RTM PROCESS ANALYSIS AND ON-LINE CHARACTERIZATION

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SUMMARY:

Resin Transfer Molding (RTM) is a widely used manufacturing technique of composite parts. It involves several complex phenomena: fluid flow, fiber impregnation, resin cure, thermal and rheological variations, etc. The combination of such phenomena and the wide range of processing parameters available in RTM manufacturing, often lead to non-optimum, sometimes inappropriate, processing setups. Selecting the adequate manufacturing conditions (i.e. temperature, pressure or resin formulation) is often a tricky decision mainly based on user's 'know-how'. In this study, a software interface has been developed for helping process engineers in the proper selection of such critical parameters. The approach is intended to help manufacturing specialists in reducing process development time while improving process robustness. The software is also combined with a new data acquisition system allowing quick identification of key material properties. The data acquisition unit developed on this work is controlled on-line through a web-based software which allows long distance characterization of cure and thermal conductivity of the resin, fibers and mold. To demonstrate the capabilities of the proposed approach, an application example is conducted on an industrial composite part.

KEYWORDS: LCM, composite manufacturing, moldability diagram, optimization

INTRODUCTION

Liquid composite molding (LCM) processes have gained significant recognition over the past decades. This is explained by the high specific properties of the manufactured composites combined to relatively low production costs [1]. Within the LCM family, resin transfer molding (RTM) is one of the processes that have received the most industrial attention. A typical RTM manufacturing starts by placing a dry reinforcement inside a rigid mold, after the mold closure, a liquid resin is injected under pressure in order to impregnate the reinforcement. Then, the resin cures and the composite part can be demolded. Many numerical models have been developed to predict each step of the RTM process leading to various commercial software, such as QUIK-FORM and PAM-RTM [2]. Nowadays, such simulation software are widely used by large RTM manufacturers to predict and improve molding conditions. However, before being able to use such software, significant investment must be made in order to gain scientific knowledge on preform shape, impregnation phenomena, rheological behavior, resin polymerization, etc. In practice, the requirement of highly qualified personnel trained in LCM simulation limits the implementation of these numerical tools. Also, a considerable gap is often observed between mold conception and process simulation due to a lack of scientific information or to the complexity of the numerical approach.

In this study, a simplified approach is proposed to assist qualified personnel in the design of cost-effective manufacturing strategies. Proper injection conditions can be chosen based on the moldability diagram of a composite part made by RTM [3]. In this work, a numerical technique was developed to build such moldability diagram on a virtual environment. According to the physical information provided, different numerical approximation can be used to calculate the boundaries of the moldability diagram. The proposed solution uses a fuzzy logic technique in order to interactively construct the diagram. This allows the user to calculate optimal manufacturing conditions in a short period of time.

The application of numerical solutions is often limited due to a vague knowledge on material properties. In order to construct the moldability diagram, key material properties such as resin cure kinetics or rheological behavior have to be known. In this work, a data acquisition unit has been developed to quickly characterize resin cure and thermal properties. The aim of this system is to reduce characterization time allowing process engineers to scientific material knowledge and obtain accurate simulation results.

PROCESSING PARAMETERS AND CONSTRAINTS

In RTM manufacturing several processing parameters have a direct and strong influence on the final properties of the part. Such parameters include resin formulation, fibrous reinforcement, part thickness, mold temperature and injection pressure. All these parameters will impact on cycle time and hence affect the production cost. From a manufacturing point of view, the easiest parameters to be adjusted are the injection pressure (or flow rate) and temperature of the mold. A first attempt to optimize (i.e. minimize) the cycle time would consist in applying the maximum allowable injection pressure at the maximum available mold temperature, transferring the most energy to the resin. This should result in the shortest cycle time. Unfortunately, the maximum pressure and temperature available on the system can violate other constraints. Fiber washout can appear due to high injection pressure, elevated resin flow rates result in non-appropriate impregnation of the fibrous reinforcement, excessive mold temperature can end in resin burnout due to the heat released during cure. The moldability diagram gives a visual understanding of the process constraints showing the limitations of each processing parameter. The moldability diagram can be seen as a rule-based process design which provides a rapid and intuitive selection of appropriate molding parameters. In this study, the following processing parameters were considered: mold temperature, injection pressure, injection flow rate, injection length, resin viscosity, resin catalyst percentage, preform permeability and fiber volume content.

Every composites molding plant has its own distinct characteristics and operating requirements. The most important feature of a molding optimization procedure is the ability to model a wide variety of constraints and configurations that can be operated in the plant. This gives the optimization engine the versatility to search multiple solutions that meet the production needs. Although this solution looks appropriate, it comes at the price of complex and time-consuming characterization of each system in the production environment. The manufacturing constrains have then to be limited to those mainly affecting the performance of the molding process. In this study, manufacturing constraints are related to the injection equipment and tool, to the fibrous reinforcement and resin used and to manufacturing costs.

The constraints related to production equipments such as injection system, mold, clamping system and oven, are key for true success of the optimization since these equipments are expensive and represent significant investments. As initial guess, some constraints can be considered as inherent of the plant. The upper limit of the clamping system (i.e. hydraulic unit) may be used to fix the maximum allowable internal pressure on the mold. The injection machine will also limit the internal pressure on the mold as well as the maximum and minimum resin flow rates. The mold temperature will be limited by the capabilities of the heating system, the mold material and thermal insulation.

Material design constraints are related to the components of the parts to be manufactured (i.e. fibrous reinforcement and resin). The liquid resin must completely fillup the mold before gelification occurs. This means that mold filling time must be shorter than gel time of the resin at molding temperature. Violation of this constraint leads to an incomplete part impregnation, known as “short shot”. During resin injection, a high flow rate may lead to displacement of the fibrous reinforcement known as “fiber washout”. Fiber washout depends on the fiber volume content and fiber topology (i.e. short fibers, unidirectional reinforcements, woven, etc), on the mold surface roughness and resin viscosity [4]. Also, due to the double-scale nature of the reinforcement, an important amount of voids can be trapped within the part during injection [5, 6]. Consequently, the injection flow rate has to be optimized in order to improve part quality [7]. In order to avoid these issues, resin pressure at inlet has to be limited to a maximum (experimentally observed) value. After injection, the resin will cure up to a certain degree, according to the resin formulation and mold temperature [8]. Since this final degree of cure may affect its surface quality during painting or the final mechanical performance of the part [9], the molding condition must be selected in accordance to this relationship. Finally, due to the exothermic nature of the polymerization reaction, the temperature at the core of the part can significantly increase during processing [3]. In some cases, the core temperature can be high enough to degrade the polymer resin and delaminate the composite part. To avoid degradation of the resin, the temperature of the part during processing has to be lower than a critical value.

Economic design constraints are associated to profitability of the process to be optimized. The process engineer has often to deal with a predefined production volume to be done in a certain time frame. This implies that cycle time may be fixed according to the number of production equipments available. If the same injection machine is used on several parts during one cycle time, then the injection time will be limited according to the time needed to setup the injection hose on the next mold [10]. For each of the constraints above mentioned, a safety factor must be applied in order to take into account the variability of the process. This safety factor is usually based on experience and can be critical when optimizing a manufacturing process.

Figure 1 shows the user interface developed in this work to setup all these constraints in an intuitive manner. This user interface was built reproducing a common industrial environment in which the user is used to work. By selecting the injection machine the user is able to setup the capabilities of the unit in terms of pressure, flow rate, temperature and catalyst percentage. The hydraulic press gives access to the constraints of the clamping system (i.e. maximum clamping force and opening/closing speed). The mold in the press opens the constraints of the molding equipment which include maximum molding temperature and maximum sealing pressure. The two rolls in the rack allow setting the fibrous reinforcement type and physical parameters (i.e. permeability and thermal conductivity). The resin barrel is used to setup the resin properties such as viscosity model, cure kinetics, glass transition temperature and thermal properties. Finally, the part inside the mold gives access to fiber and resin volume contents on it and to the flow behavior (i.e. longitudinal, radial or complex injection).

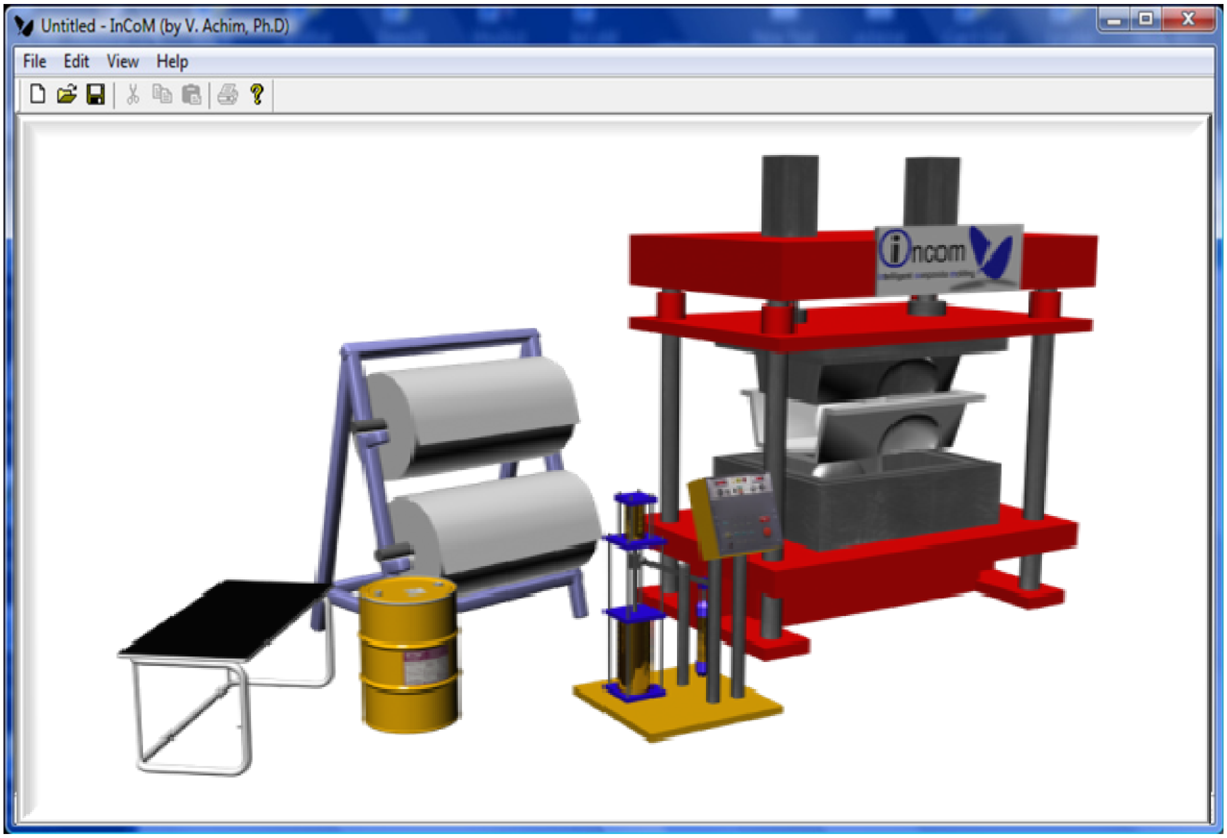


Figure 1 – User interface developed to intuitively enter all system constraints.

MOLDABILTY DIAGRAM

To make a proper RTM part, the processing parameters have to be combined in such a way that all previously enumerated constraints are respected. The zone bounded by these constraints determines the *moldability diagram* of the part to be tested [11]. Figure 2 shows the moldability diagram for an RTM part made of glass fiber and epoxy resin injected at constant pressure. The center of the chart (green color) defines the zone where a successful injection is expected. This area is called the *moldability zone* and is surrounded by all constraints (i.e. short shot, maximum injection pressure, maximum filling time, maximum cycle time and maximum temperature of the system). Selecting a combination of processing parameters outside the moldability zone (red color) will result in a defective part. The gradient (yellow color) between the moldability zone and its boundaries represents the safety factor considered for each constraint. The minimum cycle time is located at the maximum temperature and injection pressure, point (1). The process cycle with the minimum internal pressure can be obtained on the left corner, point (2). This processing setup enables the thinnest mold design. Finally, the minimum temperature cycle obtained at point (3), represent the cycle that uses the lower energy consumption to make the part.

The moldability diagram can be used to evaluate a selected processing cycle, to test new equipment or to evaluate the impact of modifying the part design. A large moldability zone implies that the molding operation can be successfully carried out over a wider range of conditions. Therefore, the process can be considered as reliable. On the other hand, a small moldability zone implies a non robust processing that may result in several trial-and-error tests. Looking at the moldability diagram is a human instinctive way of globally analyzing the process robustness. Building an experimental moldability diagram requires a huge effort of trial and error and is highly expensive and time consuming [12, 13]. Furthermore the moldability diagram is of more importance in the early stage of the process design when engineers are dealing with multiple choices and looking for some rapid insight. To overcome this difficulty, a numerical solution is proposed in this work to build the moldability diagram based on physical parameters of the part and manufacturing equipment. Combining the numerical solution with a fuzzy logic inference comes out as a fast and efficient way to sketch the moldability diagram of a RTMed part.

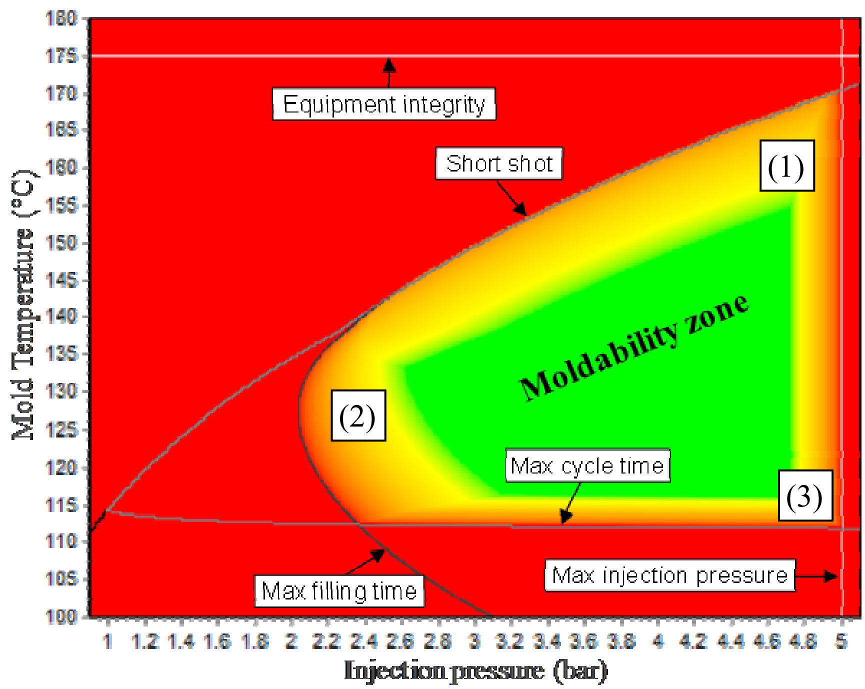


Figure 2 - Moldability diagram for a glass/epoxy composite part 1m long.

MATHEMATICAL MODELS

Darcy's law combined to continuity equation is usually applied to describe the flow evolution in RTM manufacturing [14]:

$$\nabla \cdot (\rho \mathbf{v}) = \frac{d\rho}{dt} \tag{1}$$

$$\mathbf{v}_D = -\frac{\mathbf{K}\nabla p}{\mu} \tag{2}$$

where ρ is the resin density, $\mathbf{v}_D$ is Darcy's velocity, $\mathbf{K}$ is the permeability tensor, ∇p the pressure gradient and μ the resin viscosity. The viscosity of the resin varies in time since it is a function of temperature T and degree of polymerization α [15, 16].

$$\mu = f\left(\alpha, T\right) \tag{3}$$

The degree of polymerization is also a function of temperature and time and can be modeled using different cure kinetic models [17, 18]:

$$\frac{d\alpha}{dt} = f\left(\alpha, T\right) \tag{4}$$

During polymerization, the resin changes its state from liquid to solid. This behavior is associated to the evolution of the glass transition temperature from the monomer to the polymer. Di Benedetto's equation is a wide used approach to relate glass transition temperature and degree of conversion [18]:

$$T_g = T_{g_0} + \frac{\left(T_{g_\infty} - T_{g_0}\right)\lambda\alpha}{1-\left(1-\lambda\right)\alpha} \tag{5}$$

where T_{g_0} is the glass transition temperature of the monomer, T_{g_∞} is the glass transition temperature of the fully reacted network and λ is a structure-dependent parameter.

These sets of equations can be solved simultaneously using different numerical methods such as finite difference, finite volume or finite element [19-21]. In order to do real time analysis, the solution of these combined equations has to be fast enough so that few runs can be obtained per CPU second. In this work, a fast one-dimensional approach is used based on adaptive finite volumes to minimize the degree of freedoms required while an adaptative 5th order Runge-Kutta is used for time integration. This numerical approach allows fast evaluations of the full process for simple geometries without the requirement of complex mesh generation. Also, in order to improve the quality of the solution, the proposed approach can be linked to PAM-RTM solver [2] in order to obtain a more precise evaluation of the resin flow and cure of the specific part to be analyzed.

PHYSICAL PARAMETERS

In this complex analysis, several physical parameters are required for the numerical calculation to give good agreement with experimental data. Such parameters include resin chemical and rheological properties as well as resin, fibers and mold thermal properties. Resin chemical reaction is usually modeled based on Differential Scanning Calorimetry (DSC) tests, fibers permeability has to be characterized on each principal direction and thermal properties measured using advanced instruments. A full characterization of resin, fibers and mold is usually time consuming taking months to be accomplished. To simplify the implementation of the optimization technique of this work, the developed software has been coupled to different characterization tools allowing fast estimation of physical parameters. As shown in Figure 3, the software input data can be obtained directly from *CureKinetics* and PermLab software as well as from a data acquisition unit developed in this work. *CureKinetics* [22] is a computer based software designed for quick and reliable evaluation of the cure kinetics of thermoset resins measured by DSC. It can be used to model chemical reaction of the resin, to model glass transition temperature, to build a gel time predictive equation and to model the effect of catalyst in the cure reaction. *PermLab* [23] is a characterization tool used to measure saturated and non-saturated permeabilities. It allows the creation of permability models as a function of fiber volume content and shearing of the woven reinforcement.

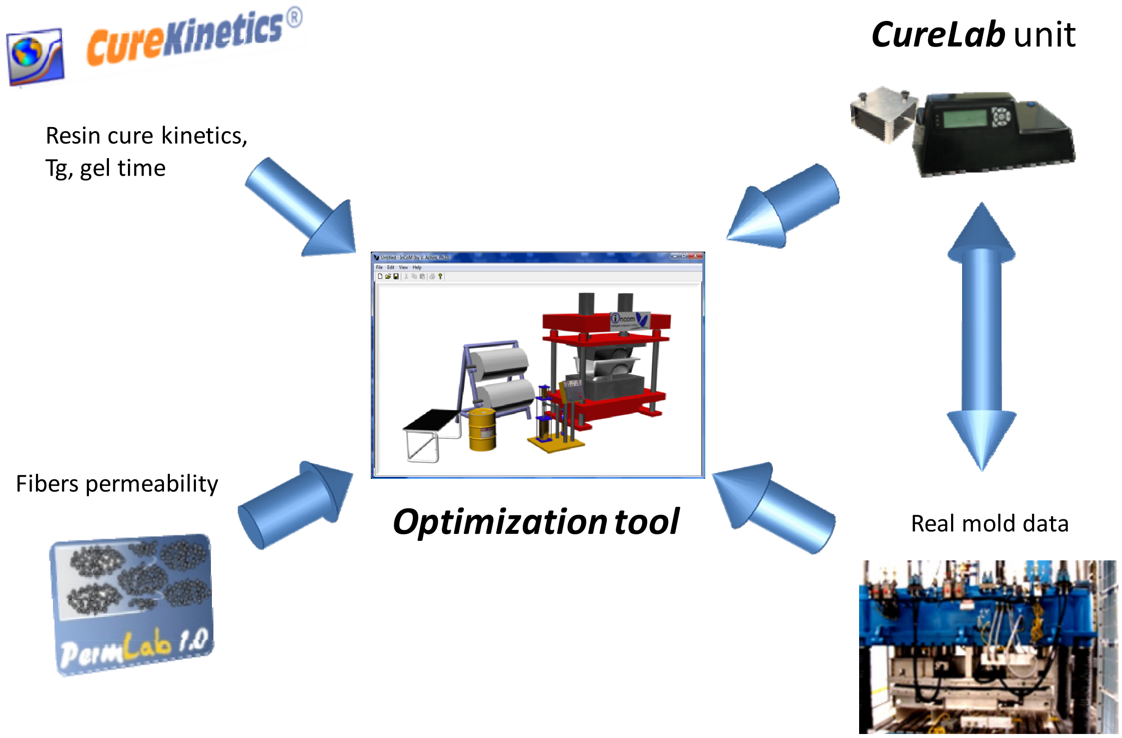


Figure 3 – Coupling of data modeling software with the optimization tool of this work.

The simplest approximation which can be used when no expert-software are available, is to apply raw data from an existing molding unit. Knowing the part size, average flow behavior and mold temperature, the coefficient $\mathbf{K}/\mu$ can be roughly estimated from the injection pressure and filling time. Then, the viscosity variation can be evaluated by injecting the part at different mold temperatures and recording the injection time. Resin gelification can also be assessed by visual inspection and recording the time to gel at various temperatures. This rough approximation of physical parameters can be used to calculate the moldability diagram of the part. However, its application is limited to the range of measured parameters.

Sometimes it is required to accurately study the evolution of the chemical reaction inside the mold, since the presence of fibers, their plastic sizing, demolding agent, or gas in the mold cavity may influence the polymerization reaction. In these cases, where accurate results are essential, data acquisition on the real process seems to be necessary. In this work, a novel data acquisition and control unit named *CureLab* has been developed to characterize resin cure. This hardware is a stand along unit that can be used for fast analysis of resin cure in the presence of fibers and can also be connected to an instrumented mold. As shown in Figure 4, *CureLab* can be coupled to real mold data via thermocouples and heat flux sensors resulting in better estimates of the real filling and curing processes. The use of *CureLab* unit reduces the process characterization time making feasible the application of the moldability diagram to parts.

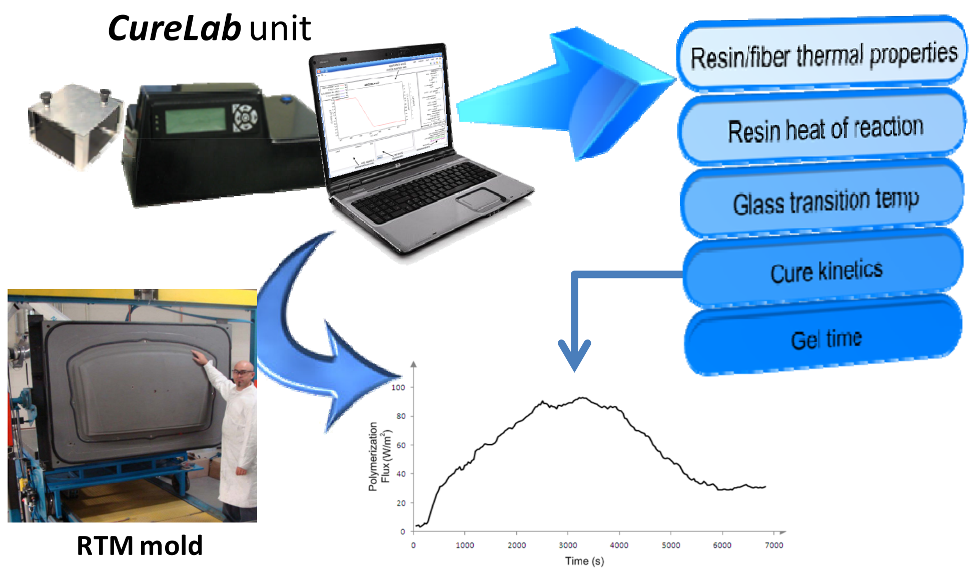


Figure 4 – *CureLab* data acquisition system developed on this work.

TEST CASE

In order to demonstrate the capabilities of the proposed approach, a test case has been carried out on a complex part. For this test case, an industrial part of 1,5m long composed of glass fibers and epoxy resin has been selected (see Figure 5). The glass fibers used for this test case were Rovcloth 2454 fabric from Fiber Glass Industries. The permeability of the reinforcement was of 2e-10m² for a fiber volume content of 40%. The epoxy resin was DER 383 DGBA with an anhydride catalyst of 1phr. The rheological and kinetic models of the resin were taken from [24]. The injection of the part was selected to be at constant pressure from a 10mm hole at the center. A numerical process simulation was initially carried out using PAMRTM software to observe the flow behavior. As shown in Figure 5, the flow behaves as radial divergent on the left side of the part while it is longitudinal-like on the right side. Since the last point of the mold to be filled is observed on the left upper corner, a radial flow behavior was chosen as representative of this injection. A distance of 70cm was measured for the flow path length. Based on this assumption, the moldability diagram of the part was constructed using a 1-dimensional radial flow. As shown in Figure 6.a, the software proposed on this work was used to construct the moldability diagram of this industrial part. Note that the zone of minimum filling time is highlighted at the upper right corner. In this case, a proper injection strategy consists of using an injection pressure of 6 bars with a mold temperature of 140°C. Using those parameters, the predicted cycle time is around 5 minutes, with 20 seconds of injection. Figure 6.b shows the moldability diagram by varying the catalyst concentration for a fixed injection pressure of 6 bars. It can be seen that that temperature may be increased to 155°C by lowering the catalyst concentration below 1%. In this case, a cycle time of 3,5 minutes was be obtained. Consequently, the optimized injection parameters are a molding temperature of 155°C, an injection pressure of 6 bars and a catalyst ratio of 1%. A new simulation using PAM-RTM with these parameters confirmed the viability of the injection strategies.

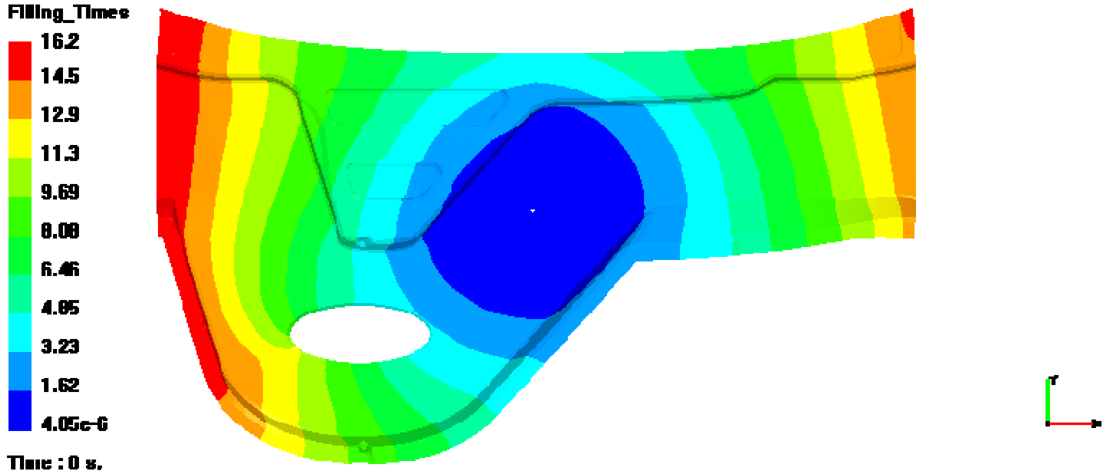
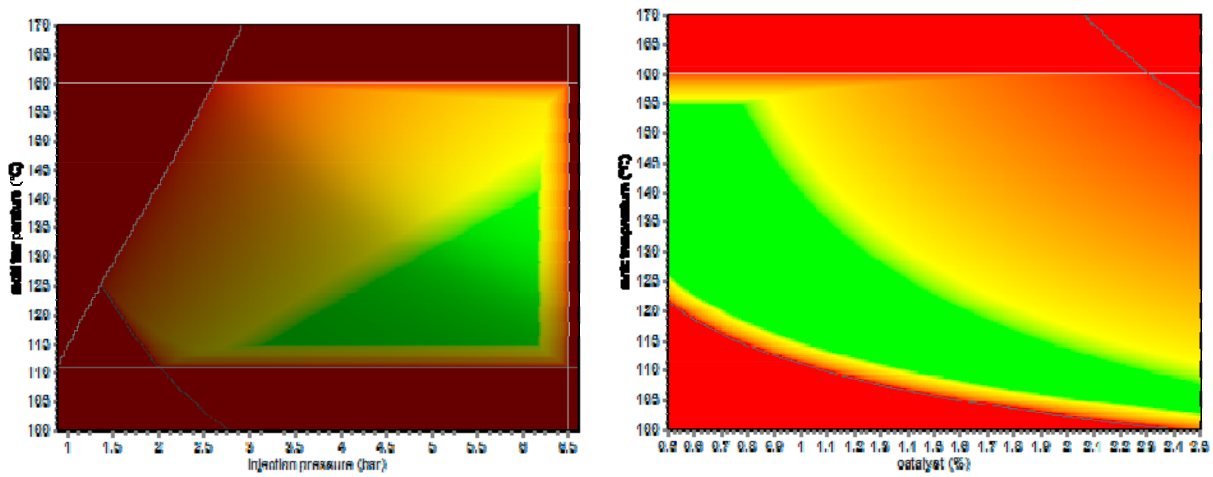


Figure 5. Industrial part used for the test case (dimensions: 1,5m long by 0,65m width and 0,15m deep).



(a) (b)

Figure 6. Moldability diagram of the industrial part. a) mold temperature versus injection pressure highlighting the minimum filling time, b) mold temperature versus catalyst percent showing an optimal combination at 0,9% of catalyst and a temperature of 155°C.

CONCLUSIONS

In this paper, a numerical methodology is proposed to simulate RTM processing. A visual software interface was developed to enable users to define and compare different processing scenarios on a real time environment. It was shown how the *moldability diagram* of a part can be easily constructed using a simplified numerical approach. Also, it was shown how optimized injection conditions can be obtained by studying the *moldability diagram*. In order to characterize the RTM process, a new characterization unit was developed. This unit is able to communicate to an instrumented mold and calculate physical parameters required for building the *moldability diagram*. Finally, a discussion was given on the advantages of using the *moldability diagram* to improve the processing of RTM parts. Future research efforts are focus on the application of this technique to a real part in order to demonstrate its practical use.

ACKNOWLEDGMENTS

The authors are grateful to the National Science and Engineering Research Council of Canada (NSERC) and the Fonds Québécois de Recherche sur la Nature et la Technologie (FQRNT) for their financial support. The authors would also like to thank CREPEC (Center for applied research on polymer and composites) for providing the research infrastructure and equipment.

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