Development of non-crimp multi-layered 3D spacer fabric structures using hybrid yarns for thermoplastic composites

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Abstract

An innovative weaving technology for the manufacturing of 3D woven double-walled spacer fabrics from high performance hybrid yarns was developed and implemented. Based on the gained technical and technological experience the woven multi-layered structures with load-oriented non-crimp fiber arrangement are realized and improved for high preform stiffness and a reproducible manufacturing. The article provides an overview of the technology for weaving of 3D spacer preforms in one production step with the required machine modifications. Furthermore the advantages of multi-layered woven fabric as well as the development of special pattern to forming and stiffening of the critical areas (joint areas) will be presented.

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Keywords: 3D woven spacer fabrics; multi layered weave; non-crimp fibre arrangement; critical area (joint area); fiber reinforced thermoplastic composites

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1. Introduction

Textile Reinforced Thermoplastic Composites (TRTC) exhibit a great potential for series production of complex, load-bearing and recyclable components in automotive and mechanical engineering. By now this potential has not been fully realized, but is currently the subject of intensive research and development, especially in the automotive sector. Among all material groups, TRTC offer the greatest flexibility to adapt the material structure according to the applied loads. Thus, they are predestined to enable a lightweight design considering complex demands, which require a multi-material design with optimized material mix.

In the development of the TRTC parts for complex applications, the reinforcement and the component structure have to be fitted to each other. This is bound to involve a close interaction of the design, simulation and manufacturing processes of both the material and the component. Thus, research at the Collaborative Research Centre (SFB 639), established at the Technische Universität Dresden, is focusing on a continuous investigation of the whole process of developing lightweight structures using hybrid yarn, in multi-material design for the future Fiber TRTC i.e. from filament up to component part. Figure 1 shows the process chain by SFB 639 for development and manufacture of TRTC (Widemuth, 2012).

![Process chain for TRTC by SFB 639](image)

The Weaving technology enables hybrid yarns (i.e. Glass/Polypropylene GF/PP) to be used for high density woven structures with load-oriented fiber positioning. Innovative textile preforms as double-walled shell structures (i.e. 3D spacer fabrics) possess low mass, high stiffness, and present great potential in the efficient production of TRTC. In this study, 3D spacer fabric made from multi-layered weaves for high mechanical properties in one production step without any additional processes (e.g. sewing or welded joint) will be presented. Furthermore, special weave patterns are developed to improve the joint area between the outer layers and the cross link.

2. Experimental

2.1. Functional and hybrid yarns

Carbon Fibers (CF), Glass Fibers (GF) and Aramid Fibers (AR) combined with a Thermoplastic matrix, as Commingled hybrid yarns, are used for the efficient production of TRTC with adjustable mechanical properties. The Commingled hybrid yarns have the highest potential for a homogeneous distribution of reinforcement and matrix components over the yarn cross section (choi et al., 1999). Moreover hybrid yarns...
can be manufactured from electrically conductive thread as core (e.g. carbon fiber and copper wire) and a matrix component as isolation wall. Those can be use for function integration. The advantage of textile semi-finished products (preforms) made of hybrid yarns is the manufacturing of composite parts without any additionally impregnation process (i.e. Resin Transfer Molding or Resin Infusion). However, inhomogeneous distribution of the reinforcing and matrix component may lead to poor and uneven impregnation. The very short flow paths achieved by commingled hybrid yarns allow a fast and complete impregnation of the reinforcement fibers bundles during the manufacturing of the composite part. Additionally the desired fiber volume fraction can be achieved by varying the number as well as the nominal linear density of the yarns during the hybrid yarn production. By using the Commingling technique it is also possible to manufacture multi-reinforced hybrid yarns with fitted properties (e.g. improved impact strength and failure behavior) consisting of two reinforcing components and one matrix component. A further advantage is the comparatively good processability of the commingled hybrid yarns by different textile-manufacturing technologies. The usage of Commingled hybrid yarns in the manufacturing of tailored textile structures leads to improved the mechanical properties of the TRTC parts and a rationalized production process compared to conventional manufacture technologies for the production of thermoplastic composites (Torun et al., 2011; Mountasir, Hoffmann et al., 2011). Moreover Textile Reinforced Plastics using thermoplastic hybrid yarns require lower temperatures and shorter cycle times during the consolidation process. Figure 2 shows an example of few mixture possibilities for hybrid yarns like as bi- and multi-component as well as electrically conductive threads.

![Fig. 2. Bi- and multi-component structures as well as functional yarns](image)

2.2. Necessary weaving machine modifications

The experimental developments were affected on a constructively modified double-rapier weaving machine VTR-23 (N.V. Michel Van de Wiele, Belgium) with a working width of one meter. The warp thread density on the weaving machine amounts 200 threads per 10 cm from high performance GF/PP hybrid yarns (410 tex). To manufacture of 3D woven spacer fabrics, a terry weaving mechanism in addition to a fabric storage mechanism and a warp pull-back mechanism are required. The terry weaving mechanism contains three deflecting rollers, of which the central roller (red color) serves to store the fabric and the two deflecting rollers (blue color) are used for the fabric transport (fig. 3). To realize the pleat as a woven cross link, the stored fabric is released, and the ground threads' float is pulled back into the machine. The back-rest roll system of the double-rapier weaving machine, creating warp tension with a lever arm and a weight, allows for the warp pull-back without an additional machine element.
For a smooth processing and reproducible production of 3D woven spacer fabrics a stretched roller take-up with automated supporting bars was developed and technically added to the double-rapier weaving machine (fig. 3). Only if the fabric remains stretched in the take-up area and the take-up forces are forwarded without buckling of cross links and stringers, the fiber sparing required for later load bearing, and form retention necessary for use as a preform can be guaranteed. These developments are indispensible for the damage-free take-up and reproducible production of 3D woven component preforms (Löser et al., 2011; Großmann et al., 2010).

To connect the production chain of the 3D woven spacer fabrics a combined cutting and storing system was developed and installed behind to the take-up system. It is used for trimming the fabric from the continuous weaving process to the preform length needed for the pressing tool. Ultrasonic (US) Cutting was chosen as the sectioning principle. This shatters the GF fibers, while the PP fibers are locally and briefly fuze at the cutting edge. The latter causes local consolidation and thus prevents unwanted fabric disintegration at the cutting edge. The cutting and storing of 3D woven preforms are realized within a same step (fig. 4), without interruption to the weaving process. This shows the advantages of the implemented constructive-technological machine modifications (supporting bars, stretched take-up, cutting and storing) for a continuous, high-quality and reproducible manufacturing of woven 3D preforms.
2.3. Development and manufacturing of 3D woven spacer fabrics

In contrast to conventional spacer fabrics (called pile weaves) connected by additional pile yarns with poor mechanical properties 3D woven spacer fabrics are constructed of woven outer layers connected by woven crosslink fabrics. For the manufacture of woven 3D spacer fabrics, a minimum of two warp systems from GF-PP hybrid yarns are necessary. At the beginning, the both warp systems weave the outer layers together with the weft threads. To weave the cross link fabric, only the one warp system is used, while the remaining threads from the second warp system form floats. When the desired length of the cross link fabric has been woven, the two warp systems weave together with the weft threads the outer layers. Afterward, half of the temporarily stored fabric length, which matches exactly the length of the floating warp yarns and twice the height of the cross link fabric, is released by the terry weaving mechanism. The floating warp threads are pulled back in warp beam direction. At the last weft’s beat-up of the cross link fabric, the reed pushes the formed cross link together as a pleat between the outer layers.

3D woven spacer fabrics are defined by the yarn material used and their structural parameters. To increase the stiffness of the woven fabrics (at the outer layers and crosslink), the weft density had to be increased. The greater weft density leads to yarn crimping, which results in a reduction or weakening of the mechanical properties (tensile strength and the E-modulus). In this case, it is advantageous to process non-ductile GF/PP high-performance hybrid yarns with a low elasticity in a non-crimped structural form. This makes it possible to manufacture multi-layered woven fabrics with greatly reduced yarn damage on the double-rapier weaving machine. This allows thermoplastic based 3D woven spacer fabric preforms using GF/PP hybrid yarns to be manufactured in one unique process step and possesses good mechanical properties such as tensile, compressive, flexural strength and impact resistance (Mountasir, Cherif et al., 2011). Figure 5 shows a 3D woven spacer fabric preform made from orthogonal multi-layered weave with non-crimped yarn arrangement and its thermoplastic composite.

![Diagram of 3D spacer fabric preform](image)

Fig. 5. 3D spacer fabric preform made from multi-layered weave (left) and its thermoplastic composite (right)

3. Selected Results

3.1. Mechanical properties of the composite sheets

*Test of the used GF/PP hybrid yarns*
The stresses placed on the hybrid yarns during processing are directly influenced by the composite’s mechanical properties. Therefore, it is necessary firstly to test the thread damage which occurs during the production. For this reason, individual yarns from fabrics made with yarn undulation and with non-crimped yarn arrangement in different weft density were removed. After that, the yarns were tested for tensile force by warp (w) and pick (p) direction. Figure 6 diagrams the results of the yarn damage.

The diagrams from Figure 6 show that the yarn damage increases with the increase of weft density during the weaving process. The hybrid yarns from fabrics without yarn undulation are processed gently resulting in minimal damage (up to 25 %) despite the increased weft density for higher fabric stiffness leading to an improved composite loading capacity, compared to yarns from fabrics with yarn undulation (45 %). The non-crimped yarn arrangement of the GF/PP hybrid yarn by the multi-layered woven fabric leads to superior utilization of the fiber substance strength in both warp and pick direction.

**Test of the composite sheets made from multi-layered woven fabrics**

The mechanical properties of the textile reinforced composite are influenced by the yarn arrangement in the fabric, the weft density, and the properties of the used hybrid yarn. Figure 7 diagrams few results of the mechanical tests on composite sheets in warp and pick direction made from non-crimped yarn arrangement multi-layer fabrics apply in 3D spacer fabrics in various weft densities (7, 10 and 14 weft yarns per cm). An uni-axial composite serves as a reference specimen (one layer of 416 tex GF/PP hybrid yarn, loaded in yarn direction) to compare the measured values (Mountasir, Kunadt et al., 2011).

The measured values of the composite sheets (such as tensile strength, flexural stiffness, compression properties, and impact properties) deliver significant and reproducible mechanical properties by multi-layered fabrics. The less fiber damage and the non-crimped yarn arrangement in the woven fabrics guarantee optimal use of the hybrid yarns fiber substance strength ultimately leading to required textile-reinforced composite for specific applications in lightweight engineering.

**3.2. Forming and improvement of joint area**

The joint area between the outer layers and cross link plays an important role and has a significant influence on the 3D preform’s strength. After pleat formation or, respectively, the set-up of the cross link, the pleat opens up again, due to the lack of joints of the warp thread systems at the beginning and end of the cross.
link fabric and the low friction force caused by the binding warps. This disintegration of the pleat causes a gap in the gusset area, leading to structural degradation and irregular geometrical deviations. An effective textile engineering solution for the improvement of pleat formation is the linking of the warp threads from skin and stringer fabrics immediately in front of and behind the stringer, ensuring the friction force between warp threads necessary to prevent the disintegration of the pleat. Figure 8 shows the structural development of the joint area and its real picture from preform and composite.

![Graphs showing mechanical properties](image)

**Fig. 7.** Mechanical properties of composite sheets made from multi-layered woven fabrics.

**Conclusion and outlook**

Woven 3D multi-layered spacer fabrics, constructed of woven outer layers and woven cross-link, are developed and produced in one unique process step. By the using of the multi-layered woven structure with stretched yarn arrangement, the applied GF/PP hybrid yarns will be processed gently with minimal yarn damage. Due to that, the fiber substance strength is optimal increased and leads to high mechanical properties of composite sheets. Furthermore, the joint area of 3D spacer fabric parts is improved and optimized for textile preform and composite. Through the high yarn crimping (see fig. 8), the improved joint area has to be optimized for required composite properties. Additionally, suitable test methods to investigate spacer fabric’s mechanical properties will be developed.
Fig. 8. (a) Developed structure for joint area on woven 3D spacer fabric; its real picture in textile (b); and (c) in composite form.

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References

Choi, BD., Diestel, O., Offermann, P., 1999. Commingled CF/PEEK Hybrid Yarns for Use in Textile Reinforced High Performance Rotors, 12th International Conference on Composite Materials (ICCM), Paris, France, 796-806.

Großmann, K., Müh, A., Löser, M., Cherif, Ch., Hoffmann, G., Torun, A.R., 2010. New solutions for the manufacturing of spacer preforms for thermoplastic textile-reinforced lightweight structures, Production Engineering 4, p. 589–597.

Löser, M., Müh, A., Hoffmann, G., Mountasir, A., Großmann, K., Cherif, Ch., 2011. Requirements for the reproducible manufacturing of spacer preforms made of glass thermoplastic hybrid yarns for composites, Techtextil Symposium, Frankfurt am Main, Germany.

Mountasir A., Hoffmann G., Cherif Ch., Kunadt A., Fischer W.-J., 2011. Newly developed textiles for function-integrating multi-material design in complex lightweight applications, SAMPE 2011, Long Beach CA, USA.

Mountasir, A., Hoffmann, G., Cherif, Ch., Löser, M., Mühl, A., Großmann, K., 2011. Innovative manufacturing technology for three-dimensional woven spacer preforms made of glass thermoplastic hybrid yarn for lightweight applications, 11th World Textile Conference AUTEX, Mulhouse, France.

Mountasir, A., Hoffmann, G., Cherif, Ch., Kunadt, A., Fischer, WJ., 2011. Mechanical characterization of hybrid yarn thermoplastic composites from multi-layer woven fabrics with function integration, Journal of Thermoplastic Composite Materials DOI: 10.1177/0892705711412814.

Torun A. R., Hoffmann, G., Mountasir, A., Cherif, Ch., 2011. Effect of Twisting on Mechanical Properties of GF/PP Commingled Hybrid Yarns and UD-Composites, Journal of Applied Polymer Science, DOI: 10.1002/app.34458.

Widemuth, J., http://www.tu-dresden.de/forschung/forschungskompetenz/sonderforschungsbereiche/sfb639/programm/inhalte_programm_de/ziele/document_view?set_language=en, Accessed 2012-09-30.