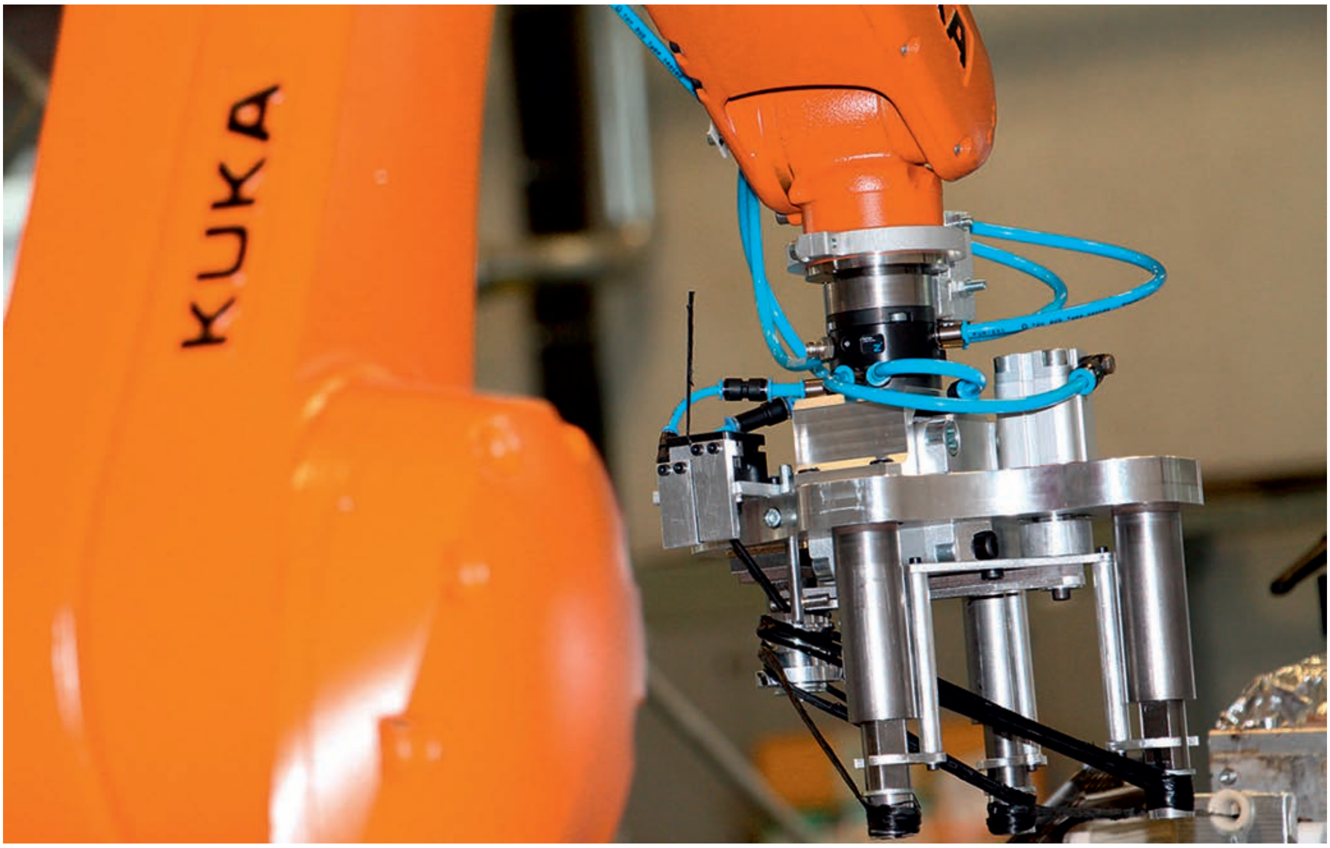
Three-Dimensional Fiber Skeleton

Local Continuous Fiber-Reinforcement through 3D Skeleton Winding Technology

Thermoplastic injection molded parts can be reinforced with local continuous fibers in combination with metallic load application elements. This also makes them suitable for structural applications such as transverse control arms and transmission mountings. A 3D winding technology was tested for potential use in a large-scale production process.



Robot-based fiber winding of complex injection molding inserts. The complex contours cannot easily be draped with flat reinforcing semi-finished products (© Fraunhofer ICT)

Continuous fiber-reinforced structural components made of thermoplastic materials are well known on the market and can be produced by large-scale extrusion or injection molding processes. They are usually produced using pre-impregnated non-woven or woven fabrics (e.g. unidirectional tapes or composite laminates), which are inserted into a shaping tool and then overmolded. If, however, the continuous fiber-reinforcements are to be used only locally and with a specific fiber direction, the flat tapes and composite laminates must be draped or formed before processing in accordance with the component geometry and the load paths. The more complex the structure, the more difficult it is to form flat reinforcing semi-finished products and to use them in components.

For several years now, the Fraunhofer Institute for Chemical Technology ICT, Pfinztal, Germany, has been investigating the local continuous fiber-reinforcement of structural lightweight components. Particular attention is paid to industrial processes, such as thermoplastic injection molding. The 3D skeleton winding technology (3DSW) developed for this purpose makes it possible to achieve highly durable, mass-optimized fiber composite winding structures ("fiber skeletons") in a robot-based manufacturing process. In addition to a large number of different fiber matrix combinations and load-oriented continuous fibers, metallic load application elements can also be integrated into the injection molding process.

In the established filament winding processes, continuous fibers are wound over the entire surface of rotationally symmetrical winding mandrels, to produce hollow profiles (e.g. shafts, rollers, pressure tanks, etc.) [1, 2]. In 3DSW, however, the continuous fiber-reinforcements are limited to the loaded component areas along the main load paths, in order to conserve resources. Compared to components with volumetric short- or long fiber-reinforcement, components with load-path optimized local continuous fiber-reinforcement offer significant advantages in terms of specific mechanical properties. These include higher component stiffness and strength as well as lower tendency to creep at high temperatures or under permanent load. At the same time, the potential for lightweight construction can be significantly increased, as component areas exposed to low loads remain non-reinforced or can be designed with very low fiber contents.

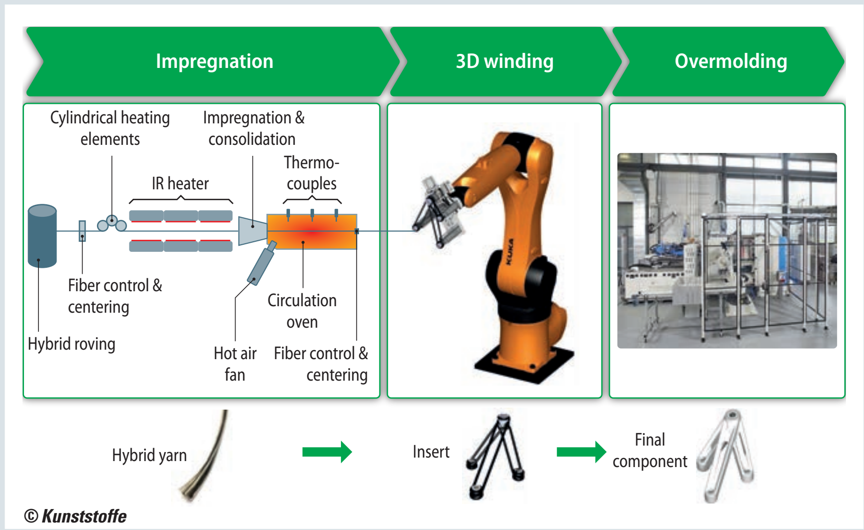


Fig. 1. The three-step process chain of the 3D skeleton winding technology. A 6-axis industrial robot places the molten hybrid yarn around the load application elements (source: Fraunhofer ICT)

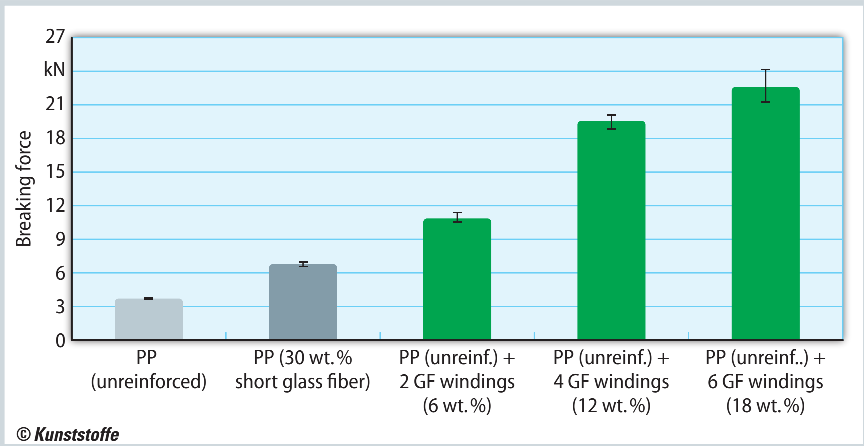


Fig. 3. Breaking forces of a simple pull loop with polypropylene (PP) depending on the number of windings. With six continuous fiber windings, the breaking load is already 500% higher (source: Fraunhofer ICT)

The 3D Skeleton Winding Process

The 3DSW process chain can be divided into three main process steps: impregnation, 3D winding and overmolding (**Fig. 1**). In the first process step (impregnation), hybrid yarns consisting of thermoplastic filaments (e.g. PP, PA6, PPS) and reinforcing fibers (e.g. glass or carbon fibers) are drawn through a heating unit with several heating zones, whereby the thermoplastic filaments are heated above their melting temperature by short-wave infrared radiation. The final impregnation of the reinforcing fibers takes place in a heated nozzle after the IR heating zones. The required pull-off force and speed is achieved by a 6-axis industrial robot (**Title figure**). The robot picks up the winding tool and coils the molten hybrid yarn around load application elements by manipulating the tool three-dimensionally in front of the centering eyelet. Before the winding process can start, metal inserts (node and load application elements) are fixed to the winding tool and the hybrid yarn is pneumatically clamped to it. After the 3D winding process has been completed and the polymer mass has cooled, the metallic inserts together with the wound hybrid yarns form a skeletal structure. This fiber skeleton insert corresponds to the local continuous fiber-reinforcement along the main load paths of the component and can subsequently be transferred to the injection molding machine to produce the final component geometry (overmolding).

Test Components for the Material and Process Characterization

In order to test the processability of new materials, Fraunhofer ICT uses two generic structural components in which applied loads can be transferred directly to the continuous fiber-reinforcement via integrated metallic load application elements (**Fig. 2**).

These fiber skeleton inserts manufactured by 3DSW are overmolded and then characterized with regard to their mechanical properties. In particular, simple pull loops provide information on tensile strength in correlation to the number of windings with different material combinations.

The material characteristics determined in such tests form the basis for structural-mechanical simulation models used to design new structural components. Using FEM-based simulation methods, on the one hand load-optimized geometries are identified, which determine the mass-optimized design of the winding structures or structural components, and on the other hand FEM simulation is used to dimension the structural components according to »

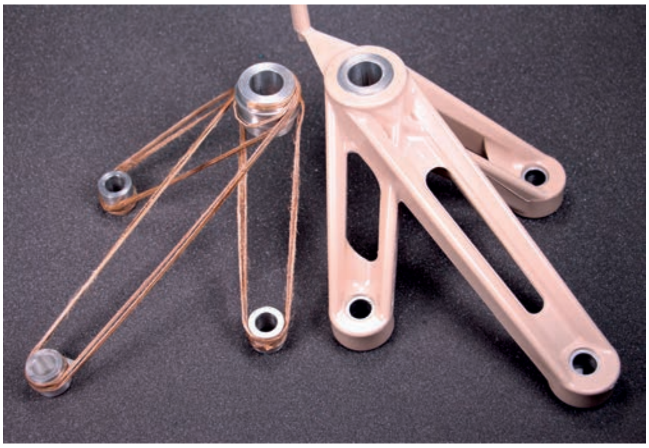


Fig. 2. Demonstrator of a three-dimensional structural component with metallic load application elements which allow applied loads to be transferred directly to the continuous fiber-reinforcement (© Fraunhofer ICT)

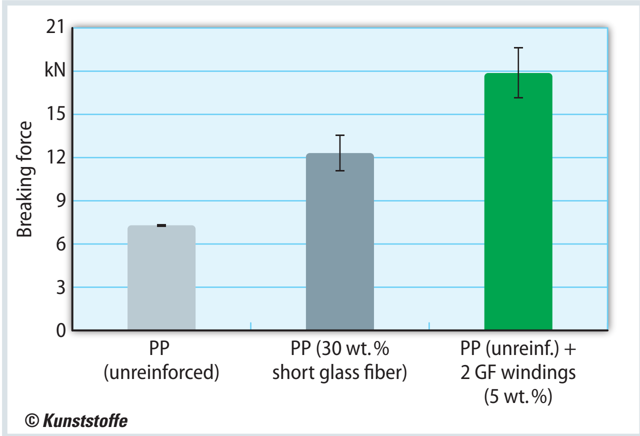


Fig. 4. Breaking loads of a generic 3D structural component with polypropylene (PP) can be significantly increased by wound continuous fiber-reinforcements (source: Fraunhofer ICT)

the load. Models currently under development for the simulation of deformations and material limitations under load will help in the construction and design of these components in the future.

If the load application points are offset on their level, the occurring forces cannot be represented by simple loop connections, which leads to new production challenges in the winding process and in force transmission in the final hybrid component. For example, the strength of the interface between the thermoplastic fiber skeleton and metallic load application elements is decisive for the functionality of the structural component when load is applied from an angle. At Fraunhofer ICT, a novel nanoporous adhesive layer is used to improve the interface strength. The plasma-enhanced chemical vapor deposition (PECVD) process is used to deposit a nanoporous SiO_2 layer onto the metallic load application elements [3]. It is only through this process step, which precedes the winding process, that the metallic load application elements can be connected to the plastic matrix in the subsequent 3D winding process as well as during injection molding.

Significant Increase in Strength with Low Fiber Contents

Based on the results of the investigations carried out, structural components can be reinforced with local continuous fiber-reinforcements in the future using topology optimizations. This allows forces to be transmitted despite a low fiber content, thus exploiting the high lightweight potential of the components. The high dimensional stability, greatly reduced tendency to creep and very good load transmission due to the local continuous fibers allow thermoplastic components to be used even in high-temperature ranges, which is why high-temperature materials such as polyphenylene sulfide (PPS) are also processed using this method at Fraunhofer ICT.

If simple structural components are subjected to traction, a correlation can be established between the increasing number of windings and the achievable breaking force (**Fig. 3**). With six continuous filament windings in combination with non-reinforced polypropylene (PP), the maximum breaking force can be increased by more than 500 % compared to the non-reinforced reference sample. For test samples with six windings, the total fiber content is 18 wt.%. A test sample with 30 wt.% short glass fibers only shows an increase in breaking force of approx. 80 % compared to the non-reinforced reference sample.

Even with more complex 3D components, the breaking force can be significantly increased by integrating local continuous fiber-reinforcements (**Fig. 4**). When a fiber skeleton is overmolded with two windings in combination with non-reinforced PP, for example, the breaking force is 147 % higher than that of a non-reinforced reference sample while only an additional 5 wt.% of continuous glass fibers contributes to the increase in component weight. ■

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