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Research Article

Influence of process pressures on filling behavior of tubular fabrics in bladder-assisted resin transfer molding

Christian Schillfahrt *, Ewald Fauster and Ralf Schledjewski

Processing of Composites Group, Department of Polymer Engineering and Science, Montanuniversität Leoben, Leoben, Austria

Abstract
Among the family of liquid composite molding techniques, bladder-assisted resin transfer molding (BARTM) enables efficient manufacturing of hollow composite parts based on tubular reinforcing textiles. However, resin injection under certain processing conditions can result in high filling times or improper parts and finding the optimal process parameters is often a difficult task. This paper studies the impregnation behavior of a biaxial braided fabric in pressure-driven BARTM under a wide range of injection and bladder pressures. Saturation experiments were accomplished by means of a specifically developed injection test rig comprising an under-sized elastomeric bladder and a monolithic transparent mold. The results obtained show significant influence of the relevant process parameters on local preform compaction, apparent global permeability and filling time. Based on the experiments, a universal moldability diagram was derived that enables identification of admissible and critical operating conditions in BARTM, which supports the finding of optimal part filling settings.

Keywords
Resin transfer molding, bladder inflation molding, braided fabrics, preform permeability, process monitoring, saturation behavior, injection pressure, compaction pressure

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Introduction
The utilization of liquid composite molding (LCM) processes and, in particular, resin transfer molding methods is increasingly gaining importance in modern composite industries. In contrast to traditional manufacturing techniques such as prepreg processing, they use dry preforms of reinforcing textiles which are impregnated with a viscous polymer matrix material in a closed-mold process.1 Bladder-assisted resin transfer molding (BARTM) terms a process variant particularly suited for the fabrication of hollow, complex shaped parts such as tube-like composite components.1–4 A schematic representation of the process chain is shown in Figure 1. A distinctive feature of the BARTM technique is the application of a flexible bladder, which acts as an internal tool part that can be inflated by compressed air or pressurized water. Choosing the right bladder usually is a difficult task, as different types and materials can be applied, ranging from thermoplastic films to elastomeric membranes that are either removable, reusable or remain in the part as a lost (and possibly functional) layer.4,5 With regard to dimensional aspects, common bladders have near-net shape or are under-sized, i.e. they need to be radially expanded based on an elastic or plastic material deformation in order to fully conform to the internal part geometry, which can prevent fiber pinching between the mold halves. While under-sized elastomeric bladders can easily be demolded and reused in the process, the occurrence of membrane stresses during the elastic expansion and their effect on preform compaction should be considered.6 In BARTM, tubular braided fabrics are typically used as continuous fiber reinforcements for highly loaded structural parts.5 Preform assembly can be realized by means of manual sleeving-on layup6,7 or through automated over-braiding,8,9 where the bladder can directly act as a braiding mandrel. The preform is inserted into the cavity of a two-part mold and compacted by applying a specific pressure to the inflatable bladder. In the subsequent impregnation
behavior and part quality. Ruiz and Achim proposed the effect of injection process parameters on impregnation in conventional resin transfer molding, many authors have studied as to minimize production rejects. With regard to component quality, reduce process development and setup time as processing window is desirable in order to increase compo-
time-consuming trial and error. Thus, prior knowledge of a state, which, in industrial practice, is still frequently done by temperature have to be adjusted to an optimum and robust vant process parameters such as injection pressure and mold temperatures to allow for a basic identification of critical and optimum processing conditions. However, the diagram was constructed based on theoretical models only and without the use of experimental data. Other works investigated the influence of resin flow velocity on the formation of process-induced voids in dual-scale porous media such as woven

table, the liquid (and mostly thermosetting) resin is typically introduced into the cavity through pressure-controlled injection. When the part is filled, the resin gate is closed and the bladder pressure is kept at a constant level in order to maintain laminate consolidation until the component is fully cured and can be demolded.

The injection stage is a crucial part in any LCM process and is influenced by various material and process parameters as well as system constraints, as summarized in Table 1. In general, a sufficient and homogenous saturation of the preform has to be ensured, which strongly affects mechanical properties of the final part. Another decisive factor is filling time, which substantially influences process cycle time and hence production costs, in particular for large parts showing long flow lengths, but also manufacturability, if fast curing resins are used. For given materials and processing system, the relevant process parameters such as injection pressure and mold temperature have to be adjusted to an optimum and robust state, which, in industrial practice, is still frequently done by time-consuming trial and error. Thus, prior knowledge of a processing window is desirable in order to increase component quality, reduce process development and setup time as well as to minimize production rejects. With regard to conventional resin transfer molding, many authors have studied the effect of injection process parameters on impregnation behavior and part quality. Ruiz and Achim proposed a moldability diagram considering injection pressures and mold temperatures to allow for a basic identification of critical and optimum processing conditions. However, the diagram was constructed based on theoretical models only and without the use of experimental data. Other works investigated the influence of resin flow velocity on the formation of process-induced voids in dual-scale porous media such as woven reinforcement materials. Acheson et al. studied the implications of preform compaction on saturation behavior and filling times in vacuum-assisted resin transfer molding (VARTM, also known as resin infusion under flexible tooling (RIFT)). They accounted for the complex effects of fiber compressibility in combination with the use of a flexible mold part, which were also studied by many other authors. The influence of process parameters in BARTM, however, is addressed in only a few works. Lehmann and Michaeli investigated the effect of bladder and injection pressures on the filling behavior of several fabrics by means of saturation experiments. Although only a few tests were conducted, they generally concluded that a difference between bladder and injection pressure should be in a magnitude of 1–2 bar. Furthermore, they stated that the internal bladder pressure has to exceed the injection pressure in order to prevent the internal bladder from collapsing, which was also reported by Fong et al.

In order to study the effect of material and injection process parameters on the impregnation behavior of textile fabrics, the application of permeameter test rigs is widely used. They enable reproducible saturation experiments under controlled test conditions and can be used to determine the textile permeability of a reinforcement material, which represents an important input parameter in flow simulations. A vast amount of different approaches and test configurations can be found in literature, but the majority concentrates on in-plane impregnation experiments of predominantly flat preforms in unsaturated conditions. They are typically based on measuring the timely flow front advancement during a pressure-driven injection through optical measurement methods or capacitive sensors. In contrast to conventional test configurations, Lehmann developed a transparent BARTM test rig for investigating the filling behavior of different tubular-shaped fabrics.

| Material parameters | Process parameters | System constraints |
|---------------------|-------------------|--------------------|
| • Preform dimensions | • Injection pressure (usually constant) | • Maximum injection pressure of the injection system |
| • Preform compaction behavior (generally different time-dependent behavior in dry and wet conditions) | • Pressure at vent (usually constant) | • Maximum closing force of the clamping system |
| • Preform permeability (usually as a function of fiber volume content) | • Preform compaction pressure (can be adjustable but usually results from cavity height, preform thickness and compaction behavior) | • Maximum resin temperature of the injection system |
| • Resin viscosity (in general as a function of temperature and time) | • Mold temperature | • Maximum mold temperature of tooling material and heating system |
| • Resin gelation characteristics | • Preform temperature (may be assumed to be equal to mold temperature) | • Mold dimensions and positions of injection and venting gates |
| • Thermal stability of the resin | • Resin temperature | • Flow lengths (depending on mold dimensions and positions of injection gates) |

**Figure 1** BARTM process chain

**Table 1** Relevant parameters and constraints regarding the injection stage of a conventional pressure-controlled RTM process (not exhaustive)
However, the system was limited to rather low process pressures to avoid deformation of the two-part mold and experimental studies only focused on plastically expandable and thus disposable tubular bladders. In recent works published by the authors,\textsuperscript{20,34} an advanced concept of an automated BARTM process permeameter comprising a monolithic mold and a reusable elastomeric bladder was implemented to allow for an accurate characterization of the saturation behavior of tubular braided reinforcing textiles.

Based on the aforementioned works, the objective of this study is to investigate the impregnation behavior of an exemplary selected biaxial braided fabric in BARTM under isothermal conditions by varying two process parameters: injection and bladder pressure, respectively. By considering the influence of an elastically expanded bladder, their interdependent impact on local compaction pressures during saturation measurements as well as on preform permeability and filling times will be evaluated for a variety of different process settings. The measurement data will subsequently be used to derive a universal process window for the injection stage of a BARTM process considering critical operating conditions and relevant system constraints. As a result, optimum process settings can be identified which enable short filling times while facilitating the implementation of an efficient manufacturing process.

### Theoretical background

#### Preform saturation

The governing equation of single phase steady-state flow in a porous medium can be expressed by Darcy’s law,\textsuperscript{35} which relates fluid flow to a driving pressure gradient:

\begin{equation}
    u = -\frac{K}{\eta} \nabla p,
\end{equation}

where \( u \) denotes the volume averaged flow velocity, \( K \) terms the permeability tensor of the porous structure, \( \eta \) represents the dynamic viscosity of the impregnating fluid and \( \nabla p \) is the pressure gradient. Equation (1) considers the anisotropic nature of most textile reinforcing materials and can also be written in expanded form as:

\begin{equation}
    \begin{pmatrix}
        u_x \\
        u_y \\
        u_z
    \end{pmatrix} = -\frac{1}{\eta} \begin{pmatrix}
        k_{xx} & k_{xy} & k_{xz} \\
        k_{yx} & k_{yy} & k_{yz} \\
        k_{zx} & k_{zy} & k_{zz}
    \end{pmatrix} \begin{pmatrix}
        \vec{\nabla} p
    \end{pmatrix}.
\end{equation}

Although the above equations do not cover the complex flow phenomena in dual-scale porous media, i.e. materials containing two different scales of pores such as typical woven or braided fabrics, they are still widely accepted as a simplified approach for evaluating the unsaturated permeability of these reinforcing textiles.\textsuperscript{20,34,37} In this case, the coexistence of micro and macro flow and the effect of delayed tow impregnation is ignored at the benefit of reduced characterization and calculation effort.

In-plane dimensions of composite parts are typically several orders of magnitude higher than the thickness of the part. Implying rather homogeneous laminate layup, permeability values of individual preform layers are fairly consistent throughout the part. Thus, fluid flow can be assumed to be dominated by in-plane permeability characteristics. Furthermore, as biaxial braided fabrics with axisymmetric textile architecture show unidirectional flow behavior along their longitudinal axis,\textsuperscript{4,34,35} it is assumed that the principal permeability values conform with the major axes of a tubular-like part. Provided that the impregnating fluid is evenly introduced across the preform’s circumference at the injection port and considering the porosity \( \phi \) of the fibrous structure, one-dimensional resin flow in the part can be expressed as

\begin{equation}
    v_x = -\frac{k_x}{\eta \phi} \frac{\partial p}{\partial x}, \quad (3)
\end{equation}

where \( v_x \) represents the actual flow velocity through the pores while \( k_x \) and \( \partial p/\partial x \) term the principal permeability and pressure gradient along the longitudinal axis of the preform, respectively. Axial permeability \( k_x \) can be simply determined by means of 1D saturation experiments.

In order to describe 1D resin flow in BARTM, which is technologically similar to VARTM with a flexible bagging film, the one-dimensional fluid pressure field has to be solved by taking into account the compliance of the preform. This in turn permits to incorporate variations in preform permeability and compaction pressure along the flow length.\textsuperscript{3,20,24} However, as this is a mathematically complex and time-consuming task, an alternative approach is followed in this work. By introducing an effective permeability

\begin{equation}
    k_{\text{eff}} = \frac{k}{\phi}, \quad (4)
\end{equation}

and using an apparent global permeability \( k_{g\text{eff}} \) instead, the 1D saturation behavior of a BARTM process can be described similar to its conventional analog with rigid molds\textsuperscript{19,20,34,39} as:

\begin{equation}
    v_x = \frac{k_{g\text{eff}}}{\eta} \frac{\Delta p}{x_f}, \quad (5)
\end{equation}

As the relative injection \( \rho \) and vent pressure \( p_v \) is usually constant in pressure-controlled injection processes, the partial derivative was transformed into a finite pressure difference \( \Delta p \) describing the pressure drop between the injection gate and the actual flow front position \( x_f \) as shown in Figure 2.

It has to be noted that the apparent global permeability represents an abstract material parameter in a flexible mold process, which depends on the preform compaction behavior and the applied compaction pressure field, unlike permeability in Equations (1)–(3), which is a purely intrinsic parameter of the porous structure.\textsuperscript{20,34,39} While for theoretically incompressible porous structures both permeability values are equal, a preform showing significant compliance yields higher apparent permeability values. This in turn leads to faster filling of the part at the expense of an emerging laminate thickness gradient (Figure 3).\textsuperscript{20} The filling time can be obtained through integration of Equation (5) and is expressed for a BARTM process run at atmospheric pressure (i.e. \( p_v = 0 \)) by:

\begin{equation}
    t = \frac{x_f^2 \eta}{2 k_{g\text{eff}} P_l}, \quad \text{(6)}
\end{equation}

In conclusion, for a part with given flow length and resin viscosity, filling times are inversely proportional to the product of the apparent permeability and the injection pressure.
In this work, experimental determination of the apparent global permeability is based on recorded temporal flow front positions, which were obtained from saturation measurements under a specific constant injection pressure using a fluid with known viscosity. According to the squared flow front method, an evaluation scheme widely used in literature, an Equation (6) can be rewritten as:

\[ \tilde{k}_{x,\text{eff}} = \frac{x^2 \eta}{2p_{r,t}} = \frac{m m}{2p_{r}} \]  

where \( m \) denotes the slope calculated by linear regression from the squared flow front positions at the corresponding timestamp values.

**Preform compaction**

In this subsection the basic relationships for describing preform compression during the initial dry compaction and the subsequent injection stage are given by considering a tubular BARTM setup and the utilization of an under-sized elastomeric bladder with purely elastic expansion behavior. The compaction stage starts with a pressure-induced radial expansion of the internal bladder (Figure 4(a)). The outer preform can be either pre-expanded to the diameter of the outer mold or follows the radial expansion of the bladder. In the latter case, it is assumed that bladder expansion is not hindered by the tubular reinforcing textile, which is especially valid for biaxial braided fabrics that show rather low braid angles. When the internal bladder pressure \( p_{b} \) exceeds a specific minimum bladder pressure \( p_{b,\text{min}} \) for full radial expansion, the dry preform is compacted between the inflated bladder and the outer mold given by:

\[ p_{c} = p_{b} - p_{b,\text{min}} \quad \text{for} \quad p_{b} > p_{b,\text{min}}, \quad \text{while} \]  

\[ p_{c} = 0 \quad \text{for} \quad p_{b} \leq p_{b,\text{min}}, \]  

where \( p_{c} \) represents the preform compaction pressure that is constant along the longitudinal axis of the tubular part (Figure 4(b)). Here, the pressure parameter \( p_{b,\text{min}} \) expresses the membrane stiffness of the elastomeric bladder and depends on its mechanical material properties as well as on the dimensions of bladder, preform and mold. For preforms with rather small absolute changes in thickness, it can be assumed to be constant. A procedure for a model-based determination of this parameter is given in Ref. 6.

As mentioned before, the non-linear fluid pressure field during resin injection causes variable preform compaction along the flow length that decreases towards the injection point, as the bladder pressure gets counterbalanced by the opposing local fluid pressure. The two relevant boundary conditions can be described by:

\[ p_{c,i} = p_{b} - p_{b,\text{min}} - p_{i}, \quad \text{and} \]  

\[ p_{c,f} = p_{b} - p_{b,\text{min}} - p_{f}, \]  

where \( p_{c,i} \) and \( p_{c,f} \) correspond to the locally acting compaction pressures at the injection gate and flow front, respectively. The latter is constant in the unsaturated preform region between the resin flow front and the venting position.

A minimum level of preform compaction is required during BARTM in order to avoid unwanted effects such as...
Experimental work

Test rig

Experimental investigation of the filling behavior of braided fabrics in pressure-controlled BARTM is accomplished by means of a specifically developed injection test rig, which is shown in Figure 5. The so-called optical 1D tube permeameter enables the realization of highly repeatable saturation measurements at different fluid and bladder pressures and further allows for an evaluation of the apparent global permeability of a tubular reinforcing textile as reported by the authors.\textsuperscript{33,34} In contrast to conventional BARTM processing, red-colored corn oil is used as a substitutional impregnation liquid in order to avoid unwanted curing of the matrix material during injection. Furthermore, this significantly reduces flow-induced fiber displacement\textsuperscript{41,42} or to reduce laminate thickness evolution,\textsuperscript{4} which is most critical near the injection gate (Figure 4(c)). Thus, the following condition has to be fulfilled throughout the injection process:

\[ p_{b} - p_{i} > p_{b,\text{min}}. \]  

A violation of this relation will lead to one of the following critical operating conditions:

- \( 0 \leq p_{b} - p_{i} \leq p_{b,\text{min}} \): Due to a high injection pressure, the bladder will locally contract until its initial dimension is reached (Figure 4(d)). This results in a loss of compaction and an introduction of excessive resin in the vicinity of the injection gate.
- \( p_{b} - p_{i} < 0 \): The bladder can collapse due to an excessive injection pressure, which leads to an undefined formation of resin-rich cross-sectional areas (Figure 4(e)).
time and effort for conducting saturation experiments. The test setup basically comprises an under-sized elastomeric bladder, a tubular preform to be tested and a transparent outer tube, which can come in different application-oriented sizes. The utilization of a tube instead of a two-part mold efficiently prevents fiber pinching and race tracking in the mold parting line. Injection gate and vent are located at the ends of the assembly. The former is equipped with a ring-shaped flow channel in order to distribute the introduced test liquid in circumferential direction first, prior to 1D fluid flow in longitudinal preform direction. The transparent mold facilitates the observation of the advancing macroscopic fluid flow front, which is recorded by a camera positioned above the assembly and evaluated online through digital image processing techniques. Saturation tests are executed fully automatically through a LabVIEW-based control system and in general are performed at room temperature and atmospheric pressure.

**Experimental procedure**

The experimental work presented in this paper focuses on the impregnation behavior of a tubular preform consisting of a biaxial braided sleeving with respect to variable injection and bladder pressures. The relevant material parameters of the tested fabric are listed in Table 2. Nominal values are given along with actual values that consider the draped state of the fully expanded preform, which corresponds to a cavity diameter of the outer mold of 21 mm. The actual values were calculated based on a draping model widely used in the literature.\(^4,5,7,40\) A close-up of the braided fabric in its draped state is depicted in Figure 6.

Table 3 summarizes the relevant process parameters of the saturation experiments conducted. A silicone rubber tube was selected as a reusable bladder, which was initially pre-expanded to the inner mold diameter in order to prevent irreversible stress-softening of the elastomeric material during further testing.\(^43\) The pressure parameter \(p_{b,min}\) was determined based on bladder expansion measurements according to the procedure presented in.\(^4\) As previous saturation tests with the same braided fabric showed rather small variability,\(^34\) a number of three repetitive test runs for each measurement was considered to be sufficient to cover statistical errors, which significantly reduces measurement effort.

An overview of the performed saturation experiments is illustrated in Figure 7(a), which shows the investigated combinations of bladder and injection pressure as well as the borderlines between the critical operating conditions presented at the end of the theoretical section. It can be seen that some measurements were conducted under operating conditions that deliberately violate Equation (12) in order to study the impact on impregnation behavior. By using Equations (10) and (11), the test overview can be transformed into the domain of the corresponding compaction pressures at the flow front and the injection gate (Figure 7(b)). Hence, this diagram depicts the relevant local preform compaction pressures during BARTM and can also be used for comparing measurements that are based on different bladder types and \(p_{b,min}\) values. It has to be noted that this transformation can yield negative values for the compaction pressure \(p_{c,r}\). Although this is practically impossible and simply corresponds to a local loss of compaction, these values can still be used to evaluate a critical operating condition.

**Results**

**Saturation experiments**

The apparent global permeability values obtained from the individual saturation measurements are presented in Figure 8. As expected, the uncertainty associated with the results is rather low, which corresponds to an average standard deviation of 4.7%. It is shown that an increase in injection pressure for experiments with constant bladder pressure generally causes increasing permeability values, which is more pronounced for lower bladder pressure levels (Figure 8(a)). This is explained as a higher counteracting injection pressure leads to lower preform compaction near the injection gate. As a result, the overall porosity of the preform is increased and thus the resistance to the incoming fluid is reduced. It should be noted that the highest permeability values were obtained for

| Table 2 | Material parameters of the tested fabric |
|-------------------------------|-------------------------------|
| **Description** | **Unit** | **Specification** |
| Material type | (-) | Toho Tenax HTS40 carbon fiber |
| Filament count | (-) | 12 K |
| Filament diameter | (μm) | 7 |
| Binding pattern | (-) | Diamond (1 x 1) |
| Number of strands | (-) | 36 |
| Nominal diameter at ±45° | (mm) | 22.9 |
| Nominal areal weight at ±45° | (g/m²) | 566 |
| Actual braid angle | (°) | ±38 |
| Actual areal weight | (g/m²) | 584 |

| Table 3 | Process parameters of the saturation experiments |
|-------------------------------|-------------------------------|
| **Description** | **Unit** | **Specification** |
| Fluid material | (-) | Red-colored corn oil |
| Fluid viscosity at 23 °C | (Pa s) | 0.065 |
| Bladder material | (-) | Silicone rubber tube, shore A 60 |
| Nominal inner/outer bladder diameter | (mm) | 12 /16 |
| Flow front measurement range | (mm) | 175 |
| Bladder pressure \(p_b\) | (bar) | 3.5/4/4.5/5 |
| Injection pressure \(p_i\) | (bar) | 1/1.5/2/2.5/3 |
| Minimum bladder pressure \(p_{b,min}\) | (bar) | 1.75 |
| Flow front pressure \(p_{c,r}\) | (bar) | 0 (atmospheric pressure) |

5 mm

Figure 6 Close-up of the tested carbon fiber braid

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shorter for mathematically negative compaction pressures \( p_{ci} \), although this is beneficial for time-efficient processing, it must again be mentioned that flow-induced fiber washout, fabric distortion, and introduction of excessive resin can occur under these critical operating conditions, which is caused by local bladder contraction that opens up a flow channel near the injection gate (Figure 4(d)). However, processing may still be valid here if fiber displacement is avoided, e.g. by means of local fabric clamping or binder-based preform fixation, and if excessive matrix material can be removed in a subsequent bleeding stage after resin injection.23,44,45 As these concepts are not considered in this work, it is recommended to perform resin injections in BARTM at low (but positive) compaction pressures \( p_{ci} \) in order to reduce filling times, which is in line with statements of existing literature.4,5 Interestingly, part filling times decrease with increasing pressure \( p_{ci} \) and \( p_{bf} \) for constant pressures \( p_{ci} \) (Figure 9(a)). A linear behavior is found for higher levels of compaction pressure, which is again attributed to suppressed preform compliance during impregnation. Similar to the findings above, the results indicate that filling times are substantially shorter for mathematically negative compaction pressures \( p_{ci} \). Although this is beneficial for time-efficient processing, it must again be mentioned that flow-induced fiber washout, fabric distortion, and introduction of excessive resin can occur under these critical operating conditions, which is caused by local bladder contraction that opens up a flow channel near the injection gate (Figure 4(d)). However, processing may still be valid here if fiber displacement is avoided, e.g. by means of local fabric clamping or binder-based preform fixation, and if excessive matrix material can be removed in a subsequent bleeding stage after resin injection.23,44,45 As these concepts are not considered in this work, it is recommended to perform resin injections in BARTM at low (but positive) compaction pressures \( p_{ci} \) in order to reduce filling times, which is in line with statements of existing literature.4,5 Interestingly, part filling times decrease with increasing pressure \( p_{ci} \) and \( p_{bf} \) for constant pressures \( p_{ci} \) (Figure 9(b)). This is explained as higher bladder pressures allow for preform impregnation at higher levels of injection pressure while maintaining a certain compaction pressure \( p_{ci} \). Shortest filling times under a maintained minimum compaction pressure of \( p_{ci} = 0.25 \) bar were obtained for saturation experiments using an injection and bladder pressure of \( p_{ci} = 3 \) bar and \( p_{bf} = 5 \) bar, respectively.
specialists in reducing process development and setup time. Furthermore, it enables comparisons of different BARTM systems and process configurations. The moldability diagram for the adjustable process parameters $p_b$ and $p_i$ can be simply constructed if the pressure parameter $p_{b,max}$ and the relevant system constraints are known (Figure 12(a)). The latter comprise the highest feasible injection pressure $p_{i,max}$ and the maximum bladder pressure $p_{b,max}$ of the BARTM system. These parameters correspond to the maximum working pressures of the processing equipment, which can be further limited based on the capabilities of the mold material, the sealing design and the clamping system (to avoid pressure-induced opening of a two-part mold). The following processing conditions can be differentiated in the moldability diagram:

1. $p_b > p_{b,min}$ and $0 \leq p_i - p_{i,max}$. Bladder contraction and loss of preform compaction near the resin gate due to high injection pressure, but maintained preform compaction at the part's end.
2. $p_b > p_{b,min}$ and $p_b - p_i < 0$. Bladder collapsing and undefined introduction of excessive fluid near the resin gate due to high injection pressure, but maintained preform compaction at the part's end.

An overall presentation of the virtual inverse filling times as 2D and 3D contour plots is given in Figures 10 and 11. For better visualization, the 2D contour maps were overlaid with the respective measurement overviews given in Figure 7. Furthermore, the test setting enabling shortest filling times while maintaining minimum compaction pressure $p_{c,f}$ is highlighted. The results clearly show the distinct influence of the adjustable pressures $p_b$ and $p_i$ as well as of the corresponding compaction parameters $p_{c,f}$ and $p_{c,i}$ on the filling behavior of the investigated tubular preform. In general, low bladder and high injection pressures on the one side and high $p_{c,f}$ and low $p_{c,i}$ on the other side yield decreased filling times, which reflects the basic outcome of the findings described above.

**Moldability diagram**

A universal moldability diagram for the injection stage of a pressure-controlled BARTM process that utilizes under-sized elastomeric bladders was derived from the contour plots. It represents a process window showing different possible operating conditions within the technical limits of a BARTM system, which can be used as a guideline to assist manufacturing specialists in reducing process development and setup time. Furthermore, it enables comparisons of different BARTM systems and process configurations. The moldability diagram for the adjustable process parameters $p_b$ and $p_i$ can be simply constructed if the pressure parameter $p_{b,min}$ and the relevant system constraints are known (Figure 12(a)). The latter comprise the highest feasible injection pressure $p_{i,max}$ and the maximum bladder pressure $p_{b,max}$ of the BARTM system. These parameters correspond to the maximum working pressures of the processing equipment, which can be further limited based on the capabilities of the mold material, the sealing design and the clamping system (to avoid pressure-induced opening of a two-part mold). The following processing conditions can be differentiated in the moldability diagram:

1. $p_b > p_{b,min}$ and $0 \leq p_i - p_{i,max}$. Bladder contraction and loss of preform compaction near the resin gate due to high injection pressure, but maintained preform compaction at the part's end.
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The moldability diagram for the preform compaction pressures at the flow front and the injection gate can be computed using Equations (10) and (11) (Figure 12(b)). This diagram is more suitable for comparing processing conditions from measurements, where different bladder types, part geometries and parameters \( p_{b,\text{min}} \) were used.

Figure 11 Virtual inverse filling time vs. compaction pressures \( p_{\text{c,f}} \) and \( p_{\text{c,i}} \): (a) 2D contour plot (red circle = optimal filling) and (b) 3D map of a contour plot section.

Figure 12 Moldability diagrams of a BARTM process utilizing under-sized elastomeric bladders, given for (a) the relevant process parameters injection and bladder pressure and (b) the corresponding preform compaction pressures \( p_{\text{c,f}} \) and \( p_{\text{c,i}} \).

1. \( p_b \leq p_{b,\text{min}} \) & \( 0 \leq p_b - p_i \leq p_{b,\text{min}} \): No preform compaction along the entire part length due to insufficient bladder pressure and fluid-induced bladder contraction predominantly near the injection gate.

2. \( p_b = p_{b,\text{min}} \) & \( p_b - p_i < 0 \): Bladder collapsing near the resin gate induced by high injection pressure and insufficient bladder expansion at the part’s end due to low bladder pressure.

3. \( p_b \leq p_{b,\text{min}} \) & \( p_b - p_i > p_{b,\text{min}} \): Moldability zone where preform compaction is maintained along the entire part length during resin injection. The moldability diagram for the preform compaction pressures at the flow front and the injection gate can be computed using Equations (10) and (11) (Figure 12(b)). This diagram is more suitable for comparing processing conditions from measurements, where different bladder types, part geometries and parameters \( p_{b,\text{min}} \) were used.
The moldability zone is defined as an operation condition where successful BARTM processing is likely to be realized. A large zone indicates robust preform impregnation over a wide range of process pressures. Hence, large values for \( p_{b,\text{max}} \) and particularly \( p_{b,\text{min}} \) are desirable, while the pressure parameter \( p_{b,\text{max}} \) should be low, which can be achieved for example by using thin-walled and highly flexible bladders or by minimizing the geometrically required degree of bladder expansion.

Based on the findings of the saturation experiments, optimal filling time reduction can be achieved by choosing the highest technically feasible injection and bladder pressures that correspond to a certain minimum compaction pressure \( p_{c,\geq0} \), which is schematically shown in Figure 12. However, the following effects significantly influencing BARTM processing are not directly addressed with this approach:

- Temperature changes during preform impregnation are not considered. Hence, the moldability diagram is restricted to isothermal processing conditions.
- Resin curing and concurrent increase in fluid viscosity is not taken into account. By choosing a pressure setting that enables a fast filling of the part, this influencing factor can be minimized.
- Preforms showing high compliance during compaction can cause considerable laminate thickness gradients when processed at low compaction pressures. Furthermore, flow-induced preform deformation can still occur under these conditions. These effects can be compensated by choosing a higher pressure \( p_{\text{op}} \) that exceeds a certain minimum compaction pressure \( p_{c,\text{min}} \).
- Void formation at high fluid velocities induced by the dual-scale nature of the fabric is not considered. By choosing a lower pressure level for \( p_{\text{op}} - p_{\text{i}} = \text{const.} \) or a higher pressure \( p_{\text{op}} \), part filling is slowed and porosities are presumably reduced.

Finally, it should be noted that the moldability diagram is also valid for bladder types other than under-sized elastomeric tubes. These are for example highly flexible bladders with negligible membrane stiffness, near-net shape bladders with negligible bladder expansion during preform compaction and thermoplastic bladders that are plastically expanded prior to resin injection. In these cases the pressure parameter \( p_{b,\text{min}} \) becomes zero, which leads to simplified equations and process diagrams.

Conclusions

In this paper, the impregnation behavior of a biaxial braided sleeving in pressure-controlled BARTM was studied under various optimal and critical processing conditions. This was accomplished through saturation experiments with a viscous test fluid using an optical 1D tube permeameter equipped with a reusable under-sized silicone rubber bladder. Different parameter settings were investigated by varying the relevant adjustable process pressures for resin injection and bladder expansion. For each measurement, the apparent global permeability and the virtual inverse filling time, which can be used for filling time comparisons, were evaluated.

The results obviously showed that low bladder and high injection pressures yield high permeability values and reduced filling times, which is attributed to unhindered preform compliance as fabric compaction is counterbalanced by the injection pressure. Under critical operating conditions, flow-induced bladder contraction near the injection gate opens up a channel that further decreases flow resistance to the impregnating fluid. However, processing under this condition is not recommended in practice, as considerable fiber displacement and introduction of excessive resin is likely to occur. Thus, a minimum amount of compaction pressure at the injection gate has to be maintained during BARTM. Interestingly, it was found that for rising bladder pressures at constant compaction pressure at the resin gate, filling times reduced, although overall preform compression increased. This is explained as higher bladder pressures allowed resin injection at higher fluid pressures, while maintaining local preform compaction at the resin inlet. Hence, the influence of increasing injection pressure on filling time is larger than the effect of decreasing apparent permeability due to increasing overall preform compaction. In conclusion, BARTM at high compaction pressures tends to be similar to conventional RTM processing, as preform compliance is suppressed.

Based on the findings of the saturation experiments, a universal methodology was proposed for constructing a moldability diagram of the BARTM process. By considering relevant system constraints, it describes possible optimal and critical operating conditions for different relevant parameter settings, such as injection and bladder pressure or compaction pressure at the resin gate and flow front. The processability of a tube-like part is defined by a system-dependent moldability zone. Here, shortest filling times can be achieved by choosing highest feasible injection and bladder pressures while maintaining a certain minimum compaction pressure. The moldability diagram therefore enables efficient identification of optimal process parameters for reducing impregnation time, minimizing trial-and-error processing, improving process robustness and hence for reducing manufacturing costs. However, it should be considered that other relevant influencing factors on the BARTM process, such as temperature-time-dependent changes in fluid viscosity, flow-induced void formation or deviations from tubular part geometries, are not addressed within this model, which is a task for future work.

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ORCID

Christian Schillfahrt http://orcid.org/0000-0002-5630-7218
Ewald Fauster http://orcid.org/0000-0002-5838-6765
Ralf Schledjewski http://orcid.org/0000-0003-3121-6771

References

1. M. Neitzel, P. Mitschang and U. Breuer: “Handbuch Verbundwerkstoffe” [Handbook composites], 2014, München, Hanser.
2. A. Hammami, and A. Al-Zarouni: ‘Investigation of the RTM/bladder molding process’ In 13th Int. Conf. on ‘Composite materials’, Beijing, China, June 25–29 2001, Paper 1060. Open access: www.iccm-central.org.

3. M. Hintermann: ‘Erforschung eines neuen Injektionsprozesses für offene und geschlossene Faserverbund-Strukturen’ [Investigation of a new injection process for open and closed composite structures], doctoral thesis, ETH Zürich, Zürich, 1998.

4. U. Lehmann: ‘Herstellung von endlosfaserverstärkten, hohlen Formteilen mit innendruckbeaufschlagten Kernen im Harzinjektionsverfahren’ [Production of hollow composite parts with inflatable bladders in liquid composite moulding], Aachen, Verlag Mainz, 1999.

5. U. Lehmann and W. Michaeli: ‘Cores lead to an automated production of hollow composite parts in resin transfer moulding’, Compos. Part A-Appl. Sci. Manuf., 1998, 29, 803–810.

6. C. Schillfahrt, E. Fauster and R. Schledjewski: ‘A methodology for determining preform compaction in bladder-assisted resin transfer molding with elastomeric bladders for tubular composite parts’, Int. J. Mater. Form., Manuscript submitted for publication.

7. S. Li, J. S. Tair and L. J. Lee: ‘Preforming analysis of biaxial braided fabrics sleeving on pipes and ducts’, J. Compos. Mater., 2000, 34, 479–501.

8. W. Michaeli, U. Rosenbaum and M. Jehrke: ‘Processing strategy for braiding of complex-shaped parts based on a mathematical process description’, Compos. Manuf., 1990, 1, 243–251.

9. C. Ayans and J. Carey: ‘2D braided composites: a review for stiffness critical applications’, Compos. Struct., 2008, 85, 43–58.

10. C. Schillfahrt, E. Fauster and R. Schledjewski: ‘Cascade injection procedure for bladder-assisted resin transfer molding’, In 21st Int. Conf. on ‘Composite materials’, August 20–25 2017, Xi’an, China, Paper 5219–2. Open access: www.iccm21.org.

11. C.-L. Lee and K.-H. Wei: ‘Resin transfer molding (RTM) process of a high performance epoxy resin’, Polym. Eng. Sci., 2000, 40, 935–943.

12. K. A. Olivero, H. J. Barraza, E. A. O’Rear and M. C. Altaf: ‘Effect of injection rate and post-fill cure pressure on properties of resin transfer molded disks’, J. Compos. Mater., 2002, 36, 2011–2028.

13. E. Ruiz and V. Achim: ‘RTM process analysis and on-line characterization’, In 17th Int. Conf. on ‘Composite materials’, July 27–30 2009, Edinburgh, UK. Open access: www.iccm-central.org.

14. V. Achim and E. Ruiz: ‘Guiding selection for reduced process development time in RTM’, Int. J. Mater. Form., 2010, 3, 1277–1286.

15. E. Ruiz, V. Achim, S. Soukane, F. Trochu and J. Breard: ‘Optimization of injection flow rate to minimize micro/macro-voids formation in resin transfer molded composites’, Compos. Sci. Technol., 2006, 66, 475–486.

16. J. S. Leclerc and E. Ruiz: ‘Porosity reduction using optimized flow velocity in resin transfer molding’, Compos. Part A-App. Sci. Manuf., 2008, 39, 1859–1868.

17. J. A. Acheson, P. Simacek and S. G. Advani: ‘The implications of fiber compaction and saturation on fully coupled VARTM simulation’, Compos. Part A-App. Sci. Manuf., 2004, 35, 159–169.

18. J. Summerscales and T. J. Searle: ‘Low-pressure (vacuum infusion) techniques for moulding large composite structures’, Proc. Inst. Mech. Eng. Part L. Mater. Design Appl., 2005, 219, 45–58.

19. N. C. Correia, F. Robitaille, A. C. Long, C. D. Rudd, P. Simáček and S. G. Advani: ‘Use of resin transfer molding simulation to predict flow, saturation, and compaction in the VARTM process’, J. Fluid Eng.-T. ASME, 2012, 134, 210–215.

20. N. C. Correia, F. Robitaille, A. C. Long, C. D. Rudd, P. Simáček and S. G. Advani: ‘Analysis of the vacuum infusion moulding process’, Compos. Part A-App. Sci. Manuf., 2005, 36, 1645–1656.

21. B. Yenilmez, M. Senan and E. Murat Sozer: ‘An experimental method for characterizing unsaturated 1D flow in tubular braided preforms during bladder-assisted resin transfer molding’, Polym. Compos., in press.

22. H. Darcy: ‘Les Fontaines publiques de la ville de Dijon’ [The public fountains of the city of Dijon], V. Dalmont, Paris, 1856.

23. R. Arbiter, J. M. Beraud, C. Binetruy, L. Bizet, J. Bried, S. Comas-Carmona, C. Demaria, A. Endruweit, P. Ermanni, F. Gommer, S. Hasanovic, P. Henrat, F. Klunker, B. Laine, S. Lavanchy, S. V. Lomov, A. Long, V. Michaud, G. Morren, E. Ruiz, H. Sol, F. Trochu, B. Verleye, M. Wietgreffe, W. Wu and G. Ziegmann: ‘Experimental determination of the permeability of textiles: a benchmark exercise’, Compos. Part A-App. Sci. Manuf., 2011, 42, 1157–1168.

24. N. Vernet, E. Ruiz, S. Advani, J. B. Alms, M. Auber, M. Barburski, B. Barari, J. M. Beraud, D. C. Berg, N. Correia, M. Danzi, T. Delavière, M. Dickert, C. Di Fratta, A. Endruweit, P. Ermanni, G. Francucci, J. A. García, A. George, C. Hahn, F. Klunker, S. V. Lomov, A. Long, B. Louis, J. Maldonado, R. Meier, V. Michaud, H. Perrin, K. Pillai, E. Rodriguez, F. Trochu, S. Verheyden, M. Wietgreffe, W. Xiong, S. Zaremba and G. Ziegmann: ‘Experimental determination of the permeability of engineering textiles’, Compos. Part A-App. Sci. Manuf., 2014, 61, 172–184.

25. A. Endruweit and A. C. Long: ‘A model for the in-plane permeability of triaxially braided reinforcements’, Compos. Part A-App. Sci. Manuf., 2011, 42, 165–172.

26. P. Simacek and S. G. Advani: ‘Equivalent’ permeability and flow in compliant porous media’, Compos. Part A-App. Sci. Manuf., 2016, 80, 107–110.

27. C. Schillfahrt and R. Schledjewski: ‘Analytical modeling of textile parameters and draping behavior of 2D biaxial braided slheevings’, Polym. Polym. Compos., 2017, 25, 315–326.

28. R. S. Parras, C. R. Schillheitseis and S. Ranganathan: ‘Hydrodynamically induced preform deformation’, Polym. Compos., 1996, 17, 4–10.

29. A. Endruweit, S. Gehrig and P. Ermanni: ‘Mechanisms of hydrodynamically induced in-plane deformation of reinforcement textiles in resin injection processes’, J. Compos. Mater., 2003, 37, 1675–1692.

30. J. Diani, B. Fayolle and P. Gilormini: ‘A review on the Mullins effect’, Eur. Polym. J., 2009, 45, 601–612.

31. E. E. S. S. M. and D. C. Rudd: ‘Liquid moulding technologies’, 1997, Warrendale, PASAE International.

32. P. Simacek, D. Heider, J. W. Gillespie and S. Advani: ‘Post-filling flow in vacuum assisted resin transfer molding processes’, Compos. Part A-App. Sci. Manuf., 2009, 40, 913–924.