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GUIDING SELECTION TOWARD COST-EFFECTIVE COMPOSITE MANUFACTURING DESIGN

Achim, V. [1, 2] and Edu Ruiz [1]

[1] *Department of Mechanical Engineering and Chair on Composites of High Performance,*
Centre de recherché en plasturgie et composites (CREPEC), École Polytechnique de Montréal,
P.O. Box 6079, Station "Centre-Ville", Montreal, Canada, H3C 3A7
[2] *Corresponding author's Email: vincent.achim@polymtl.ca*

SUMMARY: Liquid Composite Molding (LCM) regroups number of manufacturing techniques of polymer composites based on resin impregnation of dry fibrous reinforcements. It involves a large number of complex phenomena (i.e. fiber impregnation, resin polymerization, gel time, thermal and rheological variations, etc.). The combination of such phenomena and the wide range of processing parameters often lead to non-optimum, sometimes inappropriate, processing setups. In this work, a new approach is proposed in order to assist process engineers in finding optimum manufacturing conditions to reduce LCM cost while improving process robustness. A visual software interface was developed to enable users to define and compare different processing scenarios. Using fuzzy logic and semi-analytical solutions, the system is able to perform basic process simulations and optimizations. This allows users to visualize the impact of their decisions on a real-time environment. One original feature of the proposed approach consists of integrating into the optimization loop the feedback of process engineers. An application example is conducted on a typical composite part in order to demonstrate the capabilities of the approach. This case study shows how small changes of processing parameters can lead to significant cost savings.

KEYWORDS: LCM, composite manufacturing, moldability diagram, cost optimization

INTRODUCTION

Liquid composite molding (LCM) processes have gained significant recognition over the past years. High specific properties combined to relatively low production costs explain this increasing popularity. Among LCM family, resin transfer molding (RTM) is one of the processes that have received the most industrial attention [1]. RTM manufacturing is a multi steps process. It begins by placing a dry reinforcement (fibers) inside a rigid mold, closing the mold, injecting a liquid resin, curing the resin and finally demolding the part. Many numerical models have been developed to predict each steps of the RTM process leading to commercial softwares, such as

QUICK-FORM and PAM-RTM [2]. Nowadays, such simulation software are widely used by 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, resin rheology, polymerization control, 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 work, a simple numerical approach is proposed to assist process engineers in the design of cost-effective manufacturing strategies. In this paper, the constraints that define the LCM process are described and classified. Then, a brief description of the numerical models is detailed. Based on these mathematical models combined with a fuzzy logic technique, the moldability diagram of LCM part is defined. Finally, a discussion is given on how the optimal process parameters can be found and how the proposed optimization can reduce processing time and hence reduce manufacturing cost.

CONSTRAINTS

In this study, RTM manufacturing constraints are sort into three main subjects: tool, material and economics constraints.

Tool Design Constraints

Tool design constraints are related to production equipments such as injection system, mold, clamping system or oven. These equipments are expensive and represent significant investments. Consequently, for a given plant, these constraints can be considered as fixed. For example, a given injection machine possesses a maximum working pressure that compelled the process design. As well, the pressure is also limited to a maximum internal mold pressure fixed by the capabilities of the clamping system (i.e. hydraulic press), the sealing design and the material of the mold. The minimum of these constraints will set the limit of the allowable injecting pressure. In a similar manner, the mold temperature will be limited by the capabilities of the heating system, the mold material and thermal insulation. For each of these constraints, 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 LCM processing.

Material Design Constraints

Material design constraints are related to the components of the parts to be manufactured (i.e. fibrous reinforcement and resin). It is well understood that the liquid resin must completely fills up the mold before it gels. This constraint limits the allowable injection time in the form $t_{fill} = t_{\alpha_{gel}}$, where t_{fill} is the time to fill the mold and $t_{\alpha_{gel}}$ is the gel time of the resin at the mold temperature. Violation of this constraint leads to what is called a *short shot* that must be avoided in order to make a proper part. As a consequence, a large safety factor must be set to this constraint in order to ensure a safe injection methodology. After injection, the resin will cure up to a certain degree, according to the resin formulation and mold temperature. Since this final degree strongly affects the mechanical performance of the part, the molding condition must be selected in accordance to this relationship. For an isothermal manufacturing where the temperature is kept constant during injection and curing, a minimum mold temperature must be selected in order to ensure proper cure of the part. This gives the following constraint $T = T_{\alpha_{final}}$ where T is the mold temperature and $T_{\alpha_{final}}$ is the minimum temperature to reach the desired degree of conversion. Due to the exothermic reaction of the resin polymerization, the temperature at the core of the part can be significantly increased during processing[3]. In some cases, the core temperature can be high enough to degrade the polymer resin, reducing the part quality. To avoid degradation of the resin, the temperature of the part during processing has to be lower than a critical value.

During RTM injection, there is an inherent risk of fiber washout or fiber displacement due to high resin flow rates or pressure. Fiber washout depends on the fiber preform topology (i.e. short fibers, unidirectional reinforcements, woven, etc), on the mold surface roughness and resin viscosity [4]. In order to avoid fiber washout, resin pressure at inlet has to be limited by the maximum (experimentally observed) value.

Economic Design Constraints

In this study, economic design constraints are associated to profitability of the process to be optimized. For a process designer, it mostly translates to a production volume. This implies that a maximum filling time, a maximum curing time and/or a maximum cycle time can be requested depending on the number of equipments available. For example, the availability of the injection machine will limits the filling time if more than one part has to be injected with the same machine during a given cycle time.

MATHEMATICAL MODELS

Darcy's law combined to continuity equation is usually applied to describe the flow during the RTM injection [5]:

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

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

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 viscosity. The viscosity is a function of temperature T and degree of polymerization α :

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

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

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

To give an approximation of the behavior of resin viscosity and kinetic, various models have been proposed. Table 1 and Table 2 present few of them.

Table 1 Resin viscosity models

Castro-Macosko [6]	$\mu = \mu_0 \left(\frac{\alpha_{gel}}{\alpha_{gel} - \alpha} \right)^{a + b\alpha} \qquad \mu_0 = A_\mu e^{\frac{E_\mu}{RT}}$ (5)
Williams-Landell-Ferry (WLF) [7]	$\ln \frac{\mu}{\mu_r} = -\frac{C_1 \left(T - T_r\right)}{C_2 + T - T_r}$ (6)

Table 2 Resin kinetic models

nth order reaction [8]	$\frac{d\alpha}{dt} = k\left(1 - \alpha\right)^n$ (7)
Autocatalytic reaction [9]	$\frac{d\alpha}{dt} = k\alpha^m \left(1 - \alpha\right)^n$ (8)
nth order+autocatalytic reaction [10]	$\frac{d\alpha}{dt} = \left(k_1 + k_2 \alpha^m\right)\left(1 - \alpha\right)^n$ (9)
Maximum reaction degree [11]	$\frac{d\alpha}{dt} = \left(k_1 + k_2 \alpha^m\right)\left(\alpha_{max} - \alpha\right)^n, \qquad \alpha_{max} = f(T)$ (10)
General complex reaction model [12]	$\frac{d\alpha}{dt} = \sum_{i=1}^{j} w_i k_i f_i\left(\alpha\right), \qquad k_i = A_i e^{-\frac{E_i}{RT}}$ (11)
Diffusion controlled reaction [13]	$\frac{d\alpha}{dt} = \left(k_1 + k_2 \alpha^m\right)\left(1 - \alpha\right)^n \frac{1}{1 + e^{C\left(\alpha - \alpha_c\right)}}$ (12)
Catalyst effect [14]	$\frac{d\alpha}{dt} = [C]\left(k_1' + k_2' \alpha^m\right)\left(1 - \alpha\right)^n \frac{1}{1 + e^{C\left(\alpha - \alpha_c\right)}}$ (13)

During polymerization, the resin change state from liquid to solid. This behavior is associated to the evolution of the glass transition temperature of the polymer. Di Benedetto's equation is a wide used approach to relate glass transition temperature and degree of conversion [15]:

$$T_g = T_{g_0} + \frac{\left(T_{g_\infty} - T_{g_0}\right)\lambda\alpha}{1 - \left(1 - \lambda\right)\alpha} \tag{14}$$

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 theoretically equated to $\Delta C_{p_\infty} / \Delta C_{p_0}$ where ΔC_{p_∞}, and ΔC_{p_0} are respectively the differences in heat capacity between the glassy and rubbery state for the fully cured network and monomer [16].

These sets of equations can be solved simultaneously using different numerical methods such as finite difference, finite volume or finite element [17-19]. 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 (or two) dimensional approach is used based on adaptive finite volumes to minimize the degree of freedoms required and a 4th order Runge-Kutta is used for time integration. This numerical approach allows fast evaluations of the full process for simple 1D or 2D geometries without the requirement of complex mesh generation.

PROCESSING PARAMETERS

Two of the key processing parameters are the injection pressure (or flow rate) and temperature of the mold. In a first attempt to optimize the molding cycle, the resin inlet pressure can be set at the maximum available system pressure. This will transfer the most energy to the resin during injection. Consequently, it will give the shortest injection time. Unfortunately, fiber washout can occur at the early beginning of the injection. Also at that pressure, an important amount of voids can be trapped within the part during injection due to dual scale nature of the fibers. In order to avoid these effects, injection pressure has to be optimized[20]. The first attempt to optimize (i.e. minimize) the cycle time will consist in applying the maximum allowable injection pressure at the maximum available mold temperature. The proposed numerical algorithm starts with this ideal condition and searches for the optimized molding conditions that satisfy all selected constraints. In a similar manner, other processing parameters can be added to the analysis (i.e. resin formulation, percentage of catalyst, fibrous reinforcement, part thickness, number of plies, etc). All these parameters will affect the impregnation time and curing cycle and hence the final cost of the part.

MOLDABILTY DIAGRAM

To make a proper RTM part, the processing parameters must be selected in such a way that all previously enumerated constraints are respected. The zone bounded by such constraints determines the *moldability diagram* of the part to be tested [21]. Fig. 1 shows the moldability diagram for a small RTM part made of glass fiber and epoxy resin using a constant injection pressure. The green color at the center of the chart defines the zone where models predict a successful injection. This area is called the *moldability region*. Selecting a combination of processing parameters within the moldability region will result in successfully molded parts. A combination of processing parameters outside the moldability region will result in an improper part. *Moldability diagrams* can then be used to evaluate a selected processing cycle, to test new equipments or to evaluate the impact of modifying the part design. A system with a larger moldability region 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 region implies a non robust processing that may result in several trialand-error tests. This *moldability diagram* can be quickly built by using numerical models that describe the process phenomenon combined with a fuzzy logic inference.

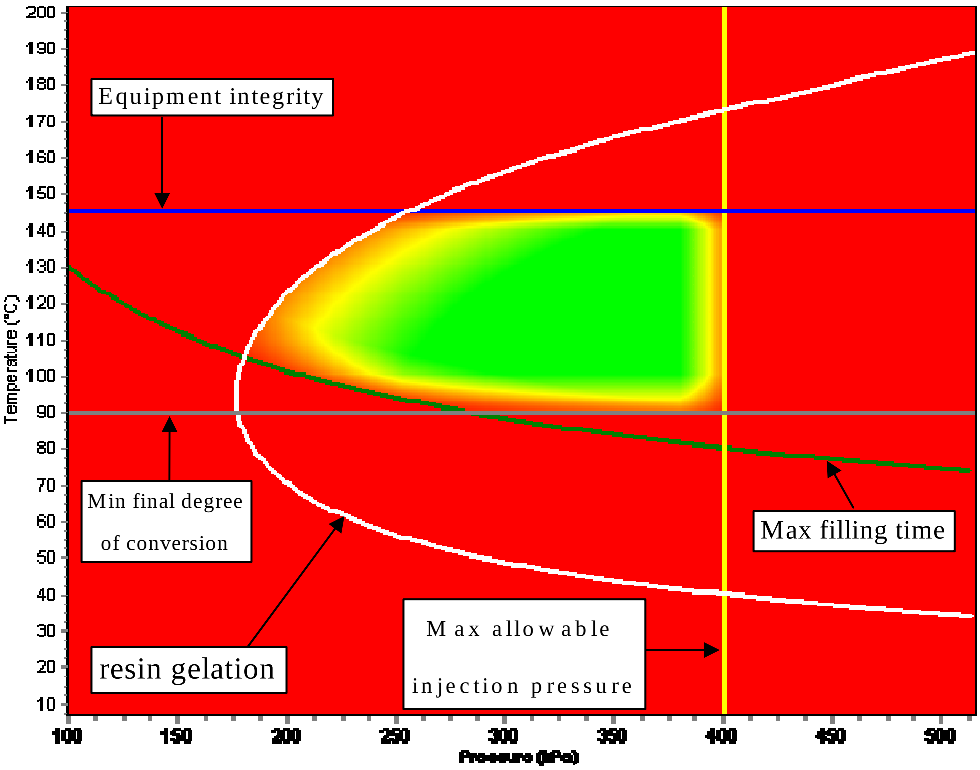

Fig. 1 Moldability diagram.

As shown in Fig. 1, the moldability region of this particular system is bounded by five curves. The system has a maximum temperature of 145°C, given by the mold and a maximum rating pressure of 4bars given by the injection system capabilities. A degree of conversion of 85% was required at the end of processing for mechanical performance. A maximum filling time of 10s was requested since the same injecting system is used for various molds. Finally, the resin used in this test gels at around 30% degree of conversion.

Fig. 2 shows a closer look of the moldability region. Depending on the requirements, many optimal values can be found. The theoretical minimum cycle time is located on the upper-right corner of the chart when the mold temperature and injection pressure are at their maximum values. A safe choice would be a combination of these parameters somewhere in the center of the chart. One interesting point on the chart is the optimal vitrification time where $T_g = T_{cure}$. When using a hydraulic press to clamp the RTM mold, it is preferable to demold the part as quickly as possible and make a post curing treatment elsewhere in order to increase the profitability.

Fig. 3 shows the time needed to reach the vitrification point of the resin as a function of temperature. This curve can be obtained by combining the gel time model of the resin with the glass transition model. Using simple line search method, the optimal vitrification time can be found. All these curves were computed using theoretical values and simplified numerical models that enable real time computation and visualization. Consequently, they do not correspond exactly

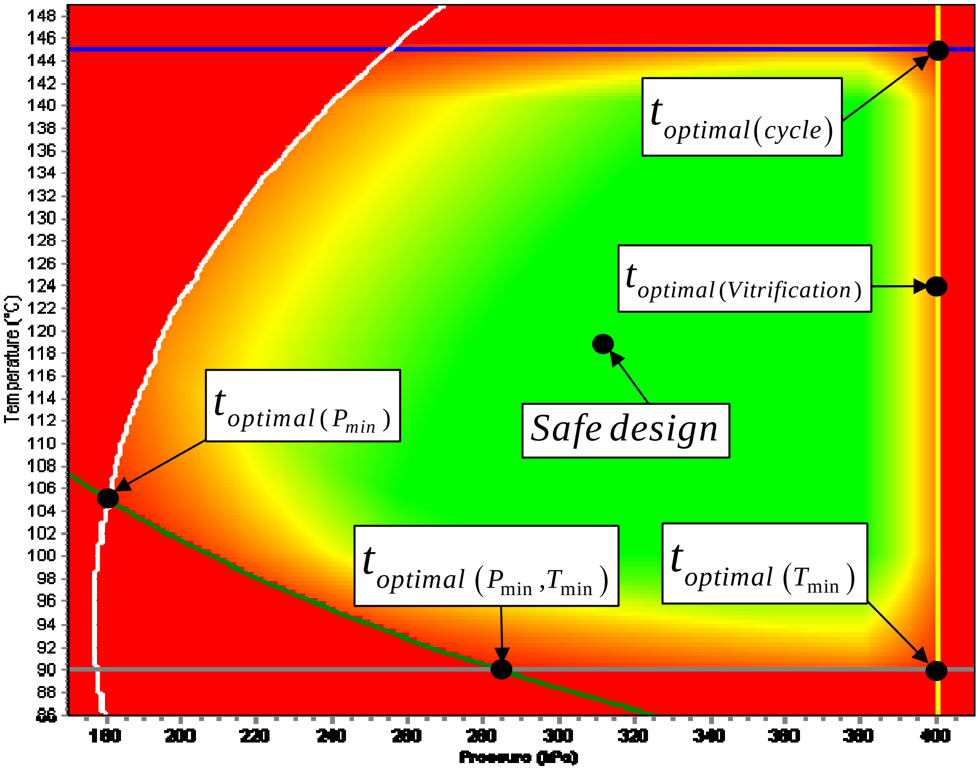

Fig. 2 Moldability diagram.

with the real life moldability diagram. However, they give a clear first attempt of the processing of such part. In order to improve this model, the proposed approach can be coupled to real mold data via thermocouples and heat flux sensors. This will give a better estimate of the real process. Also, the proposed software can be easily linked to PAM-RTM solver [2] in order to obtain a more precise solution of the flow and cure of the specific part to be analyzed.

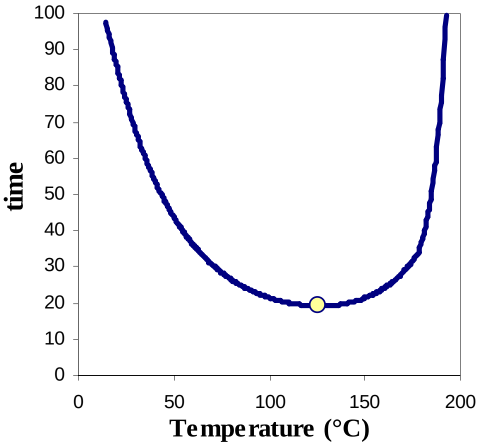

Fig. 3 Vitrification time versus temperature (isothermal curing).

CONCLUSIONS

In this paper, a numerical approach is proposed to simulate LCM processing. A visual software interface was developed to enable users to define and compare different processing scenarios. The *moldability diagram* of the part to be analyzed can be easily constructed from this numerical approach and a fuzzy logic technique. A test case shows the advantage of using the *moldability diagram* to improve the processing of RTM parts. Optimized injection conditions can visually be found according to different criteria.

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