Continuous-fiber-reinforced thermoplastics are currently the focus of many lightweight construction projects. Compared to conventional thermoset systems, they offer a compelling combination of advantages during processing, such as shorter cycle times, a high level of functional integration and less susceptibility to gaps. The first components made from fabric-reinforced thermoplastic semi-finished products, also known as organo sheets, are set to enter mass production or are being integrated into motor vehicles as seat shells, brake pedals and retaining structures. They have already found application in sports articles and in smartphones.

To reduce costly waste and to achieve reproducible, complex fiber orientations aligned with load paths as well as profiled wall thicknesses, researchers are already hard at work on the next development in lightweight construction: unidirectional fiber-reinforced semi-finished products (“UD tapes”). During thermoplastic tape layup these can be arbitrarily arranged and stacked to suit the load paths in the part during thermoplastic tape layup. For series production fast and automated machines are suited, e.g. the Fiberforge Tailored Fiber Placement (TFP) plant (supplier: Dieffenbacher GmbH Maschinen- und Anlagenbau, Eppingen, Germany).

**Thermoplastic Tape Layup with Defined Property Profile**

The following core processes make up the process chain for thermoplastic tape layup by the Fiberforge TFP method (Fig. 1):

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**The Efficient Route to Tailored Organo Sheets**

**Producing CFRP Efficiently in a Vacuum Using Infrared Radiation**

A novel process enables the efficient consolidation of high-quality thermoplastic fiber-reinforced semifinished products. The material is heated with infrared radiation and consolidated quickly and efficiently under vacuum in the closed mold.
Finally, the consolidated layup is shaped and at the same time back-molded or back-compression molded to yield the finished part.

**Consolidation as an Essential Step for Achieving Quality**

The consolidation step is key to rapid and reliable processing of the continuous semi-finished fiber product to the finished part. To ensure reproducible forming into pore-free parts, the air trapped between the individual plies must first be removed (Fig. 2). Consolidation not only joins the individual plies together without any gaps, but also improves the quality of impregnation and minimizes fiber shifting attributable to squeeze flow. The goal is to achieve the best-possible mechanical performance, preferably with minimal processing costs and without damage to the material.

The equipment used for this so far, such as hydraulic presses, double-belt presses (isochoric and isobaric) and heated pressure chambers (autoclaves), has high capital and process costs. Heat input usually proceeds indirectly by heating a solid mold. The variothermal processing approach entails cyclical heating and cooling of large thermal masses – steps which are very time-consuming, costly and energy intensive. Consequently, current research projects frequently use two-stage heating and cooling presses (so-called heat-transfer pressing (HTP)) or isochoric double-belt presses. In these approaches, the heating and cooling elements are maintained at constant temperatures and the material is transferred between the stations.

In consolidation, it is important to select a process pressure which is high enough to ensure intimate contact between individual plies, to prevent lofting (a volume increase with concomitant reduction in density as the melt temperature is exceeded) and to allow post-impregnation. However, the pressure must not be too high, as otherwise the fiber network is compacted too much and permeability to post-impregnation is reduced. Not only that, but high pressure leads to unintended squeeze flow, which reorients the fibers, diminishing the mechanical properties and increasing the tendency to warp.

**Fig. 1.** Thermoplastic tape layup combines the process steps of tape selection, tape layup, and consolidation as well as forming and back-molding or back-compression molding (left to right) (© Fraunhofer ICT)

**Fig. 2.** Scanning electron micrographs (SEMs) of consolidated layups (cross-laminate) with low (left) and high pore content (right). The pores here are identifiable from the black and white areas (© Fraunhofer ICT)
The process temperature should also be high enough to reduce the viscosity of the material and low enough to prevent degradation of both the polymer and the fiber sizing. Many materials (e.g., polyamide 6) are damaged by thermo-oxidative degradation when exposed to heat and oxygen. These materials must therefore be dried before processing and they must be processed while they are still hot, preferably in an inert atmosphere. It is hard to accomplish this with conventional rapid methods. However, a research group at the Fraunhofer Institute for Chemical Technology (ICT), Pfinztal, Germany, has now developed a new process which accommodates all these process and material considerations and addresses the economic aspect of cost reduction.

**The Operating Principle in Detail**

The UD tape layup is placed between two radiation-permeable tool walls, between which there is a compressible seal. A vacuum pump evacuates the area inside the seal between the two plates, and generates pressure on the layup. The vacuum is maintained for the duration of the consolidation process – the pump extracts trapped residual moisture, air, solvents or other gases, thus creating an inert atmosphere which protects the material against thermo-oxidative degradation. This process is called "radiation-induced vacuum consolidation" (RVC) (Fig. 3).

The tape layup is then heated with infrared radiation through the mold walls to a temperature above the melting temperature of the thermoplastic material (Title figure). Since the semi-finished product absorbs the heat radi-
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Study of Semi-Finished Product Quality

The functionality of the new process was studied with the aid of carbon-fiber-reinforced UD tapes made from polyamide 6 (PA6). The study consisted of 4-point bending tests on 14-ply consolidated layups with a (0/90) ply structure. Direct comparison revealed that the layup consolidated on the RVC line had a 25% higher modulus of elasticity and a 15% higher bending strength than the layup consolidated with an isochoric double-belt press (DBP) (Fig. 5).

Fig. 4. An organosilicon coating on the mold surface makes it possible to consolidate a tape layup without using any release agents at all (© Fraunhofer ICT)

Fig. 5. Comparison of the bending stiffness (left) and bending strength (right) achieved with RVC and a reference process reveals a far superior performance of the layup consolidated with RVC (source: Fraunhofer ICT)
Computerized tomography (CT) analyses by F. & G. Hachtel GmbH & Co. KG, Aalen, Germany, have shed light on the causes of these differences in mechanical properties. CT images of panels consolidated by both RVC and the reference process reveal that RVC confers a lower porosity (well below 1%) and almost perfect fiber orientation, whereas the reference process gives rise to fiber undulations and pores (over 2%) (Fig. 6). Fiber undulation lowers the rigidity of a fiber-reinforced thermoplastic material in the fiber direction while pores have an adverse effect on some mechanical properties, e.g., bending strength.

**Conclusion**

The new radiation-induced vacuum consolidation process lends itself to the manufacture of continuous-fiber-reinforced thermoplastic semi-finished products for highly stressed parts. It is especially notable for its short cycle time, high consolidation quality and low energy consumption. In addition, the constant vacuum helps to obtain a low pore content without fiber reorientation, which translates into high values in the mechanical properties. The RVC process, as a quality-critical component of tape layup, lends itself to efficient mass production of high-quality fiber composites.