Heating module on the RVC line. The tape layup is heated with infrared radiation through the mold walls to a temperature above the melting temperature of the thermoplastic material (© Fraunhofer ICT)

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.

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**): »

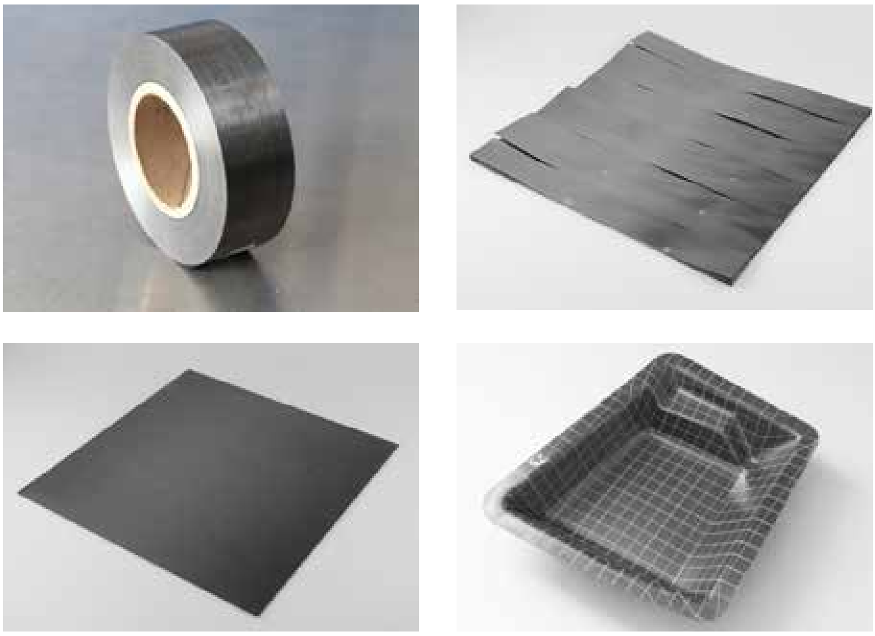

Fig. 1. Thermoplastic tape layup combines the process steps of tape selection, tape layup, and consolidation as well as forming and back-molding or back-compression molding (left to right) (© Fraunhofer ICT)

- Tape selection,
- tape layup,
- consolidation,
- forming and back-molding or back-compression molding.

Encouraged by the high level of interest shown by the automotive industry, equipment manufacturers have been working hard to develop tape layup technology. Dieffenbacher has already announced the launch this year of a new generation of the Fiberforge TFP line, delivering the much greater productivity and efficiency that is essential for mass production by the automotive industry.

UD tapes are commercially available in all kinds of polymer matrices (from PP to PEEK) and different types of fibers (glass and carbon). The corresponding semi-finished product can be selected with the desired property profile and budget in mind. For tape layup, the tape is unwound from the roll in different widths, cut to size, laid down in plies and then spot welded. This fully automated process yields customized, loosely tacked, semi-finished products with optimized fiber orientation and minimized waste levels.

The individual plies of fiber and thermoplastic material are then consolidated by applying heat and pressure to eliminate gaps and reduce the pore content. 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.

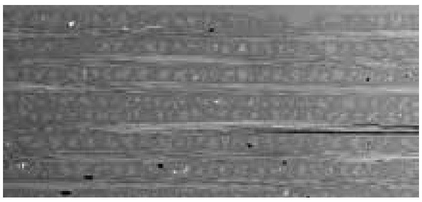

Fig. 2. Scanning electron micrographs (SEMs) of consolidated layups (cross-laminate) with low (left) and high pore content (right). The pores here are identifiable from the black and white areas (© Fraunhofer ICT)

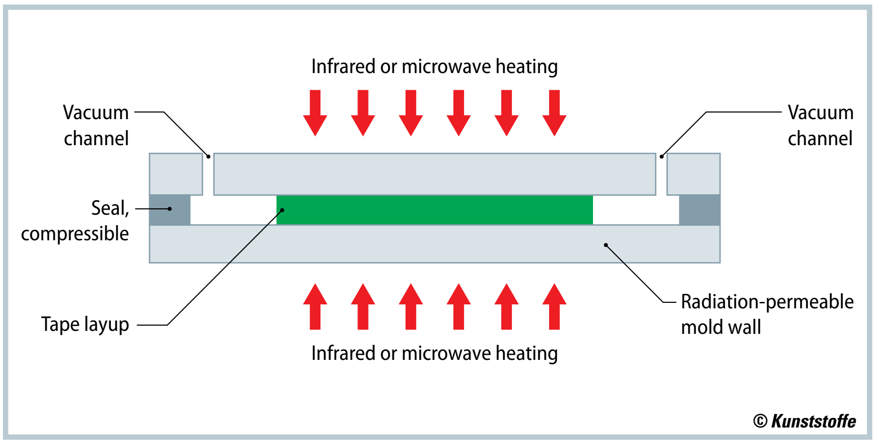

Fig. 3. Radiation-induced vacuum consolidation (RVC) protects the material against thermo-oxidative degradation (source: Fraunhofer ICT)

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- »

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)

ation directly, there is comparatively little thermal mass to be heated and cooled, and this leads to short cycle times combined with low energy consumption. The concluding cooling stage is performed in a separate module by forced compressed-air convection or by spray cooling. In the prototype setup, a rail system transfers the semi-finished product, still under vacuum, between the heating and cooling module.

The cycle time is determined not only by the lamp power and the distance to the tape layup but also, and chiefly, by the thickness of the mold wall. For thin mold walls, the entire consolidation step can have a cycle time of less than a minute. Unlike processes which employ hydraulic transfer presses or isochoric double-belt presses and which involve pressure changes, the constant vacuum in this process ensures that the pressure remains steady.

Vacuum-based methods used to date which do not employ energy-intensive autoclaves are limited to 1 bar process pressure. In this new process, however, the evacuated area is much larger than the layup area on which the resultant forces act. Consequently, pressures of more than 1 bar can be generated efficiently on the layup.

A further advantage of the RVC process is the prospect eliminating of the need for a release agent, as shown by results obtained by the Fraunhofer ICT in cooperation with the Fraunhofer Institute for Manufacturing Technology and Applied Materials Research (IFAM) in Bremen, Germany. Traditionally, external release agents have been used during consolidation for demolding the semi-finished products from the molds. However, these leave a residue on the surface of the material that can hamper further processing (e.g. bonding and coating). The researchers aimed to eliminate this problem by coating the smooth mold surface with a durable organosilicon layer (type: ReleasePlas), creating a process which does not require a release agent and yields high-quality finishes (**Fig. 4**).

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**).

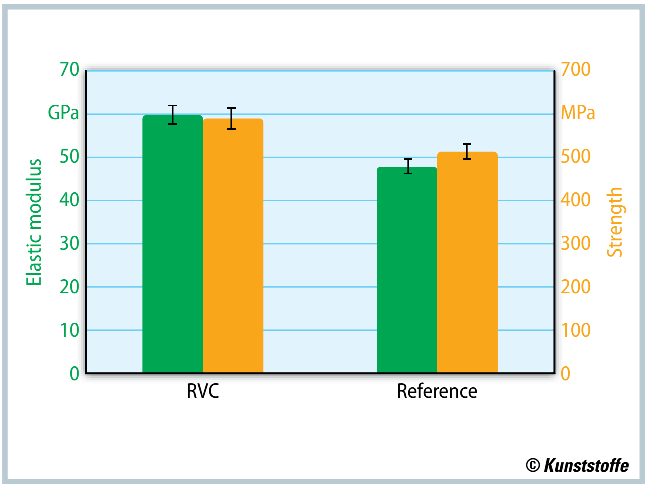

Fig. 5. Comparison of the bending stiffness (left) and bending strength (right) achieved with RVC and a reference process reveals a far superior performance of the layup consolidated with RVC (source: Fraunhofer ICT)

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Acknowledgments

The authors would like to thank the Fraunhofer-Gesellschaft for funding the project (number 827908), the Fraunhofer Institute for Manufacturing Technology and Applied Materials Research (IFAM), and the computerized tomography team at Hachtel Group in Aalen for their dependable and constructive cooperation.

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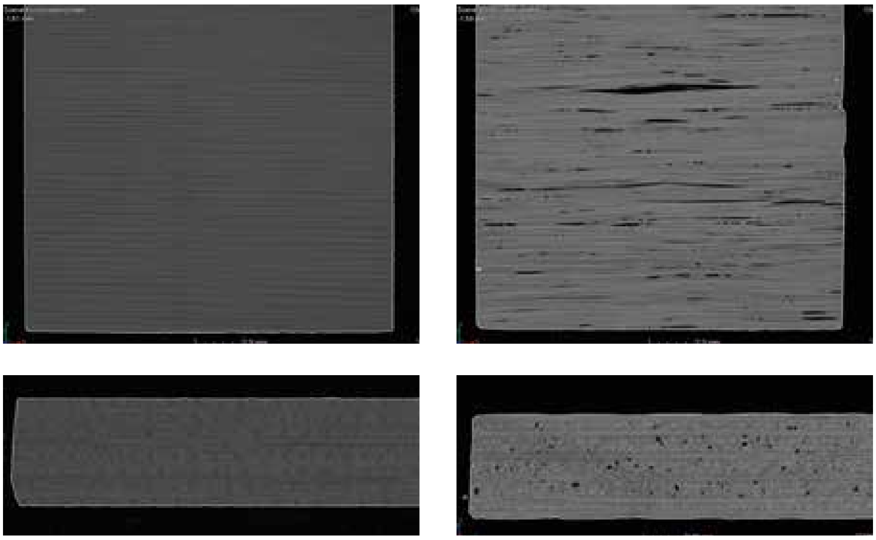

Fig. 6. CT images of the carbon fiber-reinforced polyamide 6 layup consolidated with the RVC (left) and reference processes. The top images show the representative samples in plan view while the bottom images show the same samples in cross-section. Pores are identifiable as black spots (© Fraunhofer 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. ■