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CONSOLIDATION OF CURVED COMPOSITE PARTS MANUFACTURED BY FLEXIBLE INJECTION

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SUMMARY: Flexible injection with a compaction chamber is a new way of fabricating high performance composites by resin injection through fiber beds. This process belongs to the family of Liquid Composite Molding (LCM). It was originally devised to reduce cycle time for volume production. This technique consists of a closed rigid mold separated into two cavities by a flexible membrane. In a first stage, a given volume of resin is injected through a fibrous preform placed in the lower cavity. In a second stage, the upper cavity is filled with a pressurized fluid to complete the impregnation of the reinforcement. In a third and final stage, the saturated preform is consolidated. Flexible injection was shown to be very effective to reduce filling time as compared to classic Resin Transfer Molding (RTM). However, in the case of complex shapes, the flexible nature of the mold can lead to dimensional variations, especially in regions of strong curvature. This work presents implementation results of this new process for curved parts. A series of experiments have been carried out to demonstrate the viability of this new approach for L-shaped parts. Image analysis was performed on scanned images of cross-sections to assess the geometrical quality of the parts produced. Preliminary results indicate that the preforming stage has a direct influence on the geometry of the final part. Two types of defects can be observed in the parts: (1) a poor dimensioning of the preform creates resin-rich zones in the curved sections; (2) differences in compaction behavior between the flat and curved sections result in thickness variations. These observations suggest that a suitable preforming strategy should take into account the compaction behavior of the preform and the desired volume fraction of the final part.

KEYWORDS: Flexible injection, curved composite, fiber preform, consolidation, compaction

INTRODUCTION

The Liquid Composite Molding (LCM) family covers several processes for the manufacture of thermoset matrix composites (RTM, CRTM, VARI, SCRIMP,…). Over the past decades, an important amount of experimental, theoretical and numerical work has been performed to widen the possible industrial applications of such materials. However, none of these techniques is well

suited for high volume production because of limited cost effectiveness as compared to metals and alloys processing methods. Recently, a new process called flexible injection with a compaction chamber has been proposed to allow faster manufacturing of advanced composites [1]. This technique consists of a closed rigid mold separated into two cavities by a flexible membrane. The main steps of the manufacturing cycle are presented in Fig. 1:

(1) A fibrous preform is placed in the lower cavity (injection cavity) and the mold is closed.
(2) A controlled volume of resin is injected in the injection cavity.
(3) A pressurized fluid is introduced in the upper cavity (compaction cavity).
(4) The part is cured under constant pressure.
(5) The compaction fluid is removed, the mold opened and the part demolded.

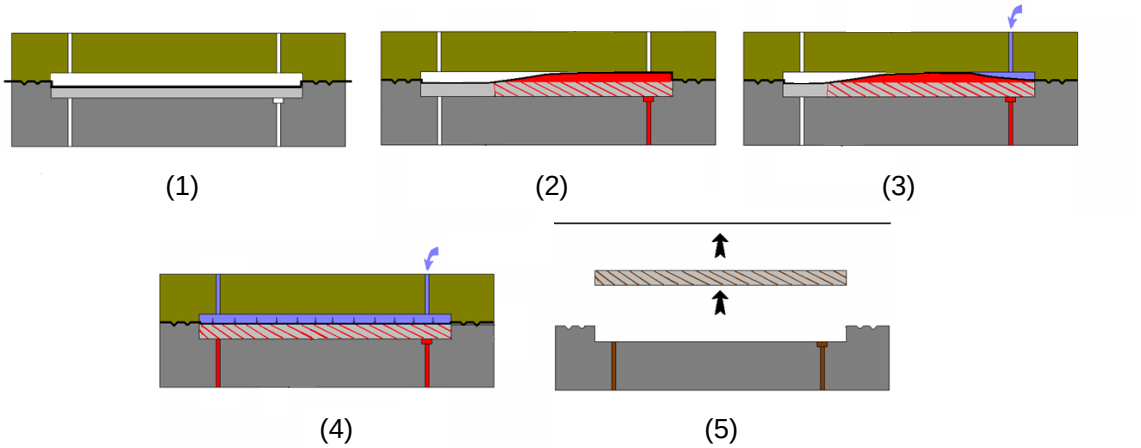

Fig. 1 Main steps of the flexible injection process.

During fexible injection, the final geometry of the part results from a consolidation stage of the saturated fiber bed. In that sense, the process can be compared to autoclave processing. The latter method has been the subject of numerous published works aiming at understanding the physical phenomena related to composite consolidation. In a review of the existing literature dating from 1998, Hubert and Poursartip [2] mentioned that most of the studies focused on flat laminates whereas very little attention had been given to complex geometries. Since then, some papers have clearly shown the particular behavior of angle shapes during consolidation. Hubert and Poursartip [3] conducted an experimental study on the consolidation behavior of L-shaped parts and observed that most of the manufacturing defects were localized at the corner. Furthermore, the presence of fibers oriented in the plane of the curve could modify the compaction behavior of the composite thus leading to thickness gradient in curved regions. The difference of consolidation behavior between flat and curved composites was also demonstrated numerically by Hubert and Poursartip [4] and Li and Tucker [5]. Using 2-D models based on the finite element method, these two studies showed that the fiber bed shear modulus had a major influence on corner thickness of angle laminates. Such local properties variations can have an impact upon the quality of the entire composite part. Feih and Shercliff [6] found that manufacturing faults (resin-rich zones and thickness gradients) experimentally observed at the corner of curved composites led to important variation of delamination strength. Radford [7] showed that the spring-in of curved composites was affected by process-induced volume fraction gradient.

Flexible injection has proved to be very effective to reduce filling time in the case of simple (plane) geometry as compared to RTM [1]. To develop further the method, it is of primary importance to evaluate its potential in the case of complex geometries. To address this issue, the present paper reports a first experimental application of the processs for curved parts manufacturing.

EXPERIMENTAL

Materials and Setup

Experimental Setup

The manufacturing experiments were conducted with the aluminum mold shown in Fig. 2(a). This mold was equipped with a flexible membrane cut out from a plane sheet of fluoroelastomer VITON from DUPONT (thickness 1/32", hardness 75 Shore A). This setup was designed to produce the Z-shaped part shown in Fig. 2(b). Because of the asymmetric nature of the process, it should be noted that the two right-angled sections have to be distinguished according to the nature of the rigid mold (convex or concave).

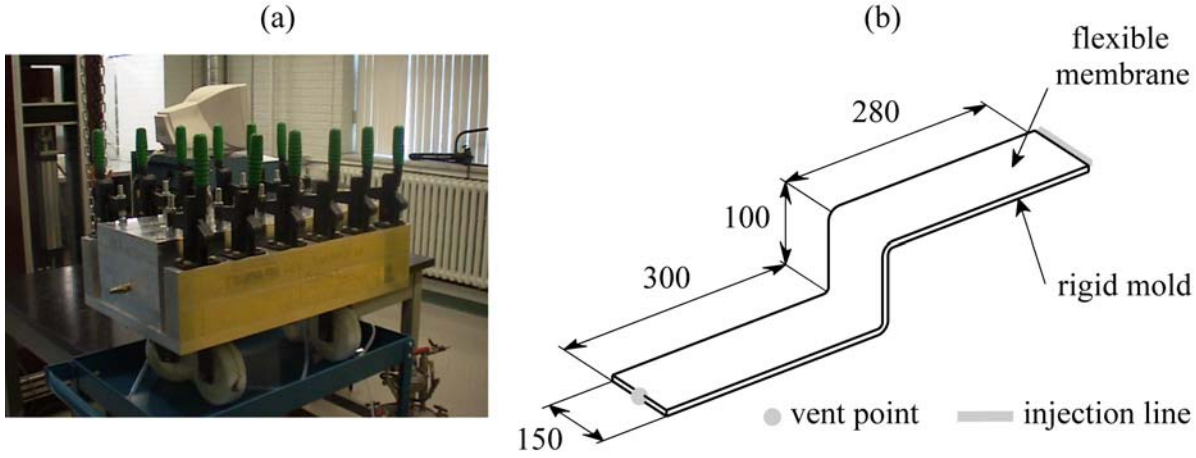

Fig. 2 Implementation of the flexible injection process for curved part manufacturing: (a) experimental mold and (b) geometry of the part (dimensions in mm).

Resin was injected with a pneumatic gun SEMCO (model 250-A). After calculating the mean resin losses in tubing, this simple device permitted a control of the injected quantity at ± 3g for a total injected mass between 110g and 183g. Compaction fluid (silicone DOW CORNING 200, viscosity of 1000 cSt at 25ºC) was controlled with a pressure tank. Rest of the setup consisted of two catch pots used to draw full vacuum from both cavities (injection and compaction). All the experiments presented in this paper were carried out at room temperature (20.5ºC - 22ºC) with constant injection pressure (P_i = 2 bars) and compaction pressure (P_c = 6 bars).

Materials

The resin used was epoxy vinyl ester DERAKANE 411-350 from ASHLAND. Methylethylketone peroxide MEKP 925-H from NOROX (1.25 phr), Colbalt Naphtenate 12%

(0.1 phr) and 2-4 pentanedione (0.08 phr) were respectively used as initiator, promoter and retarder. That type of formulation gives a gel time of approximately 2 hours under the manufacturing conditions. Reinforcement was an E glass non-crimp stitched fabric Roviply (+45˚, 400 g.m^{-2} // -45˚, 400 g.m^{-2} // random mat, 225 g.m^{-2}) from CHOMARAT. For ease of handling and to avoid fiber washout, the fiber bed must be preformed prior to injection. For this purpose, the fabric already contains an epoxy powder (20 g.m^{-2}). However, this type of binder requires a hot (200ºC) preforming mold. Because of the lack of such equipment, a simple room temperature preforming procedure was devised (Fig. 3). First, a small quantity of the thermoset system (same formulation than previously stated) was manually sprayed on both sides of each ply. The fibers were then placed between two folded aluminum plates and full vacuum was drawn from the cavity thus created. Plastic sheets were used to adjust the vertical dimension of the mold L_p. In flat sections, the thickness of the preforming cavity h_p was dictated by the compaction behavior of the fabric. In curved regions, modeling clay was applied with a radius gauge to modify the different radii of curvature. The preform was cured overnight under such preforming pressure of 1 bar. A large rigid preform (650 mm wide) made of 4 plies of fabric was thus obtained. This preform was subsequently cut into 4 smaller preforms having the dimensions of the part.

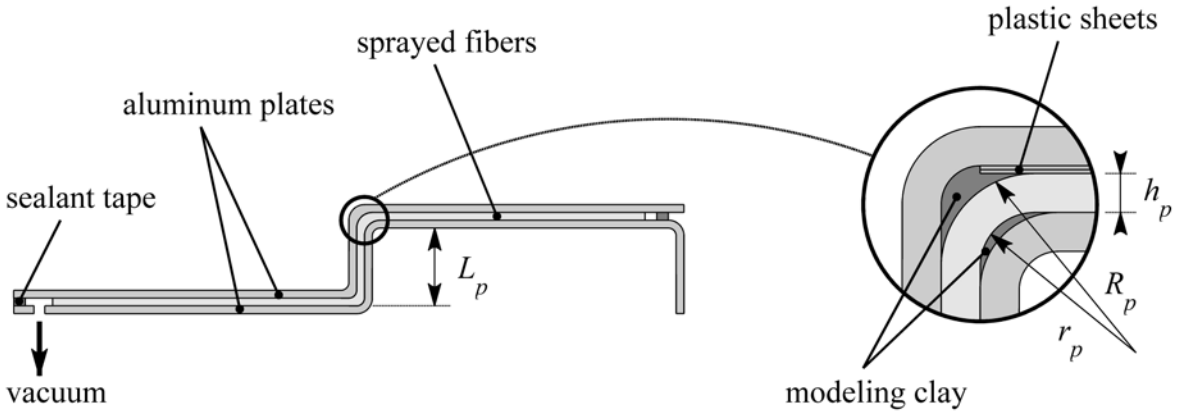

Fig. 3 Preforming procedure.

Preform Characterization

To characterize the compaction behavior of the fiber bed, a series of relaxation tests were conducted on an MTS testing machine equipped with parallel plates. Test samples were flat squares (100×100 mm) made of 3 plies of preformed fabric. Testing sequence consisted of a constant-speed loading (5 mm/min) followed by a 2-hours relaxation stage at a constant thickness. Each test was repeated at least three times for thicknesses ranging from 2 mm to 2.7 mm every 0.1 mm.

Parts Analysis

After demolding, each part was cut into three samples having a width of 35.5 mm according to the pattern illustrated in Fig. 4(a). Both sides of these samples were polished with waterproof aluminum oxide sandpaper with increasing grit from 220 to 1200. This polishing operation

removed approximately an additional millimeter from the surface of the sample. Images of these six longitudinal cross-sections were obtained with a scanner CANON CanoScan 4400F (optical resolution 4800 dpi). To increase the contrast between the part and the background, the samples were placed on a transparent adhesive tape and a layer of white paint was brushed onto the surface of the tape (Fig. 4(b)). Image analysis was performed with MATLAB. The program automatically detects the edges of the part and calculates the corresponding thickness. A mean thickness profile of the part is finally obtained by averaging the results of the six analyses.

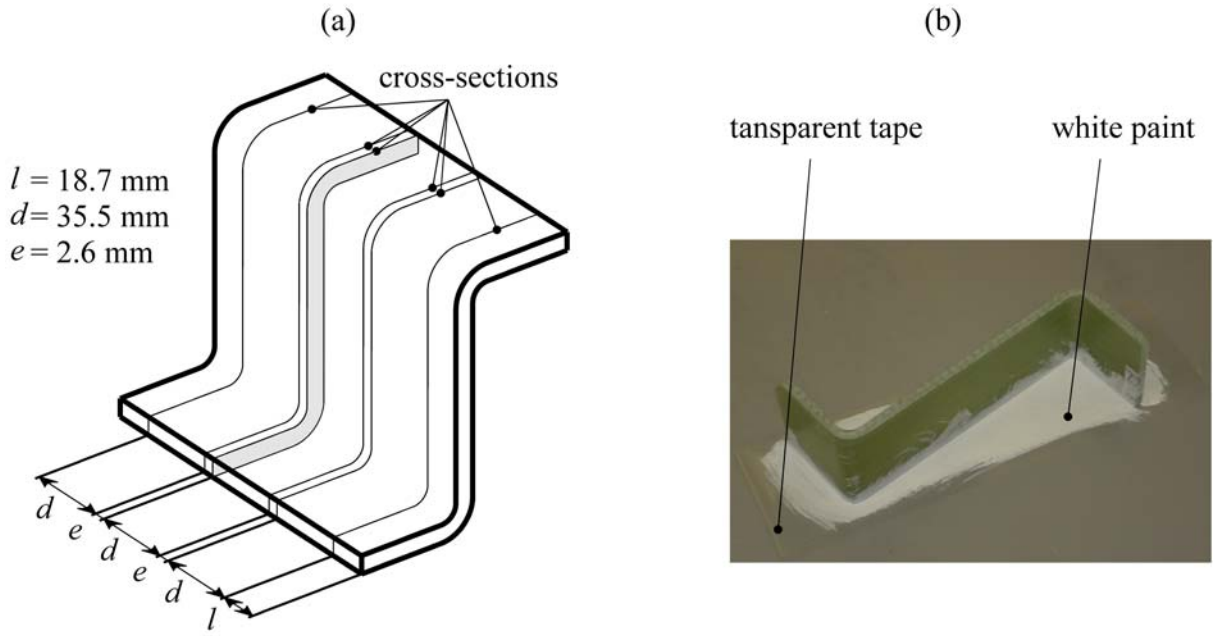

Fig. 4 Sample preparation for image analysis.

RESULTS AND DISCUSSION

Compaction Behavior

Results of the relaxation tests are shown in Fig. 5a. As expected, the preforms exhibit significant viscoelastic behavior, especially during the early minutes of relaxation. After 2 hours of testing the equilibrium does not seem to be reached but the stress decay is much smaller. The stress values obtained at the end of the relaxation tests were used to construct the compaction curve shown in Fig. 5b. The data were fitted with a common power law model relating the effective stress on fibers σ_f to the fiber volume fraction V_f:

$$\sigma_f = A.V_f^B \tag{1}$$

The time-dependent mechanical response of fiber beds is a complex phenomenon that can be affected by many factors (number of plies, strain rate, saturation). Since a complete characterization of the preform would be too time-consuming, the compaction curve of Fig. 5(b) was considered, as a first approximation, as describing the behavior of both:

- the sprayed fibers at gellation during preforming,
- the saturated preform at gellation during manufacturing.

According to the compaction model, the fiber volume fraction at gellation during preforming V_{fp} is 52.8%. Depending on the quantity of injected resin, the part can then be more or less compacted than this preforming state.

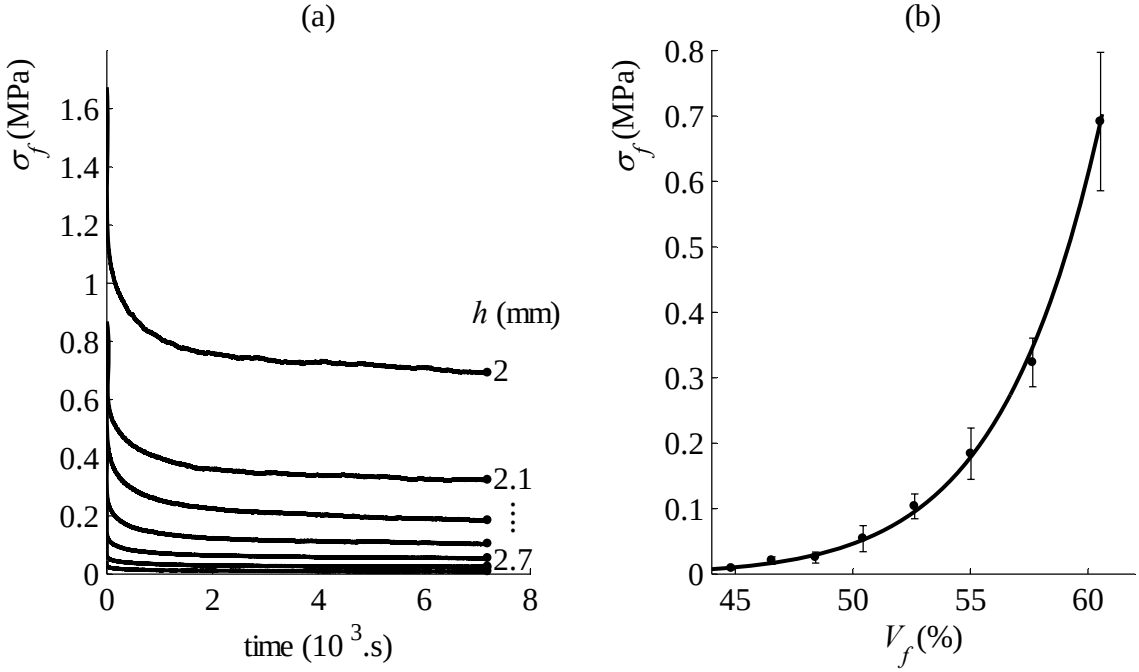

Fig. 5 Characterization of the fiber preform: (a) relaxation curves and (b) compaction law.

Analysis of Curved Region

The results presented in the following section only concern the curved region with a convex rigid mold. The experimental program comprised the fabrication of 3 large preforms labeled from A to C for a total of 10 parts manufactured. For each experiment, the mass of resin to be injected m_i was calculated assuming a constant thickness throughout the part and a fully saturated preform (no void) with the following expression:

$$m_i = \left(\frac{\rho_{fs}\rho_r}{\rho_g} \frac{1-V_f}{V_f} - \rho_{bs} \right) S_p \qquad (2)$$

Where S_p is the surface of the preform, ρ_g the glass density, ρ_r the resin density, ρ_{fs} the preform fiber surface density and ρ_{bs} the preform binder surface density. After demolding, the parts were weighted to estimate the real mean fiber fraction using the same relation.
Three target values of fiber volume fraction were used during the study:

- V_{f1} = 47.1% : low compaction,
- V_{f2} = 52.1% : medium compaction (close to preforming condition),

- V_{f3} = 57.6% : high compaction.

A summary of the experimental plan is presented in Table 1. As shown in this table, the estimated real fiber volume fractions are close to the objective values, thus reflecting a good control of the injected mass.

Table 1 Summary of the manufacturing program.

Preform	r_p (mm)	R_p (mm)	L_p (mm)	binder content (wt %)	part	V_f (%)	
						target	estimated
A	3	6	100	2.36	a	52.1	52.4
					b	52.1	52.4
					c	52.1	52.3
					d	52.1	52.4
B	3	6	100	4.24	a	52.1	52.0
					b	57.6	57.3
					c	47.5	47.8
C	3	6	101	2.88	a	57.6	58.2
					b	52.1	52.4
					c	47.5	48.2

Part to part variability

Preform A was prepared with a central dimension (L_p = 100 mm) and an inner radius (r_p = 3 mm) matching the dimensions of the mold. Since the preforming thickness h_p is 3.06 mm, an outer radius R_p = 6 mm results in a preforming cavity having approximately a constant thickness. This preform was used to fabricate 4 parts having the same targeted fiber fraction V_f = 52.1%. Visual inspection of the corresponding cross-sections reveals no important manufacturing defect (Fig. 6(a)). As can be seen on this image, the surface finish of the part differs greatly depending on the side considered. Hard fibers can indeed penetrate the soft membrane material so that variability in preform material leads to small thickness variations along the part. This effect can be seen on the different thickness profiles shown in Fig. 6(b). In the flat regions close to the corner, a small thickness increase seems to be visible but this effect is not perfectly clear and will require further investigation. Finally, the only significant variation is an important thickness decrease in the curved region. This corner thinning effect is clearly visible on the 4 parts and the repeatability of the experiments will be considered acceptable taking into account the variability introduced by the fiber bed.

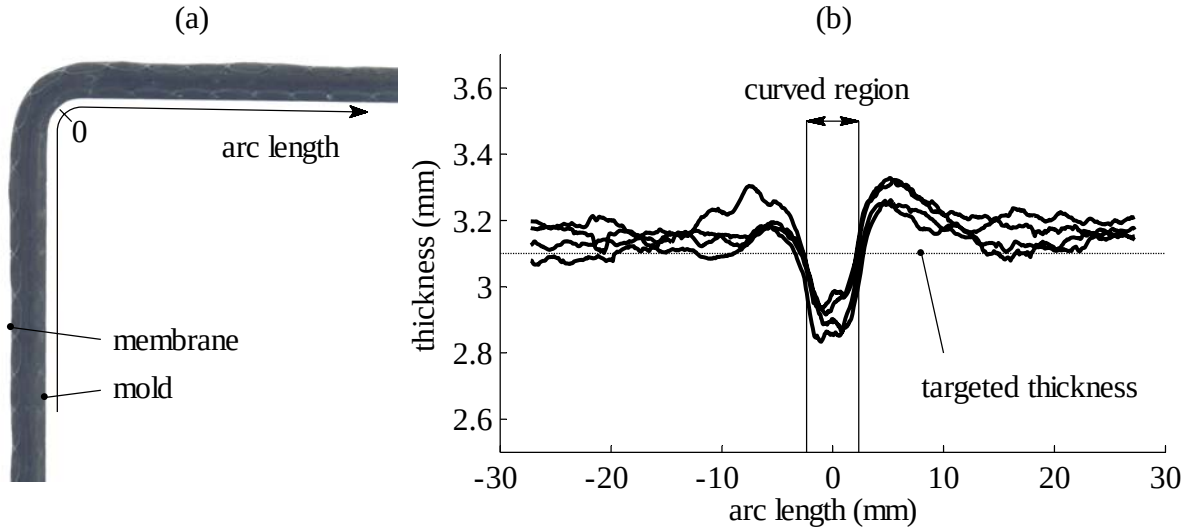

Fig. 6 Analysis of parts fabricated with preform A: (a) typical cross-section and (b) thickness profiles.

Influence of injected quantity

Preform B was prepared with the same parameters as preform A but was used to fabricate three parts having different fiber volume fractions. The corresponding thickness profiles are reported in Fig. 7. The three curves exhibit corner thinning but the effect is much more important for low fiber fraction (3.4 mm thickness). In that case, the effective stress on the fibers is small and the thickness profile observed is close to the geometry of the stress-free preform. Consequently, the preforming conditions (constant cavity thickness and preforming pressure of 1 bar) result in a preform with marked corner thinning. When the injected quantity is decreased, the corner of the part is harder to consolidate as compared to the flat sections. This difference in compaction behavior tends to attenuate the corner thinning effect for a highly compacted part (2.8 mm thickness).

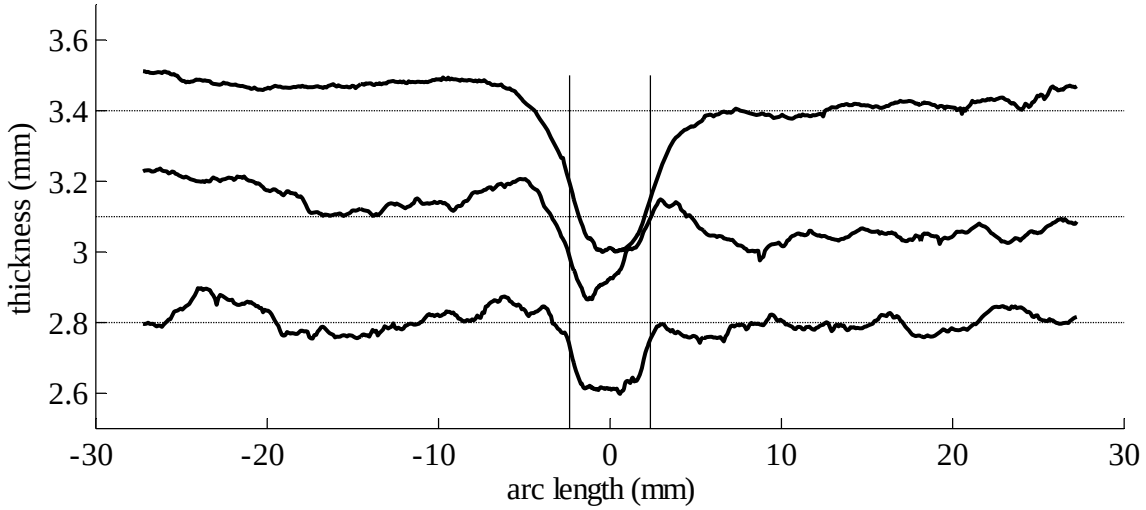

Fig. 7 Influence of injected quantity upon the final thickness profile.

Influence of preform dimensional accuracy

To assess the importance of preform dimensioning, a dimensional error was intentionally introduced when preparing preform C. The central dimension of the preforming mold was adjusted to be 1 mm longer that the manufacturing mold. Visual analysis of the corresponding cross-sections shows the creation of a resin-rich zone between the mold and the fibers (Fig. 8). For a low fiber fraction, an important resin accumulation exists at the corner and on the opposite flat section. When the level of compaction increases, the fibers are forced against the mold in the flat section and the resin-rich zone becomes smaller. When the part is highly compacted, a very small accumulation can be seen in the region of curvature.

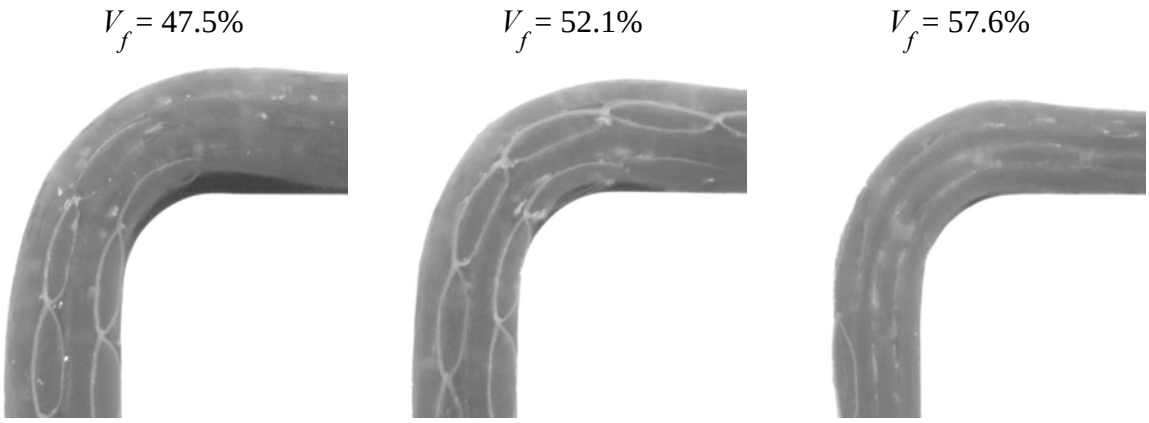

Fig. 8 Resin-rich zone creation induced by poor preform dimensioning.

The displacement of the resin accumulation can also be observed on the different thickness profiles (Fig. 9). At low level of compaction, the resin-rich zone causes an important increase in thickness. The effect is reduced when the injected quantity decreases so that no significant thickness variation is observed for the higher fiber fraction.

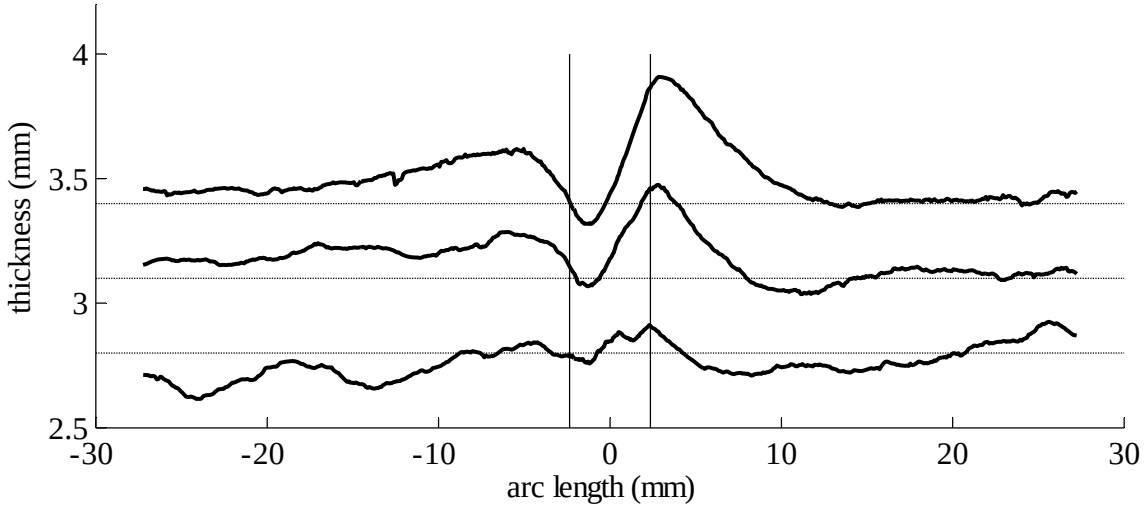

Fig. 9 Thickness profiles illustrating the displacement of the resin-rich zone.

CONCLUSIONS

The flexible injection process has been implemented for angle composite manufacturing. In the case of a convex rigid tool, preliminary results lead to the following conclusions:

- Preforming under constant thickness results in corner thinning of the preform.
- The compaction behavior of the preform differs between flat and curved sections.
- Poor dimensioning of the preform creates resin-rich zone at the corner of the part.
- Low compaction levels are likely to create more manufacturing defaults.

Future work will investigate the influence of preforming geometry and preforming pressure in order to propose a preforming strategy adapted to the desired fiber volume fraction.

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