

High Speed Reactive Resin Transfer Moulding (RTM) Process Simulation for Mass Production of Automotive Structural Parts

Mathieu Imbert
ESI Group / ECN

ABSTRACT

High speed Reactive Resin Transfer Moulding (RTM) is a promising process for the mass production of structural composite parts in the automotive industry. In this technology a low viscosity reactive thermosetting or thermoplastic polymer is injected in a fibrous preform made of glass or carbon fibres fabrics. Continuous fibre reinforcements contain two types of volume to be impregnated: microscopic voids inside the fibre tows and mesoscopic ones between the tows. Because of this double-scale structure, the saturation of fabrics with bi-disperse porous structure is not instantaneous during resin injection. The use of reactive resins aims to reduce both the resin viscosity and part cycle time by beginning curing during the filling stage. However the chemical reactions generate significant evolution in the temperature, composition and properties of the resin during injection, which can affect the filling and quality of the part. As reactive RTM is more sensitive to thermo-chemo-mechanical couplings than regular RTM, more accurate and more advanced simulation models are needed to address these new requirements in an industrial manner.

The aim of the project is twofold: i) model the thermo-chemo- mechanical coupling in the flow of reactive resin in double-scale fibrous reinforcement ii) implement this new model in ESI Group commercial software, PAM-RTM, in order to refine the filling simulation and to allow accurate definition of optimal processing windows for industrial components.

The quantities of interest: age, degree of cure, degree of crystallization, temperature and viscosity of the resin are transported and updated at each time step. Moreover, the flow is considered at the two length scales in fabrics. Flow front and quantities of interest are tracked at the macroscopic scale (observable flow in the part) and at the microscopic scale (microscopic flow within the fibre bundles). Thus potential hot spots or fully cured regions can be identified at these two scales, and the injection strategy can be adapted to ensure a complete filling of the part. Numerical simulations will be presented to illustrate the capabilities of the developed model.

CITATION: Imbert, M., "High Speed Reactive Resin Transfer Moulding (RTM) Process Simulation for Mass Production of Automotive Structural Parts," *SAE Int. J. Mater. Manf.* 8(2):2015, doi:10.4271/2015-01-0722.

INTRODUCTION

Environmentally motivated weight reduction of cars is becoming a major preoccupation for the automotive industry. In this context, reducing the mass of the car's structure is one of the available solutions. So far, car structures are mainly made of steel which is affordable, and can be quickly formed, but it exhibits a high density, around 7.5. Continuous fibre reinforced plastics, commonly called composite materials or composites, exhibit on the contrary a density about 1.7 to 2.2. They have been developed and mainly used, since many years, in the lightweight aeronautical structures, and appear today as solutions to lighten the structure of cars. These materials are composed of a fibrous structure made of continuous carbon or glass, fibre bundles included in a polymeric resin. The role of the fibres is to provide stiffness while the polymeric resin gives the overall shape to the part. Depending on the textile type, the fibrous bed can be composed of stitched, woven or braided continuous fibre tows. This textile architecture builds up a so called two-scale porosity material. Fibre tows are densely packed with fibres while gaps between the fibres are fibre-free regions. The clear difference

in fibre volume fractions (FVF) between these two regions will induce locally differentiated behaviours during the production of the composite parts.

Continuous fibres composites production processes consist in impregnating the fibre bed with resin. This step can allow producing semi-products as plates for a further use in thermo-stamping or parts with their final shape. Among the many existing processes, RTM (Resin Transfer Moulding) has been identified as a promising way to produce complex structural parts for the automotive industry. In this process, a preformed fibrous bed is placed in the closed cavity of a mould and thermosetting or thermoplastic resin is injected with a specific spatial and temporal strategy until the full impregnation of the textile. The mould is kept closed until the resin has cured or solidified and the part is then removed, allowing the placement of another preform in the mould. In order to reduce the time spent when the mould is closed that corresponds to the injection and curing/solidification times, developments have been conducted in the past years to create lower viscosity, faster curing resins. Thus,

impregnation of the fibrous bed is faster and curing begins during filling in order to reduce the overall curing time; the ultimate goal being reducing the production time of each part to a few minutes.

Despite their evident advantages, these fast curing resins used in the so called High speed Reactive RTM can also cure prematurely if the processing conditions are inappropriate and lead to the rejection of the final part. Moreover, predicting the impregnation and curing of the resin becomes almost impossible without simulation as these resins are very sensible to the thermo-chemo-mechanical coupling involved in the process and as the impregnation of the fibrous bed must be considered at two different length scales.

In this context, the aim of this work is to propose a computational strategy to simulate the flow of a reactive resin in a two porosity scale material in order to integrate it in the commercial software PAM-RTM for industrial applications. Therefore the developed model should allow accurate simulation of the process with reduced computational time. To this extent, flow at the two length scales is computed using a Finite Element Method/Control Volume (FEM/CV) method inspired from [1] in order to track the flow as well at the macroscopic level (in the channels) as at the microscopic level (in the fibre tows). A Volume Of Fluid (VOF) first order explicit approximation of the time derivative method inspired from [2] is used in parallel to deal with the transfer of the quantities of interest (temperature and degree of cure, degree of polymerisation) at each level and from one to the other.

In the following, physics and previous numerical work dealing with isothermal flow in single and double scale porosity materials will be introduced. Anisothermal flow in double scale porosity materials will then be considered and numerical treatments proposed in the literature to solve such problems will be presented. In the second section, simulation of the flow at the macroscopic level developed in the frame of this project will be detailed. The third section will focus on the simulation of the flow at the microscopic level. Once macro and micro flow will have been considered, the general algorithm to treat the reactive double scale problem will be detailed. In the last section, the capability of the model will be highlighted using some simple examples demonstrating the ability of the method to treat thermo-chemo-mechanical couplings at the macroscopic and microscopic levels.

PREVIOUS WORK

Isothermal Flow in a Simple Scale Porosity Material

Flow of a Newtonian fluid in porous materials has been widely investigated in various scientific and industrial fields as soil [3], membrane characterisation for fuel cells [4] or composite manufacturing [5]. In all these applications, the commonly used equation to characterise the flow is Darcy's law (1):

$$\bar{v} = \frac{-\bar{K}}{\mu} \bar{\nabla} P \quad (1)$$

Where, $\bar{v}$ is the Darcy velocity of the fluid and P is the pressure in the fluid. $\bar{K}$ is a tensor containing permeability values. These values, highlighting the ease for a fluid to flow through the fibrous material, depend on the architecture of the textile and can allow modelling, depending on the tensor, isotropic or anisotropic permeability properties. It can be observed in (1) that, the velocity of the fluid is proportional and in the opposite direction of the pressure gradient and depends on the properties of the textile through the permeability and on the properties of the fluid through the viscosity. Therefore, these two parameters must be considered carefully in order to propose accurate simulations of the process.

The other governing equation for a fluid flow in a single scale porous material is the mass conservation. It is commonly expressed for an incompressible fluid (thermoplastic or thermosetting resins are considered incompressible) as (2):

$$\nabla \cdot \bar{v} = 0 \quad (2)$$

Substituting (1) in (2) gives equation (3):

$$\nabla \cdot \left(\frac{-\bar{K}}{\mu} \bar{\nabla} P \right) = 0 \quad (3)$$

This equation can be solved analytically in the impregnated region for a 1D linear or radial flow with constant viscosity. However, for a 2D calculation, corresponding to a flow in a thin shell, computational methods are required to access the pressure field. Moreover, to simulate the filling of a cavity, it is required to follow and update the position of the flow front. Different methods: finite element method (FEM) [5], finite difference method [6] or boundary element method [7] have been proposed in the past to simulate the filling of a single scale porosity material with a fluid. The FEM method is nowadays the most used technique. Furthermore, two approaches of the FEM have been developed; one based on fixed meshes and the other on moving meshes, which should allow a better tracking of the position of the flow front. However, moving mesh techniques imply additional calculations to remesh the domain which can slow down the overall computation without improving significantly the precision. Therefore a FEM technique applied to a fixed mesh has been used in the presented work.

Concerning the tracking of the flow front and the shape of the impregnated area, the technique mostly associated with the FEM is called control volumes (CV). While the node grid is used to calculate the pressure, the flow front is tracked using a geometrical discretisation of the domain into control volumes. To each node or element is associated a volume to be filled and a so called fluid-fraction function or fill factor indicating the filling of the control volume. To deal with the filling of the volumes the velocity of the fluid (obtained from Darcy's equation) and mass conservation balance are used to evaluate the in- and out-coming flowing volumes from each CV. This last procedure can be either conducted using a simple mass balance to update the fill factor of each element [8] or using an advection equation applied to the fluid-fraction function ([1], [2]). In the presented work, the control volumes are the volume of the

elements themselves and simple mass balance is conducted between the elements to update the resin fraction function. Precisions on the used method are going to be given in the second section.

Isothermal Flow in a Double Scale Porosity Material

Some textiles as randomly oriented fibre materials can be considered as single scale porosity materials and the theory presented in the previous section can be applied to them. However, materials made of fibres bundles as unidirectional, multiaxial, woven or braided materials, which exhibit better mechanical properties and are more commonly used in the industry can be considered as dual scale porosity materials. The specificity of these materials is the juxtaposition of fibre tows exhibiting low permeability because of a high FVF and gaps between the fibres exhibiting high permeability. While injecting, this difference in the properties generates delayed impregnation of the fibre bundles and locally unsaturated regions behind the macroscopic flow front, located in the channels. This phenomenon has been observed experimentally and described in the literature ([9], [10]). Moreover, it has been reported that the severity of this phenomenon is intimately related to the architecture of the fibre bed and the so called pore volume ratio (ratio between the volumes to be filled in the tows and in the channels) [5]. As, for mechanical reasons, industrial parts are wished to exhibit a high FVF, this phenomenon is likely to happen in industrial processes and it appears therefore necessary to introduce it in a simulation model.

Different analytical and numerical models have been proposed in the past to take the dual scale porosity flow during the filling of a porous part into account. In [11] equation (2) is supposed to be satisfied and saturated and unsaturated permeability values determined experimentally are assigned to different regions behind the flow front. However this technique is only applied to simple geometries and does not allow simulating the filling of complex parts. Furthermore numerical techniques have been proposed to deal with more sophisticated cases. The mostly used approach for the numerical simulation of a two scale flow is based on the FEM/CV technique presented in the previous section; the main difference being the introduction of a function called sink term q in equation (2) leading to equation (4).

$$\nabla \cdot \bar{v} = q \quad (4)$$

The sink term q is an absorption volume flow rate per unit volume that introduces, in the mass balance, the information that a certain amount of fluid is removed from the macroscopic channel flow to be stored in the fibre tows. To this extent, the volume of each CV is corrected to be only equal to the volume to be filled in the gaps and a second fluid fraction function is added to follow the filling of the fibre tow. Additionally, permeability values are corrected: a specific relatively higher permeability is given for the gap while another relatively smaller permeability value is assigned to the fibre tow. The introduction of a sink term has two consequences. First, in term of flow propagation, as a certain volume of fluid is removed from each element, the propagation of the flow front (at constant channel permeability) is slowed down compared to a case with impermeable

fibre tows. Furthermore, due to this additional term, equation (3) can no more be used. Introducing (1) in (4), allows obtaining equation (5):

$$\nabla \cdot \left(\frac{-\bar{K}}{\mu} \nabla P \right) = q \quad (5)$$

As the right hand term is no more zero, it can be noticed that the pressure field will be affected by the sink term. In some works [12], equation (3) is still used, even to simulate the flow in a double scale porous material and only the volumes absorbed in the tows which slow the propagation of the front are considered. This can be acceptable under the assumption that the fibre tows are almost impermeable and that therefore q is near zero. However, if the tows are almost as permeable as the channel, the value of q will become non-negligible, pressure will be much more affected and the equation (5) will be required. In the case where equation (5) is used, additional difficulties are introduced. In fact whatever model is used to calculate the sink term (analytical expressions [12], impregnation of 2D [13] unit cell or 3D [14] unit cell to represent the local architecture of the textile) it has been reported that the sink term is a function of the saturation of the tow but also of the channel pressure. Specific features are thus required to compute the pressure field. In ([14], [15], [16]), a 3D unit cell is used to represent the local impregnation of the fibres and channel pressure is used as boundary conditions to calculate the sink term. As this boundary condition influences the absorption in the fibre tow and therefore the sink term which affect the channel pressure, an iterative procedure is used until convergence of the pressure on the whole domain. However, this procedure may be time consuming and therefore, another approach, which still takes the influence of the sink term into account, will be proposed in the second section of this article.

Anisothermal Flow in a Double Scale Porosity Material

In the two previous sections, we considered the isothermal impregnation of different types of fibre beds with a non-reactive fluid. However in the case of industrial Liquid Composite Moulding (LCM) and especially for High speed Reactive RTM, chemical reactions occur during filling, generating evolutions in the degree of cure of the resin, coupled with heat generations and modifications of the viscosity. Therefore, in order to predict the evolution of these quantities, it is necessary to introduce these couplings and the transfer of these quantities of interest (temperature, degree of cure, degree of polymerisation) in the simulated model. Different techniques have been already developed in the past.

Pillai proposed in [8] a 2D model to simulate the filling of a single fibre tow, using finite elements to determine the non-isothermal flow of a reactive resin in the channel as well as in the tow. This model is based on a FEM/CV technique similar to the one described in the first subsection. The transfer of the quantities of interest is conducted for each element, using mass, energy, or degree of cure balance associated with a time discretization. In 2009, the Flux Corrected Transport (FCT) method was adapted by Tan [11] to simulate the transport of quantities of interest in the LCM of composite moulding.

This technique is based on the FEM technique. Values of the quantities of interest are associated to the nodes of the grid and the updated values are obtained from the inversion of a “stiffness matrix” using also the boundary conditions. This iterative method requires many matrix inversions and is therefore CPU time consuming. So as to reduce the calculation time, Abisset-Chavanne [2] proposed a method inspired from Sanchez [1] based on the Volume of Fluid Method to update the values of the quantities of interest. In this method, using a fluid-fraction function, and advection equations, quantities of interest are transported from one element to the neighbouring ones according to the flow rate and direction, while contributions of the source terms are added at each time step. However, this promising method was only developed for a single scale porous material. The aim of this work is therefore to propose a two scale porosity model including the transport of quantities of interest to simulate a reactive reaction during filling.

NUMERICAL DEVELOPMENTS

In the previous section, physical aspects so as numerical treatments proposed in the literature to deal with isothermal and anisothermal flows in double scale porosity materials have been presented. In this section, the numerical strategy developed to simulate the anisothermal flow of a reactive resin in a double scale porosity material will be presented. First, the numerical approach to deal with the 2D macroscopic flow (located in the channels), will be introduced. This strategy is mainly inspired from [2], but sink and source terms to introduce the effects of the micro-scale flow on the macro-scale flow will be added. Then, the model used to compute the micro-scale sink and source terms will be presented.

Flow at the Macro-Scale

In this section, a numerical strategy will be proposed to deal with macroscopic reactive filling of a fibrous material with double scale porosity. The strategy proposed by Abisset in [2] based on a FEM/CV and VOF method will be presented and adapted to the case of a double scale porous material by introducing sink and source terms relative to the micro-scale flow in the different equations.

Presentation of the Model

The test case used in this article to highlight the capabilities of the numerical strategy is a rectangular plate with constant thickness. In the frame of this work, no variation of properties happens in the through-thickness direction so that the model can be considered in plane and two dimensional. The domain Ω is discretised in N non-overlapping triangles with length sizes respectively dx in the x-direction and dy in the y-direction. Flow through the upper, lower or lateral sides of the mould is not allowed.

To each macroscopic element is associated a permeability tensor $\bar{K}_c$ and a volume V_c to be filled by the resin. The permeability tensor corresponds to the permeability of the channel (Darcy's law (1) is supposed to be satisfied in the channel). Furthermore, V_c is the volume of channel contained in the volume of a macroscopic element packed with the real material (see figure 1). $\bar{K}_c$ and V_c are associated with the flow at the macroscopic level. In the same time, a 1D

problem relative to the microscopic flow is associated to each element. This problem is characterised by a geometry, a permeability and a volume associated to the tows which will be used to compute the sink and source terms related to the micro-scale. (More details on the micro flow will be given in the following section). Permeability and volume values are distributed so that the overall permeability and volume to be filled are the same as in the real material.

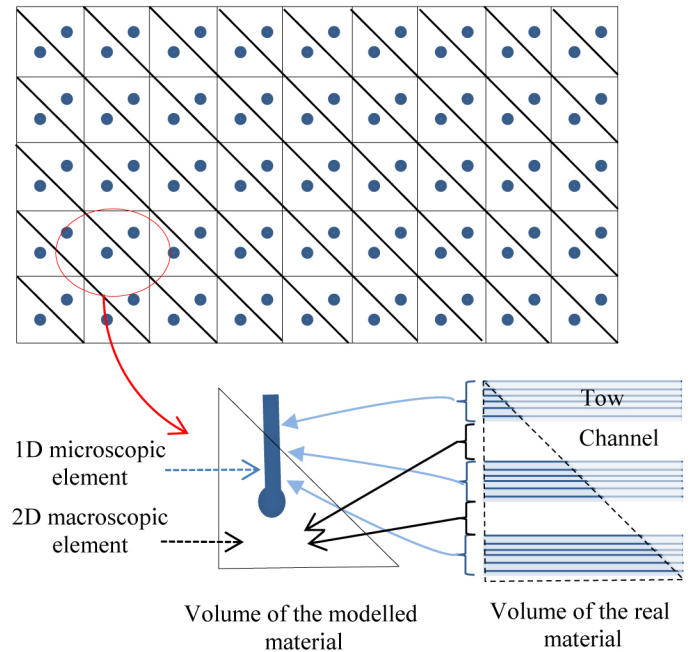


Figure 1. Geometry and principle of the model.

Introduction of the Variables

Physical quantities are associated to either nodes or elements of the model. The macroscopic channel pressure field P_c is defined using pressures values P_i and linear shape functions φ_i associated with each node i of the model.

The expression of P_c is given in equation (6).

$$P_c = \sum_i \varphi_i P_i \quad (6)$$

Furthermore, the following variables are associated with each of the macroscopic elements and satisfy the given equations during the process. As soon as one element has begun to be filled, the quantities introduced below are physically defined in the element and the associated function exhibits a constant value within this element. In order to avoid problems related to the definition of these functions on the in- and outflow boundaries of the elements, it is assumed that, on the inflow boundary of each element, the physical value is equal to the one in the upstream element.

1. $\bar{v}_c$: Macroscopic Darcy's velocity of the fluid in the element e governed by Darcy's law (7).