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OBSERVATIONS FROM THE FILLING AND POST-FILLING STAGES OF AXISYMMETRIC LIQUID COMPOSITE MOULDING WITH FLEXIBLE TOOLING.

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ABSTRACT: This paper presents experimental observations from the filling and post-filling stages of 1D axisymmetric Resin Infusion (VARTM) and RTM Light. A series of experiments have been performed to investigate the influence of mould flexural stiffness and fill mode on fluid pressure, cavity thickness, filling stage time, and post-filling stage time. Observations are also made on the effect of those parameters on the repeatability of nominally identical experiments.

KEYWORDS: Infusion, VARTM, RTMLight, Experimental

INTRODUCTION

RTM Light is a flexible tool LCM process that replaces one or both sides of the rigid mould of RTM with a semi-rigid component. It utilises cheaper tooling than RTM or CRTM, but offers more control over part thickness and surface finish than Resin Infusion, making it ideally suited for medium to high production volume components where some thickness variability is acceptable. The interactions between fluid pressure, flow evolution, reinforcement deformation behaviour, and the structural response of the tooling present challenges in the modelling and simulation of flexible tool LCM processes. An important step in that process is developing an understanding of the effect of key parameters, such as mould flexural stiffness and fill mode, through experimental studies.

EXPERIMENTAL PROGRAM

Experimental Facility

An experimental facility has been developed to perform and monitor 1D axisymmetric infusions with partially and fully flexible upper mould components (Fig. 1). This has been achieved using a circular mould with a rigid aluminium lower half and upper mould halves of either vacuum bagging or polycarbonate plates, depending on whether a Resin Infusion or RTM Light process is under consideration. The lower mould half is divided into two isolated sections: an inner mould cavity able to accommodate circular preforms up to 450 mm in diameter and an annular outer region that can be evacuated to clamp the RTM Light moulds in place. Ports located at the centre and the periphery of the mould cavity function as either injection gates or vents depending on the fill mode required.

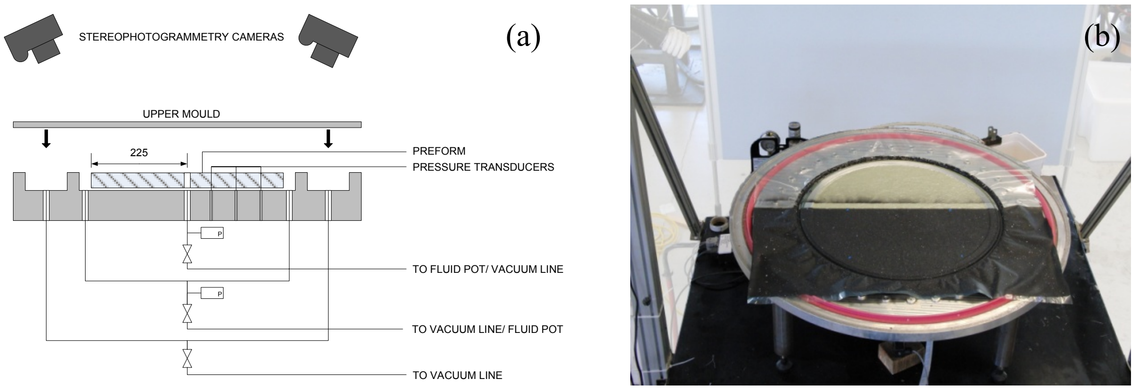

Fig. 1 (a) Rig schematic and (b) Resin Infusion experiment in progress

Five pressure transducers are fitted to the mould, measuring the fluid pressure at the gate, vent, and three evenly spaced points along the preform. Fluid mass flow rate is monitored by a mass balance supporting the fluid container. The transducers and mass balance are connected to a data acquisition system and their outputs recorded on a PC running LabVIEW. Full-field transverse thickness measurements are provided by a stereophotogrammetry system comprising a pair of digital cameras mounted above the mould and a high frequency speckle pattern on the mould surface [1]. The cameras are connected to and controlled by a pair of PCs, acquiring images at set intervals that can be processed and converted into thickness measurements. This system allows circumferentially averaged thickness values to be calculated, providing an advantage over point measurement devices.

Materials

The reinforcement used in this study was an E-glass chopped strand mat (CSM) with a nominal areal weight of 450 g/m^2. Preforms for all experiments comprised 10 layers of CSM cut into 450 mm circular sections, with a 15 mm hole punched into the centre to encourage 1D axisymmetric flow. The test fluid was a Mobil DTE Heavy mineral oil with a viscosity of 0.28 Pa.s at 20ºC.

Procedure

The preform was cut and weighed before being placed in the rigid lower mould. For the Resin Infusion experiments, an aluminium spacer ring was placed around the periphery of the preform to act as a vent line for radial filling or a feeder line for peripheral filling. The preform was then covered with a vacuum bag (Resin Infusion) or a polycarbonate plate upper mould (RTM Light) with a pre-sprayed speckle pattern for the stereophotogrammetry measurements. The data acquisition and stereophotogrammetry systems were activated to monitor and record pressure, mass flow rate, and out-of-plane thickness deviations.

Before opening the injection gate, a pre-filling compaction cycle of 10 min. full vacuum (~15 mbar cavity pressure) followed by 5 min. no vacuum (atmospheric cavity pressure) and 5 minutes full vacuum was applied; previous preform compaction studies have shown this cycling reduces variability in the compaction response of the reinforcement [2]. The injection gate was closed when the preform was fully saturated, and full vacuum was maintained during the post-filling period, which was at least twice the fill time for radial injection experiments and 10 times the fill time for peripheral injection experiments.

Schedule of Experiments

A series of six experiments were performed, allowing two fill modes and three mould stiffnesses to be compared. The two fill modes were radial and peripheral, giving divergent and convergent flow front evolutions, and the three upper moulds were a flexible nylon vacuum bag, a 6mm thick polycarbonate plate and a 10mm polycarbonate plate. Each experiment was repeated three times to account for variations in constituent materials and operating conditions.

RESULTS AND DISCUSSION

Repeatability

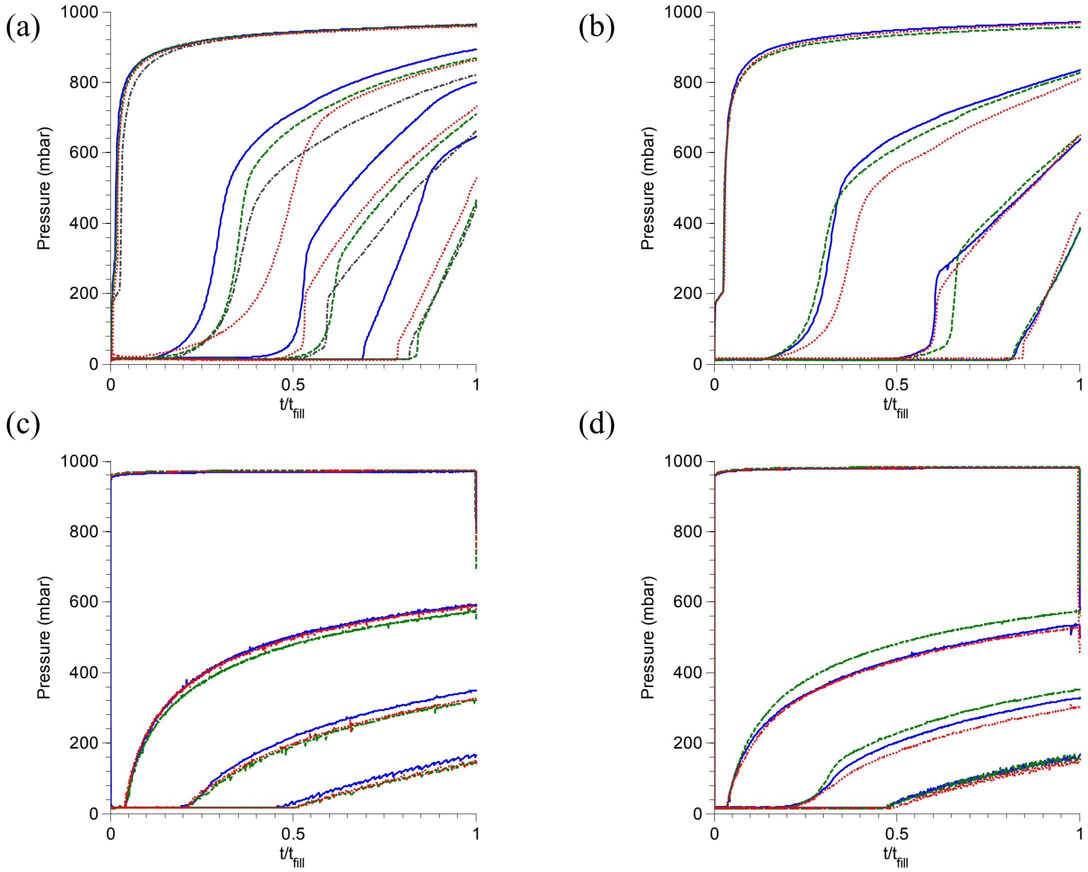

Fig. 2 Pressure traces during filling for each repeat: (a) peripheral VARTM, (b) peripheral 10 mm RTM Light, (c) radial VARTM, (d) radial 10 mm RTM Light

Fill times appeared to be repeatable, with most of the variation between repeats explained by changes in ambient temperature, and hence viscosity, between experiments. Average radial fill times for the three mould stiffnesses were between 20 and 25 minutes, and average peripheral fill times were between 4 m 10 s and 4 m 20 s. The variability not explained by temperature change is most likely attributable to variation in local and global reinforcement architecture as well as small measurement errors.

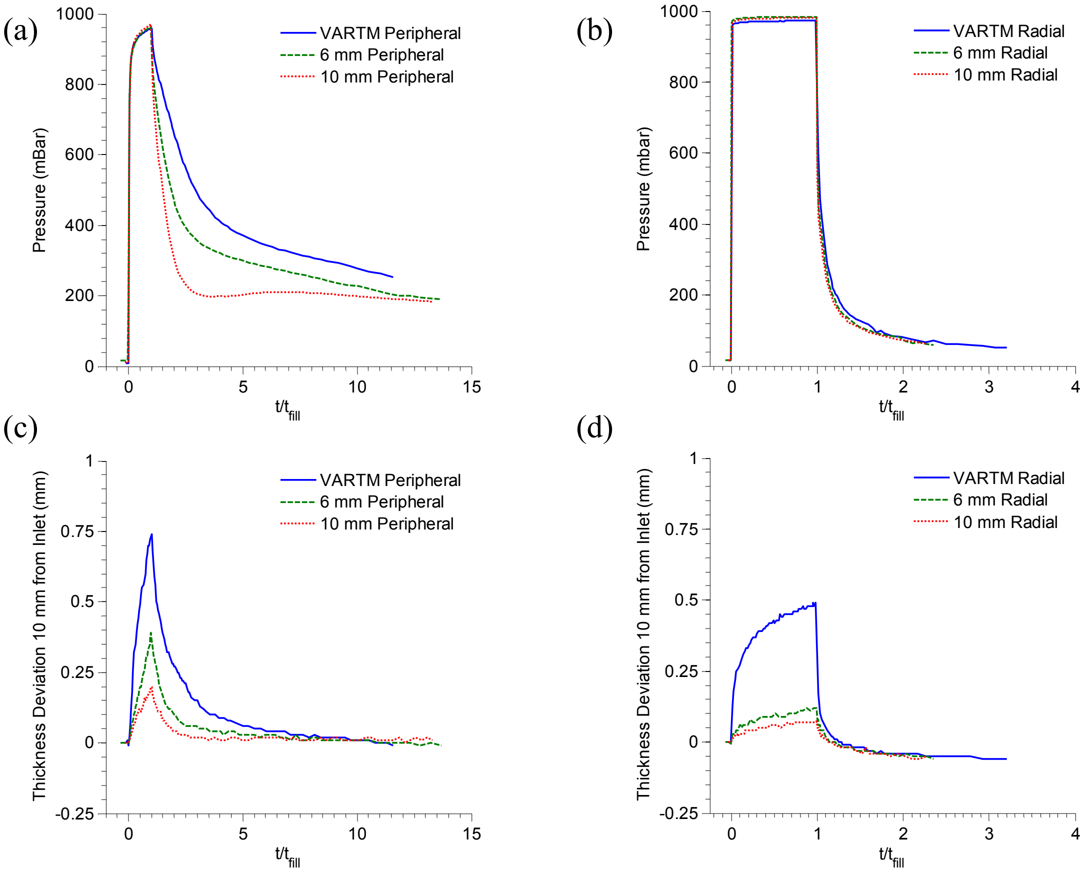

Fig. 3 Normalised pressure and thickness deviation traces at the inlet for peripheral (a) & (c) and radial (b) & (d) fill modes. Nominal part thickness is 4mm.

Although the aggregate property of fill time showed good repeatability, pressure and thickness measurements exhibited significant variability between repeats for the peripheral fill mode, particularly for the Resin Infusion experiments. Fig. 2 compares the pressure traces for all repeats during the filling stage for (a) Resin Infusion and (b) 10 mm RTM Light. The time is normalised with respect to fill time as a first attempt to adjust for temperature and preform areal weight variability. The key observation from Fig. 2 is that increasing the mould stiffness gives much more repeatable pressure profile development. Also note that the variations between experiments are largest during the periods in which the pressures are changing rapidly, and as the filling progresses there is convergence of pressure at each point. While some of the differences between repeats can be attributed to deviations from axisymmetry, indicated by the initial rise of in-preform pressure measurements occurring at different normalised times, it cannot account for all the variation.

A possible explanation for this behaviour is in the unloading process of the reinforcement as the flow front passes and the fluid pressure rises. In Resin Infusion there is larger deformation and more potential for influence of local reinforcement variability since the bag does not ‘average out’ deflection like a semi-rigid mould.

The Resin Infusion case would also have larger changes in permeability, which could help explain why there appears to be greater divergence from axisymmetry in that case.

For the radial fill mode, the pressure traces collapse with much smaller deviation, even for Resin Infusion, as shown by Fig 2. Given that the radial fill mode generates smaller deflections at a slower rate, this is evidence that some combination of rapid and large unloading of the saturated reinforcement is linked to highly variable fluid pressure behaviour. More experiments are needed to determine the relative importance of the rate and magnitude of unloading.

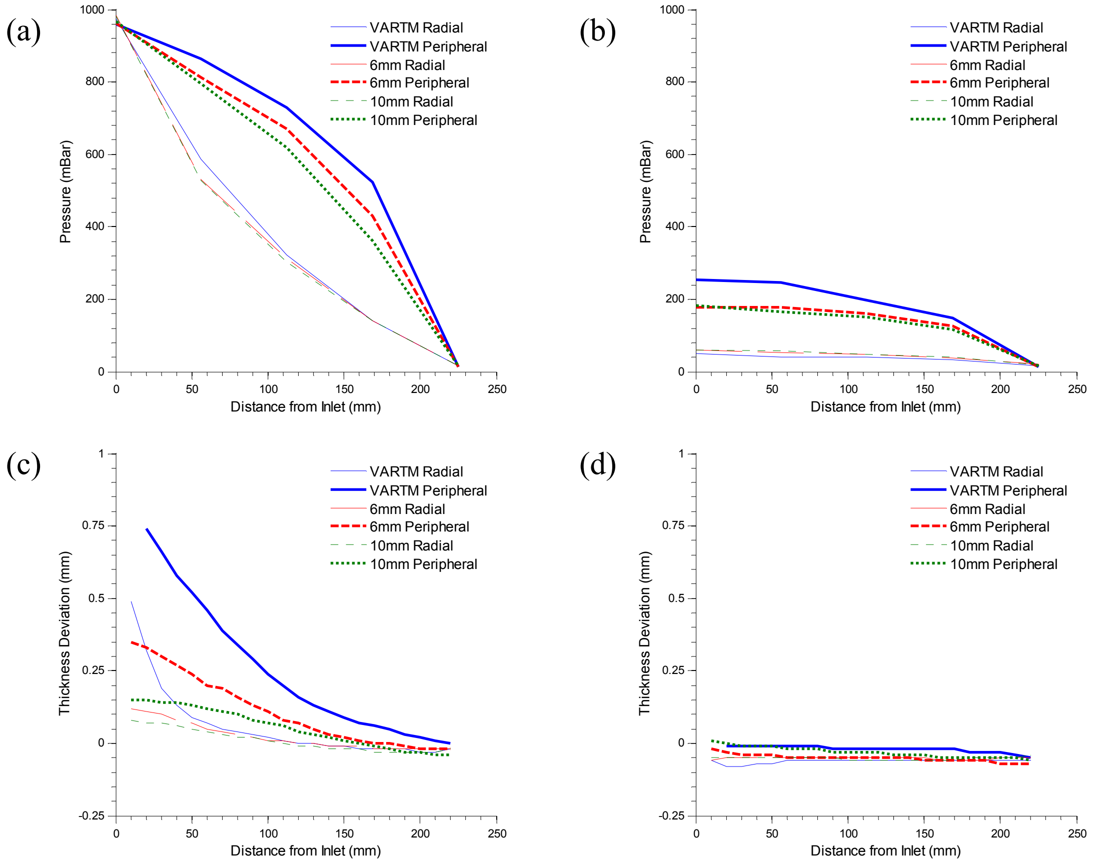

Fig. 4 Pressure and thickness deviation profiles at the completion of filling (a) & (b) and at the completion of post-filling (c) & (d). Nominal part thickness is 4mm.

Influence of Fill Mode

The most obvious distinction between the radial and peripheral fill modes are the lengths of the filling and post-filling stages, with radial filling having a relatively short post-filling period and peripheral filling having a relatively long one. For a typical experiment, thickness equilibration occurs at twice the fill time for radial and 10 times the fill time for peripheral. However, the radial fill times are approximately 5 times longer, so the total cycle time is of the same order for both fill modes.

Peak thickness deviation occurs at the inlet side of the preform at the end of filling for all fill modes and mould stiffnesses. The increasing thickness at the inlet for radial Resin Infusion, despite constant pressure, is evidence of the viscoelastic nature of the unloading process (Fig. 3(d)). It also shows the influence of the tensile stiffness of the vacuum bag, with the inlet thickness increasing as the flow front moves away from the centre and a larger area of the bag is exposed to higher fluid pressures. For all mould stiffnesses, the peripheral fill mode gives larger thickness deviations throughout the filling stage, and the thickness gradient from inlet to outlet persists longer into the post-filling period (Fig. 4). Note the residual pressure gradient at the instant where thicknesses have equilibrated is much more pronounced in the peripheral fill cases. This behaviour is consistent with prior experimental and numerical post-filling studies of unidirectional Resin Infusion, which can be viewed as an intermediate case between the divergent and convergent flow patterns shown here [2].

Influence of Mould Flexural Stiffness

Fig. 3 shows pressure and thickness at the inlet for all three mould stiffnesses against normalised time. Mould stiffness has negligible influence on the post filling-pressure for radial filling, but for peripheral filling there is a trend of more rapid pressure decrease as the mould stiffness increases. The thickness traces are consistent with expectations, showing the magnitude and persistence of thickness deviations to increase with decreasing mould stiffness. The relative deflection between Resin Infusion and RTM Light is smaller in the peripheral case due to the larger area over which the higher fluid pressures act.

CONCLUSIONS

An experimental facility has been developed to monitor axisymmetric LCM processes under flexible and semi-rigid tooling. This paper presented pressure and thickness data from a series of experiments in which the influence of mould stiffness and fill mode was investigated, in order to reveal key issues in modelling LCM processes with flexible tooling. Total cycle times for radial and peripheral fill modes were similar, despite the relative lengths of the filling and post-filling periods being different, and although fill times were generally repeatable, variability in point pressure measurements in nominally identical experiments was found to be strongly related to mould stiffness and flow speed. These results, when combined with the typically low-cycle times in RTM Light processes, show that accurately capturing the dynamic reinforcement compaction behaviour and its interaction with the structural response of the mould will be crucial to producing a useful simulation of flexible tool LCM processes.

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