THERMOPLASTIC COMPOSITE PARTS BASED ON ONLINE SPUN COMMINGLED HYBRID YARNS WITH CONTINUOUS CURVILINEAR FIBRE PATTERNS

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Abstract

Combining two innovative technologies (SpinCOM and AOPS), which were recently developed at Leibniz-Institut für Polymerforschung Dresden e. V. (Leibniz-IPF), leads to an effective and reliable way to design and manufacture structural components consisting of continuous thermoplastic and glass filaments and load optimised continuous curvilinear fibre patterns for lightweight applications. Continuous glass fibre reinforced polyamide 6.6 hybrid yarns and composites thereof meet the demands of high impact resistance, high stiffness and strength values as well as short production cycle capabilities and low material costs.

1. Introduction

An efficient technology to manufacture glass and thermoplastic hybrid roving material was recently developed at the Leibniz-Institut für Polymerforschung Dresden e. V. (Leibniz-IPF). The simultaneous melt spinning of polymer and glass filaments and in-situ commingling (SpinCOM, [1]) provides high distribution homogeneity in one processing step. Thus, additional commingling like air texturing can be excluded. With the help of the material optimisation software tool AOPS (Advanced Optimization for Principal Stress), a load adapted, variable-axial fibre pattern for high component stiffness to weight performance can be derived to exploit the full potential of continuous fibre reinforced materials in structural parts. The hence obtained curvilinear fibre pattern yields a complex and inhomogeneous outlined surface, which makes realistic modelling as well as compression moulding processes challenging and impractical so far. These constraints have now been solved by the possibility to derive surface data for the required moulding tools using the AOPS algorithms.

The sewing thread, necessary for the manufacturing using the TFP-Technology, is normally treated with an adhesion strength reducing silicone-based sizing, which leads to a significant reduction of transverse tensile and shear strength. At Leibniz-IPF a polyamide (PA 6.6) thread with a customized sizing was developed and applied to the TFP process as replacement of the conventional commercially available thread.

The SpinCOM hybrid yarns as "dry performs" offer a high potential for mass production utilization by high automation, high reproducibility and combination with insert application and injection moulding processes.

A demonstrator torque arm (Figure 1) is designed and developed in this work in order to reflect the process chain from filament spinning up to part consolidation.

Figure 1. The torque arm, made of glass fibre/PA 6.6 which is used as a demonstrator. The black colour is caused by the additional material applied by the final injection moulding step.

2. Material Design

When a thermoplastic matrix material is used, fibre impregnation is much more critical than for thermosets, due to the high melt viscosity of the thermoplastics.

Therefore, the most promising manufacturing technology SpinCOM [1, 2] has been used which advantage is the homogeneous distribution of matrix and reinforcing fibres manufactured by online melt spinning. Figure 2 shows the schematic of SpinCOM and some detail images of the process.

In contrast to air texturing, the reinforcement fibres are not damaged during commingling and an additional processing step can be avoided. Furthermore, the homogeneous fibre/matrix distribution within online spun hybrid yarns leads to high mechanical performance values and a minimal infiltration time during consolidation due to short flow paths of the melt.

The online hybrid yarn spinning leads to a highly reproducible consolidation quality. For the application presented here, a glass and PA 6.6 hybrid yarn with a fibre volume fraction of about 50 % and a material appropriate optimized sizing was used.

Besides the application of SpinCOM yarns for textile fabrics, like UD-tapes, long fibre reinforced thermoplastics (LFT), their processability for the Tailored Fibre Placement (TFP) technology has been investigated, as shown below.

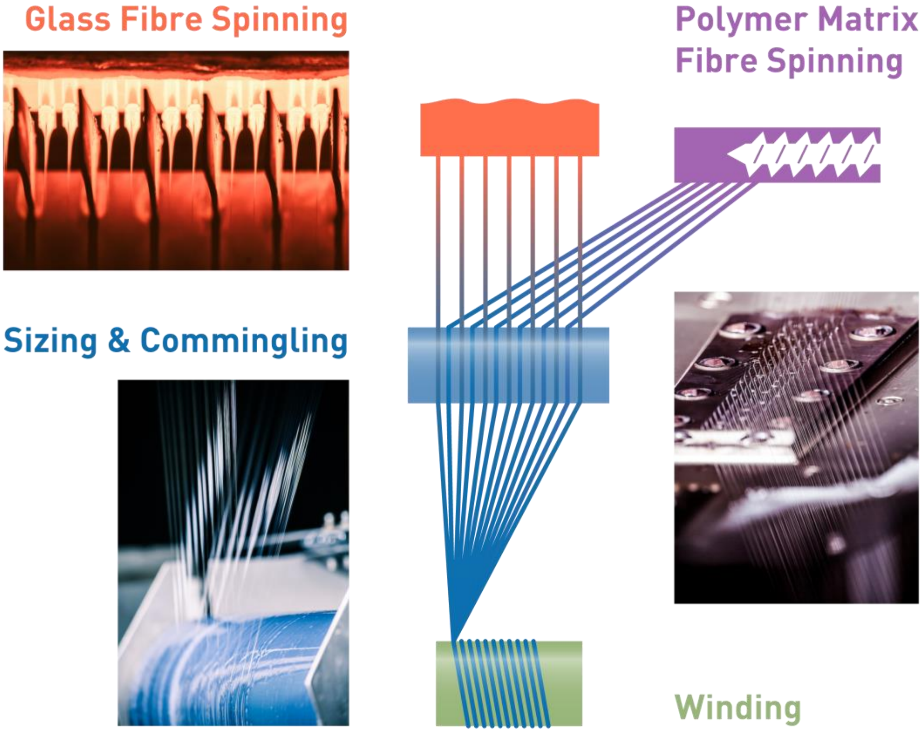

Figure 2. Principle of online hybrid yarn spinning and commingling (SpinCOM, [1])

3. Fibre path derivation and design of the part

In order to exploit the highly anisotropic material behaviour in terms of strength and stiffness, a load adapted fibre design is recommended. Under consideration of the given part geometry and in the event of a limited number of applied load cases a nonparallel, respectively curvilinear fibre orientation can lead to an outstanding material utilisation in terms of a high strength/stiffness to mass performance [3].

One field of research at the Leibniz-IPF is the structural design of such load adapted reinforcement structures. Therefore, a software tool called AOPS [4] was developed. This tool includes different functionalities as listed below.

- Stress-field aligned (principal stress) trajectory derivation for optimised curvilinear fibre designs
- Thickness derivation and surface export for tool construction
- Detailed FE models considering local thickness and local fibre orientation
- Implementation of advanced failure criteria for continuous fibre reinforced plastics (Failure Mode Concept (FMC), [5])

The design of the developed torque arm was realised using AOPS with respect to two corresponding load cases (tension and compression) as shown in Figure 3.

The FE modelling capability of AOPS in combination with failure criterion analysis (FMC, [5]) was used for the design of the torque arm. Figure 4 shows some results of the finite element analysis and inter-fibre-failure criterion analysis.

Figure 3. Load cases for the design of the torque arm and for the testing of the manufactured part

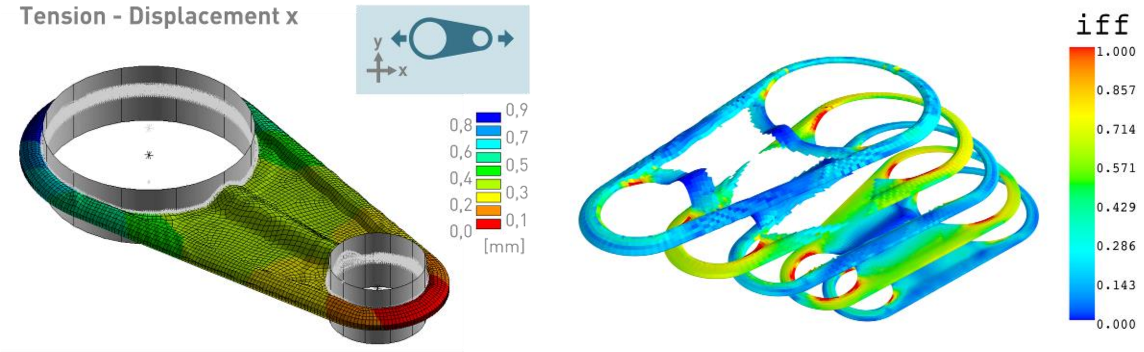

Figure 4. Displacement results of the finite-element-analysis and layer-wise inter-fibre-failure analysis in accordance with [5]

4. Manufacturing

4.1 Preforming

To produce textile preforms with a complex curvilinear fibre pattern, containing relatively small radii below 10 millimetres of the fibre paths, the state of the art placement technology is Tailored Fibre Placement (TFP, as shown in Figure 5) [6]. By using TFP machines with multiple heads high production rates for small and medium sized parts with a load adapted fibre path can be achieved, in contrast to other fibre placement technologies, e.g. Automated Fibre Placement (AFP). Figure 6 reveals the curvilinear fibre pattern and the preform of the torque arm (cf. Figure 3), derived from the tension and compression load cases.

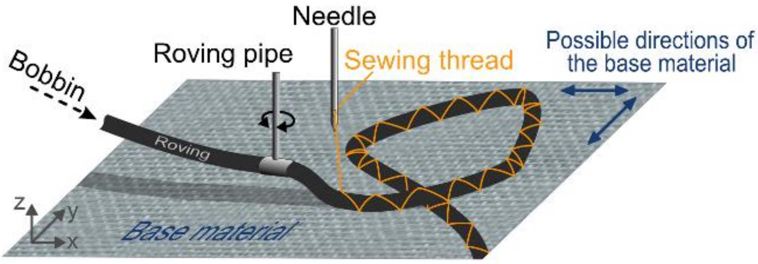

Figure 5. Principle of the Tailored Fibre Placement technology

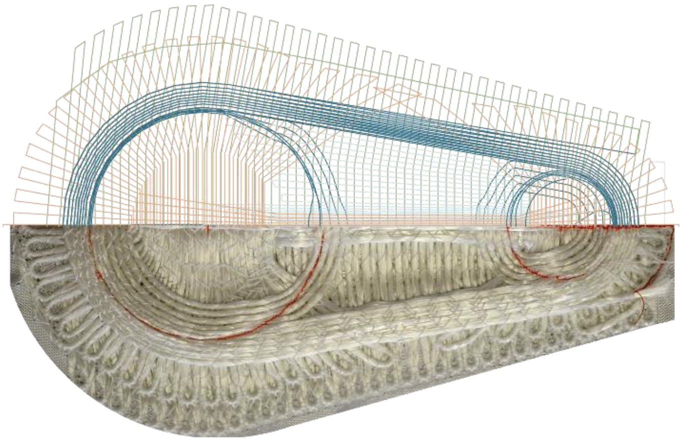

Figure 6. Curvilinear fibre pattern (top) and TFP manufactured preform (below) of the torque arm

The TFP technology is further characterised by high reproducibility and material cost saving by offering the possibility of near net shape manufacturing. In the presented case of the torque arm the preform was fringed with a specific cutting die.

4.2 Sewing thread development

One characteristic of the TFP technology is the need of a sewing thread. Commercially available threads are assumed to be finished with a silicone sizing. Due to its poor adhesion strength it notably reduces the shear strength and transverse tensile strength of the composite part. In order to solve this issue, a customised PA 6.6 sewing thread with a suited sizing for the glass fibre/PA 6.6 composite was developed at Leibniz-IPF. Figure 7 shows the increase of transverse tensile strength of TFP manufactured specimens based on a glass fibre/PA 6.6 hybrid yarn from 6 MPa for a commercial sewing thread up to more than 20 MPa applying the IPF customised sewing thread. The thread melts during the consolidating process without affecting the strength performance.

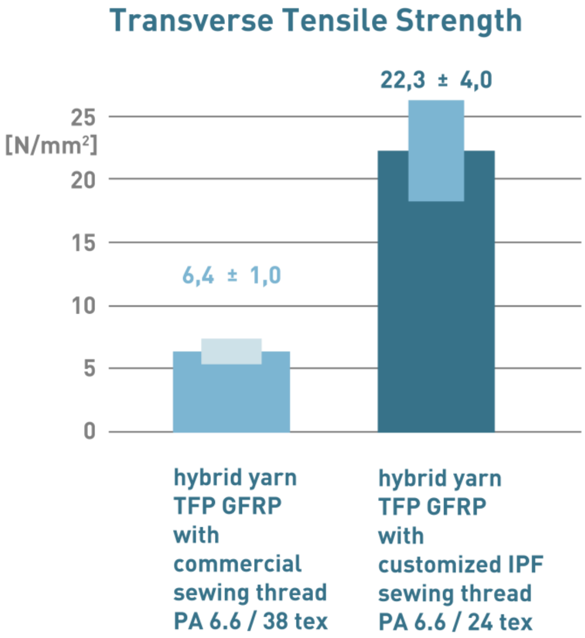

Figure 7. Transverse tensile strength of glass fibre/PA 6.6 TFP manufactured test specimen with commercial sewing thread and customised sewing thread developed at Leibniz-IPF

Furthermore the TFP induced fibre undulation is reduced due to the melting thread, which leads to better fibre parallel stiffness and strength values compared to FRP made of TFP using commercially available non-meltable sewing threads.

4.3 Surface design for tool construction

The consolidation process of preforms made of hybrid yarns can be carried out by compression moulding in low cycle times. The application of pressure and temperature melts the polymer matrix fibres and the reinforcement fibres are wetted according to the low flow paths between polyamide and glass filaments. A vacuum assisted compression moulding process is suggested to prevent voids.

When dealing with curvilinear fibre constructions the challenge is the design of a consolidation tool which reflects the thickness distribution of the preform. Furthermore an exact fitting of the preform in the tool geometry is necessary when using meltable sewing threads, because there is no further fixation of the reinforcement fibres once the thread was melted.

Using the AOPS software tool, the thickness distribution (Figure 8, left side) can be computed in high resolution based on the fibre design pattern. Hence, the consolidation tool can be designed easily with help of 3D-CAD (Computer Aided Design) software and automatically manufactured with a CNC (Computerized Numerical Control) metal milling machine (Figure 8, right side).

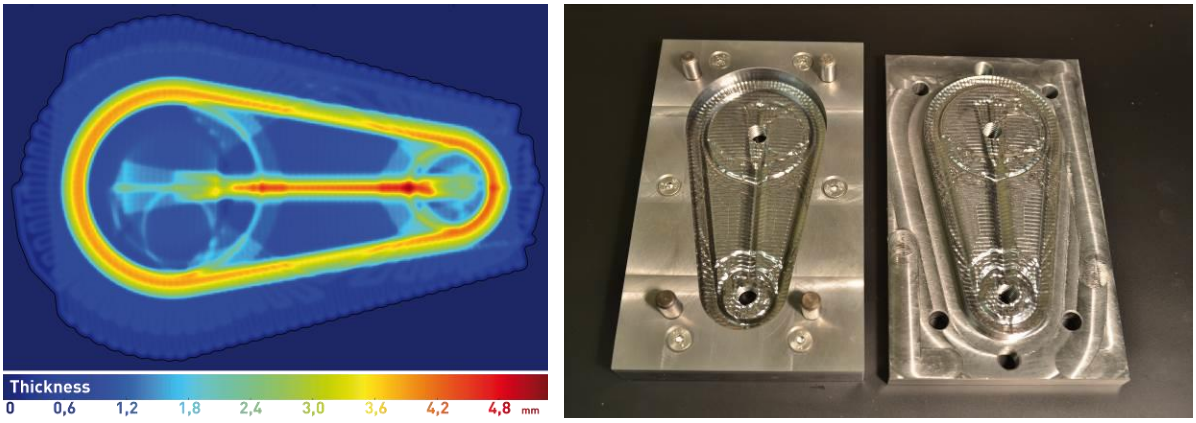

Figure 8. Thickness distribution of the torque arm (one half of the symmetrical component) computed using the AOPS software (left side) and final metal consolidation tool (right side)

The lab-consolidation process, for which a heated vacuum hydraulic press was used, took about ten minutes per part. The consolidation quality is very good and the process itself is highly reproducible and reliable.

The part manufacturing is completed with milling of the holes for load transmission and the assembling with metal inserts and a final injection moulding step for insert fixation (Figure 1).

5. Testing

A series of 20 torque arm parts was manufactured to evaluate the reproducibility of the complete process chain described above. A considerably high quality of all parts was achieved without any reject parts. Tension and compression tests illustrated the good quality with very low standard deviations.

Figure 9 shows that the failure load under tension and compression loading was increased by about 120 % compared with reference parts manufactured by short fibre reinforcement (GF/PA 6.6; 30 % w/w).

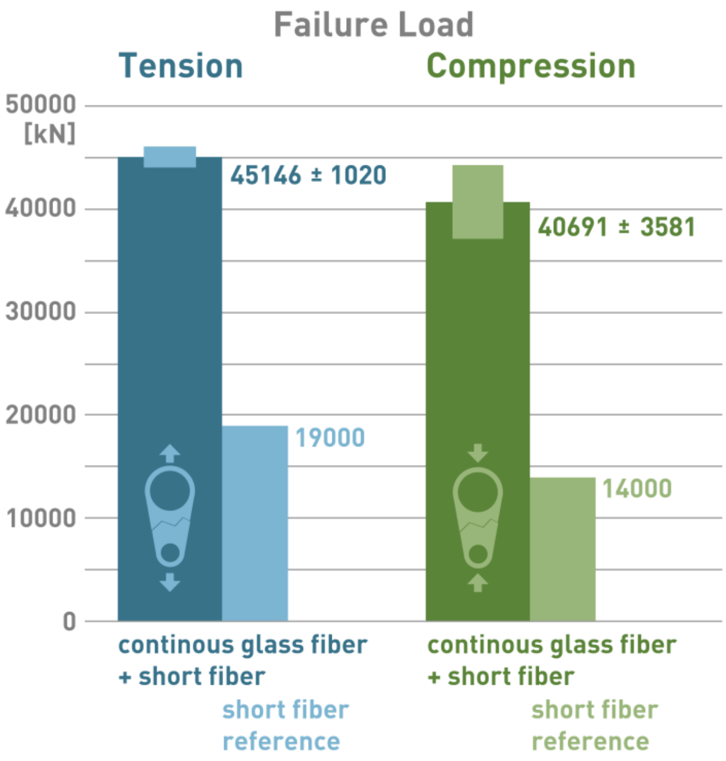

Figure 9. Failure load under tension and compression loading of the developed curvilinear continuous fibre reinforcement and short fibre reinforced reference parts

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References

[1] N.Wiegand, E. Mäder. SpinCOM yarns – from reinforcement to functional fibres. In *European Conference on Composite Materials*, Volume 16, 2014.

[2] E. Mäder, J. Rausch, N. Schmidt. Commingled yarns – Processing aspects and tailored surfaces of polypropylene/glass composites. *Composites Part A: Applied Science and Manufacturing*, Volume 39: 612-623, 2008.

[3] A. Spickenheuer; M. Schulz, K. Gliesche, G. Heinrich. Using tailored fibre placement technology for stress adapted design of composite structures. *Plastics, Rubber and Composites*, Volume 37: 227-232, 2008.

[4] A. Spickenheuer, L. Bittrich, K. Uhlig, E. Richter, G. Heinrich. A new software tool for design and simulation of variable-axial composites parts. In *International Symposium on Automated Composites Manufacturing*, Volume 1, 2013

[5] R.G. Cuntze. Efficient 3D and 2D failure conditions for UD laminae and their application within the verification of the laminate design. *Composites Science and Technology*, Volume 66: 1081-1096, 2006.

[6] P. Mattheij, K. Gliesche, D. Feltin. Tailored Fiber Placement - Mechanical Properties and Applications. *Journal of Reinforced Plastics and Composites*, Volume 17: 774–786, 1998.