RESOURCE AND ENERGY EFFICIENT MANUFACTURING OF AUTOMOTIVE LIGHTWEIGHT PARTS MADE OF RECYCLED FIBER REINFORCED COMPOSITE MATERIAL

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Abstract

In the latest research project a three steps process chain has been proposed. Aim is reusing carbon fiber material of end-of-life components and manufacturing waste.
First, a hybrid yarn made of recycled carbon and polyamide fibers has been developed to be processed in a Tailored Fiber Placement (TFP) machine. In order to achieve an embroidery pattern, an optimization loop has been conducted to demonstrate the full potential of variable fiber placement in the actual load directions. In a final back injection molding step the resulting preform has been consolidated with supporting structures. It was possible to show that the optimization procedure combined with properties of the material can enhance the specific stiffness of the component.

1. Introduction

Fiber-reinforced plastics (FRP) hold considerable potential when it comes to constructing and designing light-weight components. FRP are rapidly gaining importance in various industrial sectors. Although this group of materials combines high strength and stiffness while simultaneously being lightweight, major difficulties still arise when it comes to large production and the return of manufactured parts back into the life cycle of materials and components.

A study in 2012 [1] has shown that 50 % of general manufacturing costs of a CFRP component consists of raw material costs (Figure 1), while a steel component can be produced with only 15-20 % of the total CFRP costs. The amount of energy necessary to produce virgin fibers can be drastically reduced recycling materials.

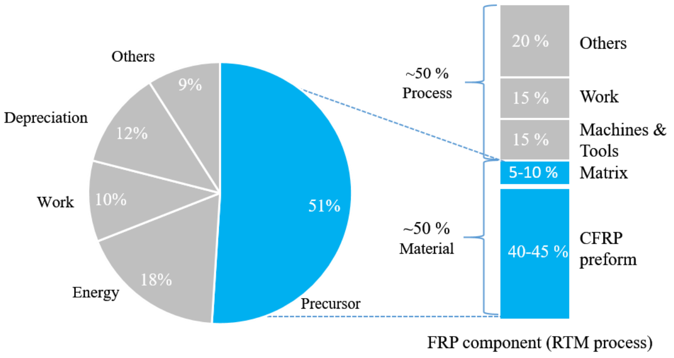

Figure 1. Manufacturing costs for CFRP components [1]

Therefore, a new approach has been investigated following the idea of producing structural components through forming and back-injection molding of preforms with a large portion of recycled fibers and matrix, without drastically compromising the quality of the mechanical properties. A brief overview is given in Figure 2.

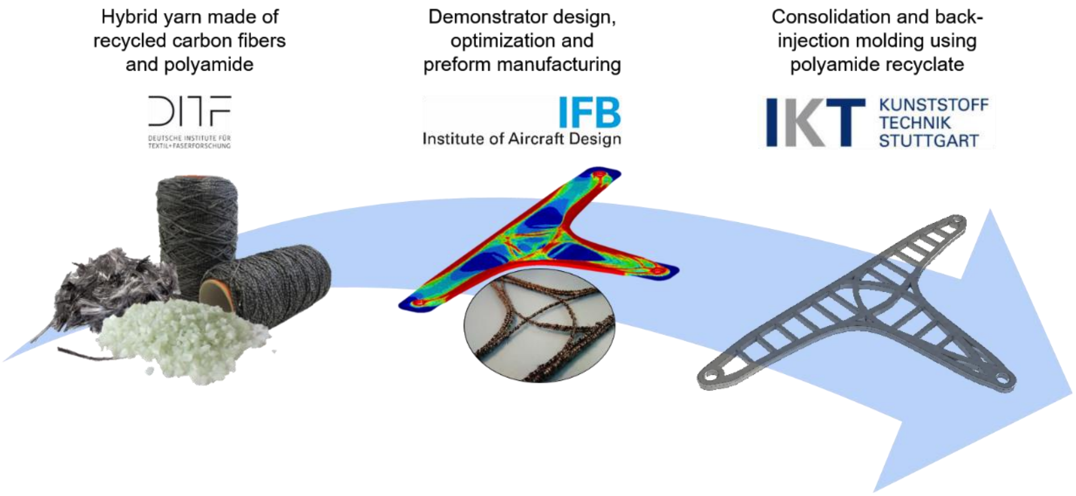

Figure 2. Processing steps from material to final component

To achieve this, carbon fibers retrieved out of a recycling process are mixed with recycled polyamide fibers and spun into a hybrid roving. Subsequently, these rovings are processed into preforms by means of Tailored Fiber Placement. This process allows for a precise fiber positioning in accordance with the component requirements, ensuring a more efficient deployment of fiber and matrix compared to present production.

Regarding fiber optimization procedures a lot of research has been conducted. P. Pedersen et al. investigated the influence of material properties and load states on the optimal behaviour of elements regarding local and global optima [2]. Furthermore, the Institute of Polymer Research, who initially introduced the TFP technology, provided an optimization procedure based on principal stresses for a single load case [3]. For other manufacturing techniques such as Automated Fiber Placement the Technical University of Delft developed an algorithm [4] referring to lamination parameters initially mentioned by Tsai and Hahn [5]. Due to high computational effort the method considered in this research is based on the work of Zink et al. [6] who analytically computed a best-fit fiber orientation for multiple load cases using principal stresses.

Finally, the resulting TFP preform is processed using back-injection molding that allows functional integration into the components, aiming for weight reduction and lowering installation effort. Recycled carbon fibers and recycled matrix granules are also used for the process to investigate their influence on mechanical properties of the components.

In the following sections more details are provided regarding each individual process step.

2. Hybrid yarn production and characterization

2.1. Yarn production

Several processes exist to extract fibers from a composite such as pyrolysis, hydrolysis or solvolysis. The challenge is to keep fibers as long as possible due to the fact that stiffness and strength of single fibers reduce drastically with a decreasing fiber length as shown in Figure 3. Once the material exists in a pure state, fibers can be processed maintaining a sufficient length and correct orientation. In order to do that, recycled carbon and polyamide fibers are mixed with an opener. In a second step, a carding machine (Figure 4) is fed with the prepared material and the remaining fiber tufts are oriented and split into single fibers or tows.

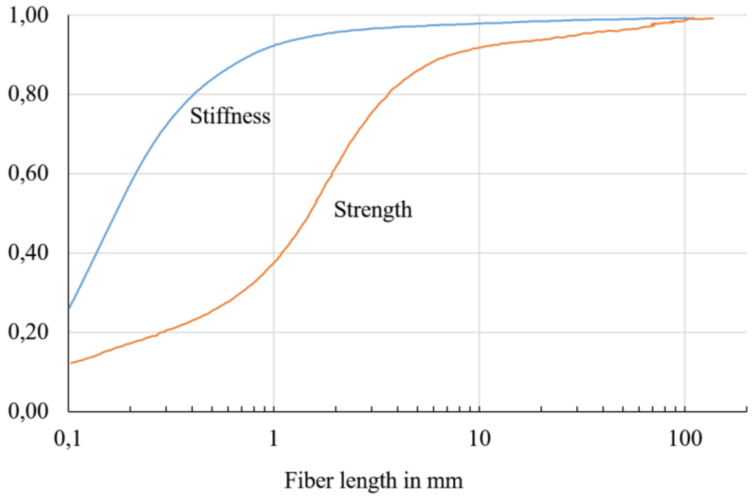

Figure 3. Influence of fiber length on mechanical properties **[7]**

It has been investigated that there is a specific relationship between card clothings, fiber throughput and sizing. Refining the card clothing sizing has become subsequently less important due to a superior fiber opening. In contrast, mass flow decreases and the probability of a process termination increases due to machine blockage. In a last step, the fiber band, gained in the carding process, is warped resulting in a final orientation (Figure 5).

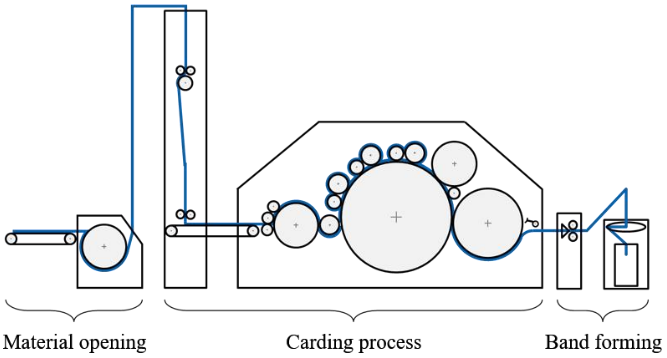

Figure 4. Carding process

Figure 5. Final hybrid yarn (800tex)

As a result, the produced hybrid yarn includes recycled carbon and polyamide fibers of 800 tex, a fiber volume fraction of 58 % as well as an average carbon fiber length of 41 mm.

2.2. Material characterization

In order to characterize the mechanical properties of this commingled yarn TFP preforms have been produced using a four headed stitching machine from Tajima. Due to the high yarn volume the optimal stitching parameters and the number of necessary layers for a high quality consolidation needed to be investigated as well. The grinding pattern in Figure 6 shows that eight layers give good results regarding compaction.

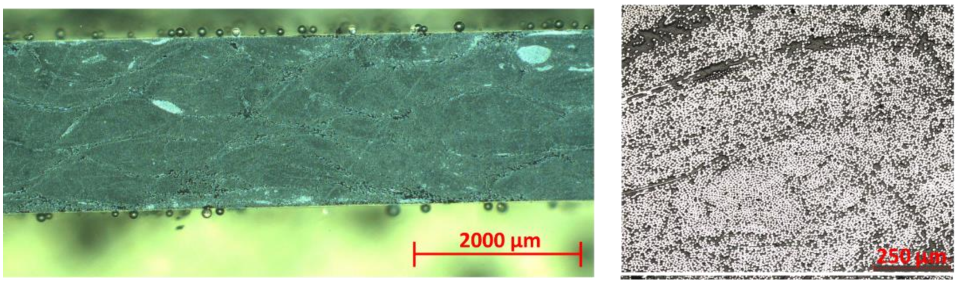

Figure 6. Grinding pattern of an eigth layer plate

In a press from Lauffer TFP preforms have been heated and consolidated to subsequently be processed into standard test specimen. The results are shown in Table 1. The decrease in the fiber volume fraction of 10 % can be explained by an additional use of polyamide in the form of stitching yarn and ground.

Table 1. Mechanical properties of the hybrid yarn

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	X_t (MPa)	Y_t (MPa)	S (MPa)	FVC (%)	ρ (g/cm^3)
94	6.7	4.8	1074	50	96	48	1.44

3. Demonstrator design

To demonstrate the performance of the new material the crossing of a brace has been chosen as a generic component to be optimized (main dimensions 135 mm x 270 mm) . The potential of TFP will be shown by aligning fiber orientations to the stress state resulting from three load cases (see Figure 7).

According to the stress state due to loads of 2-3 kN, a shape optimization has been conducted using Mattheck's method of tensile triangles to avoid notch failure. It can be shown that a stress reduction of 50 % is achieved with a mass gain of 12 % resulting in a hyperbolic notch type.

Subsequently, a material optimization has been performed based on Zink et al. as mentioned in Section 1. Each element is evaluated regarding principal stresses by computing a best-fit orientation. For this purpose, a vector is found analytically in the form of the sum of maximum projections. As a result, the algorithm evaluates whether a component should have a unidirectional, biaxial or quasi-isotropic design. Since the algorithm is based on isotropic material, the stress distribution will completely change due to the new anisotropic material assignment. Therefore, an iterative process is necessary to achieve convergence. In the past, many authors such as P. Pedersen [8] have found out that only a combined optimization of fiber orientations and element thicknesses give a significantly improved performance of the component. As a result of this, an additional thickness optimization has been performed using a simple maximum failure criterion based on a predefined strength.

After iterating through approximately 50 iterations, a material constellation could be achieved as shown in Figure 8a. Compared to the isotropic case in Figure 7 with a specific stiffness of 22 N/(mmg)$^{-1}$ an increase of 80 % could be realized with a mass of 68 g.

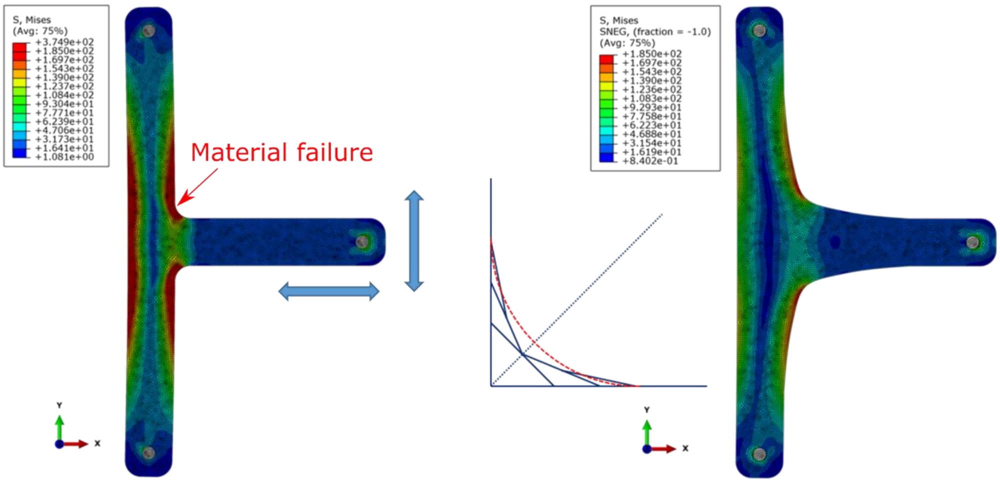

Figure 7. Shape optimization using Mattheck's method of tensile triangles

In a post optimization step, an embroidery pattern had to be created in the form of a continuous polyline due to the unavailability of a cut and restart function of the present TFP machine. Therefore, the optimization result in Figure 8a has been divided into a finite number of layers by given thickness intervals (Figure 8b). As a result, unloaded elements can be filtered, because only the main load paths are essential for the embroidery pattern. Using the CAIO method mentioned in [9] the polyline can be constructed by calculating intersection points based on mesh borders and material orientations. The result is shown in Figure 8c.

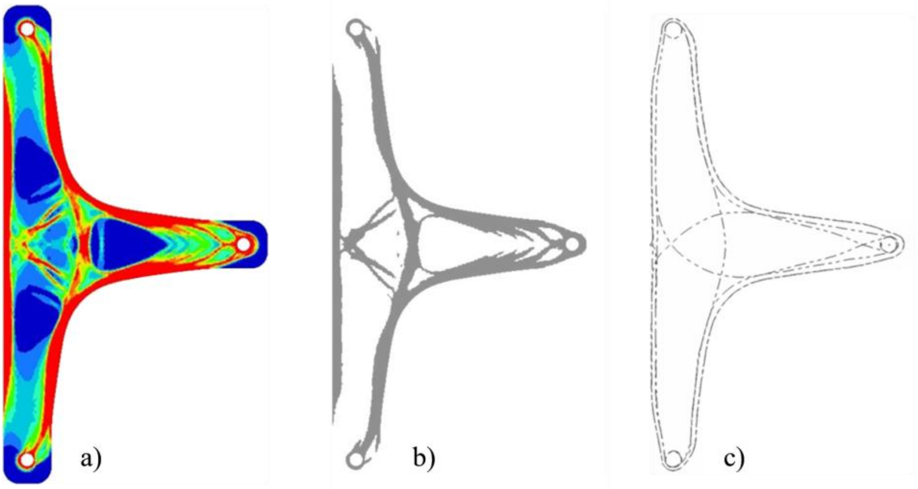

Figure 8. Overview of optimization procedure: macroscopic results – thickness distribution (a), main load paths after filtering (b), final embroidery pattern (c)

Additionally, a mesoscopic analysis has been performed to verify the global strength of the component by embedding TFP fiber paths as beam elements in a recycled short fiber polyamide. Due to the first attempt of extracting continuous polylines from the material vector field the mesoscopic results show a decrease of 70 % in stiffness referenced to the macroscopic optimization.

4. Back-injection molding

In this step preliminary tests have been conducted to investigate the degree of recycling influencing the mechanical properties of the short fiber reinforced composite. Different fractions of virgin/recycled fiber mixes have been tested resulting in small deviations in Young's modulus and tensile strength [10].

At the beginning, filling simulations have been conducted considering different positions of the injection point. It can be noted that the simulation of a component with TFP insert results in a non-uniform filling of the branches. The best result has been achieved with an injection point below the yarn crossing as shown in Figure 9.

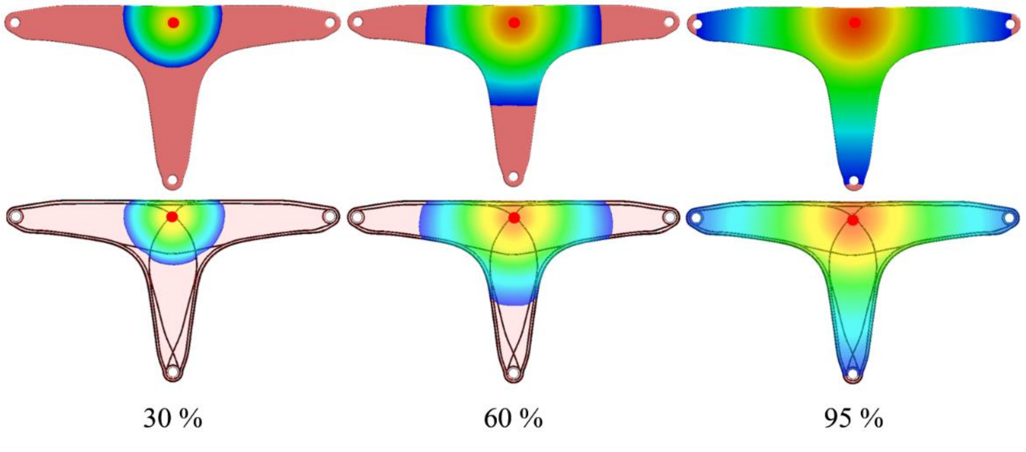

Figure 9. Filling simulation - comparison between pure matrix and matrix with TFP insert

Subsequently, first attempts have been made to develop an appropriate process to fully consolidate and coat the TFP preform with additional matrix material. In a first loop, a tooling has been constructed and tested to insert and mold a preform in a single step. As a result, it has been noted that the hybrid yarn was not able to be fully infiltrated by matrix due to the high volume of the dry material.

After further iterations, a heatable pressing tool was constructed to consolidate the preform in a previous step with a high degree of infiltration. Due to this, the prepared hybrid yarn was able to be placed realiably in the back-injection mold to avoid fiber deformations during the process. In conclusion, good results can be noted consolidating preforms in a previous step. In future investigations thermal warping (Figure 10) shall be reduced by a more accurate preform insert.

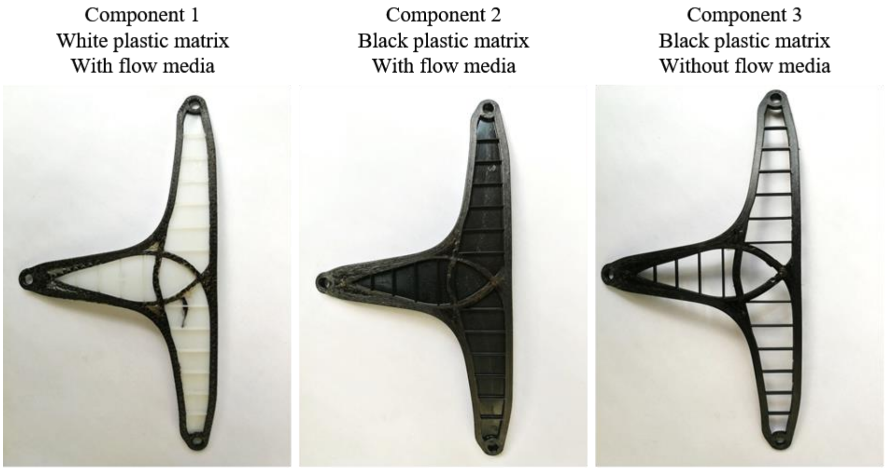

Figure 10. Final components including recycled carbon fiber and polyamide material

5. Conclusions

A three step process chain has been presented in this paper considering the production and processing of a recycled FRP material extracted from end-of-life components or waste. The method proposed gurarantees good mechanical properties compared to virgin materials. Furthermore, an appropriate demonstrator has been chosen to show the potential of TFP compared to conventional laminate stacking. In a final step, investigations have been made to infiltrate the preform with a recycled polyamide. In future work, the back-injection process needs to be enhanced to characterize components in experimental tests and other approaches for fiber path generation will be studied.

Acknowledgements

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