Monitoring Mold Filling and Resin Cure in RTM

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ABSTRACT: Resin Transfer Molding (RTM) is used to manufacture continuous fiber reinforced polymeric composite parts. A thermoset resin is injected into a mold cavity previously filled with a reinforcing porous fabric preform. Both resin flow and properties of composite part are significantly affected by improper selection and preparation of material, and design of process parameters. In this study, thermocouple sensors were used to monitor both mold filling and resin cure. These sensors have advantages and disadvantages over other types of sensors such as pressure sensors. Fiber volume fraction measurements at different sections of panel parts indicated significant variations caused by several effects such as wash of fabric when resin reached a critical pressure, racetracking channels, and nonuniform compaction of mold plates. All these show that a smart control system is needed to automate RTM and reduce part rejection rate.

KEYWORDS: thermocouple, sensor, monitoring, RTM.

INTRODUCTION

In an RTM process, near-net-shape parts can be manufactured with high fiber content to meet mechanical strength and surface finish requirements [1][2]. In this process, a fabric preform is prepared by cutting and stacking glass or carbon fabric layers. The preform is draped over a tool surface. After the mold is closed, a thermosetting polymer is injected into the mold cavity to fill the empty space between the fibers. After complete filling, the ventilation and injection gates are closed. Typically, the filling time is several minutes or less. After the cure and solidification of the polymer, the mold is opened and the part is taken out.

A major issue in RTM process is incomplete mold filling due to the variations of raw material properties and then preparation. Since resin flow pattern is affected by these variations, a mold may not be filled completely, although it is filled completely under normal injection conditions in another injection. By using a control system such as that developed in [3][4][5][6][7][8], the variations in the process can be detected during the mold filling stage, and proper control actions can be taken to influence the flow pattern so that the mold cavity is filled completely. With a similar approach, in this study, an automated RTM system had the following five ingredients: (i) RTM injection machine from Radius Engineering [9], (ii) a modular mold, (iii) thermocouple sensors to monitor the mold filling and cure of resin, (iv) data acquisition cards and analysis computer program, and (v) mold filling simulation program, LIMS [10] developed by Suresh Advani, University of Delaware. This integrated system currently has some issues to be fixed for full automation, and they will be discussed here.

MOLD, MATERIALS and THERMOCOUPLE SENSORS

Mold

A general-purpose and research-based RTM mold was designed and then manufactured in a similar approach as in [6][8]. The bottom view of the lower mold part is shown in Figure 1. As seen in the figure, 45 multi-functional threaded holes (M20 = metric 20) are used for four different purposes: (i) inlet resin (injection gate), (ii) exit air (ventilation port), (iii) insert sensors into the mold cavity, (iv) to close the holes that are not needed. Some of the major characteristics of this mold are listed below:

- As many as 45 injection gates and ventilation ports are available on the mold.
- Visualization of mold filling through a transparent mold lid: This is needed to verify the success of the control system.
- Modular mold cavity: Many composite parts with different shape and dimensions can be manufactured by replacing a few modular sections of the mold.

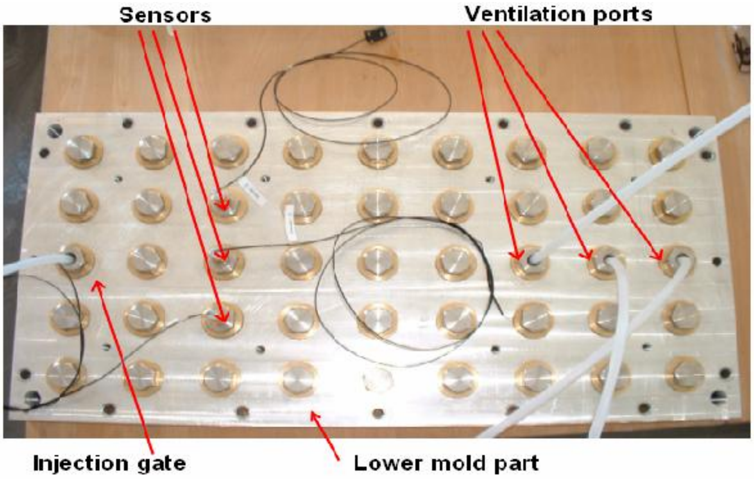

Figure 1. Bottom view of the lower mold part. There are 45 multi-functional bolts on the mold part. In this injection, 1 injection gate, 3 ventilation ports, and 3 sensors are used, and all the other multi-functional bolts are used as solid (i.e., no function).

Resin system

A room-temperature polyester, Dewester 196 (DYO Dewilux 511-0196) was used in the injections. The mixing ratio for cure reaction accelerator and curing agent was between 0.005 and 0.020 (weight based) depending on room temperature and storage time. Its viscosity at around 20^{o}C was measured to be about 0.77 Pa.s. However, this showed a significant variation with the storage time and from one batch to another. Its density was about 1.19 gram/cm^3 at the room temperature.

Fabric

E-glass plain weave fabric with an areal mass of 500 gram/m^2 was used. The fabric rolls were purchased from Fibroteks [11]. Warp and weft had the same width of about 4.5 mm. However, the empty spacing between them was about 3-4 mm in one direction and less than 1 mm in the other direction. Thirteen layers of fabric were cut and stacked, and then placed into the mold cavity with dimensions of 704 x 168 x 5 mm.

A fiber volume fraction of about 50% was achieved. Higher fractions could be obtained by compacting more layers of fabric under a press. The fabric preform had a length of 624 mm. The two empty channels with a length of about (704 – 624)/2 = 40 mm on both sides of the fabric were used to convert point injection and ventilation to line injection and ventilation.

Thermocouple Sensors

In RTM and similar processes, sensors are used to monitor mold filling and resin cure (cross-linking) for control purposes. Ideal sensors should not interfere with resin flow [12]. Some sensors (such as pressure transducers, thermocouples and direct current conductors) are placed on the surface of mold cavity, and they measure process variables such as resin pressure or temperature. Some other sensors (such as ultrasonic) are used externally [12]. One needs to consider the cost, ease of use, accuracy and reliability of the sensors when controlling mold filling and resin cure.

In this study, the following two J-type thermocouples were used: (i) National Instruments, 745685-J01, and (ii) Elimko Elektronik, 05T2JTTEA.

Compared to pressure sensors, major advantages of thermocouple sensors are: (i) they can be used for monitoring *both* mold filling and resin cure, (ii) they are cheaper.

In order to monitor the mold filling, the temperature of the polymer should be different from the ambient temperature. Although a room-temperature resin system was selected in this study, its temperature was raised above the room temperature by about 10^oC before mixing the curing agent. This was easily achieved by heating the resin barrel of the Radius Engineering injection machine.

The designed thermocouple sensors are shown in Figure 2. A small copper part with high thermal conductivity was attached to the end of thermocouple in order to shorten the time delay in detecting the resin arrival.

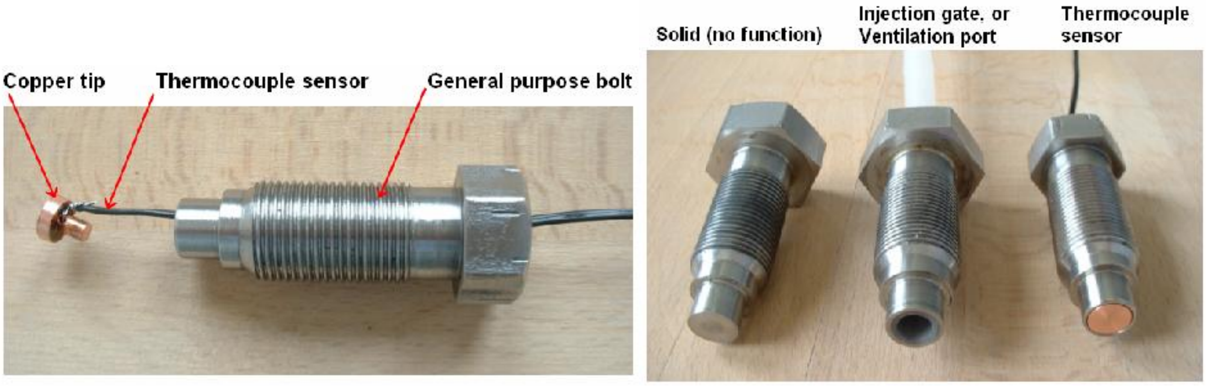

Figure 2: A thermocouple sensor and multi-functional bolts to be used on the lower mold part.

Three thermocouple readings were shown in Figure 3a during a mold filling. It took about 10 seconds to detect about 10^oC temperature rise. Compared to pressure sensors, this is a disadvantage of thermocouple sensors used in this study. The control system works in such a way that when the temperature reading of a sensor indicates a specified ΔT, it is understood that the resin arrived there. In order to make a quicker detection of resin arrival, one may attempt to use a smaller ΔT such as a few degrees Celsius only. However, this might cause misdetection of resin arrival as there is a continuous noise in temperature readings as seen in Figure 3a. A filtering of noise is needed in order to have quick and reliable sensor readings.

Thermocouple sensor readings for three separate experiments were shown in Figure 3b during the cure and solidification stage. Due to the exothermic reaction, the temperature of the composite part increased gradually, and then decreased due to the conduction of the heat to the mold during cooling. It is clearly noticed in this figure that, as the curing agent mixing ratio was increased, the release of heat happened very quickly which also made the injection more difficult since the viscosity increased more rapidly.

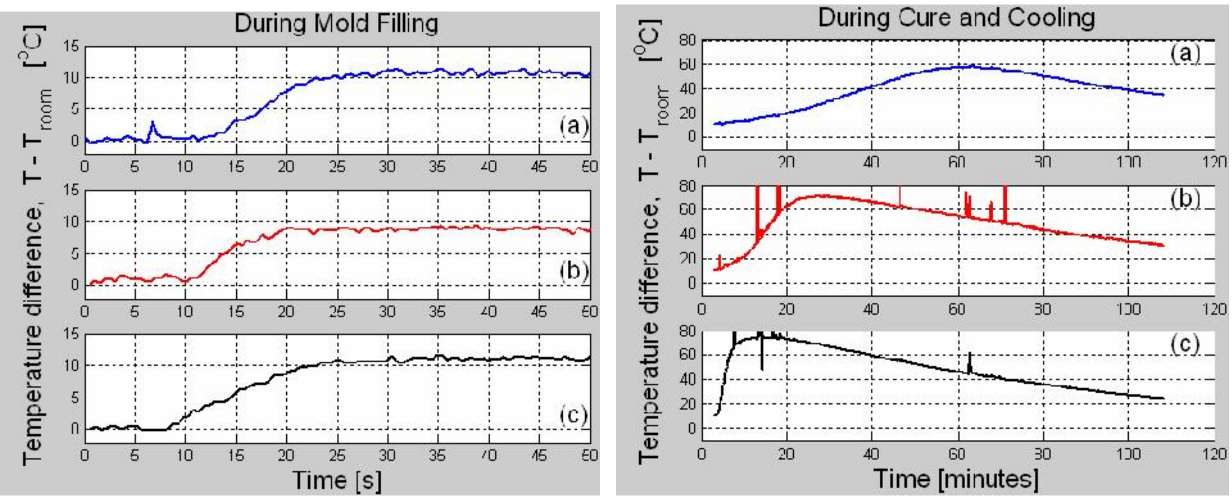

Figure 3. (Left): Temperature readings of three thermocouples during mold filling. (Right): Temperature readings of a thermocouple during cross-linking (cure) for three separate experiments. The mixing ratio of the “curing agent / polyester resin” is 0.005, 0.010 and 0.020 (weight based) in experiments (a), (b) and (c), respectively.

ISSUES

Although we tried to advance the RTM process toward more automation by using a control system, there are still some unresolved issues in this study. These are:

- Two-dimensional mold filling model was performed by using shell-like elements since the thickness dimension is much smaller than the in-plane dimensions. A sample mold filling simulation is shown in Figure 4 together with top view of the mold cavity and mesh. Due to insufficient compaction force applied by the bolts and stiffening bars, at some locations three-dimensional flow was observed through the transparent mold lid. The resin raced between the upper mold lid and the preform’s upper side while the bottom side of the preform got saturated later. This condition is definitely a contradiction to the assumption of two-dimensional flow and corresponding mold filling simulations.
- Under constant flow rate injection, when the injection resin pressure reached above 15-20 bars approximately, wash (movement) of fabric preform was observed around the injection gate and also along the racetracking channels. In one of these extreme cases, where the maximum injection pressure reached 20 bars, the fabric preform was pushed toward the center, and wrinkled very significantly.

- Material properties (viscosity and gel-time) of Dewester 196 resin varied significantly as the room temperature changed from one injection to another, and also due to the storage time. The success of the control scheme and hence the injection depends on a reliable data base of the resin properties, which we are still working on.
- Upon a close examination of the part edges, it was observed that there is a less dense section of the reinforcing fabric adjacent to the mold wall. There are a few usually unavoidable reasons for this: (i) Some of the fiber bundles fall down from the fabric during the cutting and placement. (ii) Fiber wash due to high resin pressure.
- Specimens with 20 mm width were cut from one side of a part as shown in Figure 5. Average fiber volume fractions were measured as 0.23, 0.52, 0.58 and 0.50 along sections A, B, C and D, respectively. In order to investigate the variation of mechanical properties of specimen, a universal test machine was used as shown in Figure 6. The machine is capable of doing tension, compression and three-point bending (flexure) tests. However, the tests performed so far are inconclusive as the type of fracture is not consistent. The available punch of the machine has a fixture so thick that in some experiments it causes shearing. After modifying this fixture, the tests will be continued, and their results will be presented at the conference.

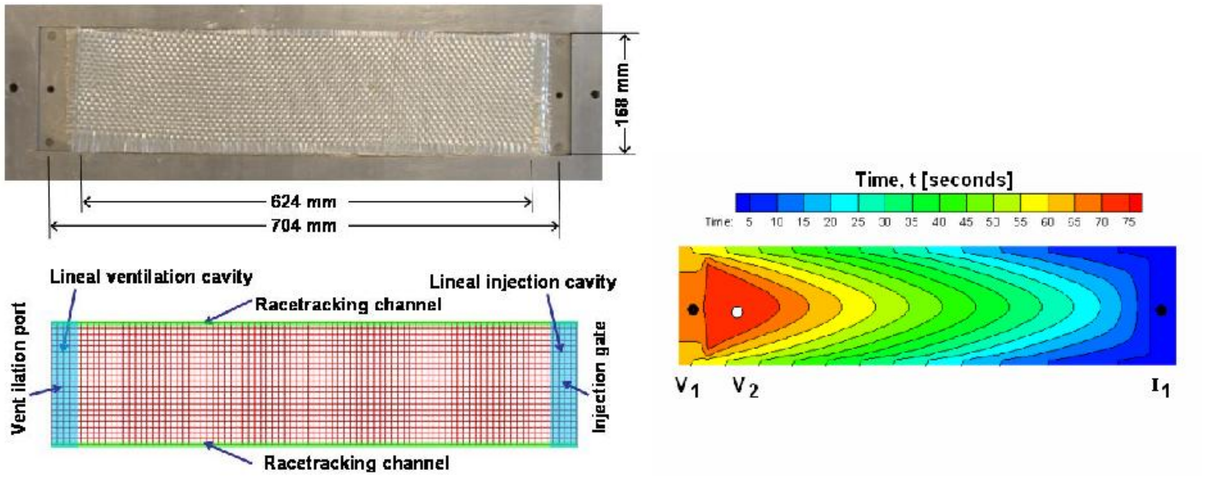

Figure 4. Mold filling simulation by LIMS [10] for a case with racetracking along the two sides. Different colors show the position of the resin flow front at different times. Simulation result suggests to activate a ventilation port at V_1 as well as V_2 in order not to entrap air, which will cause a dry spot otherwise.

Figure 5. Specimen to be cut from a composite part along the upper edge.

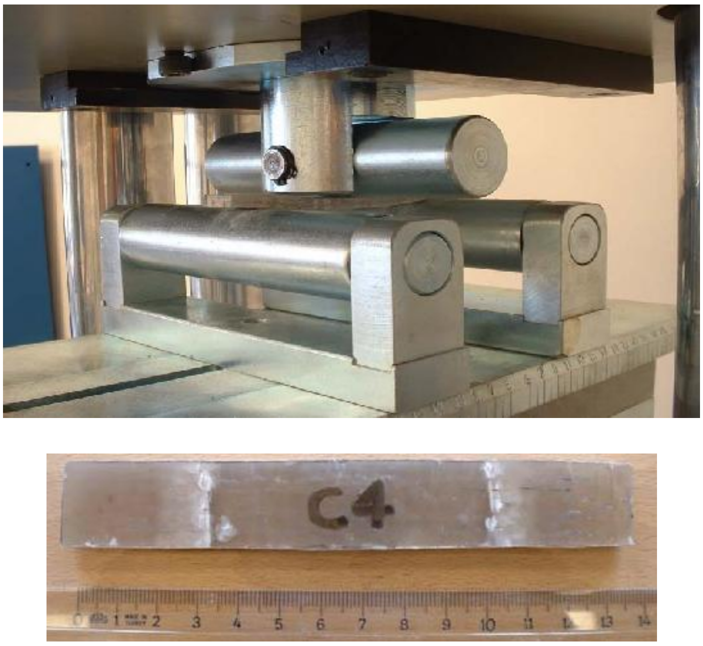

Figure 6. Three-point bending (flexure) test setup on a universal test machine; and a specimen

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