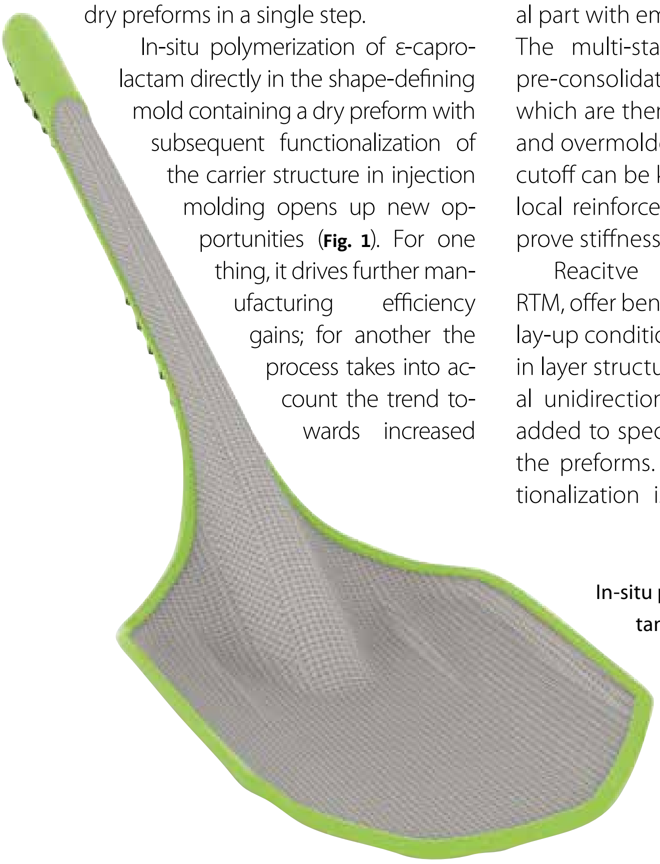
Controlled Reactivity

In-Situ Polymerization for Fully-Automated Production of Lightweight Structures

In-situ polymerization of Caprolactam to create fiber composite carrier structures with subsequent functionalization of the component through injection molding is very closely approaching the ideal of economic series production. One decisive equipment component here is the unit for preparing and injecting the reactive components. At K 2016, Engel Austria is defining the next milestone en route to series production, with a newly-developed reaction unit for which a patent has been registered.

Producing ready-to-fit components from a pelletized material in a single step is state of the art in injection molding. However, it has not been achieved thus far in the production of fabric- or NCF-reinforced lightweight components. 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 comes closest to the goal of producing ready-to-fit parts from dry preforms in a single step.

In-situ polymerization of ε-caprolactam directly in the shape-defining mold containing a dry preform with subsequent functionalization of the carrier structure in injection molding opens up new opportunities (**Fig. 1**). 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. The processing ε-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 precise injection with the use of servo-electric drives, can be carried over here.



In-situ polymerization of ε-caprolactam opens up new opportunities in the production of fiber-reinforced composite components with a thermoplastic matrix – a lightweight shovel is shown as an example (© Engel)

Finished Parts in a One-Step Process

Various processes are available for creating a three-dimensional molded structural part with embedded fabrics or rovings. The multi-stage approach, employing pre-consolidated semi-finished materials which are then trimmed, heated, shaped and overmolded is above all useful when cutoff can be kept to a minimum, and no local reinforcements are required to improve stiffness and strength.

Reacitve processes, including HP-RTM, offer benefits in the case of complex lay-up conditions and local modifications in layer structures. For example, additional unidirectional reinforcements can be added to specific areas when producing the preforms. However, additional functionalization is relatively complex with the HP-RTM process. The resulting components are based on epoxy resin or polyurethane so that joining elements and reinforcing structures typically need to be manufactured separately and fixed to the structural component.

In-situ polymerization of ε-caprolactam also uses a dry preform. However, in contrast to the previously performed RTM processing, the reaction results in polyamide 6. Functional elements can immediately be molded onto this thermoplastic matrix in a subsequent process. In a single step, utilizing an integrated production cell, users can produce ready-to-fit structural components, and this is precisely where the major benefit of the in-situ method lies.

Keeping Tight Control over Monomers

In-situ processing of ε-caprolactam is an anionic ring-opening type polymerization (**Fig. 2**). At room temperature ε-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 ε-caprolactam is excellently suitable for wetting dry fiber structures.

For in-situ processing, a catalyst and an activating agent are added to the ε-caprolactam in separate material containers [1]. These additives ensure that the polymerization reaction starts immediately after mixing the two components. The use of premixes that already contain the desired additive concentration significiantly facili-

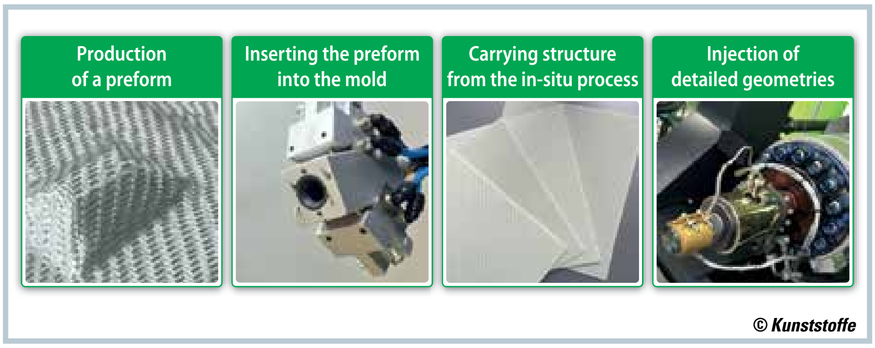


Fig. 1. Processing scheme for manufacturing in-situ components with molded detail geometries: Process integration boosts the economic efficiency of the manufacturing process (source: Engel)

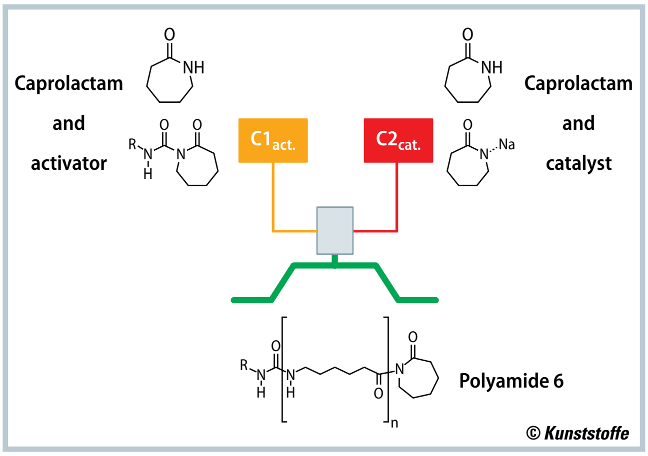


Fig. 2. Anionic ring-opening polymerization creates polyamide 6 from ε-caprolactam (source: Engel)

tates the handling of the reactive components. The important thing is to protect the pelletized material against ambient humidity. To do 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.

In the melting unit, the monomer mixtures are heated to 120 °C, which is quite close to the polymerization temperature of 140 to 160 °C. Special attention needs to be paid to mold temperature control during processing – a homogeneous mold temperature is the prerequisite for a constant reaction process and high product quality.

As it is the case in the processing of thermoplastics, it is also important to avoid unnecessary thermal exposure of the reactive components in in-situ processing. For this reason, Engel Austria GmbH, Schwertberg, Austria, developed a new reactive unit in which only the required quantites of the the material mixtures are molten immediately prior to processing. The melting units only contain liquid reacitve components for a maximum of three cycles (**Fig. 3**). The filling level is continuously measured and kept in a tolerance range that is freely definable by the user.

Precise Synchronization of the Injection Plungers

Synchronous and precise injection of the two reacitve components is the most challenging sequence in the in-situ processing cycle. The two injection plungers, which are not mechanically coupled, first independently soak the required shot volumes, and then inject these into the cavity in an electronically synchronized parallel movement. The nozzles on the mixing chamber also need to be opened and closed in » sync with the stroke movements. Engel ensures this precision on the one hand with servo-electric drives, which are also used for the injection on all-electric injection molding machines, and on the other with sophisticated process control software, specially developed for the in-situ technology. After mixing, the ε-caprolactam polymerizes in the cavity in 2 to 3 min to create a polyamide 6 with high molecular weight.

The focus of process optimization lies on reducing the cycle times and achieving minimum porosity in the structural component. While the cycle time is mainly driven by the reactivity of the recipe, and the machine operator's options for influencing this via the mold temperature are limited, the porosity can be controlled efficiently, and reduced to almost zero through process control (**Fig. 4**). The major parameters here are evacuating the mold prior to injection, and the pressure level in the mold at the end of the injection sequence.

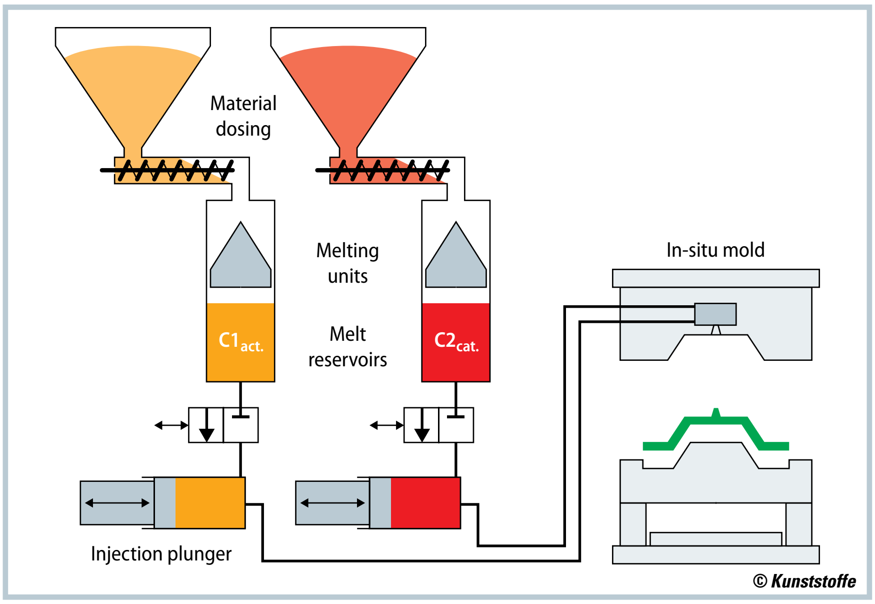


Fig. 3. The special feature of the new reactive unit is the reduced thermal exposure of the monomeric material. The melting units hold a volume required for three shots as a maximum (source: Engel)

Multi-Component Technology with Gravity as an Assistant

The combination of in-situ technology with injection molding processing offers comprehensive options for manufacturing ready-to-fit lightweight components. This involves creating from a dry prepform a carrier structure with a polyamide matrix in an initial step. This 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 mold. Like in conventional multi-component technology, features such as edge surrounds, rib structures, bosses or local reinforcements are injection molded in a second step. The preferred material used for functional integration is polyamide, e.g., with short glass fiber reinforcements; this reduces the number of different materials in the component.

Because the caprolactam additive mixtures are fed to the mixing chamber in the mold via heated tubes, the reactive unit can be freely positioned. For example, it can be installed behind the thermoplastic injection unit of the machine to save space.

The new reacitve unit can be combined with various types of Engel injection molding machines. Production systems with a vertical clamping direction offer benefits for in-situ processing in that they enable easy placement of the dry preform in the bottom mold half (**Fig. 5**). However, in case where the mold has fixtures for holding the preform, an injection molding machine with a horizontal clamping unit is equally well suited [1].

Based on a vertical machine (type: Engel v-duo 700), Engel – in collaboration with Schöfer GmbH, Schwertberg, Austria, which has established itself as a specialist for in-situ molds – has developed a complete setup for manufacturing lightweight shovels (**Fig. 6**, **Title figure**), which Engel will be demonstrating at K2016. In this application, the vertical clamping direction facili-

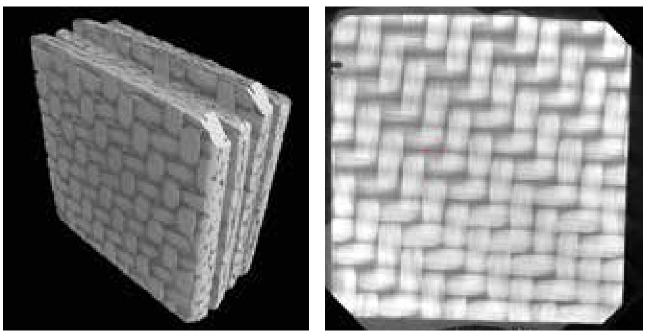


Fig. 4. Computer tomography investigations reveal that the fabric can be impregnated virtually without pores (© Engel)

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References & Digital Version

- You can find the list of references and a PDF file of the article at *www.kunststoffe-international.com/1872804*

German Version

- Read the German version of the article in our magazine *Kunststoffe* or at *www.kunststoffe.de* tates handling of the preform. There are some challenging details mainly relating to the mold, for example, in terms of temperature control, sealing of the in-situ cavity, and matching the injection molding cavity with the in-situ carrier structure.

Tailor-Made Systems for Greater Efficiency

In-situ production in the same pace as the injection molding was not yet achieved due to the longer processing cycles of the polymerization process. However, the cavity pressures required for in-situ production are by far lower than in the case of injection molding of a component of the same size. With a suitable production cell, this factor can be used beneficially. For example, multiple composite structures can be manufactured at the same time in a multiple cavity in-situ mold for downstream functionalization in a single-cavity injection mold. In an ideal case, the cycle time of the in-situ process would precisely match the time for the downstream injection molding processes.

The link between these dissimilar processes, and the key factor for high productivity, is automation. Robots handle the tasks of feeding dry preforms to the in-situ mold, transferring the carrier parts to the injection mold, and of removing the finished parts.

Conclusion

With its reactive unit, specially designed for processing ε-caprolactam, Engel overcame a major obstacle to integrating in-situ polymerization and functionalization of composite structures in a two-component

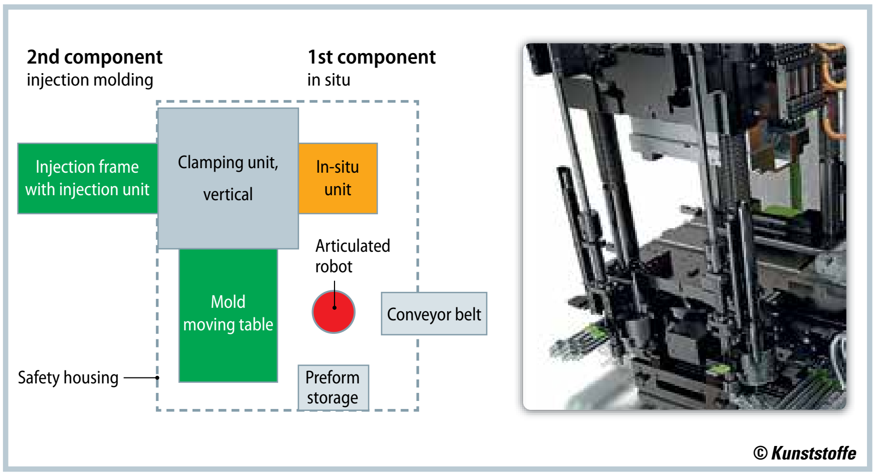

Fig. 5. Working in the direction of gravity offers benefits in many applications where preforms are used. The example shown in the figure is a system layout for an integrated multiple component process on a vertical injection molding machine (source: Engel)

Fig. 6. The production cell combines an in-situ polymerization process with classical injection molding to produce lightweight shovels (© Engel)

process. The development is based on a prototype machine for in-situ polymerization processes, which was also developed by Engel and showcased in 2012. Since then major changes have been made to the technical solution, including separating the machine's parts for preparing and injecting the reactive components.

The outcome is the first technological system that enables separate preparation as well as precise and robust processing of small shots of ε-caprolactam. This will open up additional, exciting applications for thermoplastics based composite components – and not just in the automotive industry. ■