Utilizing Fused Deposition Modeling Techniques in Composite Processing

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Abstract. In this paper a novel method to apply binder onto fabrics is introduced. Therefore, 3D-Printing technology namely Fused Deposition Modeling (FDM) is used to apply a thin melt strand onto a textile. The FDM technology uses an extruder which conveys a thermoplastic filament into a hollow cylinder. At the end of this cylinder a heated nozzle is situated. This so called Hot End delivers the melt strand on the textiles surface in predefined patterns. Those textile sheets are then stacked, preheated and compacted to a preform. Subsequently the preforms are infiltrated to investigate filling behavior. Therefore this study utilized a fully automated optical permeameter. Selected results for proof of principal are presented in this paper.

INTRODUCTION

In composite manufacturing liquid composite molding processes are of great use producing both simple and complex shaped structural and nonstructural fiber reinforced parts (FRPs). Therefore a large number of different fabrics are in use. The process chain of resin transfer molding manufactured parts involves several subsequent steps: 1) preforming, 2) infusion, 3) resin cure, 4) cured part [1]. Depending on the type of fabric as well as the part size handling difficulties can occur due to the fragile handling behavior when draping intricate fiber architectures over multi-directional faces in a mold. For instance, fraying is a common defect observed when using dry plain-weave fabrics in RTM. To address these problems binder materials were introduced in the past. Those materials are equipped with a tackifier also called binder at one side of the fabric's surface. Tackifiers are usually activated through heat and consist of either thermoplastic resin or uncatalyzed epoxy resins. Generally they are produced in solvent-based liquid form or in dry powder form applied utilizing spread technologies with a sieve type apparatus, by electrostatic spaying, or by film extruding of flat sheets. When trimming, handling or during impregnation operations the tackifier protects the reinforcements integrity [2].

Nevertheless other effects were observed as well, such as higher flow resistance, higher porosity in the cured laminate and lower spring back. For example Rohatgi and Lee [3] showed in their results that a higher degree of cure of the tackifier results in better preform dimension control. Moreover, if the tackifier was dissolved before application an even better spring back control was achieved. As reported by Shih and Lee [4] a major aspect lies within the tackifier's position in the preform, e.g. remains the tackifier on the fabric's surface without major diffusion into the fabric's tows, higher injection pressures are necessary filling the mold. In contrary lower intra-laminar porosity in the final part as well as higher inter-laminar shear strength (ILSS) in the preform were obtained.

In the present paper, a new approach for different use of tackifier is shown. Particularly, tackifier is used to alter the fabric's permeability behavior to establish a flow front advancement according to the needs for complete cavity filling.

EXPERIMENTAL

To achieve custom permeability behavior a process chain for RTM was realized. Instead of finalizing the chain with RTM permeability measurements were carried out. Therefore explicit steps were taken, namely: 1) cutting fabrics, 2) applying tackifier, 3) stacking, 4) hot pressing, 5) permeability measurements. Figure 1 shows a composition of the mentioned steps.

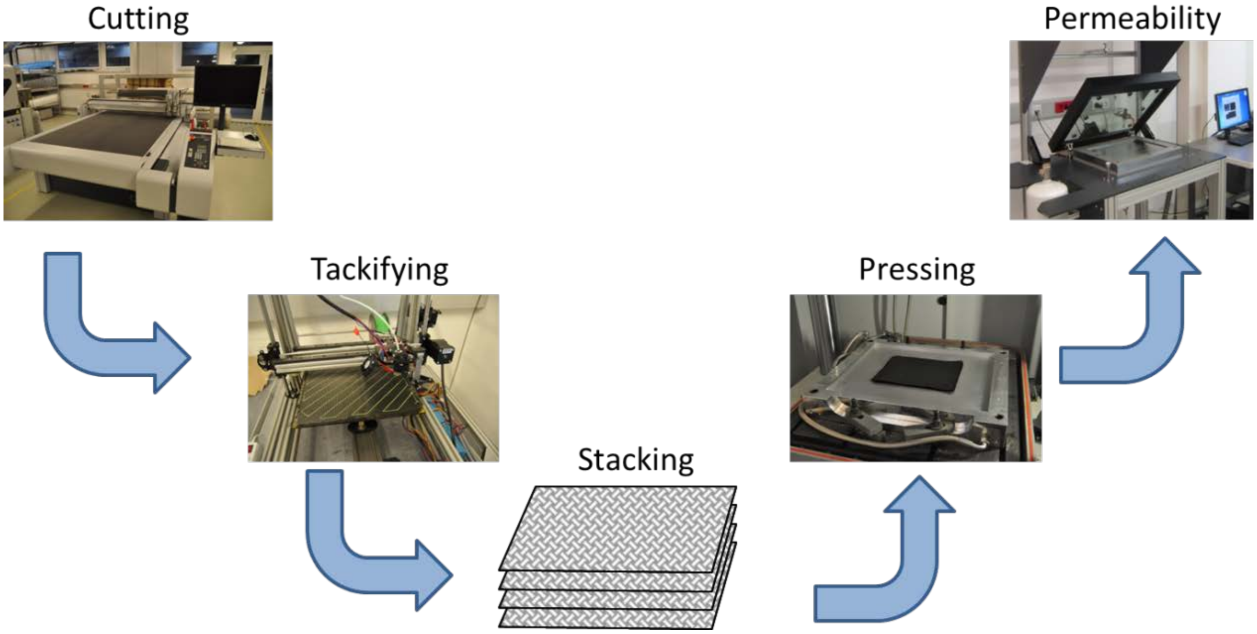


FIGURE 1. A composition of process steps to accomplish permeability measurements.

Used material for the test series was a plain-weave fabric SIGRATEX KDL 8049/120 of an aerial weight of 240g/m² consisting of wrap and weft tows of 200tex. The plain-weave fabric has an approximate thickness of 0.3mm in an uncompressed state. It was cut into patches of 350mm by 320mm with a bevel at one corner to identify the fabric's orientation. For tackifying Polylactic acid (PLA) was used since it is a standard 3D-Printing material that shows high tackiness when melted. The filament diameter was 1.75mm at a density of 1.25g/cm³ and a processing temperature of 190°C to 220°C.

Tackification station

For fabric tackification a customized version of a MendelMax 3D-Printer was used. It utilizes steppers for positioning in all three axes and another one for filament transportation. At the end effector a hot end nozzle is placed which delivers tackifier material to the desired location. To realize printer's movement standard CNC-machine G-code was generated. Through this code movement of all three spatial axes, extrusion of PLA and nozzle temperature as well as the temperature of the printer's heat bed were controlled. In order to alter the fabric's original permeability PLA used as tackifier was applied in predefined patterns.

Three different patterns where applied as shown in Fig. 2. Patterns of 0°, 90° and 45° were realized at a constant volume flow of 0.172mm of filament per millimeter of nozzle movement. That equals a mass of 1.916g of PLA for the 0°-tackification in total and a tackifier content of 10.08% by weight considering bridge connections between the linear paths are also taken into account. For the 90°-Tackification the weight of applied binder was 1.857g and percentage wise content slightly dropped to 9.77% due to the geometrical changes. The 45°-Tackification shows varying lengths and a binder weight slightly higher compared to the 0°-Tackification. The weight was 1.950g per layer correlating with 10.26% by weight.

FIGURE 2. Three tackifier patterns prepared for stacking and preforming.

The common geometric characteristic of all three tackification types lies within the distance of the binder lines. These are placed in an equidistant way of 20mm. Furthermore, each Tackification pattern has an additional version in which the binder lines show an offset of 10mm in parallel to the original pattern.

Preforming

To produce sufficient preforms different stacks were laid up. For one, dry fabrics were stacked into packs of 8, 9 or 10 layers. For another, tackified fabrics were staked in the same way. Further, each stack of tackified fabrics consisted of the original pattern and the pattern at an offset of 10mm. These fabrics were stacked sequentially to avoid binder agglomerates inside the fabrics at the distinct binder lines. Table 1 shows the number of specimens for each configuration equally divided between the stacks.

As one can notice from Table 1 the binder content slightly changes for each preform type. The reason for this results from the fact that each preform consist of one layer of dry fabric on top. This kind of stacking sequence was chosen so no binder is lost during the preforming stage.

Table 1. List of produced preform types based on different stacking and Tackification patterns.

Tackification	Layers	Binder content in % by weight
Dry	8,9,10	0, 0, 0
0°	8,9,10	8.82, 8.96, 9.07
90°	8,9,10	8.55, 8.69, 8.80
45°	8,9,10	8.99, 9.12, 9.24
Multistack	8,9	7.53, 6.69

For the actual preforming process a Wickert WKP 3500 hot forming press was used with an aluminum plate mold for forming. The temperature for processing was adjusted to 180°C, so actually below the recommended processing temperature range of 190-220°C for 3D-Printing. The reason for this decision was avoiding excessive polymer flow through thickness and consequently sealing intra-laminar flow. Pressing time was 60s in force controlled mode at 80kN. Afterwards the hot preform was removed from the mold and cooled down to room temperature.

Permeability measurements

The experiments were carried out on a fully automated optical 2D-Permeameter capable of determining the in plane permeability. It consists of a lower mold half made of steel and an upper mold half made of a composite glass plate, reinforced through a steel frame on top of it to limit deformation. Moreover light shields are installed to prevent optical reflections causing systematical errors during measurements. By using additional steel frames cavity height can be adjusted according to the available frames and their combinations. The pressure system is capable of a maximum injection pressure up to six bar. The composite glass with its reinforcing steel frame can withstand a compaction pressure up to five bar which correlates to a fiber volume content of 63% [5].

Subsequent for adjusting the cavity height the preform is placed in the permeameter and the upper mold half is closed utilizing pneumatic compact cylinders underneath the permeameter. Then the steel frame is placed on the composite glass and screwed to the lower mold half. Afterwards the live measurement can be started.

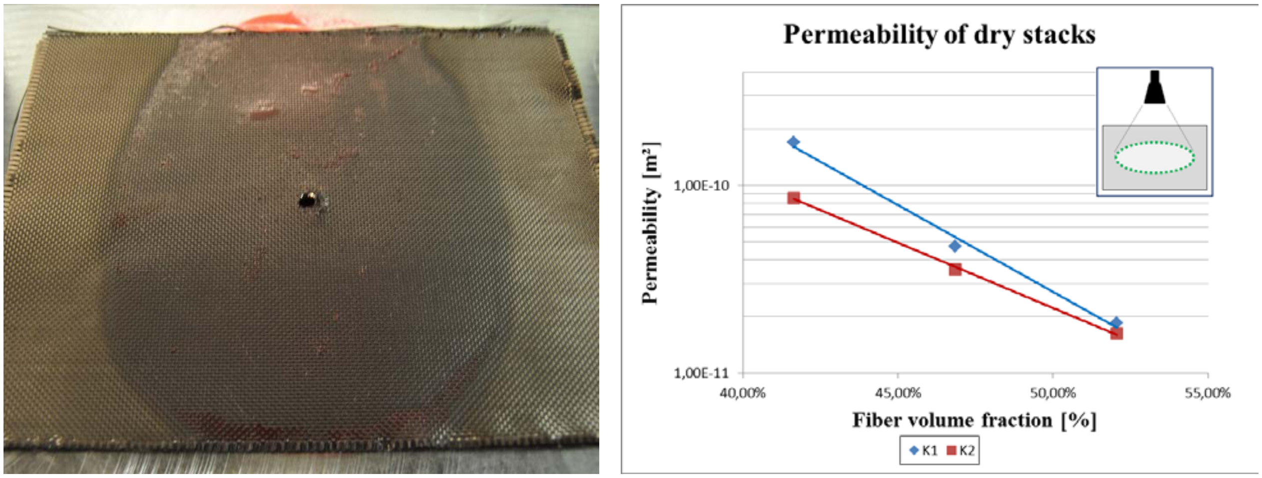
$$v_x = \frac{K_x}{\eta} \frac{\Delta P}{\Delta x} \tag{1}$$

Darcy's law for one dimensional flow through porous media forms the basis to accomplish this goal, where v_0 is the superficial velocity (m/s), K is the permeability (m²), η is the fluid viscosity (Pa s), ΔP is the imposed pressure difference (Pa) and Δx is the flow length in (m). A more detailed formulation for the two dimensional flow is described by Adams and Rebenfeld as well [6, 7].

For the measurements rapeseed oil was used as a Newtonian fluid of a known, temperature-dependent viscosity. The injection pressure was 1.5bar and the corrected cavity height was 2.59mm. The original cavity height was 2.5mm but 90µm have to be added due to the reacting compaction force and the resulting cavity deformation. The fiber volume content of the dry fabric stacks in the cavity was 41, 46 and 52%. The fiber volume content for the tackified preforms are not displayed since it differs locally due to the distinct binder lines.

RESULTS

In a first step the dry stacks were measured as a reference for the following bindered preforms. Due to the fabric's orthotropic flow behavior a characteristic ellipse was visible as one can see in Fig. 3. The major axis of the ellipse is described by K1 and the minor axis by K2. All following pictures shown in the study were taken after removing the reinforcing steel frame why dry spots on the pictures are visible.



(a) (b)

FIGURE 3. A compilation showing the characteristic ellipse of orthotropic flow behavior in (a) and the according permeability curves showing K1 and K2 in (b). Dry fabric stacks were used at 8, 9 and 10 layers.

It is noticeable when comparing Fig. 3 and Fig. 4 that the flow advancement behavior is fundamentally different. In Fig. 4 (a) the flow front behavior seems to be almost isotropic (in plane). This results from the fact that the 0°-tackifiaction of the preform in Fig. 4 (a) acts as a flow barrier in direction of K1. Therefore the measurement liquid is hindered and the ratio of K1 to K2 adjusts. This "isotropic" behavior of course would not advance indefinite. If the preform was larger and the same tackification style was applied, an ellipse would form showing opposite orientation to Fig. 3 (a). Also the overall shape is not very homogenous and race tracking effects are visible. This results from the locally high binder content and the location of the binder in the intra- and inter-layers caused by the preforming step when hot form pressing. Figure 4 (b) displays the possibility to even rotate the ellipse.

In this case the binder not only acts as a flow barrier it also acts as a deflection. It is noticeable that the race tracking effect minimizes in this case and the overall shape becomes more homogenous.

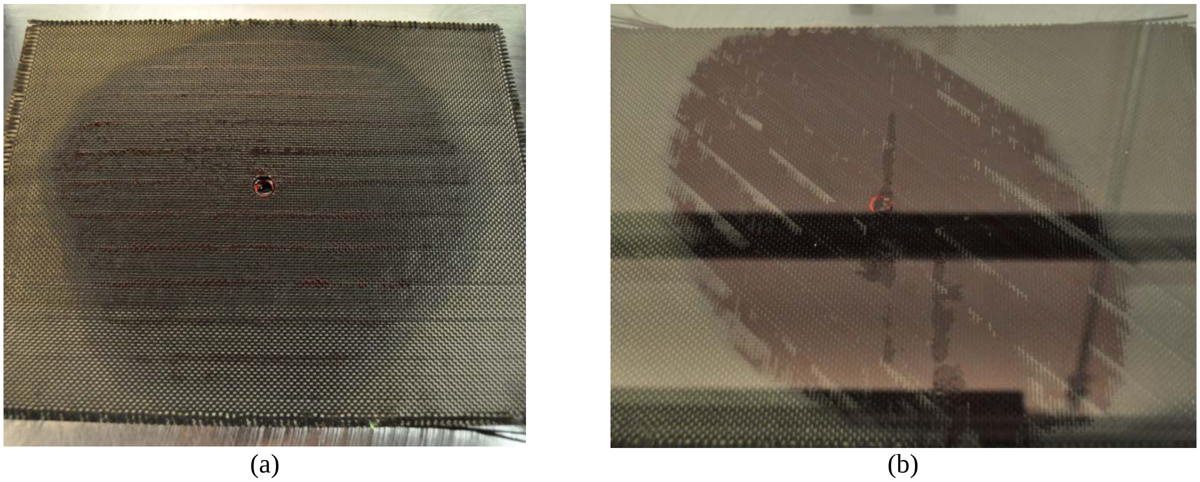

(a) (b)

FIGURE 4. Pictures showing a 0°-tackified preform after testing in (a) and a 45°-tackified preform after testing in (b) both consisting of 8 layers.

CONCLUSIONS

It can be concluded that there is a need for further investigations on this tackification method. None the less the potential is enormous if one thinks about future applications. For instance if a mold is already manufactured and shows dry spots in the final parts that cannot be eliminated conventionally this tackification method could be of great use. It would be also possible to adjust the preforming step in a way so the binder lines stay within the inter- layer location and flow channels are formed for faster impregnation.

This study can be seen as a proof of concept and although it showed an overall permeability drop compared to dry fabrics further studies could point out its usefulness.

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