EXPERIMENTAL ANALYSIS OF FLEXIBLE INJECTION FOR CURVED COMPOSITE PARTS

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ABSTRACT: Flexible Injection (FI) is a new Liquid Composite Molding (LCM) process for the manufacture of high performance composites, which consists of injecting a thermosetting resin through a fibrous reinforcement contained in the lower chamber of a double cavity mold. Resin is injected in the lower cavity, which is sealed by a membrane, after which a compaction fluid is injected in the upper chamber to compress the reinforcement. This new composite manufacturing technique, which allows a limited and controlled deformation of the membrane during processing, was shown to be very effective in reducing filling times in the case of planar or slightly curved geometries. In the present study, flexible injection is applied to strongly curved parts, namely here a composite rectangular panel with two 90^0 corners. After setting up an experimental procedure to produce the stair-shaped components out of fiberglass and vinylester resin, the analysis of longitudinal cross-sections of the parts have shown that the curvature significantly changes the lay-up quality. While flat sections consolidate adequately to nearly uniform thickness, corners of the parts are likely to exhibit manufacturing defaults. Actually two types of defects have been observed: firstly, resin-rich zones are created when the fibrous preform does not match perfectly the shape of the tool. In addition, the corners of the part may exhibit thickness gradients. Preliminary results indicate that such defects could be reduced by an appropriate preforming strategy. Finally, the study demonstrates the key role of preforming to ensure successful manufacturing by flexible injection of complex composite structures.

KEYWORDS: Liquid Composite Moulding (LCM), Flexible Injection (FI), part distortion, preforming

INTRODUCTION

Over the past decades, fiber reinforced thermoset composites have become popular in many highly demanding applications. Among the multiple manufacturing techniques available to process such advanced materials, *Liquid Composite Molding* (LCM) processes have received a growing attention because of their ability to fabricate composite structures of complex shape at a reasonable cost. The two principal LCM techniques, *Resin Transfer Molding* (RTM) and *Vacuum Assisted Resin Infusion* (VARI), have been modified to devise new process variants such as *Compression Resin Transfer Molding* (CRTM), SCRIMP, *Liquid Resin Infusion* (LRI) for faster and more reliable manufacturing. However, despite an important amount of experimental and theoretical work in these areas, none of these techniques is well suited for high volume production because of relatively long cycle times. For this reason, advanced composites fail to compete with metallic materials in several industrial applications like in the automotive industry for example. Recently, a new technology called Flexible Injection (FI) has been proposed to allow fast manufacturing of thermoset composites [1, 2].

In flexible injection, the mold is separated into two cavities by a flexible membrane. The main stages of the manufacturing cycle are schematically presented in Fig. :

(1) A fibrous perform is placed in the bottom cavity and a flexible membrane is laid upon the bottom half of the mold, which is then closed.
(2) A controlled volume of resin is injected in the lower cavity (injection chamber). To speed up the filling of the mold, the double cavity is thicker than the fiber bed so as to create an open gap on top of the preform above which the resin can flow easily.
(3) A pressurized fluid is introduced in the upper cavity (compaction chamber). The deformation of the membrane allows transmitting the compaction pressure to the resin in order to complete the impregnation of the fiber bed.
(4) After mold filling, the part is cured under constant pressure.
(5) Vacuum is applied in the compaction chamber to remove the fluid, the mold is opened, and the part is demolded.

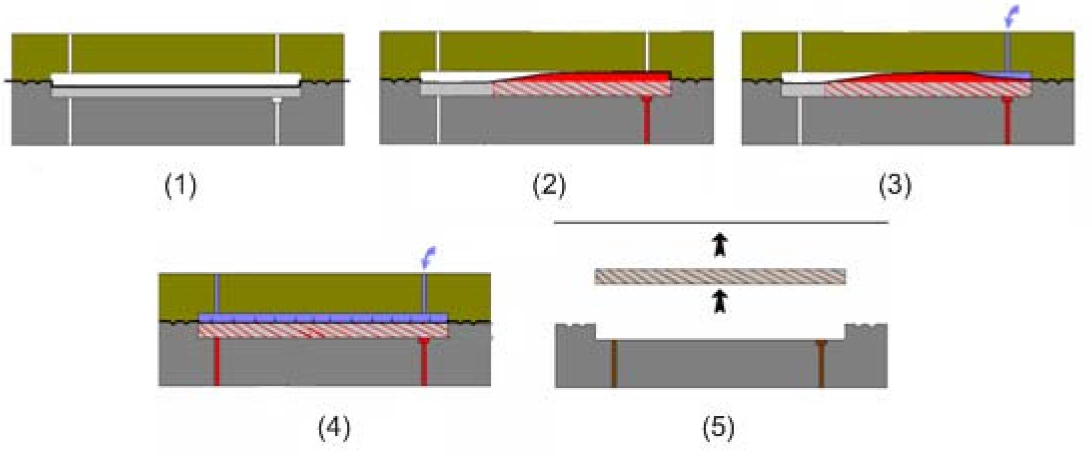

Fig. 1 Main steps of Flexible Injection

Flexible injection has proved to be a very effective way not only to reduce filling times in the case of simple (planar or slightly curved) geometry [1, 2], but also to improve part quality thanks to the stronger through-thickness consolidation of the composite provided by the compaction fluid. Further process development is of paramount importance in order to evaluate the potential of this new approach for complex geometries, especially in the case of strongly curved parts. As a matter of fact, manufacturing defects are often encountered in composites. In an extensive experimental study on autoclave processing of L-shaped parts, Hubert and Poursartip [3] showed that sharp corner regions were prone to exhibit manufacturing defects such as voids, fiber wrinkles or resin pockets. Fiber wrinkling and fiber bridging are typical phenomena appearing when one tries to drape plies of continuous fibers into a curved tool [4]. Jain et al. [5] observed that fiber bridging occurs at the corner of L-shaped laminates produced on a female mold.

Several authors have used numerical modeling to understand the specific behavior of curved sections during consolidation. Hubert et al. [6] developed a 2D finite element model to simulate the autoclave processing of angle-shaped laminates in a convex tool. They found that the consolidation of curved sections was mostly governed by the shear behavior of the fiber bed with high shear modulus resulting in important corner thickening. Based on a similar approach the influence of shear behavior was also outlined by Li and Tucker [7]. These authors suggested that the combination of low shear modulus and convex tooling could lead to the formation of defects at the corners of the part, but no experimental observation did support their numerical results. However, this hypothesis is consistent with the fiber wrinkling mechanism mentioned above. Recently, Li et al. [8, 9] used a 2D consolidation model to study the manufacture of cornered laminates. These two studies confirm that composite consolidation in curved regions is mainly governed by the shear behavior of the fiber bed. In particular, the stacking sequence has a direct influence on the thickness variations in the corners. These conclusions were well supported by experimental observations.

The present paper presents an experimental study of defects in curved composite parts made by flexible injection. The quality of the parts is evaluated by analyzing the uniformity of composite consolidation in both straight and curved sections. The observed defects are due mainly to the behavior of the fiber bed during compaction. This paper aims to demonstrate the key role of preforming to ensure quality of the composite.

EXPERIMENTAL SETUP

The manufacturing experiments were performed with the aluminum mold shown in Fig. 1a. This setup was designed to process the stair-shaped part illustrated in Fig. 1b. The part consists of three planar sections separated by two right-angled corners. Fig. 2 shows a schematic representation of the tool. The two mold halves are separated by a flexible membrane cut out from a plane sheet of fluoroelastomer VITON from DUPONT (thickness 1/32’’, hardness 75 A). A silicone gasket is glued on the top mold around the periphery of the cavity to improve sealing in both cavities. The compaction chamber is 5 mm narrower than the injection chamber to pinch off the preform and prevent fiber wash out during injection. Because of the asymmetric nature of the process, the two curved regions have to be distinguished according to the nature of the rigid tool. The radii of curvature are respectively 3 mm for the convex tool corner and 5 mm for the concave tool corner. It is also interesting to note that the central flat region is parallel to the mold closing axis. In the case of RTM, this kind of configuration could lead to preform shearing during closing of the tool. That problem does not exist with flexible injection since the overall cavity is thicker than the fiber bed.

Materials

The resin used was epoxy vinyl ester DERAKANE 411-350 from ASHLAND. Initiator was methylethylketone peroxide MEKP 925-H from NOROX (1.25 phr) and promoter was Cobalt Naphtenate 12% (0.1 phr). A gel time retarder, 2-4 pentanedione (0.08 phr), allowed adjusting the gel time to approximately two hours. The fibrous 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. Because of the presence of sharp corners, it is nearly impossible to lay up several plies of the dry fabric into the mold prior to closing. For ease of handling, the fiber bed must be preformed to the desired shape before laying it into the cavity. For that purpose, the fabric already contains an epoxy powder (20 $g.m^{-2}$) that requires a hot (200°C) preforming mold. Because of the lack of such equipment, a simple room temperature preforming procedure was devised. First, a small quantity of the same thermoset system was sprayed on both sides of each fabric ply with a pressure gun. The plies were then stacked between two folded aluminum plates and full vacuum was drawn in the cavity (Fig. 4). A self-hardening modeling clay was applied with a radius gauge at the corners of the plates to modify the different radii of curvature. After application of the vacuum pressure, the preform was left overnight to cure at room temperature.

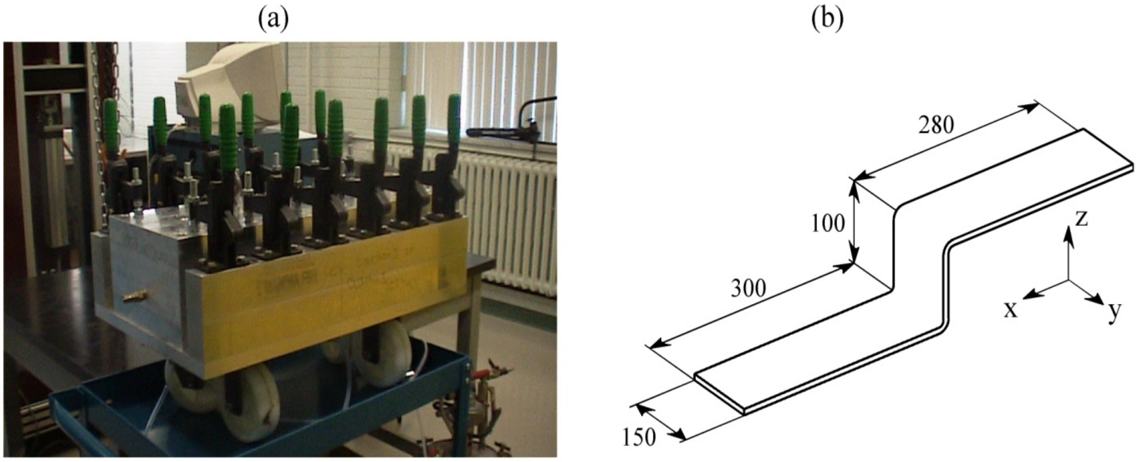
(a)
(b)

Fig. 2 Implementation of Flexible Injection in curved parts: (a) experimental mold; (b) geometry of the part (dimensions are given in mm)

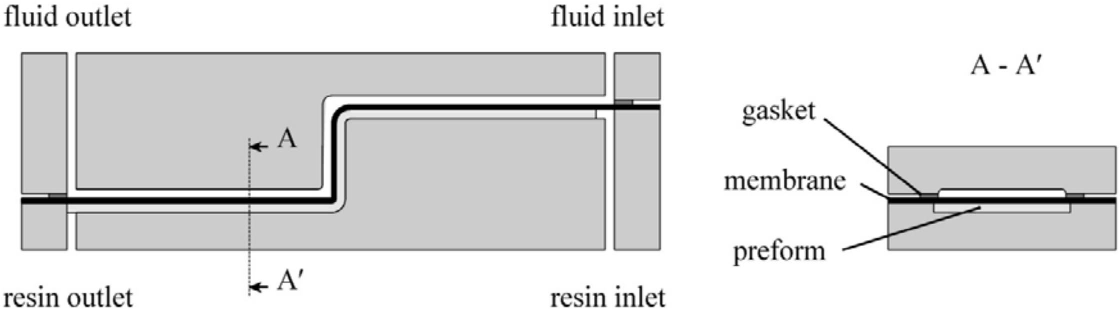

Fig. 3 Schematic view of the mold configuration

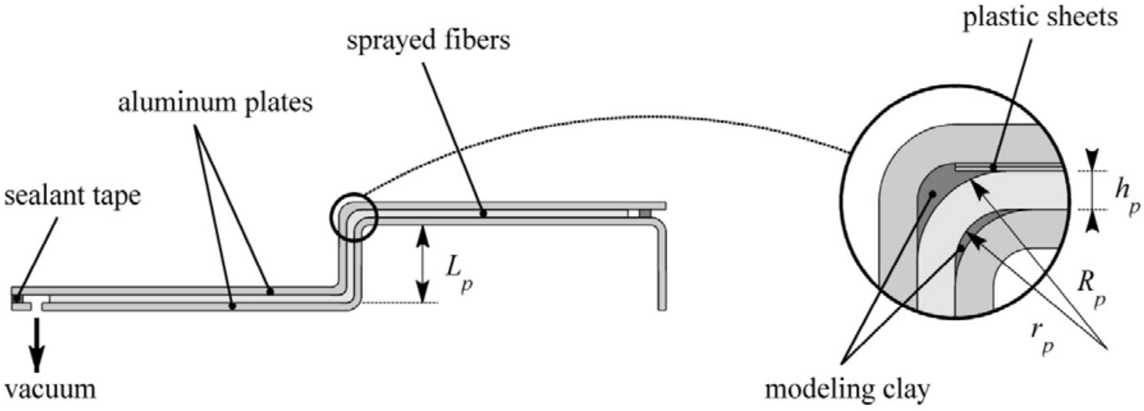

Fig. 4 Preforming procedure

The procedure described above was used to prepare large preforms (650 mm wide) with 4 plies of fabric. A typical large preform is shown in Fig. 5a after demolding. These preforms were fairly rigid and easy to manipulate. Each preform was subsequently cut into smaller samples having the dimensions of the final part (see Fig. 5b).

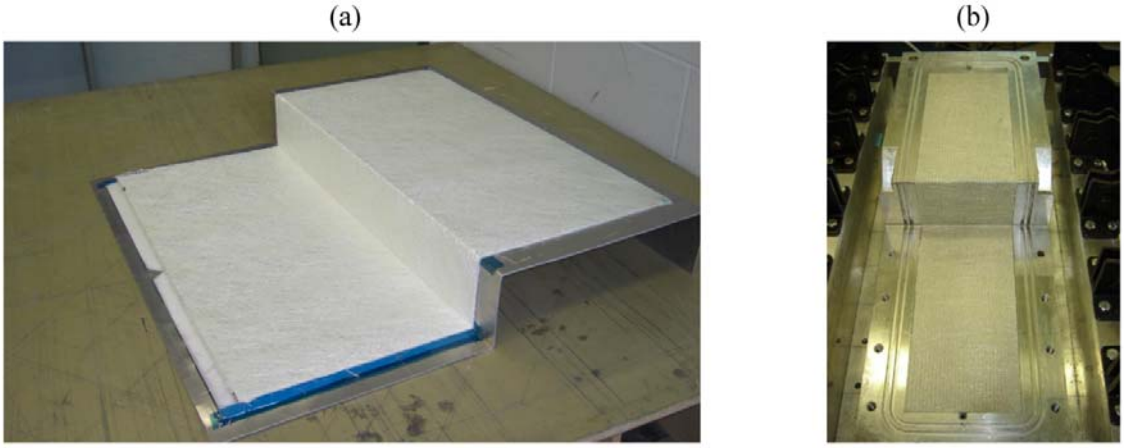

Fig. 5 Preparation of the fiber bed: (a) demolding of a large perform;
(b) small preform cut to the required dimensions and laid into the bottom mold.

Manufacturing Procedure

Firstly, the components of the thermoset system were manually mixed and the compound was degassed during 15 minutes under vacuum. After closing the mold, the maximum vacuum achievable with our vacuum pump (absolute pressure around 5 kPa) was drawn in both cavities. Resin was injected with a pneumatic gun SEMCO model 250-A. By calculating the resin losses in the tubing, this device allows controlling the injected quantity of resin with an accuracy of ± 3 g. The pressure of the compaction fluid, silicone oil from DOW CORNING 200 of viscosity of 100 cSt at 25ºC, was controlled with a pressure tank. The parts were cured overnight under the same constant compaction pressure. All the experiments were carried out at room temperature (between 20.5ºC and 22ºC) with an injection pressure p_i = 2 bars and a compaction pressure p_c = 6 bars.

PART ANALYSIS

After demolding, the central region of each part was cut into three samples having an approximate width of 35.5 mm following the pattern of Fig.6a. The surfaces of the cut specimens were polished with waterproof aluminum oxide sandpaper with increasing grit from 220 to 1200. A scanner CANON CanoScan was used to obtain images of these six longitudinal cross-sections. Two types of images were taken: images of the whole cross section with a resolution of 1200 dpi and images of the two corner areas with a resolution of 4800 dpi (see Fig. 6b). In order to increase the contrast between the part and the background, the samples were placed on an adhesive tape and a white paint was brushed onto the surface of the tape. Image analysis was subsequently performed with MATLAB. By comparing luminosity levels, the program automatically detects the pixels located on the edges of the part and generates the complete thickness profile of the cross-section treated.

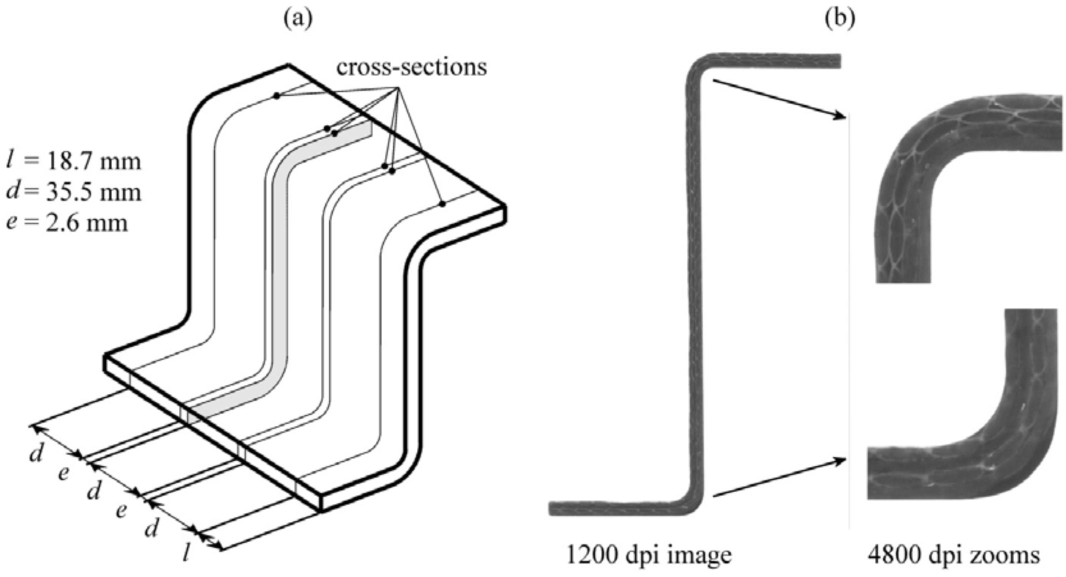

Fig. 6 Sample preparation for image analysis: (a) cutting pattern;
(b) typical scanned images of the convex (above) and concave (below) corners

EXPERIMENTAL RESULTS

Results will be shown here only in the concave corner. The radii of the preforming tool were set to 5 mm for the outer radius and 2 mm for the inner radius. This configuration matches the geometry of the manufacturing mold on the rigid tool side and creates a preforming thickness almost constant. These parameters were used for the preparation of preforms. Visual inspection of the 4 first parts manufactured with medium fiber volume fraction indicates the presence of an important defect in the curved region. As shown in Fig. 7, the fibers tend to bridge over the corner and a resin accumulation is created between the bottom mold and the preform.

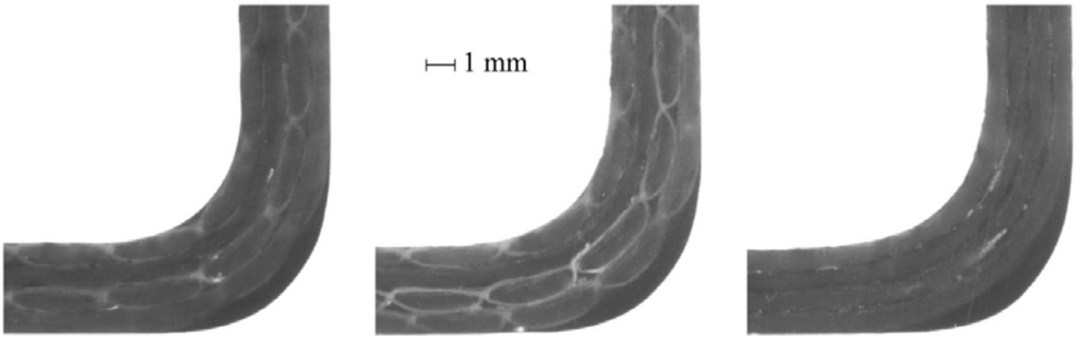

Fig. 7 Images of the concave corner obtained for medium compaction level with the initial preforming geometry

Increasing the targeted fiber volume fraction barely changes the size of the resin-rich region as seen in Fig. 8. Even at the highest compaction level, the stress applied on the preform is not sufficient to push the preform against the bottom mold because stiff fibers resist deformation in the curved region. Fig. 8 shows also that a second type of manufacturing default appears at low fiber volume fraction. Since the membrane is cut out from a planar sheet, it does not bend easily in the curved region. At low fiber volume faction, the stress applied on the membrane is not sufficient to stretch it correctly and a resin-rich zone is created also between the preform and the membrane. This phenomenon disappears when the fiber volume fraction increases, because the membrane is flexible enough to be pushed against the fibers. However, the use of a membrane possessing the same geometry as the part to be produced would certainly improve the efficiency of the process. Developing such 3D membranes represents a key step in future applications.

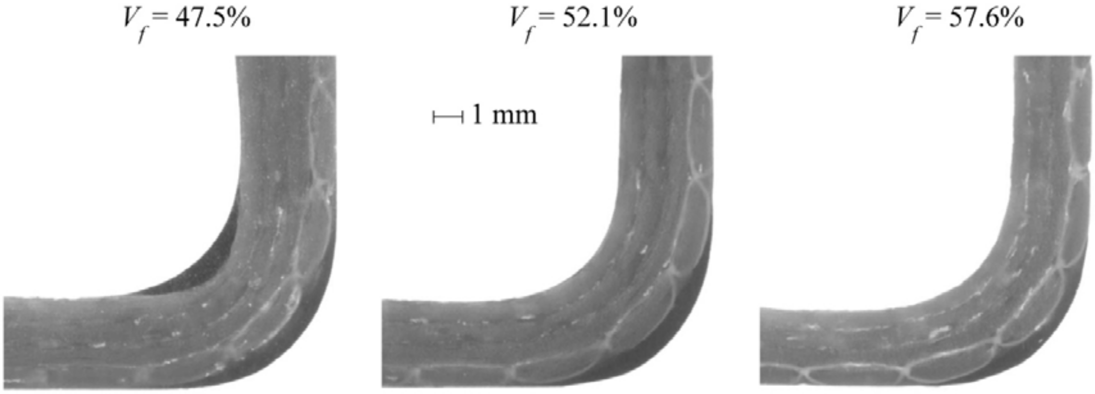

Fig. 8 Influence of the targeted fiber volume fraction on the consolidation in the concave corner with the initial preforming geometry

Additional preforms were prepared with a modified preforming tool with a sharper corner region. The inner radius was 1 mm and the outer radius 4 mm so that the thickness of the preforming cavity remains constant. As seen in Fig. 9, the size of the resin rich zone between the fibers and the bottom mold is significantly reduced with the adapted preforming geometry. The fiber volume fraction has little effect on the resin accumulation, because fiber bridging in the corner inhibits the consolidation of the preform. At low compaction levels, fiber bridging is still present and creates a resin accumulation between the membrane and the preform. As observed also in the convex corrner, this effect disappears when the fiber volume content increases.

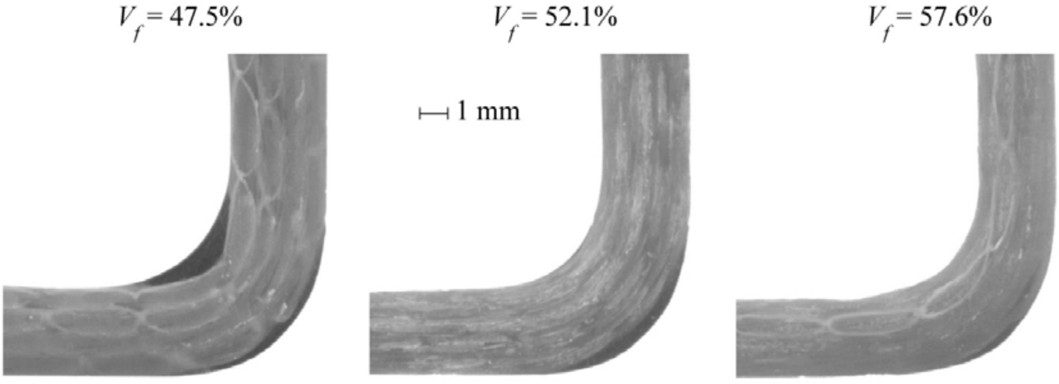

Fig. 9 Images of the concave corner obtained with the modified preforming geometry

CONCLUSION

Flexible Injection is a promising new technology for fast manufacturing of complex composite structures. In the present paper, this approach was adapted to manufacture strongly curved parts. A series of stair-shaped components made of glass fiber and vinyl ester resin have been produced with a specially designed experimental setup. Longitudinal cross-sections of the fabricated parts have been analyzed visually and by image analysis to assess the efficiency of this new manufacturing technique for strongly curved parts. The following conclusions can be drawn:

- Flexible injection provides a uniform consolidation of the flat sections along any direction. In particular, the technology can efficiently process parts having straight sections parallel to the mold closing axis.
- Curved regions are prone to create manufacturing defaults such as resin rich zones or thickness gradients. This specificity comes from the presence of stiff fibers along the curved profile that change the compaction behavior of the fiber bed. The consolidation of the preform depends also strongly on the nature of the rigid tool used for preforming (convex or concave).
- Low compaction level tends to create resin accumulations.
- Preform and membrane dimensional accuracy are key factors to prevent the creation of resin rich zones.
- The preforming stage has a direct influence on the lay-up quality in the corners of the part. An adapted preforming strategy can reduce thickness variations and limit resin accumulations.

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