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TRANSFERRING THE 3D SKELETON WINDING PROCESS TO INDUSTRIAL AUTOMOTIVE APPLICATIONS: ADVANCEMENTS AND IMPLEMENTATION STRATEGIES

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ABSTRACT

The mechanical properties of injection molded structural components can be significantly enhanced by incorporating local continuous fiber reinforcements in the highly stressed areas along the load paths. Depending on the component's complexity and the applied loads, topology optimization may indicate the need for a three-dimensional skeleton-like fiber structure to maximize the lightweight potential. The 3D Skeleton Winding (3DSW) process is a robot-based technique for efficiently manufacturing complex continuous fiber structures through 3D filament winding.
To apply the potential of the developed process to structural components in high-volume production, this paper demonstrates the transfer of the 3DSW process to an automotive application through the development of an industrial 3DSW pilot process line.

1 INTRODUCTION

The use of fiber-reinforced plastics allows the degree of anisotropy to be adapted to the existing load cases [1]. This is particularly advantageous if structurally loaded components are to be reinforced locally with continuous fibers (e.g. glass or carbon fibers) according to the existing loads. The local introduction of continuously reinforcing fibers according to the existing main load paths can thus contribute significantly to increasing the potential for lightweight design of a structural component.
Using coreless 3D filament winding processes, continuous fibers can be wound into complex, skeleton-like reinforcing structures. If these reinforcement structures are then used as local continuous fiber reinforcements in thermoplastic injection molding process, structural lightweight components can be manufactured economically in large series.
The 3D Skeleton Winding (3DSW) process developed at Fraunhofer ICT describes such a process to produce local continuous fiber reinforcements for structural injection molded components [2, 3, 4]. Compared to continuous fiber reinforcements in the form of tape layers or organosheets, which can also be functionalized in injection molding,

wound fibers can be used to create significantly more complex reinforcement structures. At the same time, waste is kept to a minimum, as only the fibers that subsequently form the load-bearing structure of the component need to be used in the manufacturing process. As the process is designed for the realization of structural injection-molded components for large-scale production (e.g. in the automotive sector), process automation is of particular importance.

2 3D SKELETON WINDING (3DSW) – PROCESS DEVELOPMENT

2.1 Process description

In principle, the 3DSW process chain can be divided into three different sub-process steps: "heating and impregnation"; "robot-based 3D winding"; and "overmolding of fiber skeletons" (cf. Figure 1).

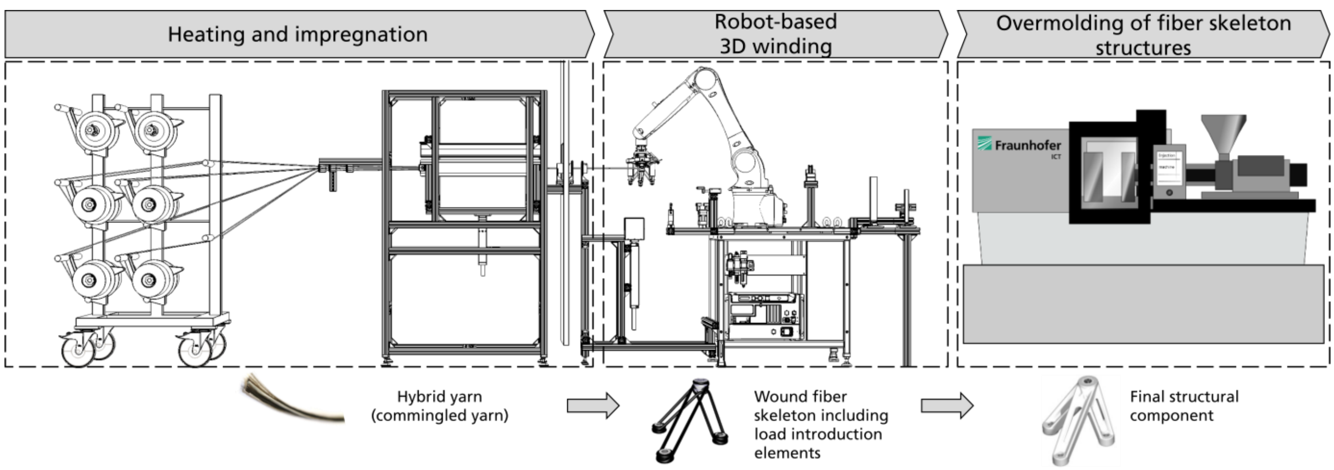

Figure 1. Process chain of the 3DSW process [2]

In the 3DSW, commingled yarns consisting of thermoplastic filaments and continuous reinforcement fibers are pulled from a roving creel and passed through an infrared (IR) heating unit consisting of ceramic hollow chamber IR panel radiators. After heating, the fibers are impregnated and consolidated into a single strand using a heated nozzle. The cross-section of the strand is determined by the nozzle geometry (e.g., a nozzle with a diameter of 2 mm). Downstream of the nozzle, a heated fiber guide eyelet is used as a reference point for robot-based winding. Fiber pretensioning is controlled by a pneumatic braking force acting on the creel's coil carrier and friction forces in the nozzle. The 3D winding area starts after the strand guide eyelet, where additional hot air blowers can be used to maintain the strand at melting temperature during 3D winding.

A conventional six-axis industrial robot, which is modified to enable infinite rotation of the sixth axis, is used for the 3D winding process. The winding tool attached to the robot flange includes a pneumatic gripper for gripping the heated fiber strand as well as cylindrical holders for aluminum inserts that are used as load introduction elements in the final component. The inserts are obtained from an insert magazine and picked up by the robot prior to 3D winding. A vertically movable gripper cutting unit provides the heated fiber strand at the start of the winding cycle. After the winding sequence is completed, the gripper cutting unit cuts the strand from the wound fiber skeleton before that latter is ejected and further processed.

The final step, "overmolding of fiber skeleton structures," involves the embedding of the wound fiber skeleton and the realization of the final component shape by using conventional injection molding process. Ideally, the same thermoplastic matrix system is used for both the initial commingled yarn and the overmolding matrix. To maximize the benefits of local continuous fibers, the reinforcement structure is strategically placed in areas of the component exposed to tensile stress. The injection molding matrix must also withstand compressive fiber-parallel stresses as well as any fiber-transverse and shear stresses.

2.2 Transfer of the 3DSW process to an industrialized production line

Based on the process described in section 2.1 and based on an existing 3DSW prototype line that was developed and validated at Fraunhofer ICT over the past years, a newly industrialized and CE-certified winding cell has been developed (cf. Fig. 2). This winding cell consists of a control unit including a human-machine interface, which is used to set all necessary process parameter settings. As for the prototype line, a roving creel is used to store and pretension the commingled yarns, which are pulled through a heating section due to the robot's winding movements. A combination of IR and microwave radiators heats the thermoplastic filaments of the commingled yarns above melting temperature. A heated impregnation nozzle finally combines the single rovings to one strand while impregnating the reinforcing fibers with the thermoplastic matrix.

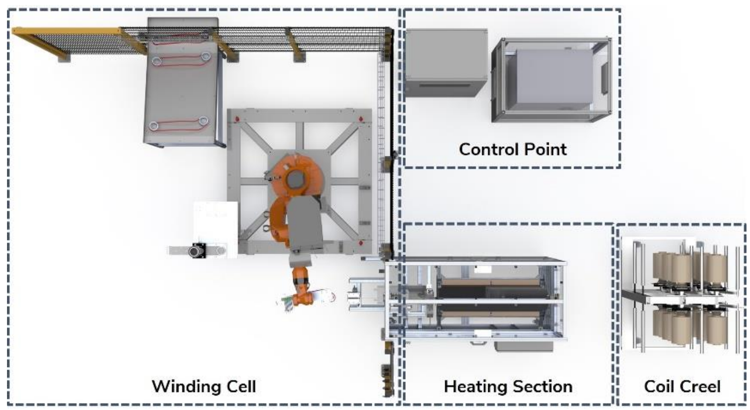

Figure 2. Industrialized 3DSW production line developed by Fraunhofer ICT and Fritz Automation GmbH (left); Illustration of the 3DSW units (right)

3 APPLYING 3DSW FOR STRUCTURAL INJECTION MOLDED COMPONENTS

3.1 Materials

To demonstrate the general lightweight potential of the 3DSW process, generic 3D demonstrator components are manufactured using a 600 tex commingled yarn from Comfil ApS (type 50G-PPS-U3020-600). This commingled yarn contains 50 wt.% E-glass fiber of a multi-purpose roving grade with PPS-suitable silane sizing (NEG TufRovTM 4588). For the overmolding of the wound skeleton structure impact modified PPS (DSM XytronTM U3020E) is used as an unreinforced grade. Furthermore, fiber skeleton structures are also overmolded using a 40 wt.% short glass fiber-reinforced PPS.

The automotive demonstrator component that was used to validate the industrialized 3DSW production line does not have any specific temperature requirements that would also have necessitated the use of PPS. Therefore, PA6/GF commingled yarns are used to realize the continuous reinforcing structure of the demonstrator component in 3DSW using a fiber weight content of 62 %. To embed the continuous reinforcing structure in the final component geometry a 20 wt.% short glass fiber-reinforced PA6 is considered.

3.2 Mechanical results of the generic 3D demonstrator component

Figure 3 illustrates the achievable tensile failure loads observed during the testing of the generic 3D demonstrator component. The unreinforced PPS reference components exhibited an average tensile failure load of approximately 17 kN. In contrast, the inclusion of short glass fiber reinforcement (SGF) resulted in a 9% increase in the average tensile failure load. By employing volumetric reinforcement with short glass fibers, a notable increase in component weight (+27%) is shown. However, when using 3DSW to produce components with local continuous fiber reinforcements combined with an unreinforced overmolding matrix, the additional weight added to the component can be considered minimal (+2.7% compared to the unreinforced reference). Despite this marginal increase in weight, the mechanical performance of the component shows a significant improvement (+100%).

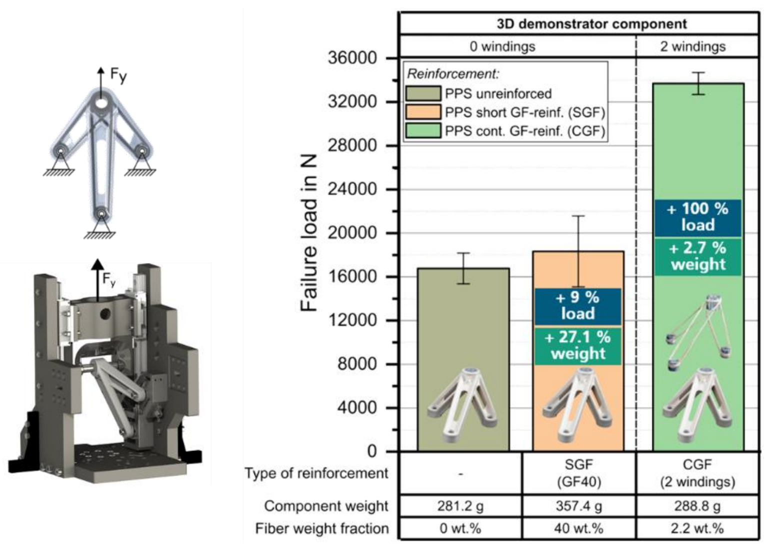

Figure 3. Failure loads in tensile direction of the generic 3D demonstrator component [2]

4 DESIGN, SIMULATION, AND DIMENSIONING OF AN AUTOMOTIVE DEMONSTRATOR COMPONENT

4.1 Virtual design and optimization of the 3DSW demonstrator component

The industrialized 3DSW process is validated by applying the process to an automotive rear trailing arm. The existing metallic design of the rear trailing arm consists of nine welded parts and is transferred into a composite design that incorporates local continuous fiber reinforcement along the primary load paths. A virtual optimization and validation approach has been developed by Simutence GmbH using Abaqus built-in modeling techniques (cf. Figure 4). The demonstrator is designed in two steps: First, a preprocessing step is carried out to define the design space, the metallic insert positions, and the relevant boundary conditions. Based on the required component loads, topology optimization is used to identify the component's main load paths as well as potential manufacturing constraints.

Second, the overmolding structure is topology-optimized and load requirements are verified using Finite Element Analysis (FEA). This iterative procedure starts with a topology optimization aiming at systematically reducing the component's mass. The outcome of this optimization step is then integrated into a CAD design and verified according to the required loads using FEA. The two-step approach used for the realization of the demonstrator component is illustrated in Figure 4.

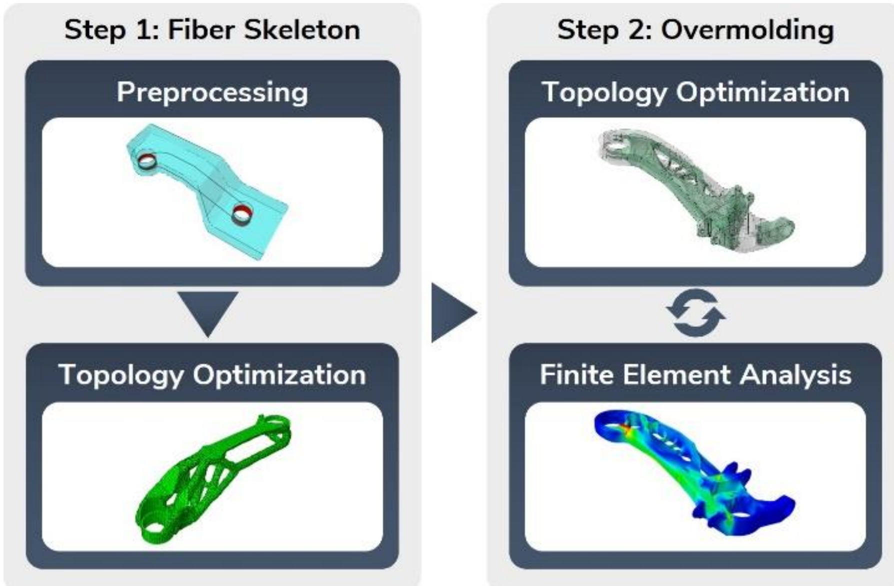

Figure 4. Schematic illustration of the algorithmic virtual optimization and validation approach for 3DSW structures

4.2 Lightweight potential of a 3DSW rear trailing arm

The fiber skeleton structure of the rear trailing arm demonstrator component resulting from optimization step 1, which has the boundary dimension of 650 x 280 x 180 mm³, is realized using the industrialized 3DSW process line given in Figure 2. The verification of the component's load requirements is carried out virtually for each of the single design iterations using FEA. The optimization of the overmolding material was conducted using a PA6 matrix with 20 wt.% and 40 wt.% short glass fibers. After several design iterations a final mass reduction of 37% compared to the metallic reference component could be shown. During the iterations, it is observed that even the lower fiber weight content of 20% is sufficient to fulfill all load requirements of the demonstrator component. The process of the single design iterations is given in Figure 5, while the manufactured demonstrator component and the final CAD assembly can be taken from Figure 6.

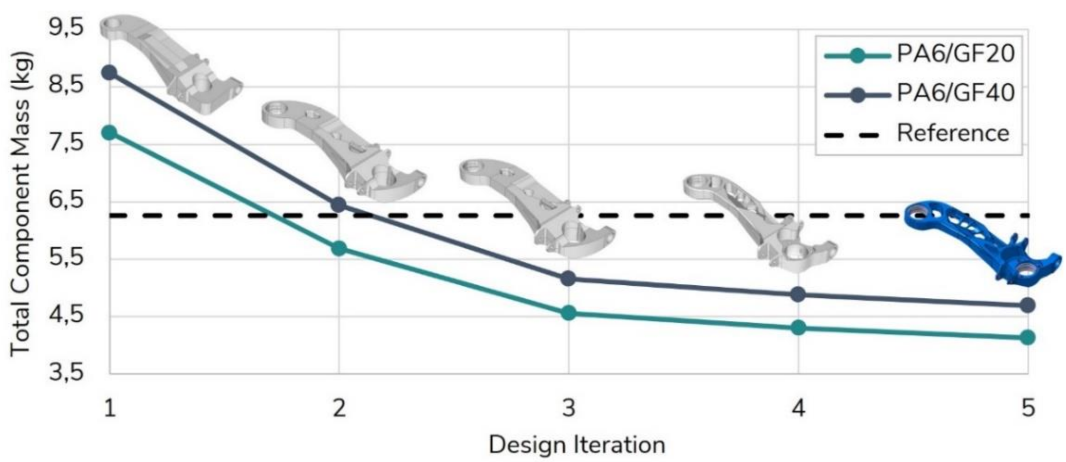

Figure 5. Evolution of component mass along with the design iterations and comparison to the metallic reference component

(a) (b)

Figure 6. 3DSW rear trailing arm demonstrator: Photograph of the demonstrator (a) and CAD assembly (b).

5 CONCLUSION

The 3D Skeleton Winding (3DSW) process offers the possibility to manufacture structural injection molded components with local continuous fiber reinforcements. Since the continuous fibers are only used locally according to the occurring load paths, the lightweight potential can be maximized, which has been exemplarily shown on a generic 3D demonstrator component. The findings gained on the developed 3DSW prototype line have been transferred to a fully automated and CE-certified 3DSW production line that can be directly connected to a conventional injection molding machine.

To demonstrate that the 3DSW process can be used for industrial applications, an automotive rear trailing arm was realized using a virtual optimization and validation approach. The manufacturing of the fiber skeleton structure was used to validate the newly developed industrialized 3DSW production line. The virtual optimizations have shown that the component mass can be reduced through 3DSW by 37% compared to the metallic reference component.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] Schürmann, H.: Konstruieren mit Faser-Kunststoff-Verbunden, VDI, Springer, Berlin, 2005.

[2] Beck, B.: Implementation of the 3D skeleton winding technology for thermoplastic structural components. Fraunhofer-Verlag, Stuttgart, 2023.

[3] Beck, B.; Tawfik, H.; Haas, J.; Park, Y.-B.; Henning, F.: Automated 3D Skeleton Winding Process for Continuous-Fiber-Reinforcements in Structural Thermoplastic Components. In: Hopmann, C.; Dahlmann, R. (eds.): Advances in Polymer Processing 2020. Springer Vieweg, Berlin, 2020, pp. 150-161.

[4] Haas, J.; Aberle, D.; Krüger, A.; Beck, B.; Eyerer, P.; Kärger, L.; Henning, F.: Systematic Approach for Finite Element Analysis of Thermoplastic Impregnated 3D Filament Winding Structures—Advancements and Validation. In: Journal of Composites Science, Vol. 6 (2022), Iss. 3, pp. 1-25. https://doi.org/10.3390/jcs6030098.