ANALYSIS OF RESIN FLOW UNDER FLEXIBLE COVER IN VACUUM ASSISTED RESIN INFUSION

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Abstract

Techniques to simulate resin infusion using classical RTM simulation software are investigated. The difference in the filling behavior between "rigid" and "flexible" molds is evaluated and explained. A model describing the evolution of permeability with pressure is developed for flexible moulds. This model takes into account the changes in thickness of the cavity following deformations of the mold cover, as well as the compressibility of the reinforcement. The model is validated by comparison of numerical simulations for a complex automobile part manufactured by resin infusion with actual test results obtained at the factory.

Introduction

Resin Transfer Molding (RTM) has become a widely used process to manufacture glass-reinforced composites. A good description of basic technical issues on RTM manufacturing can be found in the reference book of Cauchois [1]. Indeed, the RTM process is a closed mold fabrication technique which limits the emanations of styrene. In this process, a stack of dry fibrous reinforcements is placed in the cavity of a rigid mold and the resin is injected at low pressure. The stiffness of the mold is often a concern when manufacturing large parts with a high fiber volume content. The filling time is increased significantly and, sometimes, it is not possible to inject the part. A higher injection pressure could reduce the injection time, but the cost of the necessary tooling may become uneconomical for low production series. There is also an upward limit in the injection pressure in order not to distort locally the fiber of the reinforcement.

The liquid composite molding process variant known as *Vacuum Assisted Resin Infusion* (VARI) was first introduced by Marco [2]. It enables to manufacture with success large parts at a relatively low cost. In this process, a stack of dry fibrous reinforcement is placed between a stiff mold half and a plastic bag (Figure 1). The resin is injected by gravity after partial or total vacuum has been achieved in the cavity containing the reinforcement. If vacuum-driven techniques are now commonly used in many industrial applications, most of the time their development is based on trial and error testing. Williams and al. [3] gives an interesting review on the main developments in this field. From the *Vacuum Assisted Resin Infusion* (VARI) process developed by Group Lotus Cars Ltd [11] to *Seeman's Composite Resin infusion Molding Process* (SCRIMP) [4], many variants of resin infusion are now used by various companies. The main advantage of these techniques dwells in their low tooling cost compared to closed mold RTM. An original and optimized approach to resin infusion was developed by Kaizen Technologies under the name *Kaizen Infusion system* (KIS). KIS process variant will be simulated here for an ambulance roof.

The behavior of the resin during the infusion process is not fully understood yet and the processing strategy used in many applications is not always optimal. Problems of micro-porosity, irregular thickness and defects have been observed locally in parts manufactured by resin infusion. Although this is not a concern in the marine industry, the main field today of application of resin infusion, it is an important issue in aerospace applications for certification. Numerical simulation of resin injection can assist in positioning the inlet ports and vacuum intakes, especially for large and complex parts. Optimal injection strategies can be studied on the virtual model prior to prototype testing, hence helping to reduce process set-up costs. The goal of this investigation is to verify if sufficiently accurate simulations of resin infusion can be performed using numerical tools originally developed for classical RTM, i.e., to simulate the injection of resin in rigid molds.

Analysis of resin infusion using RTM flow simulation

In this section, the key points of RTM simulation in rigid mold are first recalled, while stressing the main differences with resin infusion. Then, a new approach to simulate resin infusion based on existing RTM flow simulation software is proposed.

The impregnation of a fibrous preform is usually modeled as a flow through porous media. The low resin velocity allows to use Darcy's law, which gives the flow rate per unit area in function of the pressure gradient:

$$v=-\frac{K}{\mu}\nabla P \tag{1}$$

where K is the permeability tensor (m^2), μ the fluid viscosity (Pa.s), and P the pore pressure (Pa). The average flow rate through a cross section is often called Darcy's velocity. It is related to the average velocity v_f of resin particles by the relation:

$$vf=\frac{v}{\omega} \tag{2}$$

where ω is the porosity of the porous medium. Combining Eq. 1 with the continuity equation gives the equation that governs the porous flow in a rigid mold, i.e., when porosity ω remains constant

$$\nabla.(\frac{K}{\mu}\nabla P)=0 \tag{3}$$

The numerical software LCMFlot will be used here to solve the above equation at each time step by the finite element method [5]. Then a filling algorithm is used to displace the flow front to its new position at the next time step. The accuracy on the tensorial factor K (permeability or hydraulic conductivity of the preform) is a key point to perform accurate numerical simulations of the RTM process.

The permeability of a preform depends on several factors, the main one being its porosity ω. Several analytical models have been investigated to predict the permeability of a fibrous reinforcement [8]. Usually, experimental measurements are required to obtain the values of this key parameter [7]. The most commonly used empirical model to describe permeability in function of fiber volume fraction is exponential:

$$K=A1\,Vf^{b\,1} \tag{4}$$

where $Vf=1-\omega$ is the fiber volume content. The parameters A_1 and b_1 are determined experimentally for each reinforcement.

Main differences between resin infusion and RTM

Because of the flexibility of the plastic bag used in resin infusion, the porosity of the reinforcement and hence permeability depend on the level of vacuum achieved. Moreover, the porosity changes as the resin progressively fills up the fiber bed. For this reason, the permeability measured in a stiff mold cannot be used to simulate this process. A way to avoid this problem consists of using a modified value of permeability in order to reflect the flexibility of the mold cover. The main idea of this investigation is first to model and measure a "*flexible mold*" permeability, then to examine if this modified value of permeability can be used to simulate effectively resin infusion.

The "flexible-mold" permeability

A way to take into account the flexibility of the plastic bag and the vacuum level achieved in the cavity is to measure the permeability of the fabric in experimental conditions as close as possible to the real injection. In this work, this method has been used on a part of an ambulance roof. The fabric used was the "Multimat" from Syncoglass Belgium, which is a knitted fabric supposed to have a very high permeability, a high drapability and thus is particularly well suited for resin infusion.

Luo [9] studied the permeability characteristics of the Multimat. The results of Table 1 show that the fabric is almost isotropic. So additional permeability measurements were only performed in the stitch direction. Firstly, the "rigid mold" permeability was measured using a rigid rectangular mold as shown in Figure 2 and following the unidirectional method proposed by Ferland et al. [7]. The results of the unidirectional permeability K are given in Table 2 for three fiber volume fractions.

“Rigid-mold” permeability measurements

Luo [9] employed a radial flow test method to measure the permeability of the Multimat. The permeability K_1 and K_2 in the principal material directions (stitch and cross direction) were measured for various fiber volume contents. The angle between the principal direction and the laboratory axis was also measured. As Luo’s results showed that the fabric was almost isotropic, the permeability was measured using the unidirectional method in the stitch direction. The results of Luo [9] are summarized in Table 1 in which $\overline{K}$ is an average of the directional permeability values K_1 and K_2.

Table 2 shows the comparison between Luo’s results and unidirectional permeability values for the same fiber volume fractions. The radial permeability values of Luo[9] were interpolated using the exponential model of Eq. 4. Figure 3 shows the two exponential models of the Multimat permeability. The results show a good agreement between the rigid-mold permeability measured by Luo using radial injections method and the results obtained with the unidirectional method. Note that the higher permeability measured by Luo [9] for high fiber volume contents could possibly be explained by the deflection of the Plexiglas mold used in the radial injection method. This deformation creates a non-uniform thickness in the cavity, which results in a varied fiber volume fraction.

“Flexible-mold” permeability measurements

The flexible-mold permeability of the fabric was measured with the experimental set-up shown in Figure 4. Note that this set-up has been designed in order to be as close as possible to the real infusion conditions so that the permeability measured will take into account most of the parameters involved. Table 3 summarizes the results of measurements for various vacuum levels. The reproducibility from one experiment to another is good and may enable to use these values in numerical simulations.

A simple model of “flexible-mold” permeability

We assume that resin injection through fibrous reinforcement is a slow process that can be modeled by a quasi static approximation, i.e., at each time step the plastic bag is in equilibrium between the atmospheric pressure P_0 and the effective stress of the compressed fabric and the fluid in the cavity (Fig. 4).

A porous medium follows Terzaghi’s law, which states that the total stress is decomposed into the effective stress ’ that acts on the fabric and the pore pressure of the fluid:

$$\sigma_{ij}=\sigma_{ij}'-P\delta_{ij} \qquad (5)$$

The compressibility of fabrics was studied by many authors and by Robitaille and Gauvin [10], who proposed an empirical model for the compaction pressure in function of the fiber volume content:

$$V_f=A_2P^{b_2} \qquad (6)$$

where P is the pressure applied on a fabric sample, A_2 and b_2 are experimental parameters depending on the particular fabric used. Combining Eq. 5 and Eq. 6 leads to:

$$V_f=A_2(P_0-P_{vac})^{b_2} \qquad (7)$$

where P_{vac} is the vacuum level achieved in the cavity and P_0 is the atmospheric pressure. Introducing Eq. 7 in Eq. 4, we can express the flexible-mold permeability in function of the vacuum level achieved in the mold:

$$K_{eff}=A_1A_2^{b_1}(P_0-P_{vac})^{b_2b_1} \qquad (8)$$

Luo [9] measured the compressibility of the Multimat and found $A_2 = 0.157$, $b_2 = 0.162$ when the compaction pressure P is expressed in kPa. For a level of vacuum of 50 kPa, the fiber volume fraction is $V_f = 29.7\%$. Using the results of Fig 2, we find that the equivalent permeability in these conditions is $2.17.10^{-10}$ m^2.

Numerical simulations

Numerical simulations using the flexible-mold permeability defined previously will now be carried out for an ambulance roof. The company Fibers Design, Chambly, Quebec, manufactures the ambulance roof of Figure 6 by a vacuum assisted resin infusion technique.

Description of the process

One layer of a “Multimat” reinforcement is placed between a stiff mold half and a plastic bag. The resin used is a low viscosity polyester (μ=250 cp). The resin is injected through an injection line by gravity after a vacuum level of around 50 kPa has been achieved in the cavity containing the reinforcement. Note that this process, known as *Kaizen Infusion System* (KIS), does not use any flow-enhancing layer, which is a main difference compared to classical SCRIMP [4]. Note that this feature alone represents a great improvement because it is much simpler to simulate numerically, but also to control practically a "plug-flow" impregnation process. However, KIS possesses also other original characteristics especially designed for resin infusion, such as a way to create a line injection channel and a line vacuum intake for example, that make it attractive to optimize the infusion process.

Numerical simulation of the process

Numerical simulations of the injection process have been performed with LCMFlot. The geometry was meshed using 6991 triangular shell elements (Fig. 7). We used the "flexible mold" permeability $K_f = 7.2\ 10^{-10}$ m^2 for a vacuum pressure $P_{vac} = 50$ kPa. The numerical values of the parameters used in the numerical simulation are given in Table 4. h is the thickness of the part, T the temperature and the other parameters have been defined in the previous sections.

The advancement of the flow front at different times is displayed in figure 8 both for the numerical simulation and the real injection.

Figure 8 shows a good agreement between the simulation and the infusion process for the ambulance roof. The flow fronts in the simulation and in the infusion are very close during the whole experience. The local differences that can be observed may be due to local variations in thickness of the fiber bed. In particular, in zones of important curvature the thickness of the fibrous reinforcement changes locally. It tends either to be slightly compressed in convex regions or expanded in concave regions; hence, permeability is locally modified, which explains some differences between the numerically predicted flow and the experiment. Note that some difficulties to impregnate the corners of the part are observed in Figure 8 both for the simulation and in the industrial process.

Conclusion

A simple approach to simulate resin infusion was presented. It is based on the use of an equivalent "flexible-mold" permeability to account for the deformation of the mold cover. This permeability can either be measured experimentally or derived from the compressibility and permeability of the fabric. Numerical simulations for a complex industrial part were performed. The comparison between experimental and numerical results showed reasonable agreement between the simulation and the real injection. Therefore, it is possible to simulate with a fairly good accuracy vacuum assisted resin infusion with a RTM software based on Darcy's law in closed mold injection conditions. It is now necessary to perform more flexible mold experiments for various vacuum levels and different fabrics in order to check the validity of this approach. The case of multiple reinforcement layers has not been studied yet. In resin infusion processes like SCRIMP for example, flow-enhancing layers are used, the influence of these layers need to be investigated in order to be able to simulate different variants of resin infusion.

During the vacuum infusion process, the thickness of the cavity varies in the resin saturated region. This variation has not been taken into account in our model yet. Indeed, only the notion of unsaturated permeability was used for the fabric. A more complex model will take into account the variations of permeability that occur during the infusion process. A similar process uses an elastic mold cover instead of the plastic bag. In such a case, the reaction of the mold will be different. For this reason, a more complex model needs to be developed to simulate this process variant.

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Appendix: Figures and tables

***Figure - 1**: Schematics of the VARI process*

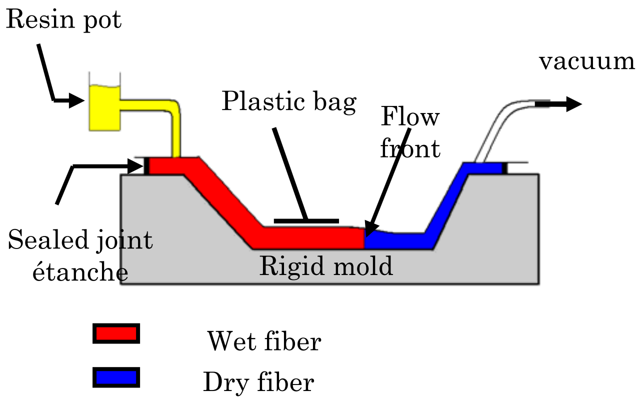

***Figure - 2**:* Schematics of the unidirectional flow method used for permeability measurements.

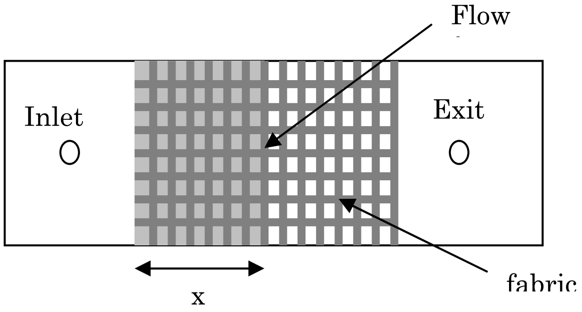

Figure - 3: Experimental curves of permeability in function of the fiber volume fraction.

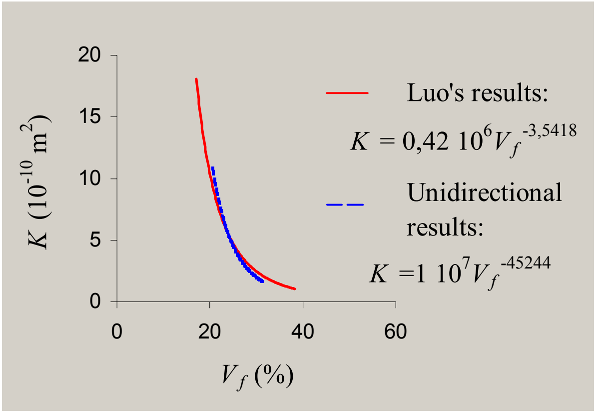

Figure - 4: Experimental set-up for measuring a "flexible mold" permeability.

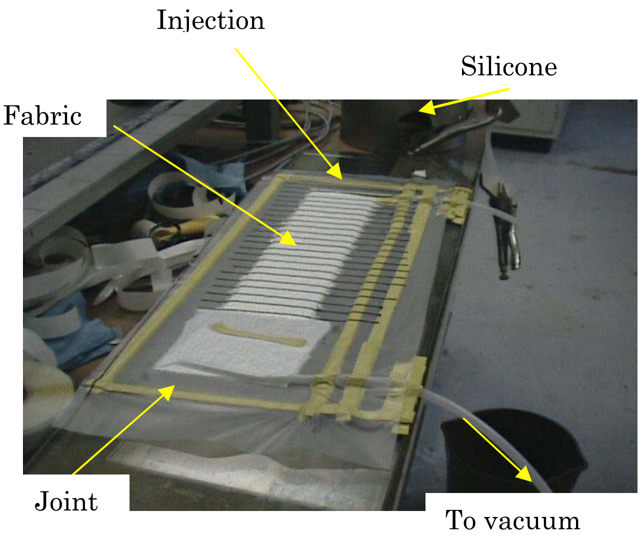

Figure - 5: The equilibrium state of the plastic bag.

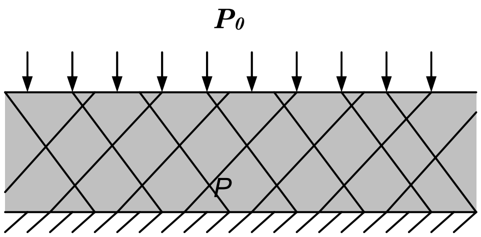

Figure - 6: Component of a composite ambulance roof with a line injection channel on the top edge and a line vacuum channel on the bottom edge.

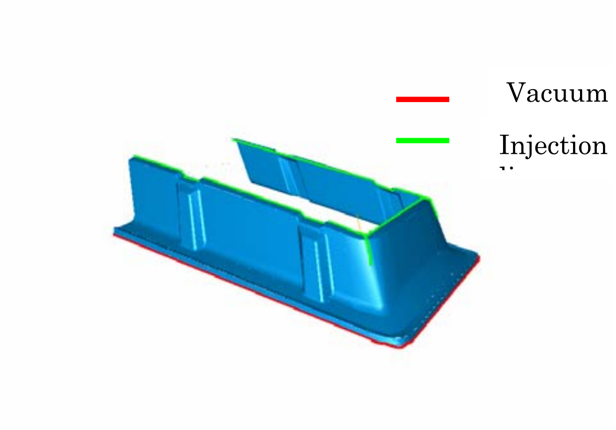

Figure - 7: Mesh of the ambulance roof.

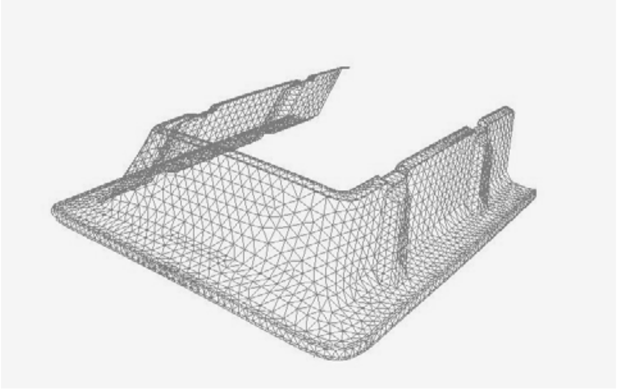

Figure - 8: Comparison between the simulation and the infusion process for the ambulance roof.

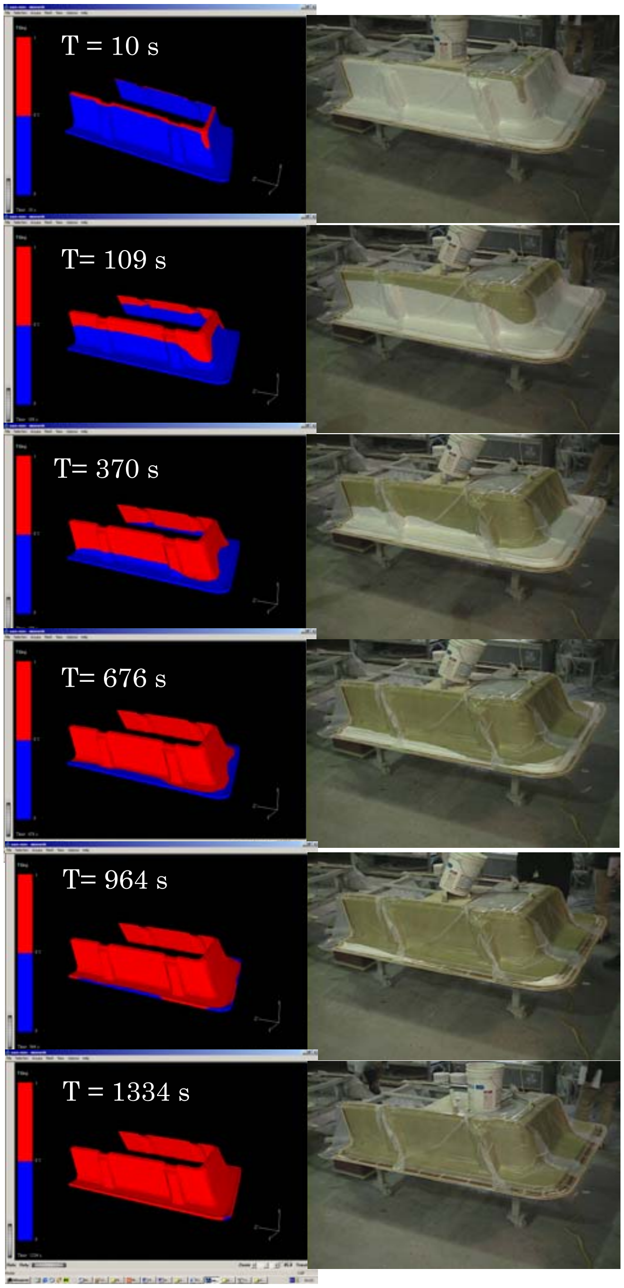

Table - 1: “Rigid mold” permeability of the Multimat measured by Luo [9].

V_f (%)	K_1 (10^{-10} m^2)	K_2 (10^{-10} m^2)	□ (°)	$\overline{K}$ (10^{-10} m^2)
17.1	18.70	17.30	-12	18.00
26.0	4.33	3.99	-5	4.16
34.2	1.66	1.39	10	1.52
38.3	1.11	1.00	-15	1.05

***Table - 2**: Comparison between results of unidirectional measurements and values interpolated from Luo [9].*

V_f (%)	K (10^{-10} m^2)	K_{int} (10^{-10} m^2)
20.6	10.6	9.33
25.2	4.7	4.57
31.3	1.59	2.12

***Table - 3**: “Flexible mold” permeability of the Multimat for various vacuum levels.*

P_{vac} (kPa)	35	35	50	50	60	60
K_f (10^{-10} m^2)	8,55	8,47	7,01	7,47	6,04	5,92

Table - 4: Parameters used in the numerical simulations.

K_f (m^2)	μ (cp)	V_f (%)	P_0 (kPa)
2.17.10^{-10}	250	29.7	101
P_{vac} (kPa)	h (mm)	T (°C)	
50	2.5	20	