A PROCESS ESTIMATOR FOR THE RTM PROCESS

B. Eck[a*], S. Comas-Cardona[a], C. Binetruy[a], C. Aufrere[b]

[a] *GeM, UMR 6183, Ecole Centrale de Nantes, 1 rue de la Noë, 44321 Nantes CEDEX 3, France*
[b] *Faurecia Group, 2 rue Hennape, 92000 Nanterre, France*
**benedikt.eck@ec-nantes.fr*

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Abstract

In this study the multi-objective optimization of a fiber reinforced composite part as a function of its mass, mechanical properties and manufacturability with the Resin Transfer Moulding process is presented. To verify the manufacturability a method for a fast, semi-analytical filling time calculation was developed, which takes into account the local material parameters. This shall be an example of a new notion, the Process Estimator which is a fast estimation of main process characteristics based on the features of the local microstructure. The presented study will compare results excluding and including processability.

1. Introduction

The automotive industry is nowadays constrained to reduce the consumptions and emissions of the produced cars. Weight reduction via the use of new materials, as fiber reinforced composites is one way to achieve this. Due to their better ratios of material properties to density, especially when using anisotropic designs, they allow weight saving in comparison to steel or aluminum parts [1].

The main disadvantage of composite materials is their high purchase costs. As in the automotive industry the possible rise in prices for a lighter version of a part is small, the more expensive material must be used in an optimal manner. This can be done by the integration of the functions of several metallic parts in a single, larger and more complex composite part. Another important way is the use of designs with anisotropic stacking sequences in order to benefit at most of the originally anisotropic material.

The mechanical simulation and optimization of parts with anisotropic stacking sequences is possible with commercial software packages. Though, the part design can also influence the cost efficiency of the manufacturing process and the cycle times, especially when producing parts in mass production. One process adapted for a composite part production with high cycle times is the RTM-process with fast curing polymers. This process can induce long distance resin-flow. These are strongly influenced by the features of the local microstructure which is, amongst others, dependent of the stacking sequence. In case of a pressure driven injection, the resin flow drives the filling time, which is a major component of the cycle time, crucial in high series production. So it will be necessary to consider the manufacturing process during a mechanical part optimization in order to avoid the design of parts, which are economically not producible.

Despite the high impact of the process on the cost effectiveness, the most common approach in the design of composite parts consists of only optimizing the part with regard to its mechanical performance. Once the optimal result obtained, the process is simulated. In the case of disadvantageous process simulation results, the mechanical optimization will be done again with further auxiliary conditions [2, 3], see Figure 1 on the left.

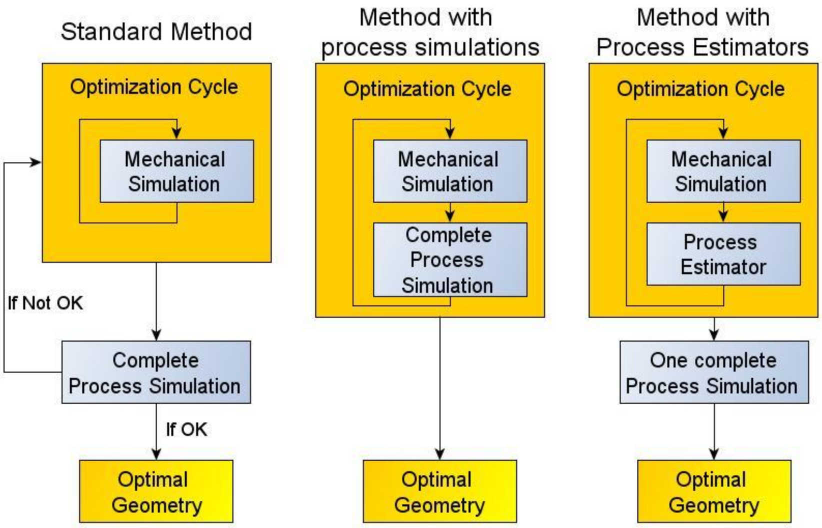

Figure 1 : Approaches to couple mechanical and process optimization

In other studies, methodologies are presented which are coupling a mechanical simulation directly with a complete process simulation in an iteration step [4], central scheme in Figure 1. The process simulation is generally done with a Finite Element model in which the features of the local microstructure can be considered. The disadvantage of this approach is that the CPU time can dramatically increase when applying this method to complex and finely meshed parts.

Some simple models exist which would allow a fast process simulation [5-7] and are sometimes already used in the optimization of composite parts [8, 9]. The major drawback of these methods is, that due to the simplification, the local microstructure is not considered. So, for complex parts, the results of these methods can differ largely from the reality.

In this work a new method for the process calculation during an optimization, a Process Estimator will be introduced. The first main characteristic of a Process Estimator shall be that such a method takes the features of the local microstructure into account. The second peculiarity will consist in the rapidity of calculation. The latter shall lie in the order of some seconds to some minutes.

Due to these two characteristics a Process Estimator can perfectly replace a complete process simulation during an optimization calculation. Based on this principle, a Process Estimator for the RTM process was developed and will be presented hereafter. It will be illustrated by the design optimization of an example part.

2. Theory

2.1. A Process Estimator for the RTM process

As aforementioned, it will be important to know the manufacturing cycle times for a part to evaluate its cost effectivity during mass production. Therefore the goal of the presented Process Estimator for the RTM process will be the calculation of the cycle time. The latter will have two predominating components, the resin filling and the resin curing time. As the part design has no major influence on the curing time, Process Estimator will concentrate on the calculation of the filling time of the part with resin.

Mesh distance-based approximations of the filling time were proposed in [5, 6] for the optimization of the injection strategy. Estimating the filling time rapidly, the drawback of these approaches is their limitation to parts without variations of the local microstructure. The application to an example as in Figure 2 on the left hand side would predict one of the external blue nodes (A, B) as last filled nodes. Nevertheless, when considering the local permeabilities, the last filled node can be recognized as the yellow corner (C).

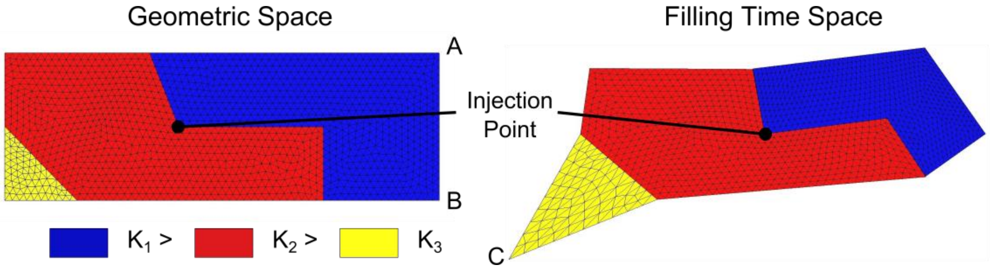

Figure 2: Space transformation

As shown in this example, a space transformation from the geometric space to a filling time based space will be necessary. To do such a space transformation, iterative equations based on Darcy's Law [10] have been developed [11]. These equations are applicable in domains with piecewise constant permeabilities K_i and porosities ϕ_i, as for examples in discretized domains with Finite Element Meshes. The index i refers to the edges of the elements of the mesh of the resin streamline. The presented equations were developed for a constant injection pressure P_{inj} and will help to calculate the filling time of the part.

For a 1D domain the total time t_{tot} the needs to cover the length of a streamline can be calculated as the sum of the filling times t_i of its segments:

$$t_{tot} = \sum_{i=0}^{L} t_i \tag{1}$$

$$t_i = \frac{\mu}{P_{inj}} \cdot \left(b_{i-1,lin} \cdot d_i + \frac{d_i^2 \cdot \phi_i}{2 \cdot K_i} \right)$$

$$b_{i,lin} = b_{i-1,lin} + \frac{d_i \cdot \phi_i}{K_i} \quad \text{and} \quad b_0 = 0$$

where μ is the viscosity and d_i is the length of the actual segment i.

With this analytical formula it is possible to transform the geometrical space (domain represented by the geometry of the part) into a filling time space. Then, in the filling time space, Dijkstra's Algorithm [12] can be used to extract the last node to be filled of a complex part. The calculation time of this method is very low, as it consists of one analytical calculation for every element edge plus one execution of Dijkstra's algorithm.

Although simplified and CPU efficient, this method takes the local microstructure into account in order to have realistic results for complex parts and is therefore a Process Estimator.

2.2. Optimization examples

To be able to use this Process Estimator, a stacking sequence optimization program has been implemented in Matlab®, based on the CMAES (Covariance Matrix Adaptation Evolutionary Strategy) optimization algorithm [13]. The main optimization goal will be the weight minimization of the part. Other possible optimization goals are for example the manufacturability, tested with the Process Estimator or the resistance to mechanical load cases, calculated in LS-Dyna.

Figure 3 gives the geometry of a part used in this study which is meshed with 22085 nodes and 21697 Quad-4 elements, corresponding to an element size of 2mm. The mechanical load case will consist of a tensile load on edge a in the x-direction while the edges b and c are constrained.

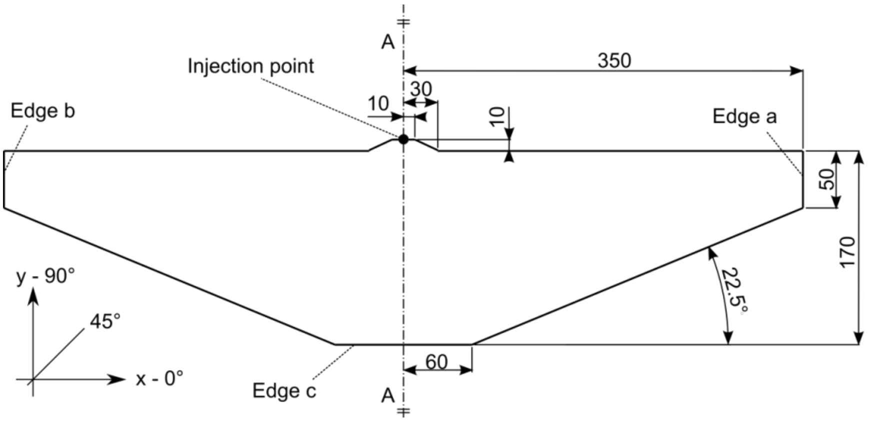

Figure 3: Sketch of the example part (dimensions in mm)

The results of two different stacking sequence optimization scenarios will be presented hereafter. In a first scenario the process is neglected during the optimization and a second where the manufacturability will be evaluated using the proposed Process Estimator. The optimizations of these examples will be done on a standard laptop with 4 CPU's (2.4 GHz) and 4 GB RAM. Once the optimization completed, the part filling time will be calculated using the commercial software PAM-RTM.

3. Results

Table 1 contains the results of the two optimization scenarios. The difference between the optimal stacking sequences of the two solutions is rather small. For the optimal solution which takes the process into account, only a 0° ply was replaced by a slightly thicker 90° ply. This small modification nevertheless helps to reduce the filling time by 39% (from 88s to 54s) while the part mass is increased by less than 17%.

Run	**1**	**2**
Optimal stacking sequence	$\begin{bmatrix} 0° & 0.25\ mm \\ 22.5° & 0.125\,mm \\ -22.5° & 0.125\,mm \\ 0° & 0.125\,mm \\ 0° & 0.125\,mm \end{bmatrix}_s$	$\begin{bmatrix} 0° & 0.25\ mm \\ 90° & 0.25\ mm \\ 0° & 0.125\,mm \\ 22.5° & 0.125\,mm \\ -22.5° & 0.125\,mm \end{bmatrix}_s$
Total mass	$221.5g$	$258.4g$
RTM filling time, calculated with PAM-RTM	$89s$	$54s$

Table 1: Results of the optimization scenarios

For 22085 nodes in the mesh, the Process Estimator CPU times were between 40s and maximal 100s. This is small compared to a mean CPU time of about 25min, needed to calculate the filling time of the same part with PAM-RTM, a commercial software package. This time still neglects supplementary CPU times arising for example in the mapping of the material parameters on a second mesh. The use of PAM-RTM instead of the Process Estimator would have increased the overall optimization CPU time to some 116h for about 100 iterations during the optimization. This would be more than 70% higher than the overall CPU time using the Process Estimator which is about 65h and which consists mainly of the CPU time for the mechanical simulations.

4. Conclusion

Cutting the injection filling time by 39% in the example part demonstrates the importance of considering the process when choosing a part design. Of course parts with balanced in-plane dimensions and isotropic loadings will lead to optimal stacking sequences less influenced by the process. However, small design-changes can still improve or worsen the manufacturability of these parts.

A good method to evaluate the RTM processability while choosing a design, for example during an optimization, is the Process Estimator, presented in this paper. Due to the simple formulation, the filling time of even complex parts and large meshes, as in the example part

(0,085m^2) with 22085 nodes, can be calculated in about one minute. So the meshes, created in the automotive industry for mechanical simulations and optimization, can be used directly for a process simulation during an optimization without an explosion of the CPU time. The rapidity of the Process Estimator is reached despite the fact, that the features of the local microstructure are considered in the calculation which is necessary to estimate the filling time of complex parts without large errors.

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