AUTOMATED CONTINUOUS FABRICATION OF LOAD-PATH ADAPTED THERMOPLASTIC FIBER PREPREGS

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Abstract

Due to the lack of suitable production processes, most up-to-date composite components show a rather simple shell design with constant laminate build-up. Such designs are also known as “black metal” and lead to high costs and incomplete material utilization. In contrast, a special load-path adapted design with a high utilization of deployed materials can increase the lightweight degree and reduce costs at the same time.

This paper proposes a first practical approach to provide the automated continuous fabrication of load-path adapted thermoplastic fiber prepregs in a calendaring process. For the complete impregnation of the textile, additional matrix is added in powder form in order to ensure a homogenous fiber volume ratio. An adjustable powder application system is proposed, which can be directly integrated into the calender and is able to follow the load-path adapted design routes provided as continuous semifinished material.

A sensor-driven control strategy for the application module is presented in order to cope with the challenge of synchronization of the conveyed semifinished textile with the positioning and powder dosing mechanisms of the application system.

1. Introduction

Fiber reinforced polymers (FRP) have recently moved into the spotlight for designers of future automobiles since they allow for weight reductions of up to 30 % compared to aluminum and 70 % compared to steel components [1]. However, current lightweight solutions cannot compensate for high material and manufacturing costs. Due to the lack of adequate production processes, most up-to-date automotive composite components show a rather simple shell design with constant laminate build-up. Such designs are also known as “black metal” and lead to high costs and incomplete utilization of the material potential due to resource waste. The application of unidirectional carbon fiber rovings for load-path adapted designs is able to enhance material utilization while adding reinforcement functionalities [2]. In order to make this technology available for the fabrication of structural components in automobile, it must be shifted to large scale production.

At Open Hybrid LabFactory (OHLF) in Wolfsburg, multiple research cooperations of private and public partners aim at providing large scale production technologies for hybrid lightweight construction. For maximum productivity, a roll-to-roll process offers the most potential with regard to large scale production, due to continuous material flow. A promising approach to impregnate flat textiles isobarically with a thermoplastic matrix is the isobarical single-stage calender impregnation process, developed in the scope of the project “KadiText” at OHLF. Results from the corresponding project “KonText” at OHLF provide the process technology for fabrication of load-path adapted hybrid textiles (see Figure 1). However, the focus of this paper is on the project “ProText”, which combines the textile fabrication and calendaring processes and therefore focuses on the automated continuous fabrication of load-path adapted thermoplastic fiber prepregs.

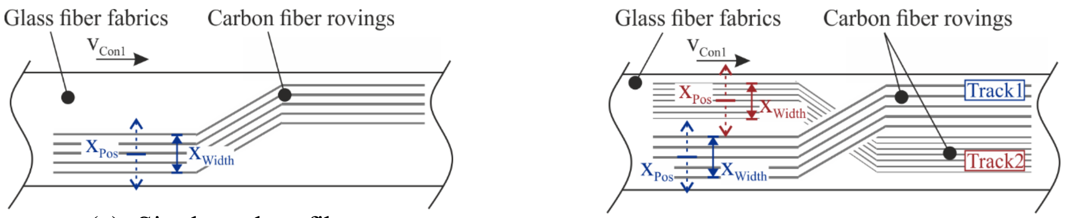
The biggest challenge for the continuous fabrication of load-path adapted prepregs is to avoid local asymmetries caused by gradients of fiber volume which can lead to a deflection of composite parts similar to resin-based composites [3–5]. Additionally, fiber washing due to local pressure differences can occur. Therefore, in order to ensure a constant fiber volume ratio and complete impregnation, it is necessary to apply additional matrix material to the load-path reinforcement fibers.

Figure 1. The load-path adapted fabrics can be fabricated at an arbitrary geometrical complexity

For the application of additional matrix to the semifinished textile material, the application of polymer foil or integrated matrix extrusion in a continuous impregnation process are generally possible methods. However, the potential design complexity of the semifinished textiles, which can be fabricated with a new warp offset technology at OHLF (see Figure 1), can be arbitrarily high. Foil application or integrated matrix extrusion do not offer the capability to apply matrix at such a high geometrical complexity. Therefore, in the scope of “ProText”, one main objective was to identify an adequate matrix application method, which is able to apply matrix to the semifinished textile at the possible level of geometrical complexity.

2. Boundary Conditions and Simplifying Assumptions for the Design Process

In the scope of “ProText”, the design complexity for the above depicted load-path adapted fabrics was reduced in such a way, that multiple carbon fiber rovings are merged to an area that has a distinct orientation, width x_{Width} and position x_{Pos} relatively to the conveying direction (see Figure 2a). Analogous, there can also be two crossing tracks of carbon fiber areas (see Figure 2b).



(a) Single carbon fiber area

(b) Two crossing carbon fiber areas

Figure 2. The carbon fiber rovings are merged a single track or two crossing tracks (schematic)

This leads to the simplification that the matrix material must be applied in a planar manner. In addition, the matrix application system must fit into the geometrical boundary conditions of the existing calender: the available design space (see Figure 3) as well as the conveying speed and working height of the semifinished textile must be considered. These simplifications and boundary conditions are the basis for the subsequent design process.

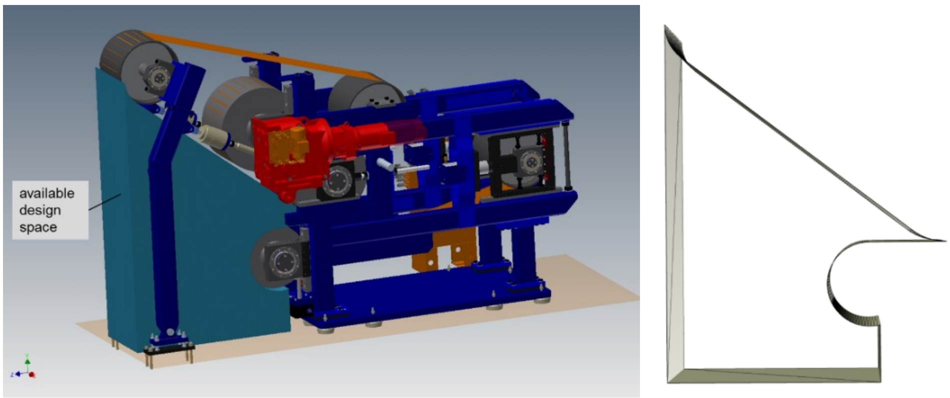


Figure 3. For the integration of the application system into the entire calendaring process chain, a determinate design space is available

3. Design of an Adjustable Matrix Application System for Integration into the Calender

In this section, the concept and design of an adjustable matrix application system is proposed. The matrix application system must be designed in such a way, that it is able to follow the described simplified load-path adapted design routes (previously described in Figure 2). To avoid aberration and corresponding cost explosion within the design process, decisions of the development team in the early stages of the design process had to be made with the maximum available knowledge. In the scope of "ProText", the design process was carried out in correspondence to the VDI 2221 guideline, which provides a systematic approach to the development and design of technical systems and products [6]. Therefore, main tasks and functionalities to be provided by the application system were defined. Subsequently, additional requirements were identified. Finally, first solution concepts were concretized and transferred into a final design of the matrix application module.

At a first step, the main tasks for the matrix application system were defined: the load-path adapted design routes need to be equipped with polymer matrix before the textile runs through the calender. In addition, to ensure a constant fiber volume content of the resulting prepreg fabrics, the task is to add matrix material to the carbon fiber routes only. Potential matrix material loss must be minimized. Overall, the system must provide robust continuous running behavior, which is to be ensured by both the mechanical configuration and the control system. These main tasks in combination with the previously identified boundary conditions are the basis for the subsequent design steps.

At a second step, the list of requirements to be met by the system design was generated on the basis of the above described main tasks and boundary conditions. Requirements must be unique, distinct, independent of each other and free of contradictions. Changes to one requirement should not affect other requirements [7]. In order to highlight the liability of a requirement, the nature of the request should also be specified. Fixed requirements (F), minimum requirements (M) and wish requirements (W) can be differentiated, while fixed and minimum requirements must be met strictly [8]. At first, already existing requirements were analyzed regarding limiting specifications (e.g. textile speed in calender, textile width, available design space etc.). Then, common methods of requirements engineering (e.g. list of main features, interface planning) were applied to complete the set of requirements (e.g. costs, precision of application, safety requirements etc.).

In the following functional phase, the task was to define main functions, auxiliary functions and wish list functions to be implemented and to specify their structures and interactions. In this context, methods such as General Function Structures and Blackbox Model were applied. For the development of solution principles that fulfil the defined functions, several creativity-based design methods (Brainstorming, Method 635, etc.) and valuation methods (pair-by-pair comparison, Cost–Utility Analysis etc.) were utilized. The solution finding for practically applicable polymer application methods resulted in several overall solution concepts (such as depicted in Figure 4), which were subsequently evaluated by the project team according to the criteria such as conversion flexibility, robustness and design space.

3.1. Application of Additional Matrix in Powder Form

As a result from the above described design phases, the application of matrix in powder form has been assessed the optimal matrix application method. In contrast to the application of polymer foil or integrated matrix extrusion as proposed in [9], matrix in powder offers the potential to be applied locally in in line during the impregnation process, as previous work shows [10, 11].

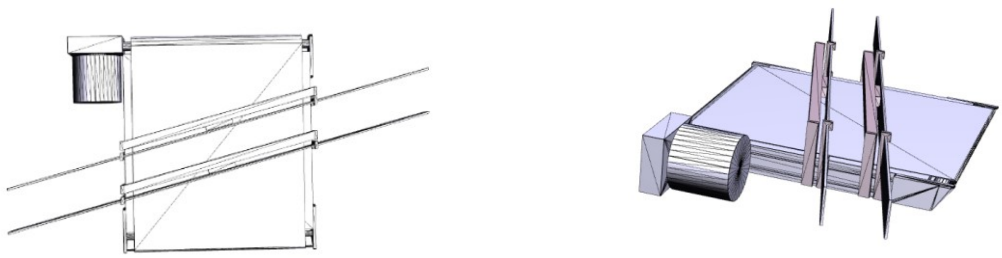


Figure 4. Schematic solution concpets were elaborated at an early development stage

For the automated powder application, a doctor blade with variable vertical and horizontal aperture is proposed as dosing mechanism. In order to evaluate the optimum powder grain size for automated powder application, preliminary tests using a doctor blade for dosing the applied powder amount were carried out. The dosing accuracy of the doctor blade module depends primarily on the ratio of the layer thickness and the powder grain size. Particle size measurements on polybutylene terephthalate and polyamide powders were carried out with a target grain size of 20-30 µm. It was found that an average grain size of 20 µm could be achieved. Partially, particles with a circular equivalent diameter up to 100 µm were identified remaining in the powder material. These can adversely affect the doctor blade process and lead to inhomogeneous layer application, as illustrated in Figure 5a. An oscillating relative movement of the doctor blade may result in a more even distribution of the powder (see Figure 5b).

These preliminary tests provide significant initial conditions for the design of an automatable matrix application system which can be directly integrated into the calender.

(a) (b)

Figure 5. Applied powder with a coating thickness of 100 µm: Fixed doctor blade (a) and oscillating relative movement of the doctor blade (b)

On the basis of preliminary solution concepts and evaluation tests for powder dosing by a doctor blade, the final design of the automated matrix application system was elaborated. Figure 6 shows the assembly prepared for laboratory tests. It mainly consists of a conveyor belt and a dosing module with a closed powder box. The dosing module is set up directly on the conveyor belt and is fed with polymer powder, which is scraped regarding the needed variation of the layer thickness and spread. After the scraping procedure, the powder is applied on the textile via the conveyor belt. The entire application system is moved via a linear axle for following the load-path adapted design routes (transverse to conveying direction), which allows for exact and fast positioning over the textile.

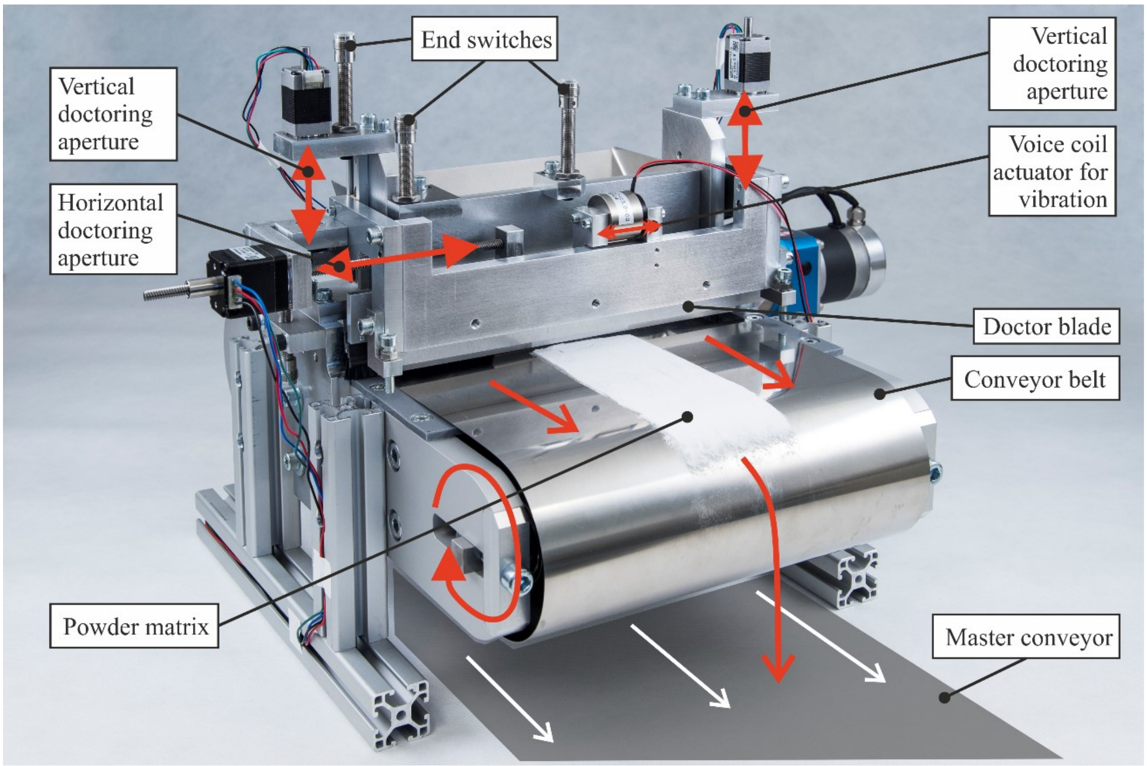


Figure 6. The powder application system contains a dosing module above a conveyor belt

4. Automated Powder Application to Load-Path Adapted Fiber Fabrics

The fundamental task of the powder application system is to apply powder exactly on top of the carbon fiber areas while the semifinished textile is fed through the application unit. The challenge hereby is that the relative positioning between the textile and the master conveyor is not known exactly. In addition, uncertainty in the carbon fiber placement on the textile may be present. These circumstances are considered in the trajectory generation proposed below.

4.1. Trajectory Generation for Positioning

A simple strategy for trajectory generation is the interpolation of NC data. Such an NC code interface could be used to program the motion paths manually or automatically by use of CAD-CAM linkage. The NC code is interpolated into trajectory commands of the transversal positioning actuators, the conveyor speed and the aperture setpoint of the dosing module. This is an open-loop control structure with low implementation effort. However, this approach relies on the assumption that uncertainties in the dosing process and the relative positioning of the textile with regard to the master conveyor remain sufficiently small. In order to compensate for these flaws, this open-loop control structure is enhanced by sensor-guided trajectory generation.

4.2. Sensor-Guided Programming Strategy for Positioning and Powder Dosing

In order to bypass the uncertainty of the relative positioning of the textile with regard to the master conveyor, sensor-guided trajectory generation is proposed. In detail, it is intended to detect the load-path adapted design route, more precisely, the carbon fiber area width (x_{Width}) and position (x_{Pos}), by means of camera-based optical detection. The feasibility of this approach is confirmed by other research: position detection of carbon fibers has already been implemented successfully in [12]. In addition, optical detection of roughness and orientation of carbon fibers is demonstrated in [13]. In the scope of "ProText", the detection is implemented by use of a line camera (depicted in Figure 7). After processing the corresponding image data, the application module the horizontal doctor blade aperture and the module x-position relative to the main conveyor in order to match the detected position and width of the carbon fiber area.

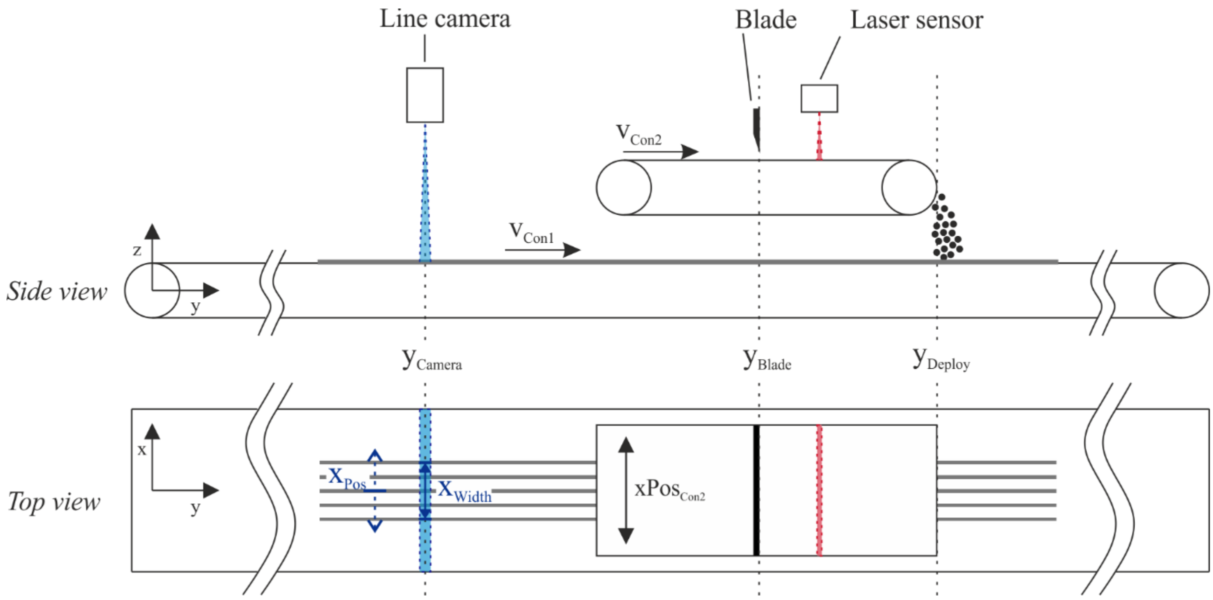


Figure 7. System configuration for automated powder application

In addition to the positioning control, the matrix application system is equipped with a closed-loop dosing control mechanism for applying the desired amount of powder to the load-path adapted textile. This is crucial with regard to the required constant fiber volume ratio. For the closed-loop dosing control, a laser sensor is installed directly after the blade. This sensor detects the dosed powder thickness and allows for a reactive adjustment of the vertical blade aperture, based on the powder application rate in kg/s. The application rate is calculated using the applied volume and the known powder density.

4.3. Timed Synchronization of Detection, Positioning and Dosing

The control-related challenge is to synchronize the camera-based detection data with the doctoring procedure at y_{Blade} and the actual powder application at the deployment position y_{Deploy}: the information about the detected position and width, acquired at a timestamp t_0, refers to a specific area of the fabrics, which will reach the powder deployment position y_{Deploy} at a later timestamp t_1. The duration for this conveying procedure between y_{Camera} and y_{Deploy} can directly be derived from the distance between both positions and the conveying velocity v_{Con1}. The conveying velocity v_{Con2} of the powder application module is set equal to v_{Con1}, which is assumed to provide the best pouring behavior. For positioning synchronization, the idea is to implement a ring buffer, whereas its length is directly proportional to the distance between y_{Camera} and y_{Deploy}. Thus, in a ramp-up procedure the buffer is filled up so as to automatically position the application module according to the previously detected position data of the carbon fiber area.

5. Conclusions and Outlook

The lightweight potential of load-path adapted design for fiber-reinforced thermoplastics has been elaborated with regard to better material utilization and new design variety. For large scale production of these load-path adapted thermoplastics, the single-stage calendaring process has been proposed. The application of powder matrix to the reinforcing carbon fiber areas, which is crucial in order to ensure a constant fiber volume rate in the prepreg, has been identified as an adequate method for the application of additional matrix material to the semi-finished textile. For realization of a simplified demo process for large scale production of continuous load-path adapted thermoplastics in the context of OHLF in Wolfsburg, the design of an automated powder application system has been proposed.

This system consists of a positionable dosing module above a dosing conveyor, which is located above the master conveyor. The purpose of the dosing module is to adjust the dosing aperture with regard to the detected carbon fiber area, so that the applied powder volume leads to a constant fiber volume ratio. This system configuration allows for a more precise powder dosing and application than, for example, integrated extrusion. Conversely, such a system configuration requires an adequate strategy for trajectory generation in order to position the module transversally to the master conveyer feed. In this paper, sensor-guided trajectory generation is proposed, based on camera-based optical detection of the carbon fiber areas. In summary, this paper proposes a feasible technological approach for automated matrix application in the scope large scale production of continuous load-path adapted thermoplastic prepregs, which will be validated in further experiments.

Future work will show if the desired impregnation quality of the calendaring process can be achieved. The integration of an additional powder application system is planned, as well, in order to enable the fabrication of load-path adapted prepregs with two separate carbon fiber tracks. Further research may focus on the development of a powder application mechanism with a higher resolution, which can be applied to load-path adapted designs of higher geometrical complexity.

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- TU Braunschweig, Institute for Engineering Design
- TU Braunschweig, Institute of Joining and Welding
- TU Braunschweig, Institute of Machine Tools and Production
- Fraunhofer Institute for Machine Tools and Forming Technology IWU
- Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM
- Fraunhofer Institute for Wood Research Wilhelm-Klauditz-Institut WKI

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