SIMULATION AND CONTROL OF THE VACUUM ASSISTED RESIN TRANSFER MOULDING PROCESS BY MEANS OF FLEXIBLE PERMEABILITY MODELS

Enrique Díaz[a], Concha Sanz[a], J. Antonio García-Manrique[b]

[a] *AIMPLAS, Instituto Tecnológico del Plástico, C/ Gustave Eiffel, 4, 46980, Paterna, Spain*
[b] *Universidad Politécnica de Valencia, Camino de Vera s/n, 46022, Valencia, Spain*

Keywords: simulation, RTM, composites, control.

Abstract

The main objective of the present work is the development of an original and innovative approach for the optimal design of the vacuum assisted resin transfer moulding processes as a suitable technology for composites manufacturing. It consists of a simplified system which is able to reduce the necessary effort for the optimization of the process and to avoid the trial and error strategy in favour of the virtual prototyping in the development of the tools required. In this paper a new design methodology has been proposed for the manufacture of composite parts by means of the definition of the flexible permeability.

1.- Introduction

Two of the main problems facing our society are the dependency of fossil fuels for the transportation of people and goods and the electric power generation with non-renewable or dangerous sources. The development of low weight and high performance materials significantly contributes to its solution. Composite materials have demonstrated useful performance in such application fields, mainly because in addition to lightness and mechanical properties, this kind of materials also offers high chemical resistance. However, in order to improve the competitiveness of composites in regards to traditional materials, a reduction of the manufacturing costs is needed. This can be achieved by means of their technological development, which would lead to an optimum reproducibility, reduced scrap and optimized manufacturing times. Closed mould approaches, in which a preform of reinforcement is placed inside a mould and impregnated by means of the injection of the resin in the cavity, lead to a high quality part with competitive cost. Nowadays, there are several types of liquid composite moulding (LCM) approaches which should be selected mainly attending on the size and number of parts to be produced. An LCM process with rigid mould and counter-mould is employed when small parts and a high number of parts must be manufactured. However, if the number of parts to be produced is small or the size of such parts is higher, a flexible counter-mould turns to be competitive. These kind of industrial techniques are known as Vacuum Assisted Resin Transfer Moulding (VARTM) and Resin Infusion, depending on the reusability of the flexible counter-mould.

In order to set up the highest competitive industrial LCM facility, a precise understanding of the following design parameters is mandatory: i) the location of the injection and venting points; it must ensure a full impregnation of the preform by the resin and the absence of voids and dry spots. In addition, the number and location of such points must be carefully selected in order to optimize the cycle time. ii) The position of the flow front at any time; it is very useful information to understand the filling stage and therefore take control decisions to improve the competitiveness of the process. iii) the curing degree of the resin; it is the parameter which determines the correct demoulding time.

During the last decades, several investigations for predicting the flow front evolution inside the LCM mould have been carried out. Fracchia [1], Bruschke [2] and Trochu [3] showed the initial developments for setting up the numerical simulation by using the control volume approach. Commercial software derived of such research is available today. In infusion, the resin flows thanks to the difference of pressure between the inlet and outlet of the mould. Such driving force leads to a distribution of pressure in the cavity which varies with time. The injection of two identical preforms with the same driving force by RTM and infusion gives different pressure fields in the cavity. This is due to the fact that in infusion, the compaction of the preform is variable with the pressure of the resin (due to the flexibility of the counter-mould). As the flow front of the resin progresses, the compaction pressure decrease, resulting in an increase of the thickness of the preform and, therefore, the porosity and permeability of the preform is also increased.

Although the variation of the thickness in infusion affects directly to the permeability and porosity of the preform and, therefore, to the flow of the resin, it is possible to model the evolution of the flow front taking into account the compacting pressure, which can be related to the fiber volume fraction as follows [4]:

$$P_{comp} = A_s \frac{\left(\frac{v_f}{v_{f0} - 1}\right)}{\left(\frac{1}{v_f} - \frac{1}{v_{fa}}\right)^4} \tag{1}$$

where As, v_{f0} and v_{fa} represent a constant of the preform, the fiber volume fraction when the compacting pressure is zero and the theoretical maximum fiber volume fraction respectively. It is also possible to find empirical expressions [5,6,7] to relate the fiber volume fraction to the compacting pressure, which obviously needs experimental tests to be employed.

Correia [8] compared the models to predict the flow front behaviour in the LCM with and without flexible moulds in unidirectional problems and obtained that the time needed to fulfill a mould in RTM can be obtained from the Darcy's law as:

$$t_{RTM} = -\frac{\phi\mu}{2K}\frac{L^2}{\Delta P} \tag{2}$$

where ϕ is the porosity, μ viscosity, K permeability and ΔP the pressure gradient. For infusion, an adimensional variable ($\alpha = x/L$) might be employed, where L is the length of the preform, what leads to the time needed to complete the injection in infusion as:

$$t_I = -\frac{\mu}{2}\frac{L^2}{\left(\frac{K}{\phi}\frac{dP}{d\alpha}\right)_{\alpha=1}} \tag{3}$$

If equations (2) and (3) are compared, it is obtained that for infusion porosity and permeability of the preform are related to the pressure gradient, which is not linear as it is for RTM. Therefore, for modeling the behavior of the resin in vacuum assisted RTM processes with flexible moulds, the variation of permeability and porosity with pressure must be known. The main conclusion is that the experimental effort to determine such relationship is considerably higher in the case of infusion, what usually increase its cost up to a level in which it is not affordable.

In addition, an international benchmarking [9] of experimental measurement of permeability (it is generally anisotropic for fibrous structures and can only be predicted for idealised simple cases) which includes the main textiles and permeability benches, concluded that the results quoted by different skilled participants for the principal permeability values at any given fibre volume fraction show very significant scatter of up to one order of magnitude. For such reason, the accuracy of a realistic computational model might be compromised by the scatter obtained by the characterization of the permeability.

The main objective of the present work is the development of an original and innovative approach for the optimal design of the vacuum assisted RTM processes as a suitable technology for composites manufacturing. It consists of an expert system which is able to reduce the necessary effort for the optimization of the process and to avoid the trial and error strategy in favour of the virtual prototyping in the development of the tools required at an affordable cost.

2.- Methodology

In order to set up and validate the expert system, the following methodology has been followed:

1. An original experimental set up has been developed for the characterization of the flexible permeability of preforms with the main aim of a fast simulation, with a reduced computational effort and limited necessity of experimental characterization of raw materials (mainly permeability), which permits the preliminary design of the infusion tools ensuring; i. the complete filling of the cavity and ii. a reduced cycle time in the infusion process.
2. The flexible permeability bench has been set up with a serial of preforms typically employed in the technology of composite materials, such as continuous fibres mats, multidirectional fabrics, hybrid reinforcements with core to enhance the flow of the resin and natural fiber preforms.
3. A commercially available software for resin transfer moulding simulation has been employed for the simulation of the infusion process by incorporating the

concept of flexible permeability. This means the development of a low cost, fast and reliable approach for the virtual prototyping of the vacuum assisted resin transfer moulding processes which, as will be explained later, require a higher cost in terms of computational effort and characterization than the one proposed in the present work

4. The experimental characterization of the flexible permeability has been employed for the simulation of the filling of an infusion mould. The results obtained have been compared to the pilot plant experimental filling trials.

2.1.- Flexible permeability

The flexible permeability of a reinforcement measures a pseudo-permeability of such reinforcement in similar conditions to those observed in vacuum assisted RTM with flexible counter-mould. The permeability bench developed in the present research has been developed in order to obtain a variable thickness of the preform as a function of the compacting pressure.

In order to carry out the present research, several commercial reinforcements have been characterised in the original experimental set up which permits the inclusion, in some manner, of the effect of the compaction. It consists mainly of an unidirectional permeability bench [10] with a flexible counter-mould; specifically an infusion vacuum bag.

Figure 1.- Flexible permeability bench

A traditional technique has been employed for the acquisition of the experimental data and the calculation of the permeability. The position of the flow front on a unidirectional permeability test is informed to the software by the operator. The difference of the pressure between inlet and outlet is automatically registered.

2.2.- Virtual prototype.

In the present work, the software PAM-RTM® has been employed for the development of the virtual prototype. The injection of the cavity has been simulated with four different reinforcements (table 1)

Table 1.- Reinforcements employed

Test	Preform
1	Mat Glass Fiber (150 g/m^2)
2	Woven Roving Glass Fiber (402 g/m^2)
3	Taffeta Jute (360 g/m^2)
4	Hybrid Mateglas® Pro1 (1000 g/m^2)

The process for the set-up of the virtual prototype is as follows:

1. A RTM type simulation is selected. Since flexible permeability is used, no changes in the thickness of the preform are considered.
2. The mesh representing the cavity of the mould (final part) is charged. In this case the mesh of the figure 2 has been used. It has 14.766 nodes and 29.298 bidimensional elements. The distribution of the elements in the space gives a 2D mesh.

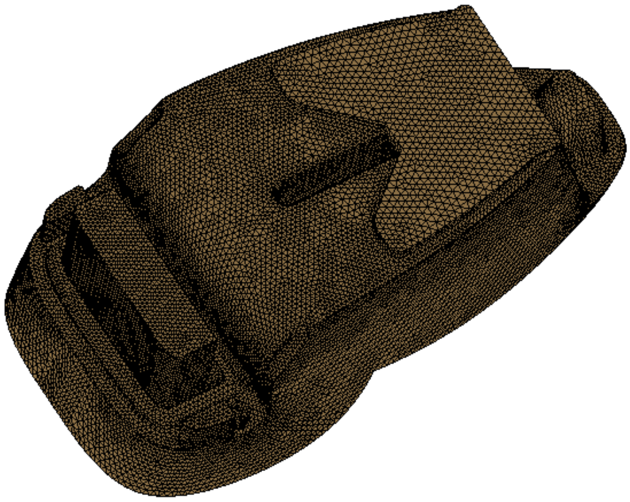


Figure 2.- 2.5D Mesh

3. The boundary conditions are selected. The nodes corresponding to the external edge of the mesh form the injection spiral tube. An additional zone of high permeability is modeled close to such nodes. Arbitrarily it has been chosen a permeability ten times higher than the permeability of the preform studied, which occupies the rest of the elements of the mesh.

Once the simulation is completed, the evolution of the flow front and pressure gradient with time is available.

2.3.- Validation at pilot plant level

The design corresponding to the virtual prototype has been transformed into a VARTM mould by using the corresponding CAD/CAM process. A polyurethane model has been transformed into the mould.

The experimental validation consists of the injection of the resin in several experimental set ups replicating the conditions of the virtual prototypes. Finally, the results obtained in the simulations are compared to the ones obtained at pilot plant level.

In the present work, the virtual prototype (based on flexible permeability) has been validated at experimental level only for the Glass mat fiber preform (150 g/m2) of table 2. Althoug the simulation of the filling stage with all the preforms detailed in table 2 has been already performed, their validation at pilot plan level will be carried out in a future work.

3.- Results

In order to validate the methodology proposed for the optimization of the LCM processes, a comparison between the mould filling predicted by the flexible permeability and the one obtained at pilot plant level, has been carried out.

3.1.- Flexible Permeability.

The table 2 shows the results of the permeability measurement of several preforms employed in the present work. The preforms corresponding to the anisotropic materials (woven roving and taffeta) have been characterised in three different directions in the plane, in order to fully determine the tensor of *flexible permeability*.

Table 2.- Flexible permeability of preforms

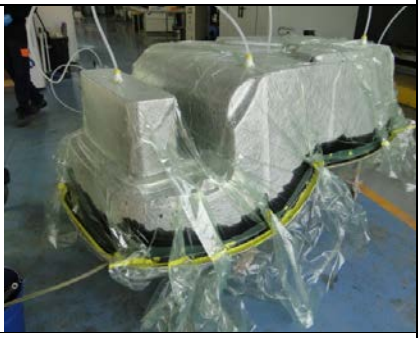
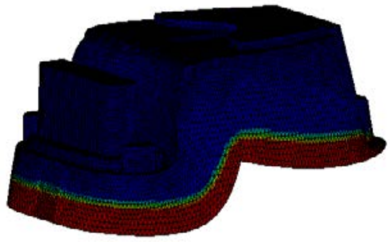
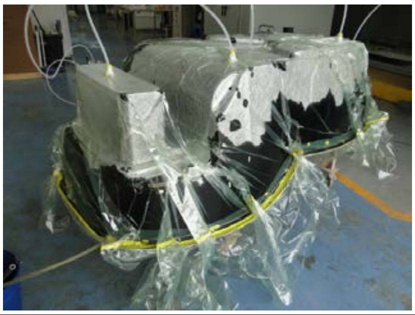
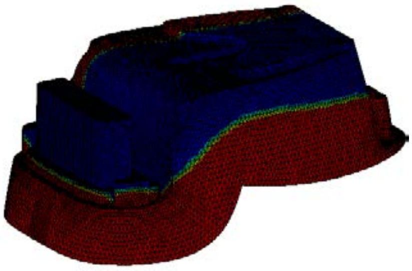
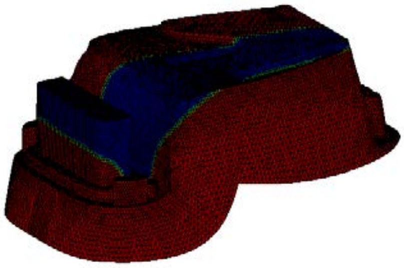
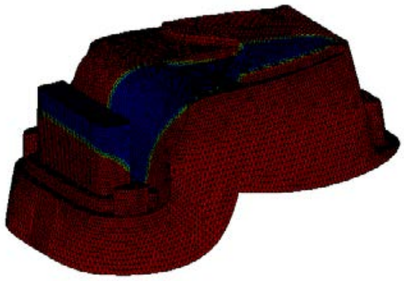
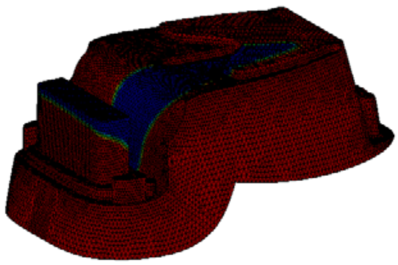
Preform	Direction	K_{FLEX} (10^{-10} m^2)
Mat Glass Fiber 150 g/m^2		4.81±1.71
Woven Roving Glass Fiber 402 g/m^2	0	2.64±0.45
	45	3.07±0.68
	90	2.71±0.47
Taffeta Jute Fiber 360 g/m^2	0	6.67±0.20
	45	6.41±0.72
	90	7.54±0.77
Mateglass® Pro 1 1000 g/m^2		24.5±3.10

3.2.- Validation at pilot plant level.

In this work, a comparison between the simulation of the flow front with flexible permeability and the experimental filling at pilot plant has been carried out. Several pictures have been taken at different times during the filling stage which have been compared to the predicted flow front position by the simulation.

In table 3 the evolution of the flow front with the test bench is compared with the one predicted by the model based on flexible permeability when the preform is made out of the glass fiber mat of table 2.

Table 3.- Glass fiber mat comparison

Time (min)	**Pilot Plant**	**Simulation**
1		
5		
10		
15		
20		

As it can be seen in table 3, the simulation correctly describes the evolution of the flow front. There exist important sources of scatter due to the flow of resin through the irregularities of the vacuum bag, which cannot be modeled.

4.- Conclusions.

The simulation of the vacuum assisted RTM processes is a useful tool for the design of moulds which permit the positioning of the key points (injection and outlet) with an optimization of the cycle time and a defect free manufacturing of composite parts.
In the present work, it has been developed a low cost approach (in terms of computational and characterization effort) for the inclusion in the design stage of a virtual prototype as a tool for increasing the competitiveness of the composite materials. It has been experimentally validated.

5.- Next tasks.

Additional pilot plant experimental validation will be carried out by using the preforms detailed in table 2. The influence of the anisotropy of preforms will be checked.

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