From Laminate to Component

**Continuous Fiber-Reinforced Thermoplastics.** Because of their great potential for lightweight construction and recycling, continuous fiber-reinforced thermoplastics are rapidly gaining importance. Especially in auto manufacture, the replacement of metals by thermoplastic laminates is set to continue thanks to their good mechanical properties combined with efficient processability by injection molding. Here, with its new product and service package, BASF offers not only tailored materials but also comprehensive simulation, testing and processing know-how.

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The trend towards lightweight construction – especially in the mobility sector – is opening up a wide field of application for engineering plastics in semi-structural and structural parts. The high mechanical property requirements for such components can, however, no longer be met by short and long glass fiber-reinforced plastics alone. Continuous fiber-reinforced plastics – which have been used in, for example, the sports equipment and aerospace sectors for many years – offer a considerable increase in mechanical property values and energy absorption capacity here. But wider use of continuous fiber-reinforced plastics will be contingent on the ability to provide economic processing with fast cycles similar to those in injection molding, especially in automotive applications because of high volumes and immense price pressure. This is where thermoplastic-based fiber-reinforced composites can exploit their strengths over thermosetting matrices. Thermoplastic-based components also score in terms of repairability and recyclability.
Complete Development Platform

Large-scale production processes suitable for continuous fiber-reinforced thermoplastics have often not yet been optimized and pose a special challenge for many plastics processors. For this reason, BASF SE, Ludwigshafen, Germany has now expanded its activities in the area of engineering plastics to include a completely new approach. Besides, the conventional range of short and long fiber-reinforced engineering thermoplastics, the company has recently also started supplying continuous fiber-reinforced laminates and tapes. Under the trade name Ultracom, BASF is offering a package of continuous fiber-reinforced semi-finished products, specifically adapted overmolding compounds, and the necessary engineering support.

The basic components of the Ultracom system are laminates based on woven glass (Ultralaminate) and unidirectional glass and carbon fiber tapes (Ultratape) impregnated with polyamide. Overmolding materials from the Ultramid (PA) range have been specifically developed for use with these semi-finished products (Table 1). The use of semi-finished products often only becomes commercially attractive in combination with the conventional injection molding process. With this approach, the continuous fibers are used only at precisely defined locations where high mechanical reinforcement is required. Additional functions, e.g. ribs and connecting elements, can then be incorporated in the component by the overmolding compound. The new Ultramid COM materials ensure optimum bonding and load transmission to the semi-finished products.

Processing Expertise with Production Cell

A key part of the new service package is a pilot production cell on which it has been possible to produce multifunctional composite test components in one operation (Table 1). The steps of laminate forming (draping) and overmolding for functional elements are directly combined in a single process and injection mold. The production cell makes it possible to expand the company’s expertise and provide optimum support for the customers in component development. It is a logical extension of BASF in-house processing facilities. For many years now, numerous special injection molding processes for engineering plastics have been trialed and optimized here on 20 injection molding machines with clamping forces from 5 to 1,500 t. Similar development work on extrusion processes for engineering plastics has also been carried out on more than 10 extrusion lines, including a seven-layer film line.

The aim in designing the Ultracom production cell was to achieve a fully automated process with typical injection molding cycle times. The challenges for process and plant design involved: parallelizing the individual process steps,

<table>
<thead>
<tr>
<th>Property</th>
<th>Ultralaminate B3WG13 WR01</th>
<th>Ultratape B3WG12 UD01</th>
<th>Ultratape B3WC12 UD02</th>
<th>Ultramid B3WG12 COM</th>
<th>Ultramid B3ZG7 COM</th>
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<tbody>
<tr>
<td>Product characteristics</td>
<td>Twill fabric 2/2 offset, 600 g/m², 66 wt.-%</td>
<td>GF UD tape, 60 wt.-%</td>
<td>CF UD tape, 60 wt.-%</td>
<td>PA6-GF60 impact modified</td>
<td>PA6-GF35 impact modified</td>
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<td>Density [g/cm³]</td>
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<td>1.46</td>
<td>1.72</td>
<td>1.38</td>
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<td>33</td>
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<td>Tensile strength (tr.) [MPa]</td>
<td>450</td>
<td>770</td>
<td>1,800</td>
<td>250</td>
<td>145</td>
</tr>
</tbody>
</table>

Table 1. Properties of the Ultracom range: semi-finished products and compounds
The most suitable concept for a production cell depends on numerous factors. The main ones are part geometry, size and complexity of the laminate, laminate structure and thickness, method and duration of laminate heating, as well as draping and overmolding times. The choice of production cell concept is also strongly influenced by the requirements for the mold and injection molding machine, necessary plant flexibility, available space, investment budget, and number of units required.

For easy handling of even the most complex laminates, it is an advantage to heat the semi-finished product close to or directly in the draping mold. But in this case, carrying out the operations of laminate heating, draping, and overmolding sequentially is a loss in time. If, on the other hand, the laminate is heated outside the mold parallel with the injection molding process, the cycle time can be considerably shortened by parallel process steps. In the most favorable scenario, the duration of draping and overmolding will determine the cycle time, provided that the steps of heating and handling the laminate do not take longer. In this scenario, however, the heated, pliable laminate insert must be transferred reproducibly from the heating station to the mold. This can be done by needles, (vacuum) grippers, diaphragms or clamping frames.

To provide maximum flexibility and short cycle times suitable for mass production, BASF has opted for an external heating station and a clamping frame for laminate handling. At the center of the production cell built by FPT Robotik GmbH & Co.KG, Amtzell, Germany, is a six-axis robot (manufacturer: Kuka Robotik GmbH, Augsburg, Germany) that loads the clamping frame, transfers the laminates to the oven and then to the mold, and finally removes the finished part (Fig. 1). For these operations, the robot is equipped with a complex gripper that enables it both to pick up the laminate and finished part by vacuum cups and also fix the clamping frame.

After laminate tailoring by water jet cutting, milling, sawing, laser cutting or ultrasonic cutting, the precuts are fed to the process via a magazine. It is important to avoid delamination, burrs or jagged edges as well as localized thermal damage to the edges during the cutting step. Processing aids should also be chosen with caution in order not to inhibit adhesion of the overmolding compound.

In order to ensure a constant position in the mold without costly sensors for each process step, accurate gripping and precise placement of the laminate in the clamping frame are essential. A simple but ingenious solution is the inclined arrangement of the laminate magazine. This allows the vacuum cups to pick up different laminate shapes and transfer them to the loading station in a reproducible way (Fig. 2, left) without the aid of sensors.

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The clamping frame is designed in two parts and clamps the laminate via matched spring assemblies from the time it is laterally fed into the loading station until active opening in the injection mold. Through the defined clamping of the laminate in the frame, further handling in the molten state is greatly simplified and the laminate position in the mold is clearly defined. The secure clamping also permits rapid robot movements without damage to the laminate, such as wrinkling. The disadvantage is that the laminate is inadequately heated at the clamping points. These points must therefore be minimized in a defined way that ensures the laminate is securely clamped in the frame without compromising draping in the mold.

A second loading station allows the laminate to be fed manually to enable flexibility in working with different laminates and materials.

The laminates are heated by medium-wave infrared heaters from Krelus AG, Oberentfelden, Switzerland. The heaters, optimized for the absorption behavior of plastics, permit rapid, energy-efficient heating for about 20 to 25 s to around 260°C. To prevent temperature inhomogeneities, due to convection currents for example, the laminate is positioned horizontally in a closed, thermally insulated oven chamber and heated from both sides. Temperature measurement and control at the top and bottom of the laminate are carried out by specially arranged pyrometers. An adjusted output regulation of the heater zones prevents overheating and therefore local surface damage to the material.

Special attention must be paid to the subsequent transfer path of the heated laminate from the oven to the mold. Rib pull-off tests show the effect of transfer time from the oven to the mold on the strength of the bond between the laminate and overmolding material (Fig. 3). For this reason, the transfer time must be kept as short but also as reproducible as possible. With an additional pyrometer integrated into the gripper, the temperature of the laminate during transfer can be controlled and hence constant insert temperatures ensured.

**Flexible Mold for Demonstrator Part**

The clamping frame is positioned in the mold via guidance bars on the moving mold half. As the mold closes, the frame is precisely opened via pins and releases the laminate for draping. The mold (manufacturer: Georg Kaufmann Formenbau AG, Remetschwil, Switzerland, see Fig. 2, right) is a key part of the Ultra-com process and was designed to offer high flexibility. Through interchangeable inserts, variable leader pins and the use of shearing edges, different geometries and laminate thicknesses can be accommodated and the limitations of laminate draping explored. Via a hot runner system with six needle shut-off nozzles that can be opened independently through a cascade control system, individual component areas can be selectively injected. So the mold is also suitable for highly filled, long glass fiber-reinforced molding compounds such as Ultramid Structure. In addition, it is equipped with a comprehensive sensor system to measure pressure and temperature at different component positions. The hydraulic injection molding machine used is from KraussMaffei Technologies GmbH, München.
(KM 300 1400C2 with 3,000 kN clamping force).

**Demonstrator Part with 20 Functions**

The laminate is draped to form the carrier structure shown in the center of the demonstrator part (see Title figure), before further functional elements are overmolded. Altogether, numerous characteristic features and problems of composite production can be simulated with the 360×360 mm² multifunctional part and its about 20 individual functions (Fig. 4). Besides the ribbed, U-profile carrier, the features of the component include a rib field for special crash tests, differently designed rib/wall thickness transitions of the laminate and overmolding material, as well as "sewing points", i.e. points at which the laminate can be through-molded via varying cross sections.

For economic component production without post-machining steps such as edge trimming, defined closure of the draped laminate edge is necessary. For this reason, it is overmolded in different variants: with overlaps on one side, on both sides or in offset configuration as a mounting surface for adjacent component assemblies. To fix the laminate in the variant overmolded on both sides, holding bars are integrated into the edge region. The design of the long, peripheral flow channel proved a special challenge. The aim was to achieve complete filling of the whole periphery, including the 0.6 mm overlapping areas – even with the 60 wt.-% glass fiber-reinforced grade Ultramid B3WG12 COM. To meet this challenge, not only draping but also subsequent fill-
ing with the overmolding material were simulated (Title figure) and the gate positions and opening sequence of the needle shut-off nozzles optimized. Following targeted modification of highly filled Ultramid B3WG12 COM, the required filling pressures are not substantially more than for the impact modified 35 wt.-% filled variant Ultramid B3ZG7 COM.

Finally, typical mounting elements such as circular recesses of different diameter are incorporated in the component. They can be created by opening out the fiber bundle during draping or subsequent punching directly in the mold. In the first option, needles are advanced as the mold closes and pierce the laminate, laterally displacing the fibers. A computer tomography scan of the component during in-house testing shows visible evidence of the advantage of this process option, which is gentler on the fibers. The scan provides a ready basis for further optimization of the needle movements (Fig. 5).

The fully shaped and overmolded component and the empty clamping frame are then removed by the six-axis robot from the fixed mold half. The clamping frame is then ready for re-loading.

If the process is run with a high degree of parallelization, three clamping frames are used simultaneously. While the first clamping frame is in the injection molding machine, the second holds the laminate in the IR oven, and the third is re-loaded by the robot (Fig. 6). In this way, cycle times of less than a minute can be achieved, corresponding to those of a standard injection molding process. Consequently, a key requirement for the use of this process in large-scale production has been fulfilled.

**Complex Draping Simply Achieved**

While it is relatively easy to assess the drapability of the Ultracom laminate to form a straight U-shaped carrier, components with more complex (especially asymmetrical) draping geometries pose considerably greater challenges for component design – as the rear seat back made from Ultralaminate in Figure 7 shows. It is therefore important to clarify at an early stage of the project the key question as to whether wrinkle-free draping is possible. The next step is then to determine the necessary laminate geometry. Drapability and laminate precut geometry have a crucial influence on overall mold and process design, e.g. on the required positioning of the needles and leader pins.

![Fig. 7. Rear seat back as an example of complex draping geometry (manufacturer: Johnson Controls)](image)

A typical, practically relevant design element for stiffening flat components is that of stiffening corrugations. In the Ultracom test mold, a corrugation is therefore incorporated at an angle of 30° to the feed direction of the laminate. Through this offset arrangement, possible fiber displacement in the individual layers of the 1.5 mm thick Ultracom laminate can be detected. As Figure 8 shows, a 70 mm × 20 mm corrugation can be formed with high quality and precision. Besides being visually assessed, fiber orientation was also analyzed in a computer tomography scan and compared with the draping simulation of the component area. The high correlation between the simulation-based
and the measured fiber orientations provides a basis for making highly accurate predictions of the mechanical properties of continuous fiber-reinforced components.

The second test geometry selected was an asymmetrical L-profile carrier, whose short arm is slightly angled at the end. Higher degrees of draping, sharp edges, and small radii pose a particular challenge for laminate forming here but can be accomplished cleanly and wrinkle-free with Ultralaminate (Fig. 9). Besides draping, another task in producing the L-profile carrier was to achieve a rectangular edge finish, which, as with the straight carrier, could be overmolded all round with a 5 mm wide edge. On the basis of the laminate determined in the draping simulation, it was possible to implement this geometry successfully without tedious iteration steps. This reliable prediction, even of complex draping processes, is a key advantage of the Ultrasim simulation tool, which helps avoid multiple adjustments of the clamping frame geometry or damage to the shearing edges by locally oversized laminates.

**Processing of Ultratape and Natural Fiber Mats**

Besides handling, draping and overmolding of impregnated fabrics, the use of unidirectionally reinforced tapes is often of great interest. The two continuous fiber-reinforced semi-finished products fulfill different functions in the component. While thermoplastic laminates are more suitable for large, quasi-isotropically stressed hybrid components, tapes are particularly good for local, stress-optimized reinforcement of injection molded, short glass fiber-filled components.

Here, they can fully exploit their advantage of undulation-free orientation. There is no additional fiber deflection, like in fabric laminates, and the fibers can specifically follow the load path. Tape inserts can be constructed in very different forms and vary in handling difficulty according to their layer structure. To build up processing expertise in this area, too, tape structures were processed in the Ultracom production cell and characterized. Both homogeneous sheets with fiber orientations of 0° and 90° and symmetrical 0°/±45°/90° combinations were used. During heating in the IR oven and subsequent forming, the Ultratape structures were stable in all cases. Overmolding was also possible without separation of the tape layers (Figs. 5 right and 10 left). Stability is naturally greatest with combined structures, while unidirectionally oriented tapes can be partially displaced by the injection pressure. So, once again, in addition to careful selection of the tape structure, determination of the most suitable gate positions and injection parameters using Ultrasim is recommended.

Other materials, such as thermoplastic, Acrodur-bonded natural fiber hybrid nonwovens can also be pressed and overmolded in one operation in the novel production cell (Fig. 10, right). In this way, multi-functional, ready-to-use components with new properties in terms of weight, appearance, and recyclability can be economically produced.

**Conclusion**

The challenges in terms of weight saving, cost efficiency, and performance encountered in the production of thermoplastic-based fiber-reinforced composites can only be solved by taking into account the interaction of all relevant factors. Here, the availability of the material portfolio and application development with simulation, processing, and test laboratory facilities under one BASF roof makes it possible to provide support for customers throughout the process chain from material characterization to the launch of full-scale production. In the manufacture of complex composite components, it is particularly important for automated processes to become available in the near future so that widespread market penetration can be a tangible reality. The new production cell is therefore a key element in the successful development of highly efficient composite components.