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Multi-objective composite part mechanical optimization enhanced by a Process Estimator

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ABSTRACT

In this study the multi-objective optimization of a fiber reinforced composite part will be presented. Additionally to the weight and the mechanical properties, its manufacturability with the Resin Transfer Molding process is considered during the optimization. For the last mentioned, a new CPU-time efficient method, called Process Estimator, was developed. Based on the local material parameters it allows to calculate the filling times of complex and fine meshed parts with varying permeabilities and porosities in some seconds to minutes. The rapidity of the method will be illustrated with the help of three example parts. These examples demonstrate the importance of the process consideration during a mechanical design optimization.

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 polymer 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].

For the automotive industry, these materials hold two main challenges. Firstly, few processes will permit the production with high cycle times of about one minute, adapted to the mass production of cars. One process having the potential to achieve such cycle times is the Resin Transfer Molding with fast curing polymers.

The second main disadvantage of fiber reinforced composites is their high raw material cost. In the automotive industry, the possible rise in prices for a lighter version of a part is small. A more expensive material must therefore 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. Furthermore designs with anisotropic stacking sequences are advisable in order to benefit at most of the originally anisotropic material. An endless number of possible stacking sequences exist. For example, the ply number, the orientations of every ply and the nature of materials can be varied. Hence the optimization of the stacking sequence is necessary to choose the optimal design adapted to the specifications.

Already implemented in commercial software packages, the most common approach to optimize such anisotropic stacking sequences is a weight optimization considering mechanical load cases and eventually design rules. Once the optimal stacking sequence determined, the manufacturability of this design will be tested by a subsequent process simulation [2,3]. If the part cannot be produced efficiently, for example by exceeding maximum cycle times, another optimal design must be determined by rerunning the optimization with supplementary auxiliary conditions, Fig. 1(a).

Other methodologies propose the coupling of a mechanical simulation with a complete process simulation in an iteration step to avoid such cascades of optimizations, Fig. 1(b) [4,5]. The CPU time of the Finite Element based process simulations are generally high for complex and fine meshed parts. Thereby the implementation of such solutions in an optimization cycle can dramatically increase the total optimization time.

In order to avoid high CPU times, manufacturing constraints [6] or simplified models [7–9] can be used for the optimization of composite parts [10–12]. Nevertheless, such approaches are limited to simple parts. Variations of the local microstructure, induced during forming, cannot be taken into account. Therefore the predictions of these methods will differ largely from the reality for complex parts.

In this work a new approach, the use of a Process Estimator, will be proposed, Fig. 1(c). Within the optimization loop, a complete

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process simulation is replaced by a fast process evaluation, as it is done in the last-mentioned approaches. Although simplified and CPU efficient, the Process Estimator takes the local microstructure into account in order to guarantee realistic results for complex parts. The approach will be illustrated hereafter by design optimizations using a Process Estimator for the RTM process.

The general principles of a Process Estimator are detailed in Section 2.1. The next Section 2.2, presents the Process Estimator for the RTM-Process, implemented in an optimization cycle, see Section 2.3. Hereafter three example parts are introduced in Section 2.4. In the last section before the conclusions, Section 3, the results of stacking sequence optimizations with the example parts will be compared. For every part, two scenarios are presented. An optimization run without process considerations will be opposed to one where the manufacturability by RTM is taken into account via the RTM Process Estimator.

2. Theory

2.1. Definition of a Process Estimator

In this article, a new notion for methods linking the process optimization with a mechanical optimization is proposed. It is based on the wish to evaluate the manufacturability of a part in some seconds or minutes and thus to be able to compare easily different part designs and processes. To guarantee the rapidity of the evaluation, only the cost-driving process characteristics like cycle time, necessary machinery or material waste shall be estimated via approximations and simple calculations, admitting small errors.

Besides the rapidity, the second desired characteristic consists in an automatic consideration of the features of the local microstructure. Industrial parts generally have rather complex geometries with a varying local microstructure, as continuous fibers must fit complex shapes. Fig. 2 shows with an example cross-section that the geometry has a large influence on the microstructure. In zone B, the fiber volume fraction is higher than in zone A. So the mechanical properties in zone B will be higher than these in zone A. On the other hand, when injecting resin in the fibrous preform, the resin flow velocity in zone A will be higher.

This example demonstrates that the local microstructure, imposed by design, can have an ample influence on the manufacturability of the part. Therefore it is important to consider this microstructure during process and mechanical simulations to avoid important errors in the approximations of the main process characteristics of complex parts.

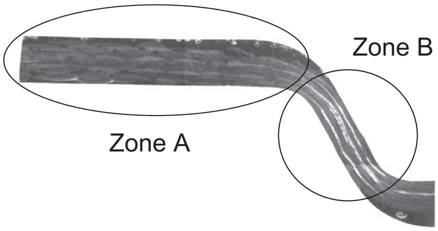


Fig. 2. Automotive microstructure.

The method will replace a full process simulation for example in optimization calculations or in preliminary studies. It gives an evaluation of the process costs of a design with a specific process. Thus different designs and production processes can be compared with this method and the best one can be selected.

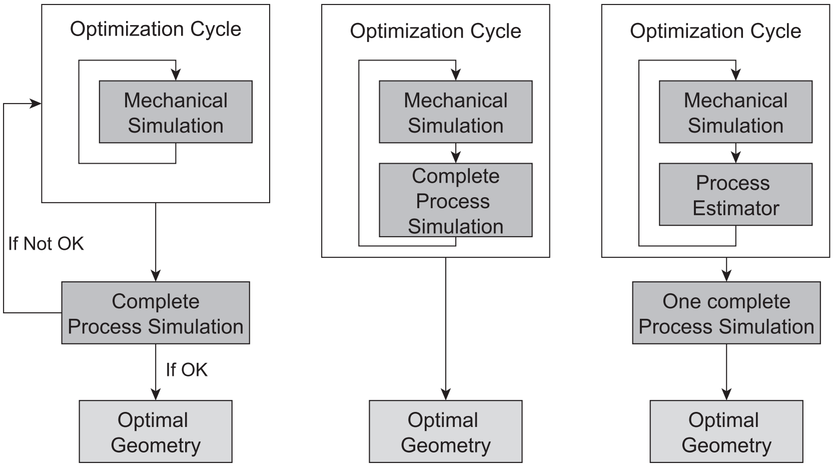
Hereafter this method is called Process Estimators.

2.2. A Process Estimator for the RTM-process

As aforementioned, a process allowing to achieve automotive cycle times is the Resin Transfer Molding process. It can roughly be separated in three phases: preforming of the dry fiber mats, injection of the resin and polymerization/curing of the injected resin. With an automated process, the necessary time to preform the dry fabrics will be independent of the chosen stacking sequence and is therefore neglected in this work just as the curing time. The latter is neglected as it depends mainly on the chosen resin. Hence the presented Process Estimator will focus on the estimation of the main process parameters of the injection phase.

The injection can be realized at a given injection pressure or injection flow rate, which implies a given injection time. Here the injection pressure is kept constant and the filling time is calculated. However, following this approach, a Process Estimator for the injection flow rate driven RTM-process could also be developed.

Analytically, the resin flow in a fibrous preform can be described by Darcy's Law [13]:



(a) Optimization without process consideration
(b) Optimization with process simulations
(c) Optimization with Process Estimators

Fig. 1. Different optimization approaches for complex parts.