PROCESS DEVELOPMENT FOR COMPLEX RESIN TRANSFER MOLDING (RTM) COMPONENTS: OPTIMIZATION OF RESIN INJECTION AND LAMINATE POROSITY

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ABSTRACT: The development of complex RTM components is still time-consuming and mostly based on trial-and-error procedures. Whereas geometrically simple parts might be produced by well-known injection strategies as radial or peripheral injection, complex 3D components demand more advanced injection patterns. Simulation software may support the development of such strategies, but still depends on user experience and human intuition. Moreover, the inclusion of quality relevant criteria such as laminate porosity is hardly possible.

Using an optimization software tool based on Evolutionary Algorithms, an injection strategy for a complex wing nose (leading edge) demonstrator component is developed. Both development process and the resulting injection strategy are compared to the commonly used trial-and-error methods. While a reliable injection strategy cannot be found within a reasonable period by trial-and-error, the optimization software proposes a more robust, reproducible injection pattern within short time. The optimization includes minimizing of voids as well as complete filling of the cavity. The results show that optimization software contributes to efficient process development and might significantly enhance laminate quality.

KEYWORDS: Resin Transfer Moulding RTM, Optimization, Laminate quality, Resin injection, Evolutionary Algorithm

INTRODUCTION

Today, RTM is most commonly used for the manufacture of relatively simple, shell-like structures. These components allow basic injection strategies like radial, peripheral or single line injection [1] that deliver adequate laminate quality and reproducible, complete filling. In the future, RTM will complement and substitute traditional autoclave processes, with the objective of manufacturing complexly shaped, high quality parts. The process development tools and injection strategies available today do not offer the necessary means to reach that target [2].

RTM PROCESS OPTIMIZATION USING EVOLUTIONARY ALGORITHMS

Simulation and optimization substitute long-term trial-and-error procedures, which require the manufacture of a large number of prototypes. These processes are transferred to a virtual test environment. The best resulting set of process parameters is then implemented in the manufacturing process. The optimization contributes to shorten development time: instead of trying multiple filling patterns in a repeated trial-and-error optimization process, the choice of input parameters is transferred to an Evolutionary Algorithm engine, which can evaluate a nearly unlimited number of input parameter sets and find the best solution: The long and unreliable trial-and-error approach (Fig. 1, left hand side) is replaced by a systematical approach which assures the finding of an optimal input parameter set (Fig. 1, right hand side).
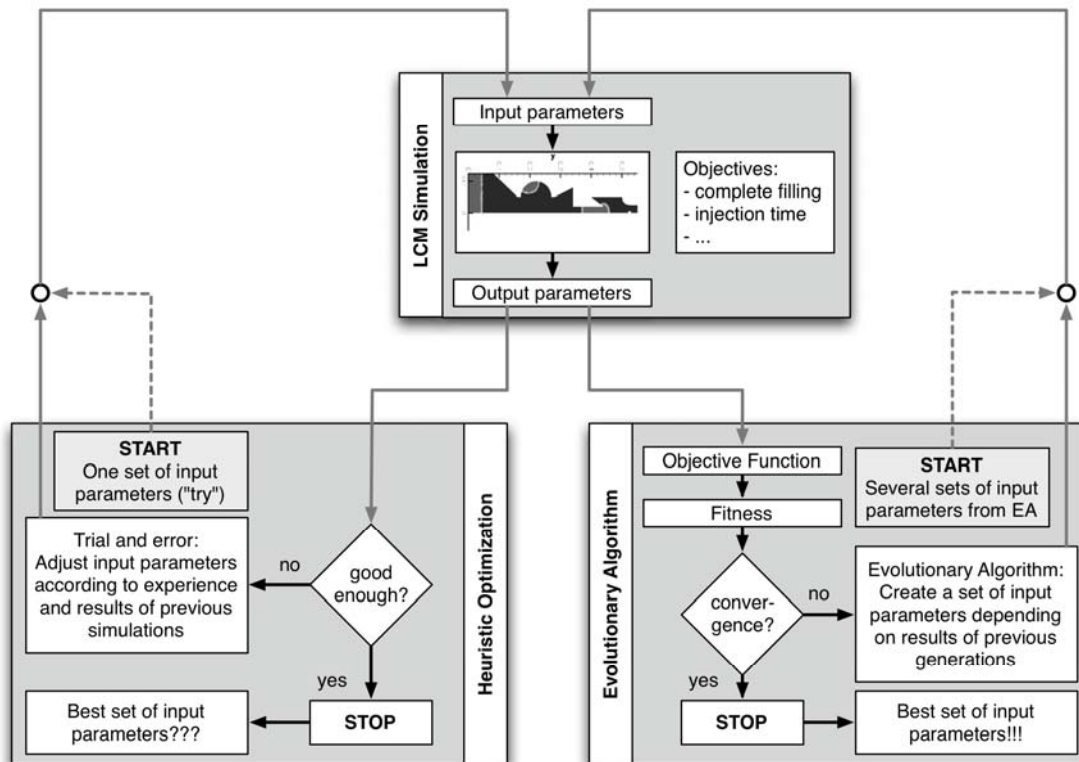

Fig. 1 Comparison between trial-and-error and evolutionary optimization

Systematic RTM process optimization using Evolutionary Algorithms or other stochastical optimization methods mainly include optimization of the filling process (process time, fill grade) at the moment. The optimization either approaches the early process design by searching an appropriate placing of gates and vents and/or adjusts timing and pressurization (or volume flow) of the gates, or a combination of both. Up to now, the main objectives of RTM optimization have been complete cavity wet-out and shortest possible filling time, but other important process parameters such as flow front velocity or filling pattern have been ignored. For the use in structural applications, the laminate quality would be an important optimization objective, but this requires the inclusion of such effects into the simulation and optimization code. Ruiz et al. [3] and Leclerc and Ruiz [4] presented an approach to optimize the injection flow rate and thus minimize porosity, based on the average modified capillary number at the flow front. The Centre of Structure Technologies has developed a RTM simulation and optimization tool (eoLCM) which is capable of optimizing the classical parameters filling time and wet-out, but additionally provides criteria for laminate quality optimization based on flow

front velocity and converging flow fronts. This tool is tested on a complex geometry, to quantify the benefits of the optimization in terms of process development, cavity filling, reproducibility and part (laminate) quality.

PROCESS DEVELOPMENT FOR A WING NOSE IN RTM

A wing nose (Fig. 2) is chosen as demonstrator component. Normally, the wing nose consists of several components riveted together. In this case, it is possible to produce a wing nose including the planking in just one step. This requires the removal of (lost) cores, which are used during production, or the integration of an inflatable bladder.
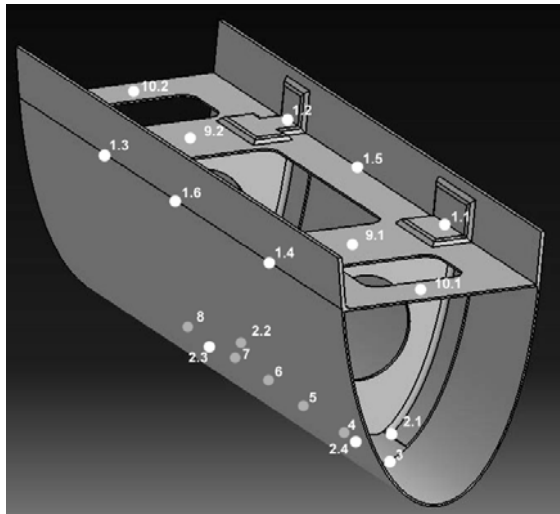

Fig. 2 Wing nose component with potential injection gates

As Fig. 2 illustrates, the development of an injection strategy for the wing nose is difficult. It is assumed that permeability and viscosity of the resin are known and constant. However, zones of different permeability and race tracking channels are likely to occur. Race tracking at the edges of the mold are a stochastic problem (from the optimization point of view), whereas race tracking on joints between planking, stringers and spar are predictable to some extent. Two different approaches for an injection process development are analyzed and compared: (1) Trial-and-error process development, where an injection process is developed solely by human intuition and then verified by the simulation software. This is done until satisfactory filling is reached. (2) Purely optimization based process development, where the injection process is developed by the optimization software based on some specifications (maximum injection pressure, pot life of the resin, additional constraints) given by the user.

Trial-and-error process development

The basic idea of the gate placement shown in Fig. 2 is to fill the cavity from bottom to top in a sequential manner. This is the starting point to develop an injection strategy. The leading edge gates (No. 3-8 in Fig. 2) start first, followed by the planking gates (2.1-2.4) and eventually by the spar gates (9.1-10.2). It is assumed that race tracking will occur at all joints of the wing nose, and an equivalent permeability model [5] is used in these zones. However, due to these introduced race tracking channels, the development of an appropriate injection strategy is not obvious. Mostly, the race tracking

channels lead to large-scale dry spots, because different flow fronts converge along the channels. After more than 20 iterations, a fill grade of approx. 90% can be reached in the simulation software (Fig. 3, left hand side).

Process development using Evolutionary Optimization

Instead of trying multiple injection strategies using simulation software, the task of applying a set of input parameters is handled to an optimization engine [6]. Each generation of input parameter sets (injection pressure, gate timing) is evaluated based on an objective function, the fitness value is calculated and the next generation is created through crossover and mutation of the best individuals of the precedent generation. This assures the finding of an optimal input parameter set after reaching a pre-defined convergence criterion (e. g. 20 generations of equal fitness). The optimization objectives include the following parameters: Fill grade, flow front velocity, flow front confluence length and flow front confluence angle. The proposed filling pattern is illustrated in Fig. 3 (right hand side).
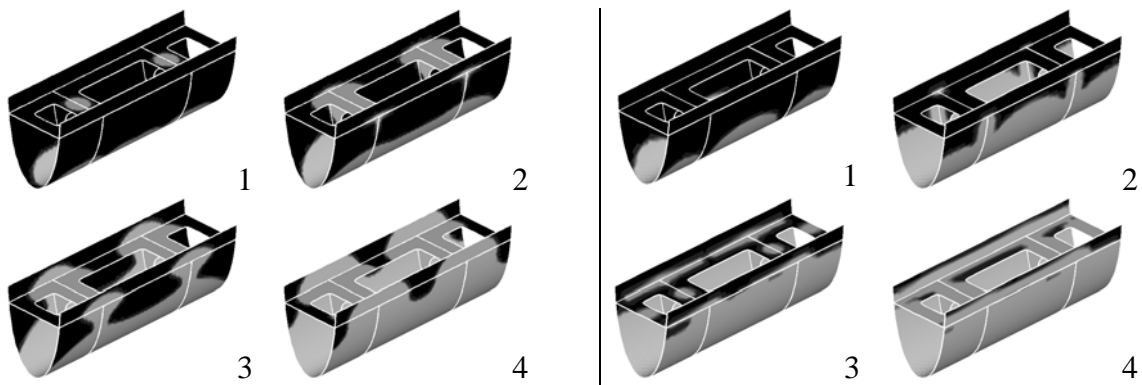
Fig. 3 Comparison of trial-and-error (left hand side)
and Evolutionary optimization (right hand side)

CONCLUSIONS

The process development greatly benefits from the use of optimization software: Development time is significantly reduced – the optimization of the wing nose injection strategy takes place in less than 24 hours – the trial-and-error development of injection strategies needs several days and does not implicitly lead to an optimal injection process. Experimental investigations including the manufacture of several wing noses have shown that the reproducibility is better with the optimized injection strategy. However, although complete filling of the cavity was reached based on the optimized injection strategy, minor disturbances in permeability or race tracking (differing from the assumed values in simulation/optimization) might influence the filling procedure and thus render a part unusable. Therefore, the simulation/optimization code should include stochastic variations of preform permeability.

The enhancement of the laminate quality in terms of porosity is one of the optimization objectives. The porosity of the produced wing noses is measured in different part zones using micrographic images, to compare the trial-and-error and the optimized injection strategy and to quantify the potential benefits of the optimization. Table 1 illustrates the results of the micrographic image processing and shows the general benefit by using the optimization software. However, with the optimized strategy, the upper zone of the

planking is filled at last and the flow front stops after reaching the flash face. With the trial-and-error strategy, the spar gates start earlier and lead to a flushing of the upper planking zone, thus air bubbles agglomerated in the flow front are pressed towards the vent. After the flash face is sealed, the remaining pressure compresses and mobilizes the air bubbles, which are further pressed towards the top of the mold. This explains the significantly lower porosity (<2%) of the upper planking zone in this case. Therefore, it is important to use after pressure or the packing and bleeding process.

Table 1 Compared average porosity [%] between trial-and-error and optimized process

Inj. strategy	Planking, near gates	Planking, near stringer	Stringer	Planking, near spar	Spar
Trial & error	9.04	10.08	3.95	1.88	9.01
Optimization	4.71	4.56	5.65	9.41	8.44
Benefit opt.	48%	55%	-43%	-400%	6%

Regardless of the porosity of the samples, a complete filling has only been reached after using the optimized injection strategy. Obviously, combining Evolutionary optimization as first step and interpretation by human intuition as second step leads to a reliable injection process.

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