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HIGHLY REACTIVE RESIN VISCOSITY PREDICTION IN LIQUID COMPOSITE MOLDING PROCESSES

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SUMMARY: Recent development of structural composite manufacturing in the automotive industry was dedicated to fast injection and curing of a highly reactive resin during Resin Transfer Molding process for high fiber volume content preforms. This development was carried out for the SuperLIGHT-CAR collaborative Research & Development project. This project is co-funded by the European Commission under the 6th Framework to bring lightweight automotive technologies closer to high volume car production while fulfilling a wide range of automotive requirements in areas such as stiffness, crash performance, fatigue and corrosion resistance. In order to reduce cost and cycle times, prepregs are excluded in the favor of high speed Resin Transfer Molding processes, which can be considered when highly reactive resins with short curing cycle are used. Mixing of the resin system components takes place just before the mold inlet so as to reduce catalyzed resin life time. In order to model injection of such parts, curing kinetics and induced viscosity changes are thus to be taken into account. During on-line mixing of resin components, viscosity and curing rate history are to be considered as a function of the mold filling history. For instance, curing will be more advanced at the flow front than near the inlet. This topic will be discussed here for mixed constant flow rate and pressure injection schemes. A solution that could be implemented in a RTM simulation package was developed and validated first with analytical solution in the case of a simple shape part. Example of the importance of cure kinetics consideration was then conducted on a complex shape automotive part demonstrator manufactured by Alcan Airex with Renault partnership.

KEYWORDS: Resin Transfer Molding (RTM), cure, automotive composites

INTRODUCTION

SuperLightCar is a European project co-funded by the European commission and gathers nine countries for the exploration of material and manufacturing solutions to reduce vehicles weight while fulfilling cost reduction requirements. In this context, the Resin Transfer Molding manufacturing process was evaluated for the production of an automotive part. Resin Transfer Molding is generally known as a long cycle process and reserved to low to medium volume manufacturing batch. The automotive industry is however interested in that technique to develop composite parts. In order to render RTM competitive and highly productive, cycle times need to be reduced by increasing the injection speed and reducing cure cycle, which infers mold heating to reduce resin viscosity during filling and to catalyze polymerization kinetics. A good solution for the injection would thus to have a fast resin cure right after mold filling. Instead of using a trial and errors development, optimization of the process cycle implies accurate prediction of the injection time to ensure complete mold filling before gelling of the resin. During fast injection techniques such as in SRIM processes, viscosity changes are either considered non relevant during the injection stage or mixing of the resin components is previously performed in a barrel [1, 2]. However, before gelling of the resin, polymerization has been initiated, inducing a viscosity increase during mold filling which generally can be expressed as an exponential law [3]. This viscosity increase can greatly affect filling parameters such as filling velocity or internal pressure in the mold, and as a consequence, filling time. The purpose of this article is to propose an algorithm that will take into account resin viscosity evolution during mold filling using an injection simulation code called LIMS [4]. Application of this solution was validated on an industrially produced part with the help of Renault (Car manufacturing, France) and Alcan Airex (composite parts manufacturer, Switzerland).

NUMERICAL IMPLEMENTATION

The consideration of RTM process in the automotive industry implies fast injection cycle through high injection pressure, and also fast curing cycle, so highly reactive resin system consideration, in order to insure a competitive manufacturing cycle. As a consequence, a two component resin system is used with a mixing head located at the mold inlet so that no reaction kinetics is involved prior to injection. Resin components and mold are heated to insure the initiation of the resin polymerization during the filling stage. Because resin system is pre-heated, heat transfer effects at the mold inlet can be neglected. Accurate simulation of the filling stage of this process thus requires the consideration of the resin kinetics through the elevation of the resin viscosity as the mold is being filled. However, because mixing of the two components is performed on-line, resin viscosity is not expected to be spatially homogeneous in the part. The purpose of this paper is to describe two implementation solutions, one for a constant flow rate injection and the second one for a constant pressure injection.

The simulation is considered to be performed with isothermal conditions. In that case, resin kinetics can be described through the evolution of resin viscosity with time for the given temperature. The main issue is thus the implementation of spatial and time viscosity variation during injection. Actually, the first resin droplet injected will remain in the mold longer than the last resin droplet. The part will then cure first close to the mold outlet and then at the mold inlet [5, 6], which also implies that resin viscosity at the mold inlet and that at the mold outlet are not the same. The derived algorithm thus considers the elapsed time spent in the mold for each resin droplet to be able to evaluate the resin viscosity at any time and location in the mold.

If the injection is conducted at a constant flow rate, the travel time of the resin to reach a specific location in the mold is constant during the whole mold filling. The time dependant viscosity can be transferred to a spatially dependant viscosity. However, in the case of a constant pressure injection scheme, resin velocity decreases as the mold is being filled. Tracking of the injected volume is then required.

Constant Flow Rate Injection

Flow in a porous medium is governed by Darcy's law:

$$v = \frac{K}{\mu} \nabla P \qquad (1)$$

where v is Darcy's resin velocity, K is the porous medium permeability, μ is the resin viscosity and ∇P is the pressure gradient in the mold. The LIMS simulation code solves for Darcy‘s equation combined with the mass conservation principle using a finite element and control volume approach.

During a constant flow rate injection with on-line mixing, viscosity will remain spatially constant. In that case, the algorithm monitors the time at which a given location is reached and to update once at each location the viscosity parameter. In LIMS, filling status is given at the nodes, while viscosity is a global parameter. In order to account for different viscosities in the mold, the ratio $\frac{K}{\mu}$ appearing in Darcy's equation is considered as a whole. Permeability is thus the varying parameter during simulation.

At each calculation step, flow front advances in the mold. A time step is calculated and the filling status of the nodes is updated. The algorithm will run a test on the nodes to see if their status has changed during the calculation step. If they are newly filled, the elapsed time since the beginning of the injection is taken to calculate the new viscosity which is updated at the control volume associated with the node. This algorithm is represented in Figure 1.

Constant Pressure Injection

In the case of a constant pressure injection, the travel time of a resin droplet from the inlet to a given location will increase as the flow front advances. The resin travel time is conducted through the tracking of the injected volume quantity. A first injection simulation is performed in order to record the volume injected before each node is filled. During a second injection simulation, for each calculation step and for each node that is filled, comparison of the injected volume with the volume recorded during the first injection allows to define the viscosity change by considering the time taken to inject the considered volume. Figure 2 highlights the main steps of that algorithm.

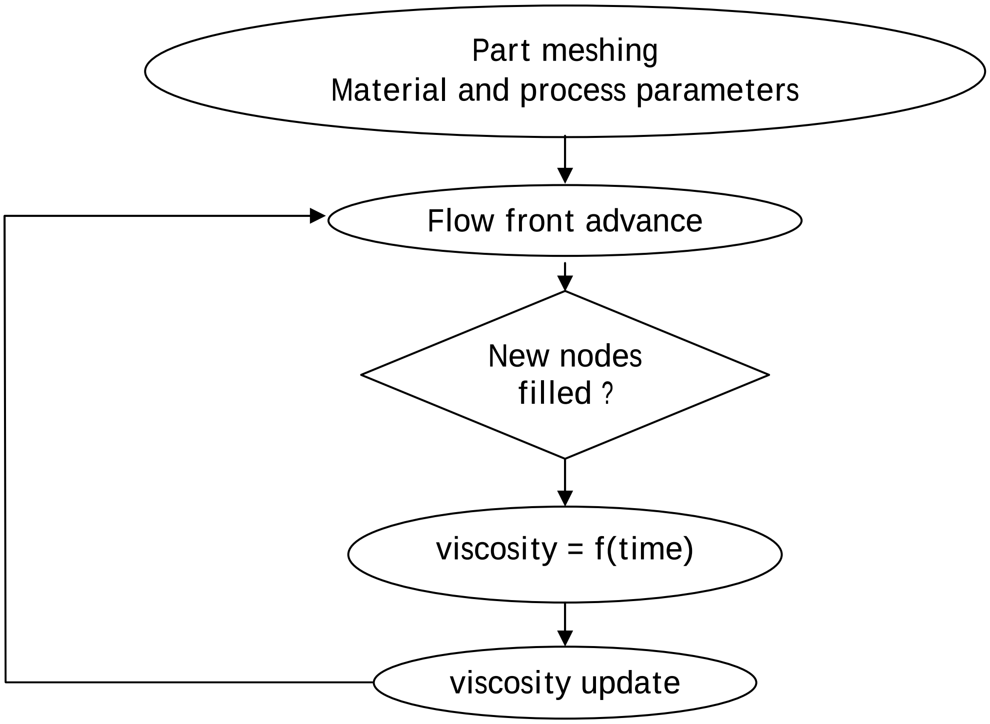

Fig. 1 Constant flow rate injection with on-line mixing algorithm.

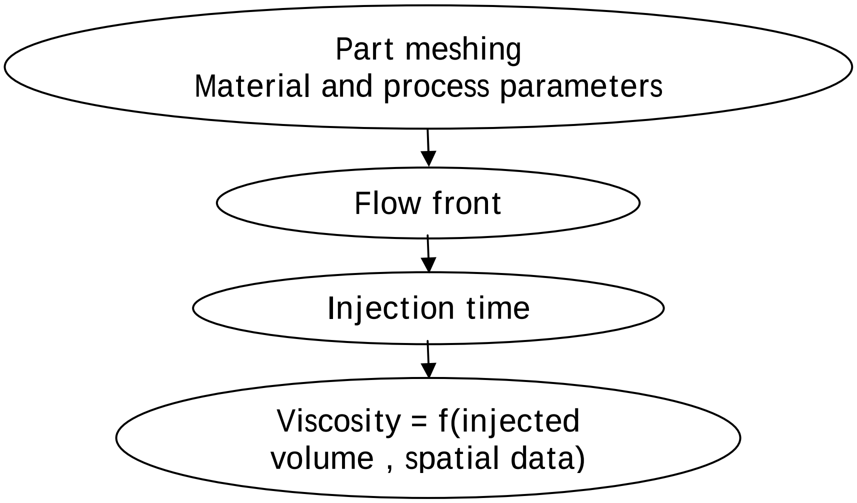

Fig. 2 Constant pressure injection scheme with on-line mixing algorithm.

The two algorithms presented were implemented and compared with analytical solutions. In both cases, total agreement between the numerical and analytical filling profiles was obtained. The numerical code was then applied to the case of an industrial part.

APPLICATION TO AN INDUSTRIAL PART

Implementation of the algorithm for constant pressure injection was used on a demonstrator representing a low B-pillar part using an industrial RTM process. The part is composed of two preforms with an overlapping cross-section. Thus two different thickness cavities are represented in Fig. 3, where the studied part is shown. Prior to simulation of the injection of this part, study was conducted on the mold and preforms definition. Permeability was measured with a linear injection set-up for the different preform configurations used (cavity thickness and preform type). Glass and carbon fiber preforms were studied in this project. It was observed that the carbon fiber preform gave a lower permeability than the glass fiber preform.

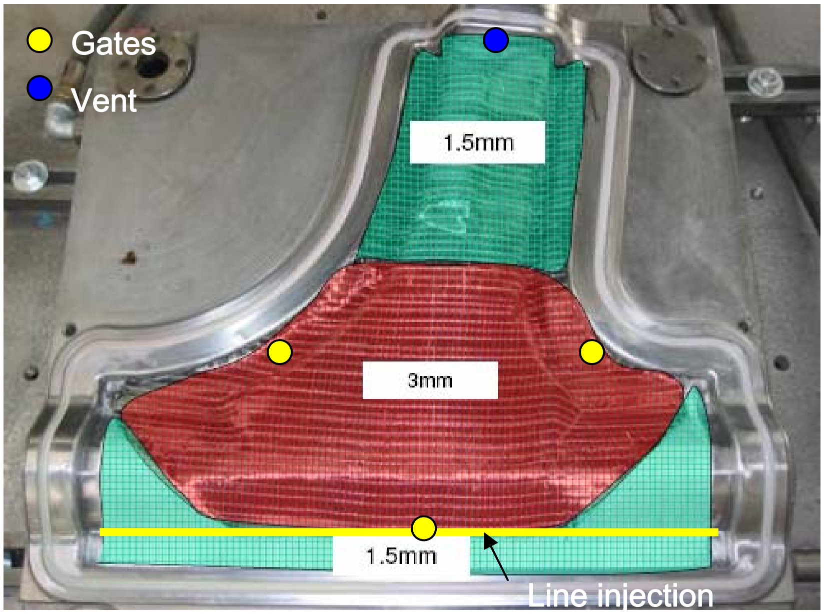

Fig. 3 Thicknesses and gate locations for the demonstration part.

Epoxy system resin characterization was conducted at the University of Peruggia and resin viscosity time history at the injection temperature (80°C) is reported in Fig. 4. Viscosity increases slightly at the resin component mixing and increases rapidly after 40 s.

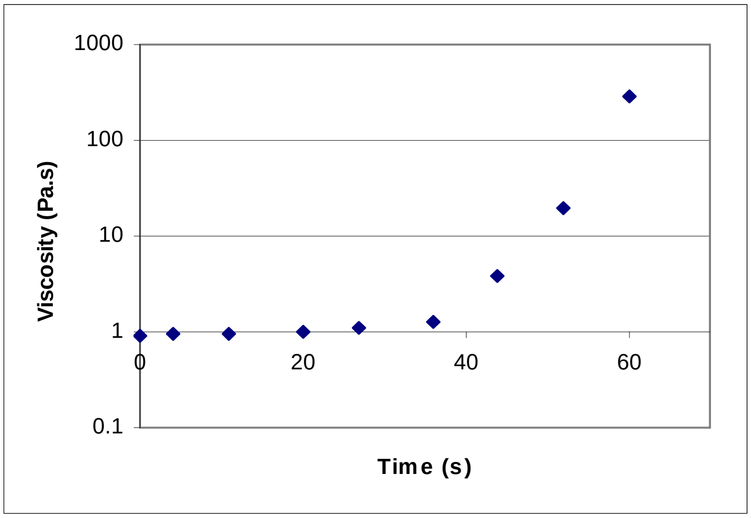

Fig. 4 Viscosity time-history at 80°C of the epoxy resin system.

Injections were performed at a constant pressure of 1 MPa in a mold heated at 80°C. The injection gate is located on a line-injection channel at the bottom of the part while a point vent is located at the top. Two secondary injection inlets are available on each side of the mold and were used for the carbon preform injection. The vent and gates locations are reported in Fig. 3. Two injections were conducted with the glass fiber preform, one until complete filling of the part, and the second one is stopped after 30 s (short shot) in order to compare the observed flow front shape at that time with the one obtained from the simulation. The filling profiles reported in Fig. 5 show that a good agreement was obtained between the predicted and the real injection flow front shapes. Complete filling of the part was obtained after 57 s during trial, while simulation gives a total filling time of 58 s. Figure 6 shows the simulated filling profile in time.

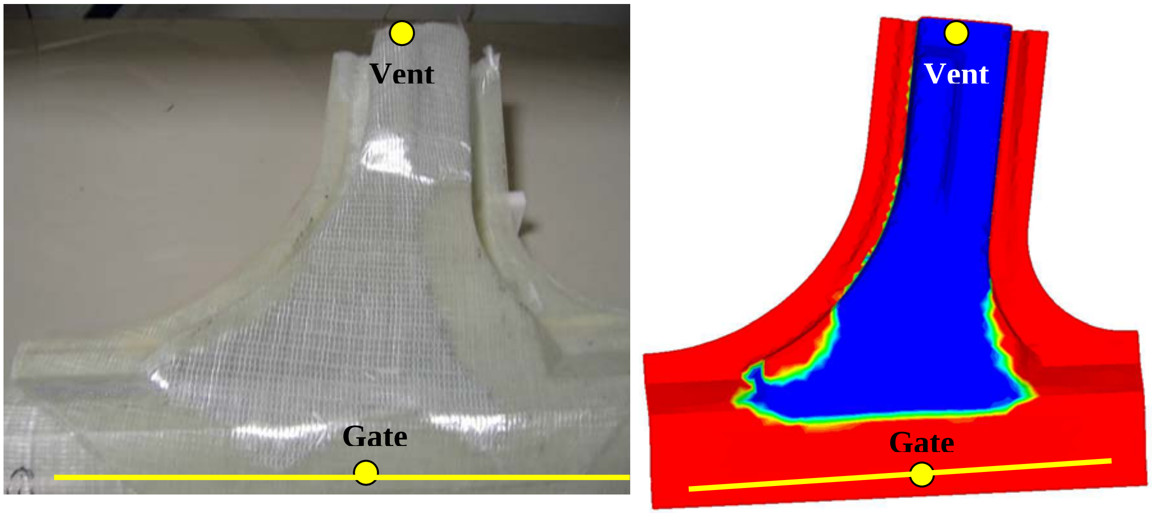

Fig. 5 Filling profile of the glass preform part after 30 s (short shot).

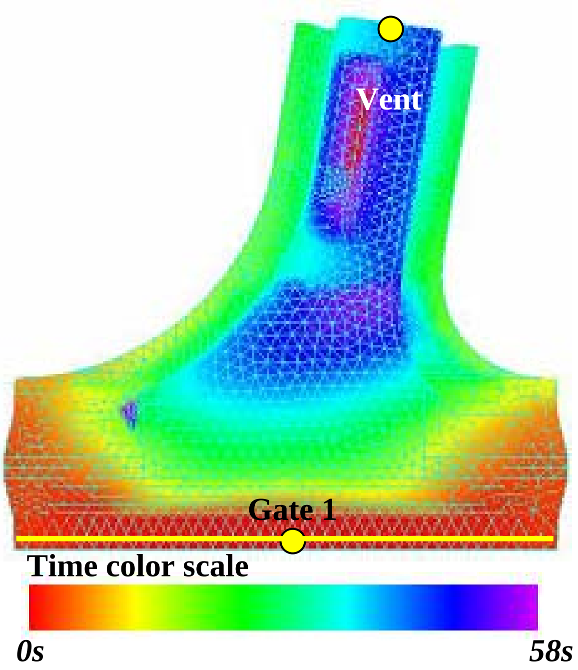

Fig. 6 Numerical filling profile in time (experimental injection time : 57 s).

Injection of the carbon fiber preform was conducted using the line injection and the two secondary injection gates. Because of the low permeability of the carbon fiber preform, injection velocity is slower in this case than in the glass fiber preform case. Injection stopped after 67 seconds, due to the resin polymerization and the viscosity increase. From fig 4, it is easy to see that resin viscosity reaches high values after 67 seconds. The injection pressure at that level is not sufficient to induce a flow front advance. The part obtained is shown in Fig 7 along with the simulated flow profile after 67 seconds. Again, the flow front shape was accurately predicted by the simulation.

Fig. 7 Filling profile of the carbon preform industrial part after 67 s.

CONCLUSION

Simulation of the injection of a highly reactive resin is not straightforward when considering an on-line mixing injection head. Viscosity changes are not spatially homogeneous any longer and should be considered when resin kinetics is involved during the injection phase. This problematic could however be solved using an injection simulation software with a simple algorithm by considering viscosity as a function of time for each mold location. Although development was performed for two injection cases, constant flow rate and constant pressure injections, mixed injection scheme can also be considered by combining the two algorithms. This project proved that the composite solution for structural automotive parts fulfill the automotive manufacturing cycle requirements. Further development of the code would be to consider non-isothermal injection cases, which requires proper resin kinetics modeling as a function of time and temperature, following a Kamal-Sourour model for example [7].

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