T-RTM TECHNOLOGY AND PROCESSING
OF THERMOPLASTIC TAPES – TWO TECHNOLOGIES
MANAGING A COMMON CHALLENGE

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Abstract

Automotive production of lightweight components requires both, high resultant part performance and fully automated production. On the one hand in situ processing of (epsilon-) caprolactam with a novel high pressure reactive equipment matches these requirements and provides high quality T-RTM parts.

On the other hand, fully automated production of lightweight parts from thermoplastic composite tapes also provides high performance components. In this case, a pick-and-place approach is employed together with use of a vision system that enables high accuracy.

For both technologies, aspects of process feasibility, robustness, part performance, and final part costs were evaluated. There are important pros and cons that make a specific technology preferable for certain parts. However, even promising advancements that are combining the benefits of both technologies are possible. The next level might be T-RTM components with local tape reinforcements to fulfill the demands of highly loadable or crash relevant applications.

Different raw Materials lead to competitive Products

In situ polymerization of caprolactam for creating fiber composite structures with subsequent functionalization of the component through injection molding is very closely approaching the ideal of economic series production of composite parts.

Figure 1: Processing scheme for manufacturing of in situ composite components with molded features.

The starting point for this process chain are dry the fabrics or tapes in the shape of a preform and the monomers for the polymerization of Nylon-6, Figure 1.

Another important path for the large-scale production of thermoplastic composites start with semi-finished products that are either organic sheets with fabrics inside, or composite tapes
providing a unidirectional reinforcement in a thermoplastic matrix. The first processing cells for manufacturing of thermoplastic composite components in automotive application with the use of organic sheets have reached the series production stage. Further developments are now focused on processing solutions for thermoplastic tapes reinforeced with glass and carbon fibers, Figure 2.

Thermoplastic tape versions with matrices made of PA, PP, PE, PC+ABS, PPS, and PEEK have only recently gained in importance. They can be processed faster than it is the case in a typical reactive processing approach (epoxy, polyurethane, caprolactam), but require an entirely different processing technology, which in turn exhibits clear parallels to organic sheet processing [3]. In the form of single layers, carbon- and glass-fiber-reinforced tapes have a thickness of just 0.14 to 0.30 mm. However, a single tape layer is inadequate for most applications. In practice, layups (stacks) consisting of several, sometimes up to 20 tape layers, are built up.

Heart of a production line is a tape laying cell that is based on the pick-and-place principle. Parts made by such a technology are used in ENGEL’s robot system for small injection molding machines, Figure 3. The intention of the project was, on the one hand, first to achieve a prove of principle for the pick-an-place approach in a real series application. On the other hand, the second aim of the project was to increase the performance of the robot system.
Due to the innovative manufacturing technique, a 37% weight reduction of the robot’s rotational axis was gained. In this way, the robot’s movements can be significantly faster, and require less energy. To meet the high demand on stiffness, the majority of tapes are inserted in the longitudinal direction of the rotational axis. In addition, several tape layers are introduced at angles of ±45° and 90° to the longitudinal axis.

Both technologies - T-RTM processing as well as manufacturing of tape based composite parts - can provide high performance thermoplastic composites with load oriented arrangement of the fiber reinforcement. Therefore, an evaluation is indicated with a consideration of different viewpoints. Amongst them are the processing aspects, the process feasibility, and the cost characteristics.

**T-RTM Technology**

For *in situ* processing, a catalyst and an activating agent are added to the caprolactam in separate material containers [1]. These additives ensure that the polymerization reaction starts immediately after mixing of the two components, Figure 4.

![Figure 4: Ring-opening polymerization of (epsilon-)caprolactam with use of a catalyst and an activating agent. The polymerization takes place directly in the mold.](image)

The processing of (epsilon-)Caprolactam, which is almost as liquid as water in its molten state, needs tailor-made machine technology. However, many proven injection molding solutions, such as high accuracy injection with the use of servo-electric drives, can be employed as well for the *in situ* processing.

In the melting unit of the processing device, the monomer mixtures are heated to 120 °C, which is quite close to the polymerization temperature of 140 to 160 °C. The melting units contain liquid reactive components that is sufficient for a maximum of three cycles, Figure 5.

The two injection plungers first independently soak the required shot volumes, and then inject these into the cavity in an electronically synchronized parallel movement.
Figure 5: The special feature of the reactive unit is the reduced thermal exposure of the monomeric material. The melting units hold a volume required for three shots as a maximum.

At room temperature caprolactam appears as a white crystalline solid. The monomer has a melting temperature of 70 °C and is extremely easy-flowing in its molten state, with a viscosity of approx. 10 mPa·s. This is the reason why caprolactam is excellently suitable for wetting dry fiber structures. Figure 6 shows a computer tomography investigation on four \textit{in situ} specimens having thickness of 1.5 mm each. No pores were found using this sensitive method.

Figure 6: Computer tomography investigations reveal that the fabric can be impregnated virtually without pores.

\textit{In situ} polymerization of (epsilon-)Caprolactam directly in the shape-defining mold containing a dry preform with subsequent functionalization of the carrier structure in injection molding opens new opportunities. For one thing, it drives further manufacturing efficiency gains; for another the process takes into account the trend towards increased use of thermoplastic matrix materials, where glass fibers as well as carbon fibers can be used as a reinforcing component.

Automotive body in white (BIW) made of carbon fibers with epoxy resin as a matrix material are already in use. In general, the \textit{in situ} processing of caprolactam might allow a similar approach, where - this is a particular advantage - the injection molding might be used for efficient addition of any necessary stiffening structures, Figure 7.
One of the most challenging aspects with composites is the joining of several components. However, in the case of in situ parts with a partial overmolding, typical welding operations might be used for the assembly of a large structure, Figure 8.

**Figure 7:** Large components for an automotive BIW using in situ processing for the composite structure an injection molding for the frame and the stiffening features.

**Figure 8:** Joining of large components for an automotive BIW using welding techniques as, for example, heating by means of hot plate, hot gas, vibrational welding and infrared welding.

**Processing of Thermoplastic Tapes**

The predominant aims of any tape processing technologies are:

- To obtain the **highest possible performance** with a minimum amount of material,
- and secondly, to design the layup in a fashion that **as little scrap as possible** is produced,
- and, as a third target, to **keep the number of tapes low**.

An ideal combination of lightweight design and economy is not always possible. While the optimum structural-mechanical design often results in a layup with a large number small tapes, the actual number of tapes and their load-optimized arrangement most time need to be limited to
a practical amount for reasons of economy, Table 1. Consequently, considerations regarding the overall productivity of the production cell are made already in an early stage of the development of the process.

The expected total weight of the final part together with an estimation on the proportion of tapes in the finished component are important indications for the productivity requested from the tape laying cell.

Table I: The effectiveness of producing a tape stack (tape: PA-CF; thickness: 0.14 mm; density: 1.46 g/cm³) can be estimated by means of component weight, the weight fraction of tapes, and the tape format. Stacking duration (3 s per tape) - green: up to 1.0 min; yellow: 1.0 up to 3.0 min; orange: 3.0 up to 5.0 min; red: more than 5.0 min

<table>
<thead>
<tr>
<th>Stack Operation</th>
<th>100</th>
<th>250</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part weight [g]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight fraction of tapes</td>
<td>40%</td>
<td>60%</td>
<td>80%</td>
<td>40%</td>
</tr>
<tr>
<td>Tapes 300 x 450 [mm]</td>
<td>1.4</td>
<td>2.2</td>
<td>2.9</td>
<td>4.0</td>
</tr>
<tr>
<td>Tapes 200 x 300 [mm]</td>
<td>3.3</td>
<td>5.0</td>
<td>7.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Tapes 140 x 210 [mm]</td>
<td>7.0</td>
<td>10.0</td>
<td>13.0</td>
<td>17.0</td>
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<tr>
<td>Tapes 100 x 150 [mm]</td>
<td>13.0</td>
<td>20.0</td>
<td>26.0</td>
<td>33.0</td>
</tr>
<tr>
<td>Tapes 60 x 100 [mm]</td>
<td>33.0</td>
<td>49.0</td>
<td>65.0</td>
<td>82.0</td>
</tr>
</tbody>
</table>

The laying cell's output must be matched to the production cycle of the processing machine. What's more, if an appreciable weight reduction is to be achieved, it should be considered that a substantial part of the overall component structure must consist of tapes. With a component weight of e.g. 250 g, the tape blanks should have, in an average, a surface area of at least 300 cm². This is necessary to ensure that some 20 to 30 laying operations are enough to produce a stack weighing 100 to 200 g. This in turn corresponds to a proportion of 40 to 80% of total component weight engaged by the tapes.

Stacking Operation

To obtain the required high dynamics during the stacking operation, a fast articulated robot is used (type: Agilus KR 6; manufacturer: Kuka Roboter GmbH), Figure 9. Demand-oriented removal of the tapes from the magazines is done independently of the actual stacking operation, so that the robot's laying speed is not reduced by slow removal movements.

The quality of a tape stack depends mainly on the accuracy of the positioning of the tapes. If tapes overlap, severe fiber shifting occurs during consolidation, i.e. the fibers slip sideways as they compensate for local deviations in the tape layup thickness. If the tapes are laid with spaces, linear areas without fibers are created during consolidation, resulting in reduced stiffness and strength.

There is an important difference to thermoset tape layups. The gaps between the thermoplastic tapes are frequently not closed completely during consolidation, because the viscosity of the thermoplastic matrix is several decades higher than e.g. with an epoxy resin. Therefore, it is essential that the tapes are positioned precisely, even at high laying speeds. Often, laying accuracies with gap widths of max. 1.0 mm are requested, sometimes even below 0.5 mm.
Figure 9: Investigating direct and indirect illumination during imaging; illumination is a key factor for exact edge detection.

The dimensional deviations during tape laying are partially due to inaccuracies of the blanks or the punching operation. Moreover, the tape stacks cannot be aligned perfectly precisely in the magazines, and the handling operations during tape removal or the take-up by the laying head can lead to additional positioning errors.

Dimensional deviations of the blanks cannot be compensated even by utmost precision. Therefore, the equipment must be able to detect and correct faults as far as possible, to ensure that the tapes are laid exactly parallel to each other. Hereby, obtaining minimum gap widths or overlaps has a higher priority than an accurate outer contour of the tape layup.

![Figure 10](image.png)

Figure 10: Tape laying sequence with use of a vision system for the detection of the edge lines of the cutouts.

**Optical Measurement Technology for High Precision**

Laying accuracy of the individual tapes can be considerably improved with the help of a fast and high-resolution optical measuring system, Figure 10. A digital image of the tape is taken that is converted by means of a threshold value method [2]. Additional calculations provide information e.g. about the edges and the tape's center of area.
These measurements permit correction values for the position and the angle orientation that need to be determined separately for every tape. These values then are transmitted to the robot control system, which takes them into account during laying. One of the key factors for precise edge detection is appropriate illumination while taking the image, Figure 9.

The cutouts of the tapes are prepared in previous steps, e.g. angled or straight cutting from the tape roll, punching with curved contours, as well as cutting the tapes with an ultrasonic knife, whereby the cutouts can be stored in magazines or are processed immediately.

The first tape layer is kept in position on the laying table by vacuum. The following layers are spot welded to the respective lower layer. The tapes can be bonded by means of ultrasonic sonotrodes as well as with electric heating pins within just 0.2 s. The main advantage of the heating pin lies in its far more compact design.

Apart from tape laying step, the multi-stage process for tape processing involves a consolidation step, the subsequent infrared-heating and the shaping of the heated blank, plus cutting and joining operations, see Figure 2.

Figure 11: Appropriate Heating and cooling of thermoplastic composites (organic sheet an tape blanks).

However, as soon as an appropriately consolidated tape blank is obtained, the subsequent processing might be done with the same means as for the processing of organic sheet. E.g., infrared heating of the tape blanks needs to be done in a fashion that ensured proper melding also in the center area and, at the same time, no overheating of the surface, Figure 11.

**Pros and Cons of the Technologies**

The *in situ* processing does not required a semi-finished product as it is the case with the tape processing. However, in the case of the matrix material, also caprolactam-premixes are employed that already contain the desired additive concentration. This significantly facilitates the handling of the reactive components.

With both technologies functional elements, as for example stiffening ribs, can immediately be molded onto the thermoplastic composite structure. In the case of the tape processing, it is possible to work with the same mold for the shaping of the heated tape blank and for the molding of the functional elements. Nevertheless, some applications, where high surface quality is required, also request separate molds for the shaping and the overmolding.
The process chain for *in situ* processing always required separate molds for the reactive processing of caprolactam, on the one hand side, and for the overmolding with thermoplastic resin on the other hand. This is because of the significantly higher mold temperature and the necessary sealing an evacuation of the *in situ* mold prior to the injection of the reactive caprolactam mixture.

An important task in *in situ* processing is to protect the pelletized material against ambient humidity. To achieve this, it is sufficient to follow the typical handling rules for moisture-sensitive materials; that is, moving the material into the production shop early enough for proper temperature conditioning, quick refilling from transport bags to the air-tight sealable dosing containers on the reactive unit, and carefully resealing the bags if any residual quantities are left over. Though, also tapes with nylon matrix are sensitive to humidity, besides of appropriate storages, for the most applications there is no special effort necessary with respect to humidity issues.

The two technologies lead to different types of processing scrap. In the case of *in situ* processing the lost material is dry fiber cutoff that accumulates already during preform production. Those dry fiber materials can easily be recycled, e.g. as fibers mats that might be used in another *in situ* product. With the cutoff from tapes, it is more difficult to achieve an appropriate recycling since the fibers are already wetted and contaminated with the matrix. However, since the matrix is thermoplastic in nature, the cutoff can be used at least as a recycling fraction in injection molding grades.

Once a consolidated tape blank is obtained, the subsequent processing - infrared heating, shaping and overmolding - can be done in a one-minute cycle time. The critical point is the stacking of the tapes that needs to be done also in one minute. *In situ* processing requires 2 to 3 minutes for the polymerization of the caprocactam inside of the mold. To come up with a comparable productivity to tape technology, the line setup needs to be changed somewhat. One *in situ* machine might produce 2 to 4 composite parts at once that are finished in sequence on a separate injection molding machine.

Consideration on the investment need to be done with a close look at some other boundaries. The pure *in situ* equipment is a lower investment as the tape laying plus consolidation equipment. However, when for an *in situ* part also an investment in a preforming line is necessary, the overall investment might be higher for the complete *in situ* setup. Furthermore, detailed calculations on economics also need to consider material cost, material consumption an energy aspects.

With both technologies, production cells with a vertical clamping direction offer benefits since they enable easy placement of the dry preforms or the heated tape blanks respectively.

**Summary**

The economic efficiency of the manufacturing process is key to more widespread use of high-performance fiber composite parts. Of the processes used in industry thus far, HP-RTM technology and wet compression molding, both using thermoset resins, come closest to the goal of producing ready-to-fit parts from dry preforms in a single step.

The combination of *in situ* technology with the injection molding process offers comprehensive options for manufacturing ready-to-fit lightweight components on a thermoplastic basis. This involves creating from a dry preform a carrier structure with a polyamide matrix in an initial step. The stiff and solid composite structure is removed from the *in situ* mold by a robot immediately after the polymerization process and transferred into the cavity of the injection molding mold.

The technology was proven in a full line for manufacturing of lightweight shovels. Based on a
vertical machine (type: Engel v-duo 700), Engel - in collaboration with the moldmaker Schöfer GmbH, Schwertberg/Austria - demonstrated the technology at the K show 2016 in Dusseldorf.

Figure 12: Mold arrangement for the fully automated production of lightweight shovels using in situ polymerization of caprolactam and functionalization by means of injection molding. Rear: in situ mold, front: injection molding mold.

The link between the processing steps, and the key factor for high productivity, is automation. Robots handle the tasks of feeding dry preforms to the in situ mold, transferring the composite parts to the injection molding mold, and of removing the finished parts.

Figure 13: Test part for processing of consolidated tape blanks that enables temperature measurements during shaping and overmolding.

In the case of tape processing, the automation serves for the transfer of the tape stack to the consolidation press. From there, the consolidated tape blanks are brought into the infrared oven and finally in the mold where shaping and overmolding is performed. For a processing line demonstrating this approach, a test part was designed that will be used in the investigations to come, Figure 13.
Tape stacking with optical image processing and using the *pick-and-place* procedure is flexible in application and is not limited to specific tape widths. Image processing is used to detect and effectively correct deviations resulting e.g. from tape production or cutting operations, so that a high-quality tape stack is produced for further processing.

If the tape stack, which has been created in parallel to the injection molder’s cycle time using the *pick-and-place* procedure, matches precisely to the component geometry, subsequent processing steps such as consolidation, heating in the IR oven, plus forming and functionalization in the injection molding mold can be carried out without any intermediate or additional trimming.

Another important characteristic for both technologies is the estimation on the technology readiness level\(^1\):

- **TRL4** states “validation in laboratory environment”,
- **TRL5** states “validation in relevant environment”, and
- **TRL6** states “prototype demonstration in relevant environment”.

For both technologies, the laboratory level was clearly overcome and some demonstration parts were already made and tested. However, considering the demands in automotive industry, the technologies lead to new material systems, where a proof is necessary that they fulfill the part’s specific requirements, i.e. test series must be carried out and optimizations need to be performed.

Although, from the processing viewpoint, *in situ* processing is the more sophisticated approach, there is a processing technology available ready for use in real parts in both cases - *in situ* processing and tape technology.

**References**


\(^1\) Detailed information: https://en.wikipedia.org/wiki/Technology_readiness_level