (Fig. 2). The present study aims at studying *in situ* this flow front.

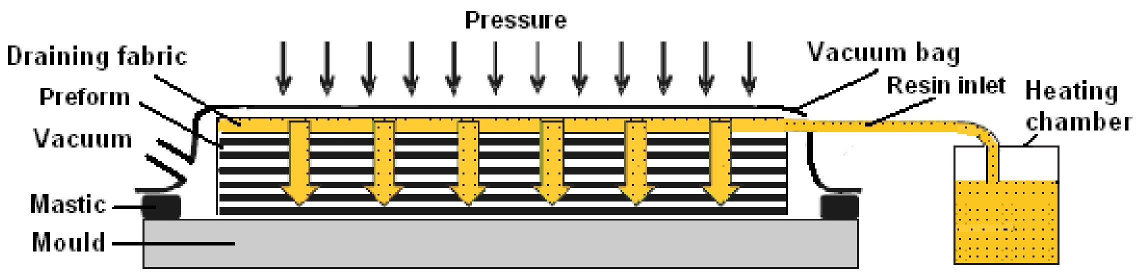


Fig. 1 Principle of LRI process.

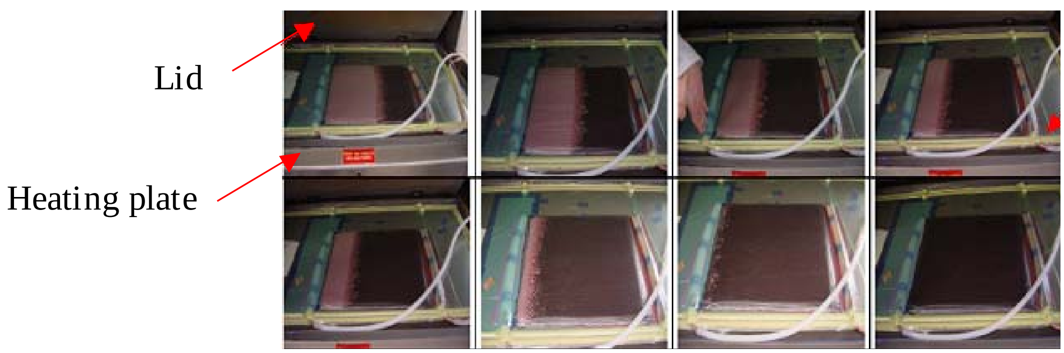


Fig. 2 Infusion of a plate carried out by LRI process : resin front advancement.

In order to obtain internal measurements during the infusion process with little disruption, a series of micro-thermocouples have been embedded at strategic locations in the preform. The injected resin is at a temperature lower than the one the preform (generally 80-90°C for resin and 120°C for preform), hence we can expect a local temperature decrease in the preform as the resin arrives. By observing and monitoring the temperature change in each thermocouple we aim at characterizing the resin flow process.

Two kinds of tests are presented here: 1) LRI on the heating plate with the lid open. This will allow us to compare our results with an optical full-field method (fringe projection), and 2) LRI on the heating plate with lid closed. This is the conventional requirement for a more uniform heat.

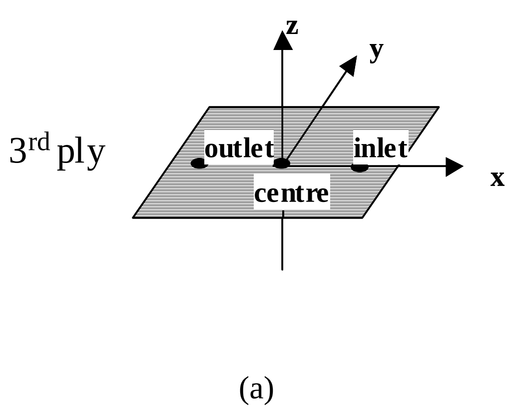
EXPERIMENTAL SET-UP

Characteristics of the Test Specimens

Experiments are conducted using 24-ply composite plates $[90_6/0_6]_S$, made up of “UD fabric” reference G1157 E01 produced by Hexcel Corp. These carbon fabrics are plain weave with 96 % weight in the warp direction and 4 % weight in the weft direction. The preform stacking dimensions are 335 mm × 335 mm × 6mm. For the resin, the experimental LRI tests have been performed using an epoxy resin (HexFlow© RTM-6). Before injection, the resin is preheated to 80°C in a heating chamber. In both experiments, one with the open lid and another one with the closed lid, the preform was heated by a heating plate located below the molding, the external pressure is uniform and equal to the local atmospheric pressure. The filling temperature is 120°C and the curing temperature is 180°C maintained for a period of two hours.

Experimental Procedures

Two experiments were performed on the described specimens. For the purpose of comparison and validation of the measurements with micro-thermocouples, a first experiment using thermocouples and an optical full-field method has been carried out. In this experiment, the fringe projection method permits to follow the advancement of the resin front by measuring the swelling of the preform during infusion. This method, however, requires to maintain the lid open. In order to measure the largest possible values of swelling, the thermocouples should be placed near the bottom of the plate. We have positioned the three thermocouples between the 3rd and 4th ply (Fig. 3-a). The second experiment, with a closed lid, has the most realistic thermal conditions. Seven thermocouples placed in the preform as shown in Fig. 3-b. This arrangement enables us to obtain a transverse information across the thickness of the preform along with a longitudinal information in the mid-plane.



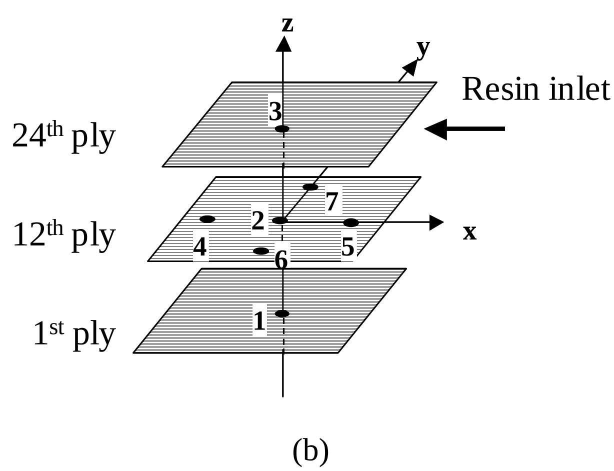


Fig. 3 Thermocouples location in the preform stacking: (a) test 1 with a open lid, 3 thermocouples (b) test 2 with a closed lid, 7 thermocouples.

Micro-Thermocouples and Data Acquisition Unit

The experiment uses micro-thermocouples of type-K, the most commonly used in industry. This type suites well to harsh environment and presents a wide range of temperature, between –75 °C and 250 °C. This type of micro-thermocouple is composed of 2 wires with 79 µm in diameter, it causes very little disruption during our infusion process. Data is acquired through an acquisition unit Agilent 34970A, a multi-acquisition system with 20 channels for measuring electric current, voltage and resistance. The frequency acquisition meets our requirements (maximum frequency of 20 values/sec), and its resolution is 0.1°C in temperature measurement. The calibration of the measurement system has been achieved in an oven during 3 isothermal conditions and compared with a platinum probe (PT100). The resolution of this calibration is closed to 0.1°C.

RESULTS AND DISCUSSION

Validation of the Detection with Thermocouples

As stated previously, one test has been achieved with the lid kept open during the infusion stage. This test was realized in such conditions to permit the use of a full-field optical method, the fringe projection method (see [5], Drapier et al. in FPCM9), in order to cross-validate both methods along with numerical predictions.

Fig. 4 shows the temperature change of the three thermocouples placed in ply 3, at the bottom of the stacking, positioned along the same line corresponding to the expected infusion direction (Fig.3). These three curves of Fig. 4 have similar shapes. Let us consider, as illustration, the response of the thermocouple placed at the center of the plate. The initial temperature increase (zone 1) is the preheating phase of the preform with the lid maintained closed. As soon as the lid is opened, the test begins and the cold resin penetrates progressively in the draining fabric, this tends to cool down the system. Then, the temperature is stabilized and begins decreasing (zone 2) due to the growing quantity of resin present in the preforms. One could argue that this temperature decrease may be due to the lid left open, but this decrease is also observed when the lid is left closed (see next section). In zone 3, the temperature decrease is marked, and a minimum is reached. In zone 4, resin is very rapidly heated by conduction, and eventually the saturated preforms reach a stabilized temperature at about 1500 s.

By comparing thickness variations measurements obtained through full-field optical method [5] and the response of these thermocouples responses, it appears that there is a concomitance between the occurrence of this minimum temperature and the thickness variation (*see* [5]). Since these thermocouples are placed close to the stacking bottom, resin comes down to reach the stacking bottom, and subsequently tends to make the preforms swell if resin is still fed in. This demonstrates what could be inferred, this minimum in the thermocouple response corresponds to the arrival of the resin over the thermocouple.

Considering that the thermocouple minimum corresponds to the resin detection, it can be verified in Fig. 4 that resin reaches in tight delays the inlet and center positions, respectively at 457 and 480 s. After 180 s, the outlet position is reached. The optical method permits to assess that the filling is not homogenously distributed over the preform; the plate is thicker at the outlet position. This delay may be related to this heterogeneity.

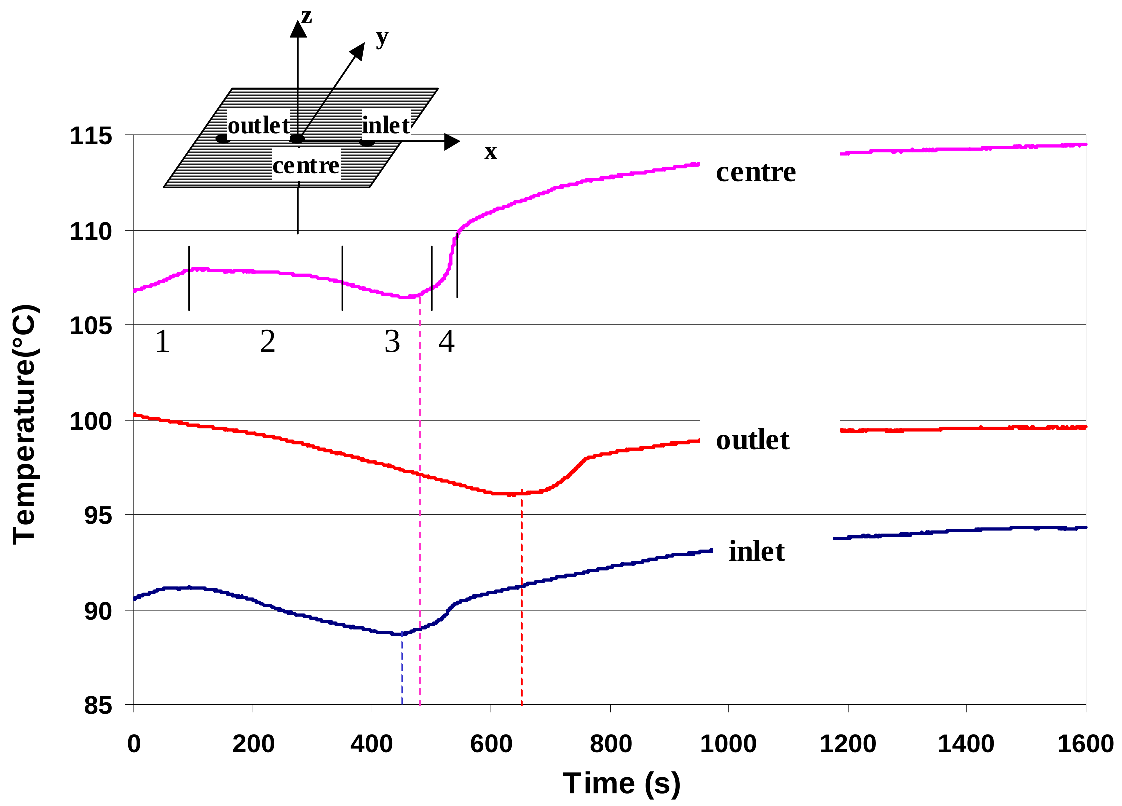


Fig. 4 Change in time of the three micro-thermocouple signals in the lid-open test.

Resin Infusion Test with a Closed Lid

The principle of detection of the resin front is validated. Let us now consider the scenario of the preform filling during infusion processes. As stated, it is expected that resin will fill in the system in two stages, the first one corresponds to the filling of the draining fabric and the second one the filling of the preform across their thickness. In order to detect those two types of flow, the composite plate was equipped with 7 thermocouples, the location of which is shown in Fig. 3-b : 1 below the draining fabric on top of ply 24, 5 in the preform mid-plane on ply 12, and 1 in the first ply in contact with the heating plate.

Fig. 5 and 6 show the temperature change in time for each thermocouple in the closed lid test. Time 0 corresponds to the beginning of the infusion process, when the resin is left free to fill in the circuit. Temperature is first equal to the one of the dry preform, and then decreases, this confirms the presence of the resin that tends to cool down the preforms. After some time the temperatures rise again to reach a plateau. Let us notice that temperature gets stabilised about 400 s after resin has arrived, whereas in the first test achieved with an open lid, temperature was stable after 1500 s.

Considering the minimum of the temperature as the detection of the resin, it is noticed that the resin reaches the mid-plane around time 120 s, with a delay of 50 s observed for TC2 (centre of the plate). This delay may be due to race-tracking effects which favour resin flow along the contours first. Times of resin arrival over the thermocouples are reported in Table 1.

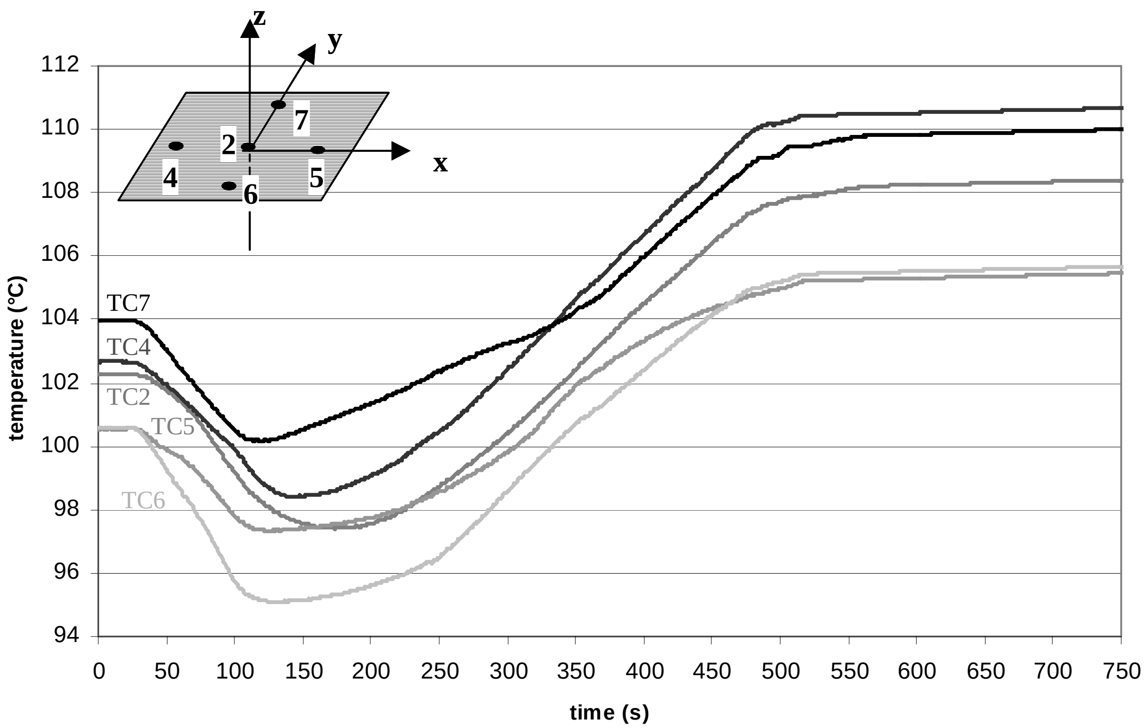


Fig. 5 Change in time of the signal of the thermocouples placed in the mid-ply.

Table 1 Times of resin arrival over the thermocouples used the closed-lid test

Thermocouple	TC1	TC2	TC3	TC4	TC5	TC6	TC7
Time (s)	NK	175	96	115	125	129	127

It is established that the resin infusion is homogeneous through the laminate thickness. Fig. 6 shows some results across the thickness by using thermocouples TC1, TC2, and TC3, placed along a vertical line going through the centre of the plate (Fig. 3-b). The resin first reaches TC3 at 96 s, on ply 24 underneath the distribution layer, and then TC2 in the mid-plane, at 175 s. As for TC1, the temperature measured may not be so reliable since the sensor is placed over ply 1, close to the heating plate. But considering TC1 response before and after the critical period, it could be inferred that this response might be of the same form as TC2 and TC3 responses but shifted in time. This point will receive a particular attention in future experiments.

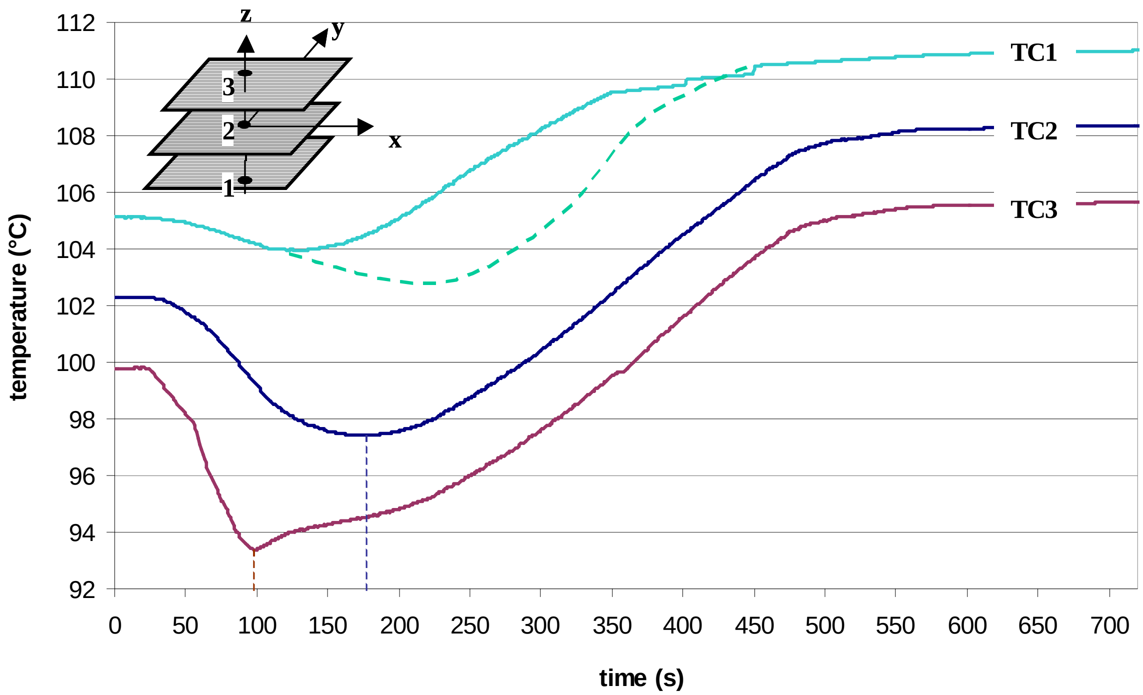


Fig. 6 Change in response of the thermocouples placed across the thickness signal vs. time.

Discussion

The thermocouple measurements permit to verify that the scenario retained for the numerical model is founded: resin first fills in the draining fabric and then infuses across the preform thickness, filling the plies homogeneously. Moreover, these experiments were achieved in industrial conditions.

But regarding the first test, with a lid maintained open, the resin front reaches the right hand side of the preform at first, where the resin inlet is located, then it reaches the center, and at last the left hand side of the preform. This scenario and corresponding times are confirmed by the preform swelling found using fringe projection [5]. Further experiments are under progress to sort out the various effects which may induce this change. For instance, this variation may be related to thermal conditions which evolve during the infusion process due to the lid left open.

CONCLUSION AND FUTURE WORK

It was demonstrated in this paper that thermocouples could be employed to detect the resin front position. This measurement technique is an indirect and non-intrusive method for detecting the resin front. It could improve our knowledge about resin flow in the preform during LRI process. This technique has been first validated by comparison with optical method measurements of the thickness variations [5]. Then, it has permitted to validate the scenario used for the infusion simulations developed by Celle *et al.* [1, 2] : resin first fills in the draining fabric, and then infuses gradually and quasi homogeneously across the preform thickness.

This technique is promising, but there have been some difficulties encountered during our tests realized in industrial environnements. Moreover, the measurements may be disturbed by the high thermal conductivity of carbon fibers. Glass fibers preforms are to be tested for comparison. The issue of homogeneous thermal conditions will lead us to carry out other tests in an oven where the acquisition of optical full-field method can be done without creating additional gradient temperature due to the opening of the lid.

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