HYBRID TEXTILES – THE OTHER WAY OF FORMING HIGH-PERFORMANCE THERMOPLASTIC COMPOSITES FOR PRIMARY STRUCTURE

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Abstract

In the context of the LuFo IV-Project “VIA-Hybrid” a new technology for the manufacturing of highly integrated parts with endless-fibre reinforcement is being developed. The demonstrator consists of an endless-fibre reinforced structural insert, combined with an injection moulded component. Both sub-parts, consisting of fibre-reinforced PEEK, compose a complex formed window frame for passenger aircrafts. A high degree of innovation is accomplished through the combination of thermoplastic and carbon fibres in hybrid preforms (NCF- and TFP-based) for the production of the structural insert. After preforming the preform is thermoformed inside a compression mould to consolidate an endless-fibre reinforced structural insert. By CT-scans the microscale structure is examined to filter the effect of press parameters and lay-up variation on part quality. Finally an overmoulding step is performed with integrated structural insert. Contour fitting pre-heating of the insert with subsequent overmoulding thus leads to a highly complex and hybrid-fibre reinforced PEEK-structure.

1 Introduction

To meet the needs of emerging markets the CFRP manufacturing processes require significant cost reduction. A promising strategy is processing of thermoplastic composites due to their short consolidation times. However thermoplastic CFRPs are usually manufactured with prepreg or organo sheet materials which results in limited drapability. This disadvantage can be obviated by hybrid textiles consisting of thermoplastic- and carbon fibres. This class of reinforcements combines the excellent drapability of dry textiles with thermoplastic matrices. In addition the cost intensive thermoplastic materials can be processed with minimum scrap. In case that complex geometries are demanded, overmoulding with short-fibre reinforced thermoplastic material is a promising approach.

Figure 1. Process Chain

Thus key challenges for developing a hybrid structure consisting of a thermoplastic insert with endless-fibre reinforcement and overmoulding component are illustrated below.

2 Development of hybrid textiles

Hybrid textiles for thermoplastic composite structures consist of a combination of reinforcement fibres and thermoplastic fibres that supply the matrix structure during consolidation. This class of textiles offer the drapability of a dry textile combined with thermoplastic matrices. The process stability is advantageous, since the process step of matrix-integration is transferred to the textile manufacturer leading to a homogeneous matrix distribution even in draped regions.
To benefit from these advantages a hybrid non-crimp fabric (NCF) is developed by Karl Mayer GmbH and FIBRE. To provide applicable yarns, a development and a screening of hybrid yarns are performed in cooperation with Digel Sticktech GmbH for further production in the Tailored Fibre Placement (TFP) process.

To ensure a stable process during consolidation the shrinking behaviour of the hybrid yarns must be considered. Thermal shrinking, mainly induced by relaxation of the semi-crystalline structure during rise of their temperature above Glass Transition Temperature (T_G), must be reduced to a minimum [1]. Thermal Shrinking leads to displacement of the hybrid preform inside the tooling cavity during heating between T_G and the melting-point (T_M). The absolute effect of shrinkage primarily depends on temperature, degree of crystallinity and yarn structure. Especially thermoplastic yarns for hybrid textiles thus need to be optimised for minimum shrinkage. This is achieved by relaxation of the semi-crystalline structure during spinning. Also the yarns design takes immediate influence on the consequence of shrinkage. Stretched yarns are more prone to shrinkage than commingled yarns, which are part wise curled and interrupted in between.

During processing, the thermoplastic yarns are heated above T_G inside a press tooling. Yarns that tend to shrink can be fixed by compressing, so that shrinkage is suppressed. However strongly compressed yarns tend to disorientate the reinforcement fibres, when T_M is exceeded. Then the flow of the thermoplastic melt affects the orientation of the reinforcement fibres. Therefore it is important to use shrinkage optimised yarns, so that the pressure during heating can be reduced to a minimum.

The temperature dependent thermal shrinkage can be determined by Thermal Mechanical Analysis (TMA). In this context a market screening of existing and self-produced thermoplastic yarns is conducted, to obtain an overview of feasible thermoplastic fibres for hybrid yarns. For testing a Q400 TMA by TA Instruments is used at FIBRE. The yarns are clamped into a tensile testing unit inside a temparturised chamber. During heating the acting force is 0,025 N.

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Table 1. Thermal Shrinkage of thermoplastic yarns

Yarn Manufacturer	*Material*	*Specification of thermoplastic yarn* (tex, filaments)	*Elongation (%)* below T_g	above T_g
FIBRE	VICTREX PEEK 151G	385 f100	0,3	-0,75
FIBRE	BASF_Ultramid-B27	504 f100	-0,2	-0,4
Comfil	57C-PEEK-1400	600 f-	-0,3	0,8
Schappe	NM32_Carbon-PPS	-	-0,05	-0,1

All investigated fibre specifications provide adequate values for being processed as yarns for hybrid textiles. Values below ± 1% illustrate an excellent construction or relaxation during spinning.

The yarns by Schappe and Comfil are commercially available and also deliver excellent values. The commingled PPS-CF yarn by Schappe Techniques provides the smallest values for shrinking. This can be explained by the construction of the yarn with similar curls or discontinuities of single carbon and thermoplastic filaments. Hence the advantage for processing is combined with reduced mechanical properties.

For manufacturing hybrid textiles a suitable combination of reinforcement- and thermoplastic fibres has to be found. In this context the chosen reinforcement fibre is TohoTenax HTS 45 12K with P12 sizing which has advantageous adhesion properties in combination with thermoplastics [2]. As matrix and sewing yarn, self-developed fibres from VICTREX PEEK 151G are chosen. The developed construction enables Fibre Volume Contents of 54% and an engineered ply thickness of a single ply carbon fibre is 0,23 mm.

3 Process Development

3.1 Preforming

Two different principles are combined for preforming. To deposit the carbon- and PEEK fibres in parallel into the circumferential geometry, Tailored Fibre Placement (TFP) is an appropriate method. Therefore a hybrid roving is deposited in spirals and fixed by a sewing-yarn from PEEK onto a film made of PEEK. Consequently the later consolidated structure will not be disturbed by any foreign material. Although the TFP-unit is only able to deposit single hybridrovings, the process efficiency is high, due to the possibility of multiple parallel running stitching units.

For positioning fibres with other than continuous 0°-direction, the efficiency of the TFP process would be reduced due to required loops that decrease the process velocity. Hence fibres with ±60° direction are integrated by draping hybrid NCF. To evaluate an appropriate NCF, different configurations, produced by Karl Mayer, have been investigated. The objective was to configure a NCF with a high degree of in-plane drapability and furthermore a low tendency to narrow while being draped. To examine the most promising configuration, three NCF with different stitching pattern and stitch distances are developed and compared by DRAPETEST studies and picture analysis of the fibre orientation [3].

Figure 2. Hybrid NCF, Drapetest, WindowFrame Preform (f.l.t.r.)

Both variants, Hybrid-NCF and TFP-Hybridroving, are combined by stitching to assemble the preform. If all TFP stitching units are considered, preforming of the Window Frame can be reduced to 25 min per part and therefore by 70% compared to a Window Frame preform for a conventional RTM-process [4].

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3.2 Thermoforming technology

A major challenge for processing hybrid textiles is the mechanical and thermal design of the press tooling, which in this context is developed by HBW-Gubesch Thermoforming GmbH and FIBRE. The heat management of the press tooling follows a variothermal approach. For melting PEEK processing temperatures up to 400°C are required to reduce the melt viscosity and improve fibre bundle impregnation. Technology principles that enable tooling temperatures to 400°C are:

- Electric heating by cartridges
- Oil tempering (cooling and/or heating)
- Inductive heating of metal tooling surface
- Microwave heating of tooling surface

In this case heating is supported by electric cartridges and cooling by oil. Electric cartridges provide the advantage of fast and precise heat transfer into the tooling and minor costs, whereas cooling of high tooling mass from 400°C requires pressurised oil.

The layout of the cooling system is designed based on simulation results, giving recommendations for the optimum positioning of cooling channels for oil and the heated zones of the flexible tubular heaters close to the tooling surface. The knowledge of the temperature distribution is very important to predict the local thermal expansion of the tooling to prevent contact of upper and lower die and to achieve a uniform heat transfer into the laminate.

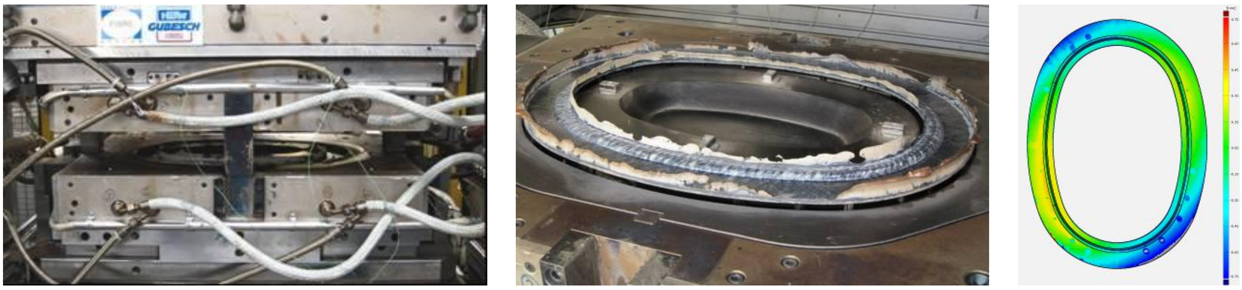

Figure 3. Compression Mould, Consolidated Preform, Thickness Analysis (f.l.t.r.)

After consolidation the oval insert-geometry is controlled a by an optical part scan to examine effects of inhomogeneous influences like temperature distribution or geometrical asymmetries. The components resulting warpage compared to the CAD-model of -0,7 mm - 0,5 mm (diameter approx. 550 mm), measured by a GOM-ATOS system, indicates a sufficient homogeneity of the temperature.

3.3 Consolidation process

The process steps for thermoforming can be divided into:

- heating up to processing temperature (390-400°C)
- consolidation at processing temperature
- solidification by cooling

The final two sub-steps gain the most significant influence on the part quality. Considerable parameters for impregnation quality during consolidation are material parameters (fibre bed elasticity, fibre and matrix distribution, flow length, ply thickness), which are set, and as well duration and

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pressure. During solidification phase the degree of crystallinity is determined which again influences the impact resistance, the chemical resistance of the thermoplastic and the thermal shrinkage amongst others. Since the material parameters are fixed, an experimental setup for the influence of pressure is performed. Three different pressure cycles are compared by manufacture of laminates on coupon level. These are also set in contrast to formerly produced laminates with polyamide 6 as matrix system:

- Hybrid-NCF CF-PEEK, 0_4
- Hybrid-NCF CF-PEEK, $(+45/-45)_{2s}$
- TFP Hybrid-Roving CF-PA6, $(+45/-45)_{2s}$

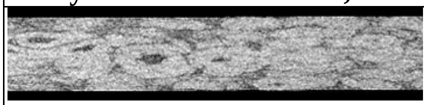
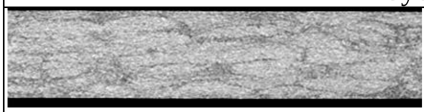
Chosen pressure and time parameters are listed below:

Table 2. Consolidation Parameters

Process parameters		Cycle 1	Cycle 2	Cycle 3
Pressure	(bar)	10 (20 during cooling)	20 (40 during cooling)	5-40 (stepwise)
Impregnation time	(min)	20	20	20
Cooling rate	(K/min)	17	17	17

To outline the effect of pressure, impregnation time and cooling rate are kept unchanged. The laminates quality is determined by CT-scans (Phoenix-xray v|tome|x m) which provide information about the fibre-matrix distribution, cracks, or voids. Therefore scans with voxel-size of 14 µm were performed for each specimen. The obtained results are illustrated below.

Table 3. Analysis of laminate microscale (CT and micrograph image (right))

<table>
<tr><th>Hybrid-NCF CF-PEEK, 0°</th><th>Hybrid-NCF CF-PEEK, ± 45°</th><th>TFP Hybridroving CF-PA, ± 45°</th></tr>
<tr><td>
Void content: ~7%</td><td>
Void content: ~4%</td><td rowspan="6">
Cycle 10-50 bar stepwise, Impregnation time 10 min (micrograph image)</td></tr>
<tr><td colspan="2">Cycle 1</td></tr>
<tr><td>
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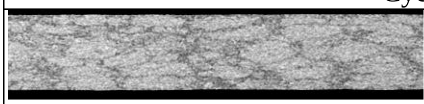
Void content: ~4%</td></tr>
<tr><td colspan="2">Cycle 2</td></tr>
<tr><td>
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Void content: ~2%</td></tr>
<tr><td colspan="2">Cycle 3</td></tr>
</table>

For both fibre orientations, 0° and ± 45°, the pictures show a significant better impregnation of the reinforcement textile for the higher process pressures at cycle 2 and 3. The values for the void content are approximated by an optical analysis of the CT-scans. It is shown that comparatively low pressures of 10 – 20 bar seem to be inappropriate for impregnation in 20 minutes. A high degree of improvement is achieved by increasing the pressure to values between 20 - 40 bar. Especially stepwise increase of the pressure is a promising method.

A second identified effect is cracks inside bi- or multidirectional lay-ups. In this case laminates with ±45°-orientation contain numerous inter-fibre-failures which mostly appear in between single filaments inside rovings. A hypothesis explaining this phenomenon is related to process induced thermal shrinkage of the thermoplastic matrix during cooling. During cooling the thermoplastic matrix shrinks. For bi-directional laminates shrinking of the matrix is suppressed by reinforcement fibres in adjacent plies with differing orientation. This process-induced tensile stress thus results in inter-fibre-failure, as it already analysed for thermoset composites [5]. In comparison to polyamide-based matrices, especially PEEK seems to be prone to this effect. An explanation is the high temperature difference between solidification (343°C) and room temperature. A range of more than 370K temperature difference in combination with a thermal expansion coefficient of PEEK of $55\text{-}140 \cdot 10^{-6}\ K^{-1}$ has to be covered [6]. These internal stresses must be withstood by the fibre-matrix adhesion which is difficult to maintain especially for thermoplastics.

Approaches to prevent these material characteristic problems could be to reduce the ply thickness of adjacent plies by spreading carbon fibres to an increasing degree. This would effectuate a reduced stiffness and therefore reduced stresses while shrinking. Parallel a more homogeneous distribution of the fibres inside the matrix and reduced impregnation times by shorter impregnation distances would be achieved. However the effort for preforming would be raised.

4 Overmoulding

To achieve a complex three-dimensional geometry the flat structural insert is further combined with injection moulding. The objective of the developed process is to realize a substance-to-substance bond between the PEEK of the insert and the injection moulded Victrex PEEK 90HMF40. During this overmoulding process step, performed by Ferdinand Stuekerjuergen GmbH and KraussMaffei Technologies GmbH and supported by SLK-TU Chemnitz, FIBRE and HBW-Gubesch Thermoforming GmbH, the structural insert is positioned and fixed inside the tooling for injection moulding. The injection moulding unit furthermore is capable of automated and form-fitting pre-heating of the insert prior closing of the mould to enable the material bond during injection.

The experiments show that overmoulding of structural inserts with PEEK as matrix system can lead to accurate combinations of fibre-reinforced thermoplastic structures. Consequently the feasibility of overmoulding of structural inserts made from hybrid textiles and injection moulding granules is demonstrated. Nevertheless prospective research projects should focus problems that appeared during the process. Especially thermal shrinking while cooling of the injection moulded structure, which is a main reason for warpage (approx. 3 mm), should be analysed since it also affects internal stresses in the interface region. Hence in further activities, design methods for overmoulding structures to minimize warpage and internal stresses must be developed [7]. In addition, methods for pre-heating the insert will be persued, validated and industrialised to provide a homogeneously heated insert surface which enables equal interface quality, independent of the insert geometry.

Figure 4. Pre-Heating of structural insert, Overmoulded WindowFrame, CT-Scan (f.l.t.r.)

5 Conclusions

The presented results illustrate the feasibility to create complex fibre architecture with high performance thermoplastics. Endless-fibre reinforced structures from hybrid textiles, as well as overmoulded geometries, are reproducibly to manufacture. The obtained results show key challenges to be accepted in the future. For processing hybrid textiles this means to understand the formation of internal stresses during cooling, especially for high performance thermoplastics with high processing temperatures. Here the internal stresses need to be comprehended to deviate rules for material and process design. In addition a design method for overmoulding with PEEK must be developed, now that the general feasibility was proven. Here the influence of the required pre-heating temperature and the short-fibre orientation on the interface strength must be analysed. In parallel the developed technology needs to be raised to a more industrial level.

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