High-performance lightweight multifunctional composites based on 3D-shaped multilayered woven fabrics

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ABSTRACT

Textile preforms for fibre reinforced plastics (FRP) made from continuous fibre-reinforced thermoplastics allow for the preform adjustment to various, possibly layered load cases, just as much as they enable the realisation of complex forms in a single, integral surface formation step.

By using thermoplastic matrix materials, the manufacturing of lightweight and complexly formed, high-productivity, cost-efficient and high-quality composites becomes possible. To ensure the demanded short cycle times while simultaneously guaranteeing highly specific properties of structure components, the most suitable method is hot pressing, using deep drapable multilayered and 3D shaped thermoplastic preforms based on thermoplastic hybrid yarns. The advantages of GF/PP as well as GF/PET hybrid yarns are their homogenous mixing of the used continuous filaments, as well as their great yarn compaction, which permits further textile technological processing. Commercially available yarn materials can be used in widely varying forms, and the individual intra-yarn content percentages can be adjusted to preference on an extensive range. 3D-shaped multilayered weaves, in comparison, are suited for the reinforcement of higher-gauge FRP due to their use of thicker and preferably compact fabrics, as their multilayered structure facilitates the minimisation of the usual stacking of multiple individual reinforcement layers. Multilayered preforms with an additional reinforcement in z-direction are predestined for FRPs in case of three-dimensional load cases and transverse impact loading (with risk of delamination). The realised fabrics were characterized as well. Here, the draping and load- elongation properties are of special interest.

The provided structures are introduced into a plate-type, two-part steel tool and inserted into a thermopress. The laminates are manufactured in a hot pressing process. Because the developed multilayered fabrics are supposed to be used in reinforced thermoplastic composites the establishment of composite parameters is a crucial criterion for their quality assessment. The load-adjusted position of reinforcement yarns makes it possible to fully exploit the fibre substance strength.
The EU-funded 3D-LightTrans project focuses on these research activities and provides groundbreaking, highly flexible, efficient and adaptable low-cost technologies for the manufacturing of integral large-scale 3D textile reinforced plastic composites. It includes innovative approaches for the individual processes and their integration in complete manufacturing chains, which will allow to move the large-scale composites from their current position in cost intensive, small series niche markets, to broadly extended mass product applications, not only in transportation, but also in other key sectors, like health and leisure.

3D-LightTrans will open the way to a totally new concept for the design, manufacture and application of composites for low-cost mass products in a wide range of sectors.

Keywords: hybrid yarn, multilayer fabric, 3D-LightTrans, 3D shaped fabric, textile reinforced thermoplastic polymer component

1. Introduction

Advanced high-tech polymer composites combine the superior properties of the reinforcement material (e.g. glass) with the ultra-light weight and low cost of polymer matrix materials. These properties are nowadays used, for instance, in aircraft structural components to achieve high strength and stiffness combined with light weight, leading to an important decrease of the overall weight of the vehicle with resulting energy efficiency [1], [2], [4]. In particular, textile reinforced thermoplastic polymer components (TRTC) with continuous-fibre reinforcement in the form of woven fabrics display enhanced performance, compared to short-fibre reinforced composites, They also allow for a better control of the distribution of the reinforcement material, and can be easily tailored to obtain customized material properties. In spite of the impressive progress in research on textile reinforced thermoset polymer components (TRPC) during the last years, they are currently used for a number of selected applications only (e.g. in aeronautics. and aerospace, high value sports equipment etc.). Although TRPCs possess a huge potential for widespread use in many mass markets and for introduction of novel applications, their use remains hindered by the wide range of possible constituents and difficulty to process them, the high cost due to slow, inflexible and expensive production processes, the mostly handmade draping as well as lay-up processes and the lack of flexibility in the realization of complex 3D pre-forms [3], [5], [6] .

Figure 1 shows a schematic representation of the 3D-LightTrans approach, in comparison with the state-of-the art processes used nowadays. This provides a comprehensive overview of the progress beyond state-of-the art introduced by 3D-LightTrans.

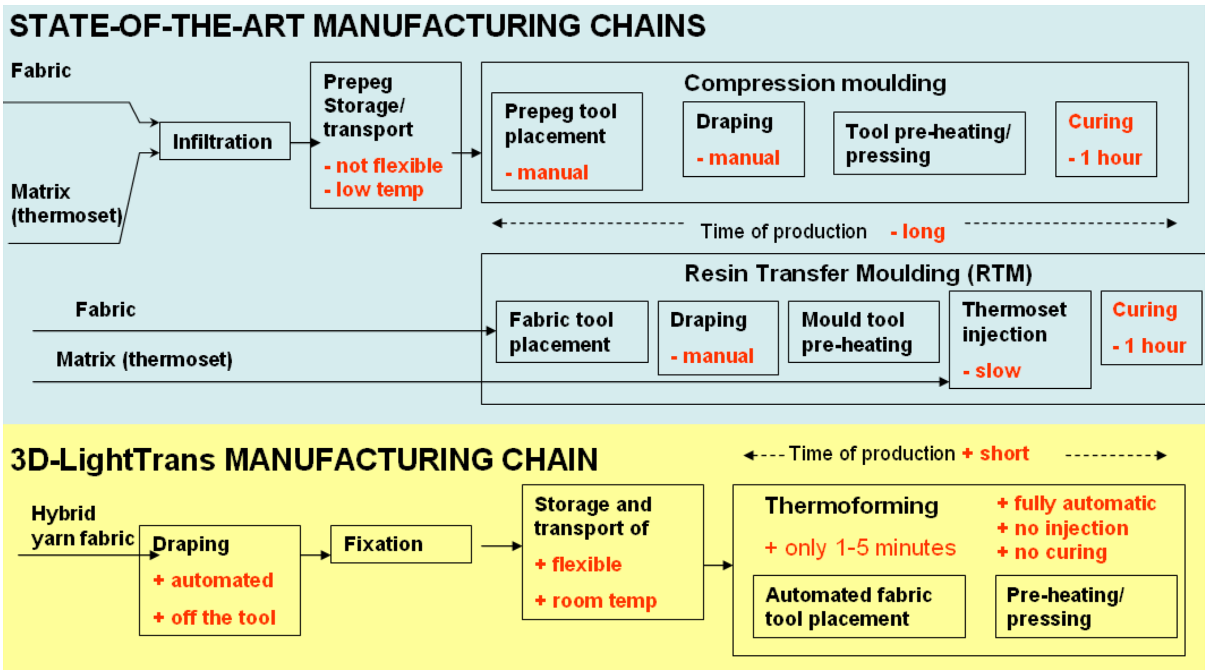


Figure 1 Comparison between state-of-the-art and 3D-LightTrans manufacturing chain to produce TRPC and the proposed 3-D LightTrans process to produce TRTC

The 3D-LightTrans advanced processes and equipment for highly efficient weaving of multilayered and 3D shaped textile fabrics will enable innovative applications and new functionalities based on 3D-TRTC (e.g. multifunction integration for cooling, wiring, sensing, acoustic, etc.). Moreover, the 3D-LightTrans fully automated and highly flexible manufacturing chain will not only enable cost-efficient mass manufacturing, but also employs a mass customisation concept, based on highly adjustable modules which are flexible enough to be adapted to new technologies and uses. Other cost- and time-efficient production technologies (e.g. braiding, knitting) can be used and adapted to the tailoring needs of high-tech customized products (multi-material components, local reinforcement, functional integration) for different application sectors.

The 3D-LightTrans manufacturing chain will be developed following two distinct industrial technologies. This will enable a major progress in the state-of-the-art with regard to attainable geometries and types of structures in low-cost mass manufacturing of textile reinforced plastic components. The first one will be for 3D textile constructions (spacer fabrics) for function integration, while the second will be for highly draped multilayer fabrics with complex 3D geometry.

(a) (b) (c)

Figure 2 (a): prototype of simple spacer fabric structure, produced by available basic technology;(b): potential application combining spacer and deep draped multilayer technologies in a car door; (c) deep draped multilayer composite;

A key innovative aspect of the 3D-LightTrans technology concerns its extremely high degree of flexibility and adaptability. Not only will the whole manufacturing chain be implemented on the basis of lean modularity and adaptability principles, but also the technologies and the equipment themselves will be developed together, meeting strict compatibility requirements. Polymer matrices can e.g. be selected, depending on the product requirements, among a wide choice of thermoplastic materials. But the most striking aspect of the proposed technology is that it will permit pioneering approaches for highly flexible and extremely powerful technology combinations, such as:

- Integration of multifunctional textile constructions (spacer technology) and complex 3D-geometries (multilayer technology) within a single final product
- Composite products with multi-material textiles, integrating e.g. carbon yarn (for stronger reinforcement in specific areas or localised tailored properties) with low cost glass fibre fabric
- Alternatively the 3D-LightTrans weaving equipment can also be used to produce fabrics with raw yarn (containing no thermoplastic matrix), to be subsequently post-processed with RTM or compression moulding state-of-the-art technique.

2. Experimental

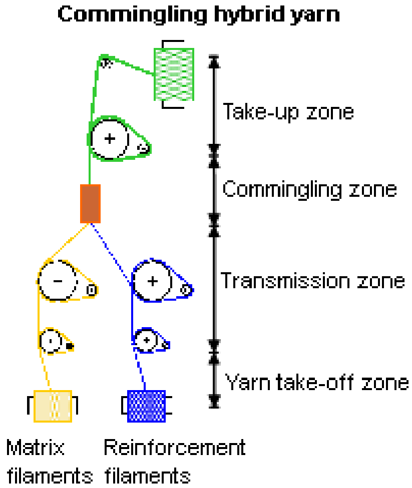
2.1 Manufacturing of hybrid yarns

In air texturing, the hybrid yarn is produced by the pneumatic opening of the filament yarn by cold or hot pressurized air, and the subsequent reallocation of the initial filaments in a special air nozzle. Commercially available yarn materials of a large range of setups can be processed, and the ratios of individual components are widely variable.

The research priorities were on the attainment of a homogenous distribution of the individual components along the thread cross section, and the gentle processing of reinforcement threads in relation to selected process parameters.

At TU Dresden, an air texturing machine RMT-D (manufacturer: Stähle GmbH) is available for the production of commingling hybrid yarns. Figure 3 shows a view of the machine and the principle of hybrid yarn manufacture. The air texturing machine features a socket for various air nozzle types and is fitted with a suitable system for the suction removal of flying fibers. The reinforcement and matrix filament yarns are guided in individual supply feeds, reaching the air jet (manufacturer: Temco), where the filaments are opened and mingled by the air flow. It is due to this principle that the commingling hybrid yarns' structure does not feature a fully parallel alignment of reinforcement and matrix components along the yarn axis. Other influencing parameters on the hybrid yarns' features and their appearance are the nozzle construction and adjustment, air pressure, overfeeds (the relation of filament yarn feeding speed and the hybrid yarn's haul-off speed), as well as the general process speed. The components' mass ratio can be modulated by adjusting the number of threads fed [7], [8]. To minimize thread damage and homogenize the two filament types' distribution along the yarn cross section, the aims are a gentle opening of the filament yarns and the merging of reinforcement and matrix filaments at preferably low air pressure.

(a) Machine View



(b) Air texturing process schematics

Figure 3 Modified Air Texturing Machine RMT-D

For example, numerous measures taken to minimize thread strain during transportation of the filament yarns to the commingling zone could successfully be used in recent tests.

The following process parameters were ascertained as optimal for GF/PP manufacturing:

- Delivery speed of components GF: 102 m/min; Thermoplast PP: 104,5 m/min

- Take up speed of the hybrid yarn 100 m/min
- Nozzle design type LD 5.05 (TEMCO)
- Air pressure 0,4 MPa

The machine settings were chosen to achieve a reinforcement thread ratio of at least 60 per cent mass fraction. For the GF/PP hybrid yarns, the assesment of reinforcement thread ratios was based, in accordance with DIN EN ISO 1172 on a one-hour incineration at 625° C, for which representative samples were stored in a Nabertherm-Controller muffle furnace until reaching constant weight.

2.2 Weaving technology of multilayer fabric

Textile semi-finished products, which are produced to have a multi-layer reinforcement in two directions, can be reinforced in the z-direction as well. The reinforcing in z-direction is of importance especially in 3D stress and impact loading. Such multi-layer textile semi-finished products improved by the reinforcement in z-direction, improve the delamination behavior and the out-of-plane properties. Studies have shown that textile structures which have an additional reinforcement in z-direction show a higher resistance to delamination [13], [14].

According to the demonstrator requirements different patterns for fabrics with z-reinforcement in different orientations as well as without were developed. They were analysed according to their weavability. The hairiness of the yarns as well as the chronology of weft insertion has a large influence on the process stability. For a large scale manufacturing of multilayered weaves it is essential to adapt a conventional weaving loom. In cooperation with Lindauer Dornier the design and functionality of a new loom was defined and designed.

At least four different designs were evaluated and realised in different weft densities (Figure 4).

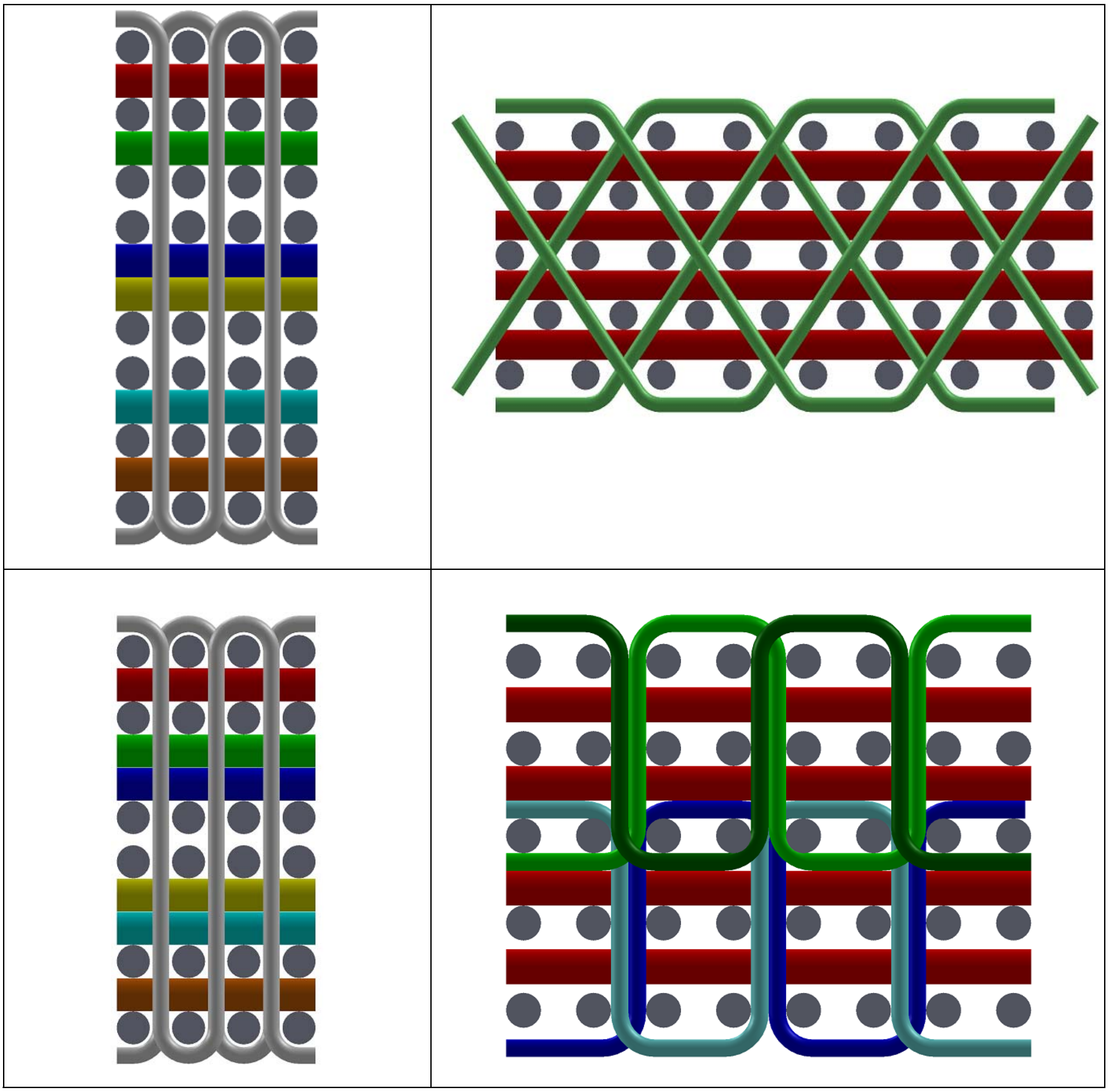


Figure 4 Interlock of provided fabrics

To get the desired structural behavior of a 3D-formed component, the reinforcement fabric must be arranged to the load paths. The required reinforcement is usually carried out by a structural analysis of the composite part and depends on the geometry, material and loading as well as boundary conditions. To analyse the forming of the fabric into a three-dimensional geometry a simulation at macroscale is used. At that the textile structure is represented by shell elements. To describe the material behavior a user defined material model is used [10], [11]. This material model considers the nonlinear anisotropic characteristics of the used textile structures. The input parameters for the material model are the tensile-, shear- and bending behaviour of the fabric. These material characteristics were determined with the tensile test, the picture frame test and a bending test. With the simulation of the draping behaviour of textile structures the fibre orientation after forming and zones for a local structure fixation can be determined. For the local structure fixation the thermoplastic component in the hybrid yarn is locally melted, so the structure becomes stiffer and the handling behavior of the fabric can be improved.

2.3 Weaving technology of 3D shaped fabric

Woven Spacer fabrics are a hollow structure with two shell layers connected by ribs. The special feature of these structures is that the ribs do not consist of individual pile threads, but are also made of textile fabric sections. Through a custom weave it is possible to arrange the reinforcing filaments in such a way that they combine securely the top layers with the ribs [15], [16]. Michel Van de Wiele is looking to industrialize the modified machines available at TU Dresden and adding extra functionality to increase the flexibility in weave structures.

2.4 Thermoforming process

The laminates are manufactured from the unidirectional pirns and gauze fabrics, using a Collin P300 PV laboratory platen press (Manufacturer: Dr. Collin GmbH, Figure 5). The system allows for the thermic pressing of textile structures with thermoplastic components, which can be either a part of the textile weave (e.g. by incorporating hybrid threads) or added as thermoplastic sheets or non-woven fabrics.

Figure 5 Laboratory press (Collin 300 PV)

Based on experience from previous research projects at TU Dresden for GF/PP hybrid yarns, it was possible to reach an optimum pressing cycle for the manufacture of thermoplastic hybrid yarn composites especially based on GF/PET and GF/PP materials without any air locks. The pressing process runs in five program-controlled phases. During the first phase (Preheating), the press is preheated to the desired initial temperature. In the second phase, heating-up, the press is warmed up to the required maximum temperature, at a ramp of 10K/min. The third phase serves to thoroughly warm the pressing instrument. During the fourth phase the actual pressing process takes place under an increase in applied pressure. To minimize fibre damage, the pressure is only applied after attaining the matrix's molten state. The fifth and final phase is used to cool the laminate, which is also performed at a ramp of 10K/min. The cooling rate enables an influencing of the composite's degree of crystallinity, which turns out lower the faster the pressing machinery is cooled. Low degrees of crystallinity cause a decrease in tensile strength and dimensional stability at high temperatures [9]. In order to avoid the growth of air locks in thickness direction and ensure dimensional accuracy, the applied pressure is maintained during the cooling phase. Additionally, the interior air pressure can be modified with a vacuum pump. The standard value of choice for the production of laminates is 0.05 MPa.

3. Result and Discussion

3.1 Simulation of the draping behavior

The simulation of the draping of multilayered weave structures allows analysing the fibre orientation of the fabric after forming to a three-dimensional geometry. In Figure 6 the fibre angle distribution of a formed hemisphere is shown as a result of the simulation. As can been seen there are zones that display no or only a low shearing. These unsheared areas are well suited for a local structure fixation [12]. If these zones are fixed the handling qualities of the textile structure can be improved without influencing the drapability.

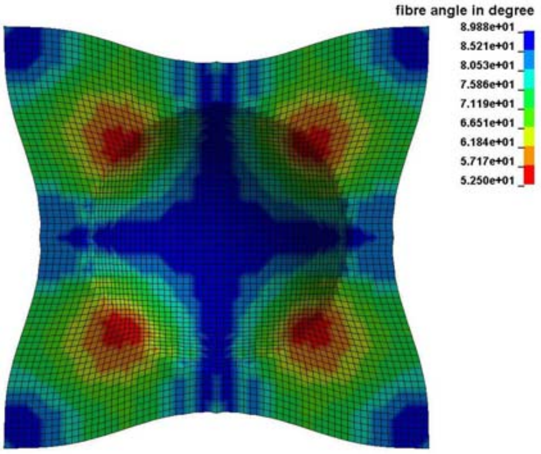
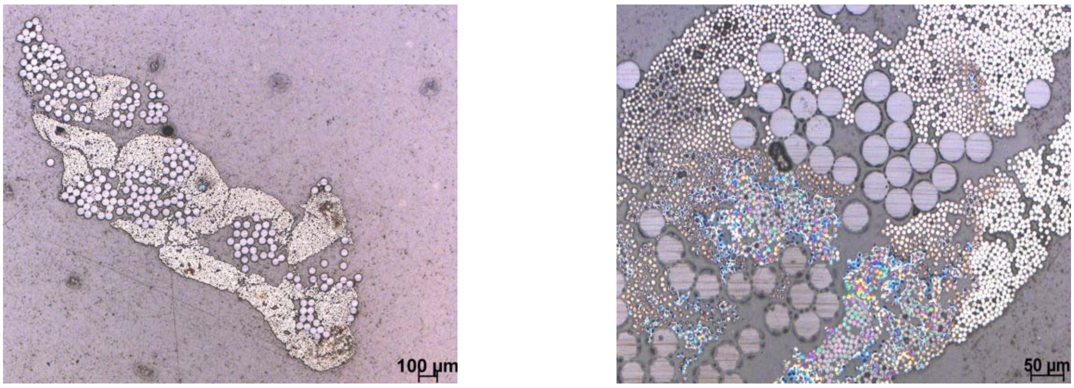


Figure 6 Fibre angle distribution after forming a hemisphere

3.2 Homogeneous distribution

Figure 7 shows the thread cross sections of the commingling hybrid yarn. The main focus was on the assessment of the rate of mixing of reinforcement and matrix component.



(a) Complete Thread Cross Section (b) Detailed View

Figure 7 Microsections of the Thread Cross Sections of a hybrid yarn made of a comingling process

3.3 Tensile and Bending testing UD composite in 0° and 90° direction

According to DIN EN ISO 527-5 tensile tests of different UD-winded-composites based on several yarn architectures of GF/PET 840tex, provided by PD-GOschatz were tested. The results of the most satisfying Composite plates (UD) are shown in Table 1.

The tensile strength and the tensile module were first tested on the unidirectionally reinforced composites in fibre direction (0° direction) and transversely to it (90° direction). An analysis of the test results in 90° direction is redundant, as the fibres are not oriented in tension direction and accordingly exhibit extremely low values.

The differences in strength-elongation behaviour previously encountered in hybrid yarns and dependent on the reinforcing component's material are tendentially mirrored in the tensile strength of the composites.

Table 1 Tensile properties of UD-composite laminate consolidate from GF/PET (70/30 mass%) hybrid yarn

Tensile test	0°-direction	90°-direction
E-modulus in GPa	36,9	4,6
Breaking strength in MPa	717	21

3.4 Tensile and bending tests of different multilayered fabrics

According to DIN EN ISO 527-5, tensile tests, and according to DIN EN ISO 14125, bending tests of consolidated multilayered fabrics were performed. They prove a large influence of the orientation of the threads as well as of the weft density. The more elongated the yarns are arranged, the higher the stiffness of the composite will be. Increasing weft density causes higher stiffness in weft direction. On the other hand, the weft density has great influence on the stiffness in warp direction as well. Because of the stress enhancement during the manufacturing process the stiffness in warp direction of the composite decreases.

4. Conclusion & Outlook

After extensive analyses of GF/PP, the matrix material was changed. For its higher temperature stability, which is particularly relevant for the cathodic dip coating of the vehicle structure components pursued in this project, PET was selected.

Therefore, it became necessary to evaluate a suitable yarn material and to adapt the machine and manufacturing parameters determined in the production of GF/PP hybrid yarns to that new material. After substantial cooperative research by TU Dresden and PD-GOschatz, the following yarn specification was defined. GF/PET hybrid yarns with a mixture ratio of 70:30 mass content % (55:45 volume content %) and a yarn count of 840 tex was determined as preferable yarn architecture.

Based on an enormous increase in quality and reproducibility, thanks to the automation of the handling and draping process, it is possible to reach huge reduction in manufacturing and handling time and costs for multilayered and deep draped textile performs to meet the requirements of demonstrator. The 3D-LightTrans technology will also lead to a significant increase in the resulting quality of the final product, since fixing the preform will only be done locally to minimize its influence on the final composite product, using knowledge gained by simulation and modelling of drapability.

Advanced industrial equipment will be developed for low-cost weaving of 3D-textile fabrics enabling efficient mass manufacturing of reinforcing textile preforms with customized multifunctional structure. In addition, handling and robotic processes will be implemented to drape the 3D-shaped fabric into complex preforms, which will then be fixed by a special fixing process.

5. Acknowledgment

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