The method of RTM process modeling using porous medium

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Abstract. This paper proposes a method to simulate the Resin Transfer Molding process by using Ansys Fluent software. The offered approach permits to calculate impregnation time, to predict dry zones after impregnation and proposes a method to calculate porosity of the final product to predict the mechanical properties. The method is illustrated in the plate resin impregnation case.

1. Introduction

Resin Transfer Molding (RTM) is a manufacturing process in which a liquid resin is injected into a closed mold pre-loaded with a porous fibrous preform, producing complex composite parts with good surface finishing. Resin flow is a critical step in the process. One of the greatest difficulties in applying RTM and LRTM processes is related to mold filling, i.e. to guarantee that the fibrous reinforcement is completely impregnated by the resin inside the mold. Besides, in order to manufacture quality composites through RTM, it is necessary to minimize the void content inside them. The presence of voids is harmful to predict the mechanical properties of the parts, such as the decreasing of shear, compression, impact and fatigue. There are different approaches to simulate this process. On the one hand there are some special commercial software e.g. PAM Composite (ESI Group), in particular module PAM-RTM. The proposed software permits to simulate composite manufacturing process, but this software doesn’t work with 3D composite materials. On the other hand, the offered software simulates air voids by using empirical formulas.

The mechanical characteristics of the obtained material with a given distribution and void size can be estimated by using the homogenization method. To do this, you can use any commercial software package for modeling the mechanics of a deformable solid or special software e.g. Digimat (e-Xstream/MSC Software Corp.).

In this paper the manufacturing process is described as a part of the unique framework. The last one takes into account the product life-cycle. It means the manufacturing process results are used in stress analysis. This approach develops the concept of Virtual Manufacturing. It means that for fiber reinforced polymers (FRPs) the process from modeling of the textile reinforcement material behavior on tool, impregnation and curing. All these processes are associated with defects such as air voids, incomplete polymerization, residual stress and unplanned shape distortion. It is the result of decrease in strength properties and deterioration of product characteristics. Product defects, acquired during the manufacturing process, can be taken into account in the simulation process. The proposed approach can be used to the conceptual design of the product and permits to decrease the final product cost. It is
radically important, because 75% of the product cost is based on the results of the conceptual design stage [1].

In this work, the numerical study of the resin flow in RTM applications was performed by employing a general Computational Fluid Dynamics software which does not have a specific RTM module, making it necessary to use the Volume of Fluid method for the filling problem solution. The porous medium model is used for reinforcement modeling. These models are implemented in the ANSYS Fluent commercial code. Examples were presented and compared with experimental and numerical results showing the validity and effectiveness of the present study, with maximum difference among these solutions of around 5%. On the other hand the air voids development permits to analyze the strength properties of the product. In the contrast of existed approaches, offered method takes into account the manufacturing process to create the conceptual design of the product. It means we can predict the strength properties of the product in the early development stage.

Voids in composite products are known to seriously impair the mechanical properties of the substance. For example, according to the aviation standard ASTM, a product with a porosity >2% should be rejected [2]. Therefore, the mechanism analysis of pore formation and ways to reduce porosity is of great importance for improving the composite parts quality.

The paper remainder is structured as follow: in Section 2 states-of-the-art is presented, Section 3 is devoted to method description, and finally section 4 present the conclusions.

2. State-of-the-art

In last decennaries composite materials have come into position of significant and beneficial high-productivity material solution in different areas like automobile and city transport, aviation and rocket and space technology shipbuilding, bridge building, oil refining industry and other. The necessity of improving performance, reliability and quality of products led to strictering requirements which have to meet the composites industry. The resin transfer molding (RTM) is a complicated production process. A preformed reinforcement of glass or carbon fiber is placed in a closed mold and a viscous resin is injected into the mold. The intricacy of the process occurring in the production of composites does a trial and error approach effect less. Partially, the problems can be solved by designing the process and integrating the simulation into the design cycle. Accordingly, performing numerical optimization is perspective. For distinguish and improve optimum settlement parameters it is necessary to elaborate methods relating predictive simulation with numerical optimization way. G. Struzziero et al.[3] reviewed numerical and experimental results concerning the optimization techniques and methodologies implemented in literature to address the optimization of thermoset composite manufacturing processes.

M. Hattabi et al. [4] proposed a procedure of simulation the flow in the LCM (Liquid Composites Molding) processes by finite difference discretization in a curvilinear coordinate system adapted to the shape of the saturated zone. They simulated two-dimensional mold filling of Newtonian fluid through the porous reinforcement under an isothermal condition. They proposed the concept of the capillary number to explain the variations of the permeability obtained for pressure values lower than 0.25 Bar.

In the RTM process the mold contains three constituents including fibres, resin and gas. Due to its similarity to a porous medium, the process can be modeled within the Theory of Porous Media (TPM), where the simulation of the moving resin front generates an inherent difficulty. Commonly used two approaches are: the moving resin front is either approximated roughly, such that an interface thickness of multiple finite elements arises, or respectively by a sharp interface with zero-thickness which requires a special numerical treatment. Dammann C. et al. [5]applied regularized sharp interface theory as a branch of phase-field models which go back to the classical Ginzburg-Landau equation. In this way, the sharp discontinuities between different phases, i.e. resin and gas, are approximated by smooth transitions of suitable order parameters, of which one is the resin fraction. Thus, the sharp interface topology as well as the surface energy of the interface are smeared out over a region proportional to a chosen regularization length scale. As an additional advantage, the phase-field method facilitates a thermodynamic treatment of phase interfaces rendering it more physically consistent in combination with the TPM, which also works within a thermodynamically sound framework. To this end, a coupled finite-element strategy was presented accounting for both, a Ginzburg-Landau- and Cahn-Hilliard-type regularization scheme for the interface. Two boundary value problems were formulated in the context
they consider a multiphase-system, represented by deformable fibers interacting with the resin saturating the pores that was coupled to one of both regularization schemes. Accordingly, two numerical examples demonstrate the capabilities of both regularized formulations by simulations of RTM process.

Liércio A. Isoldi et al. [6] performed numerical studied of RTM by employing a general Computational Fluid Dynamics software which does not have a specific RTM module, made it necessary to use the Volume of Fluid method for the filling problem solution. J. da S. Porto et al. [7] investigated a numerical model developed in the FLUENT package to study the resin flow behavior in the LRTM process. The mold filling process during resin-transfer molding has been simulated numerically by Moon Koo Kang et. al [8] by using a modified control volume finite-element method (CVFEM) along with a fixed-grid method to handle problems associated with the moving resin front. The fixed grid was refined in an adaptive manner, by dividing the flow-front elements into two regions using the estimated flow front. Imaginary new nodes were placed at the intersections between the original element border and the temporary flow front. By using the mass conservation of resin, the pressures at these newly added ‘imaginary’ nodes were expressed in terms of the pressure at the old ‘real’ nodes. Through this elimination, the imaginary nodes do not affect the size of the global matrices and thus do not increase the computation time. The proposed method, referred to as the FINE method, yielded smoother flow fronts and reduced the error in the pressure at the flow front that plagued the conventional fixed-grid methods. The solution accuracy was considerably higher than that of the conventional method for the same number of nodal points and elements, without a significant increase in the computation time.

Anita Zade et al. [9] had presented the isothermal mould filling simulation using Ansys Fluent for LCM process. 2-D rectangular geometry was used for analyzing the effect of process and raw material parameters on filling time. Sensitivity analysis was done using velocity and viscosity of injection resin and orthotropic permeability of reinforcement.

In full 3D analyses the major concern is computer time for calculations in RTM flow simulations. F. Trochu et al. [10] proposed to simulate 3D composite shells with multi-layer reinforcements with several enhancements. The first one is connected with appropriate domain discretization. The second consists of using prismatic finite elements instead of tetrahedrons to reduce the number of degrees of freedom in 3D analyses. The third improvement concerns the different levels of coupling that can be implemented between in-plane and transverse calculations.

Modeling the inhomogeneous microstructures of fibrous tows is important for analyzing the process of resin transfer molding because dual-scale pores in a preform can lead to void formation. Shigeki Yashiro et al. [11] developed a microscopic flow analysis method to predict the impregnation of fiber bundles. The moving particle semi-implicit method was adopted to model the microstructure of a fiber bundle explicitly and interparticle potential force was introduced into the numerical model to take account for the capillary effect. The predicted process of impregnation and void formation agreed with empirical observations. The developed approach was applied to predict the relationship between the modified capillary number and void content to identify the optimal molding conditions to reduce micro voids.

3. Method description and case study
The proposed method permits to calculate the impregnation time for the composite material. This approach uses model, based in Ansys Fluent. This software is based on the Finite Volume Method (FVM) and to solve this problem the Volume of Fluid (VOF) model are used. Proposed by Hirt and Nichols in 1981 [12], the VOF model solves the fluid dynamic and heat transfer problems of two or more immiscible fluids. Through VOF, it is possible to identify the position of the interface among different phases of fluid. In addition, the fluid phases are well separated and the volume of a phase cannot be occupied by another one. The computational modeling of the RTM process in both two-dimensional and dimensional geometries has already been validated by Porto et al. [13].

In this approach two earlier phases are defined – air and resin. The plate is presented as a porous medium with porosity 0.5. This method is based on [13]. The proposed approach is used in the set of cases based on [14]. The set of cases are presented in the figures 1.
As the input the offered approach uses results of periodicity cell impregnation. The information about air traps [15] is transferred to model in the Ansys Fluent. These air traps are included to the model as an additional fluid domain with air.

Set of three cases are completed in this paper – diagonal impregnation on diagonal and lengthwise direction. The last one is calculated for one and two outputs. In all cases 200 mm length, 300 mm and 5 mm thickness plate is used. Permeability is isotropic. The additional domain with air is added to emulate the air traps. There is a set of equally spaced elements in this domain. The 1 mm3 size of these elements are chosen.

It is known that the heterogeneous flow of the binder is due to the heterogeneous microstructure of the wavy preform and the air is trapped along the flow front of the binder during the impregnation process. In the microstructure of such textile forms, you can find two types of pores with very different sizes: micropores (inside fiber bundles), which occupy a tiny space between individual fibers of the filler, and micropores, which are the empty space between individual threads.

Thus, this method permits to analyze the porosity of the final composite material by means analysis of the created voids. We take into account only macrovoids created in air traps without account sources of porosity [16].

Most studies [17]–[20] describe semi-empirical models for air void prediction. These approaches calculate the size and distribution of the air voids using experimental data and semi-empirical formulas. It is experimentally established that air void formation correlates with the capillary number:

$$Ca = \frac{\mu \cdot u}{m \cdot \gamma \cdot \cos Q}$$

where: $\mu$ is the resin viscosity; $u$ is the resin velocity; $m$ is the porosity of the textile preform; $\gamma$ is the interfacial tension between resin and air; $Q$ is the contact angle.

The PAM-RTM software implements the determination of the air voids size depending on the capillary number according to formula 1.

According to experimental observations and the formula 1 there is an optimal resin flow velocity at which the number of macro-and micro-voids will be minimal [16]. It is about 0.002-0.003 m/s. At a low flow velocity of the resin, the air voids between the yarns (macro-voids) prevail, at a high flow velocity of the resin – inside the yarns (micro-voids).
In this paper, we offer only to model the macro-void formation between individual yarns. The micro-void formation inside the yarns is not considered. The flow rate resin at each point of plate allows you to obtain the fraction of voids using the graph in Fig. 2. The voids are modeled with additional fluid domain with air. The distribution is done hand using the velocity and Fig. 2.

Proposed method is a part of the perspective model of the composite components conceptual design development presented in the Fig. 3. In perspective this model will takes into account the manufacturing stage permit to develop the composite component.

**Figure 2.** Dependence of macro- (rectangles) and micro-voids (circles) on resin flow rate [15].

**Figure 3.** Method diagram.
4. Conclusions
This method can be used in industry and science. At further research we will use multiphysical approach – using of thermal and CFD approaches, also we guess to add automatic procedure of macro-void distribution by means Fortran or Python software. On the other hand, this approach permits to simulate all production process in one unique framework.
Size and distribution of air voids will be obtained when modeling the unsteady flow through the unit cell of textile depending on geometry of unit cell and impregnation direction at each point of the dry textile.

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