SPRIFORM: A HYBRID TECHNIQUE FOR SERIAL PRODUCTION OF 3D PARTS OF CONTINUOUS FIBER REINFORCED THERMOPLASTICS

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Abstract
C-FRPs consisting of a textile fiber component and a thermoplastic matrix component gain influence due to very short process cycle times, almost unlimited storage life and good mechanical, particularly impact behavior. The most common processing variant of organosheets is thermoforming. This paper introduces a new hybrid technique that combines the advantages of injection molding and thermoforming of organosheets. Furthermore, an analytical method to predict the anisotropic elastic behavior of woven fabric reinforced plastics is shown.

1 Introduction
Shortage of resources, environmental protection and increasing energy costs figure out current challenges for engineers, especially in the field of automotive constructions. This is the motivation to save some weight by consequent structure light-weight design. The sum of force fractions required to move a vehicle consists of the four summands $F_{kinetic}$, $F_{potential}$, $F_{roll\ resistance}$ and $F_{air\ resistance}$. Every summand, except of $F_{air\ resistance}$, contains the vehicles mass. By decreasing this term, a huge amount of energy for moving the vehicle can be saved. Due to lower required energy, smaller engines can be used, thus emissions and costs will be reduced. Due to lower vehicle weight, bigger or heavier batteries can be mounted; otherwise, the load capacity of the vehicle can be increased. Last but not least, lower weight leads to higher driving dynamic and thus makes cars more attractive to the customers.
Lightweight design has many faces like conceptual, structure optimized, conditional and material lightweight design [1]. Commonly, lightweight materials like carbon, aluminum and magnesium alloy are associates with this wording. In general, light-weight materials are characterized by high strength and stiffness as well as low density.
Continuous fiber reinforced plastics (*C-FRP*) save a high potential for light weight components and thus are used for the construction of highly stressed structural components.
Figure 1 gives an overview over some technical relevant lightweight construction materials and fiber reinforced materials, in particular carbon, glass and aramid fibers. C-FRPs consist of a textile fiber component and a thermoplastic matrix component. These so called *organosheets* gain influence due to very short process cycle times, almost unlimited storage life and good mechanical performance, in particular impact behavior.

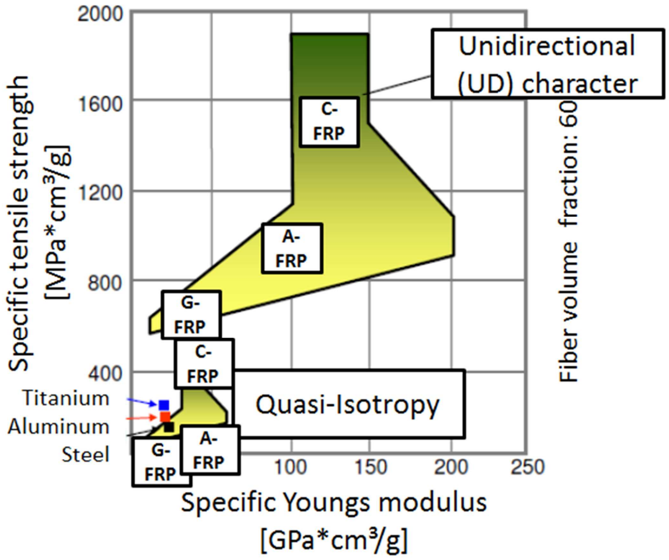

Figure 1. Weight-specific mechanical performance of different materials. FRP: Fiber reinforced plastic. C: Carbon, G: Glass, A: Aramid

The most common variant of organosheet processing is thermoforming. The blanks are plasticized by heat input and then are shaped by means of a tooling. After cooling, the organosheet remains in a stable shell-geometry.
This paper introduces a new hybrid technique that combines the advantages of injection molding and thermoforming of organosheets. In the context of a public promoted project, the so called *SpriForm* technique was established as a capable-of-series production using the example of a technology demonstrator. This part was designed in the style of a car door crash element.
Parallel to the practical realization of the SpriForm technique, FE simulations were carried out. Therefore, the complex strain rate and temperature dependent mechanical behavior of the organosheets was investigated experimentally.

2 Production of C-FRPs: TEPEX® dynalite

Currently, there are various principles of fiber reinforced plastics with different types of fibers (short, long, continuous fibers), textiles (woven, non-crimp fabrics, fleece and random mats) and matrix materials (thermosets, thermoplastics). This paper deals with continuous woven fiber reinforced thermoplastics, in particular fully impregnated and consolidated semi-finished parts in form of blankets. For this kind of material, in German language use the wording *organosheet* was established.
Organosheets are fully impregnated and consolidated, thus there is a very small remaining amount of air / inclusions (< 2 Vol.-%) inside the material. Furthermore, every single filament of the reinforcing fabric is completely included and surrounded by the thermoplastic matrix. In the following, the organosheets produced under the trade name *TEPEX® dynalite* by the company Bond-Laminates are observed. TEPEX® consists of glass, carbon, aramid, flax and others or hybrid textiles as reinforcement. For the thermoplastic matrix, PA, PP, TPU, HDPE, PPS, PC or others are used.
TEPEX® dynalite organosheets are produced in a continuous, fast process. Woven fabrics and thermoplastic matrix material are combined by means of high temperature and high pressure. In the most cases, double belt presses are used to join thermoplastic films and fabrics similar to a continuous film-stacking process (Figure 2). In this process, the fabric is penetrated by

the melt completely and air is evacuated from the laminate. After passing a cooling zone and then leaving the press, the material can be cut into blankets or spooled on a roll for storage or further processing.

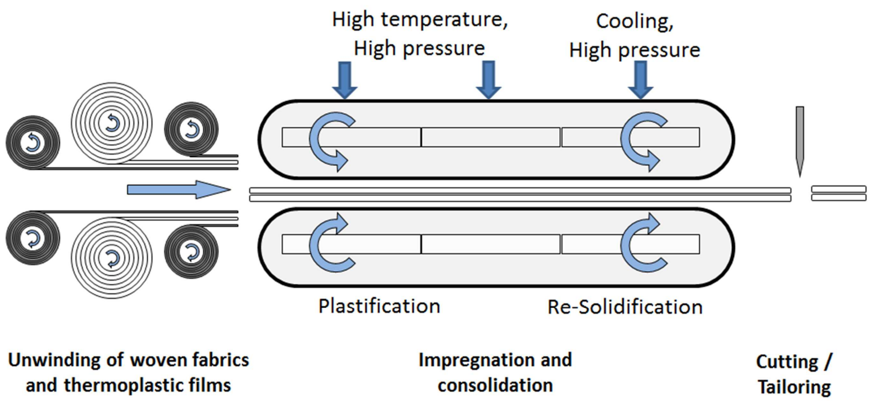

Figure 2. Schematic continuous TEPEX® dynalite organosheet production process

3 Further processing of organosheets: Thermoforming and SpriForm technique

Due to the thermoplastic matrix, there is a multitude of technological advantages compared to thermoset systems. The thermoplastic does not pass through a chemical transformation, thus there are no reaction components. The final mechanical performance is already included in the semi-finished part. The impact resistance of the rigid thermoplastics is significantly higher than of comparable thermoset systems. Furthermore, the drape-ability of plasticized organosheets is better than that one of dry fabrics without matrix, that is used for processing related to hand-laminating techniques, because within organosheets, the fibers “swim” in the thermoplastic and thus are lubricated when displaced.

However, the most important advantage is the distinctive suitability for high-volume mass production. Reasons for this are in particular the high output of the TEPEX® dynalite production processes and the thermoplastic processing principles that lead from the semi-finished part to the finished part. The most simple and most common processing variant for the shaping of organosheets is thermoforming of pre-cut plates. Under the influence of heat, the matrix plasticizes and becomes soft and formable, thus forming processes like match-mold forming or diaphragm forming can take place. The required forming pressure is quite low, because there is no air to be evacuated and the materials mechanical behavior is already implemented in the semi-finished part. As a conclusion of this, the requirements of press force and tooling are lower than e.g. for metal forming processes.

Figure 3 exemplarily shows a typical TEPEX® dynalite thermoforming process. At first, the organosheet with the temperature T_{OS} has is clamped at room temperature (T_r) and handed over to a heating unit. The heating can be performed via infrared radiation, heat conduction or via convection in e.g. a circulating air oven. After passing the plasticization temperature (T_m), the softened sheet is handled over into the forming and cooling tool (T_{mold}). Due to the decoupling of heating and forming/ cooling processes into two separate stations, the complete process can take place in less than one minute even for big parts. An adequate edge trimming via water-jet or laser cutting, sawing or die cutting (even possible in the forming tool) finally leads to the finished parts.

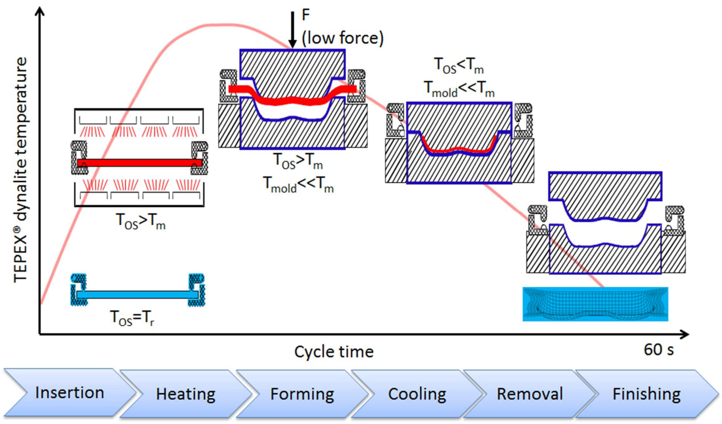

Figure 3. Schematic TEPEX® dynalite thermoforming process

By the thermoforming technique described above, complex shell parts can be shaped. Limitations exist concerning the possible complexity of the parts geometry. Neither complex 3d parts nor detailed structures like appropriate for function integration can be realized by simple thermoforming processes. This leads to the idea of hybridization of organosheet-thermoforming and thermoplastic injection molding processes in order to combine the advantages of both processes: On the one hand the outrageous mechanics of continuous fiber reinforced plastics, on the other hand the high level of detail of injection molding.
Within a public promoted research project under cooperation of several companies with the title "SpriForm – Combination of thermoplastic injection molding and thermoforming of continuously fiber reinforced thermoplastics for crash structures", a new hybrid process was developed at the example of several demonstrators.
Figure 4 schematically shows this SpriForm process cycle. Similar to the conventional thermoforming process (Figure 3), a pre-cut blanket is clamped and provided to a heating station. By increasing the temperature above the melting point T_m, the blanket softens and then is handed over to a separate forming tool. This special mold has melt-guiding channels and is mounted on an injection molding machine, thus the cavity can be flooded by molten plastic after inserting the organosheet and closing the mold. The contour edges of the organosheet are sealed by melt, thus an out-of-tool finished part is produced within a cycle time less than one minute. Within the context of the international plastic trade fair K2010, a technical demonstrator, approximated to a rear car door crash beam was produced. This demonstrator was one of the technically realized results of the SpriForm project.

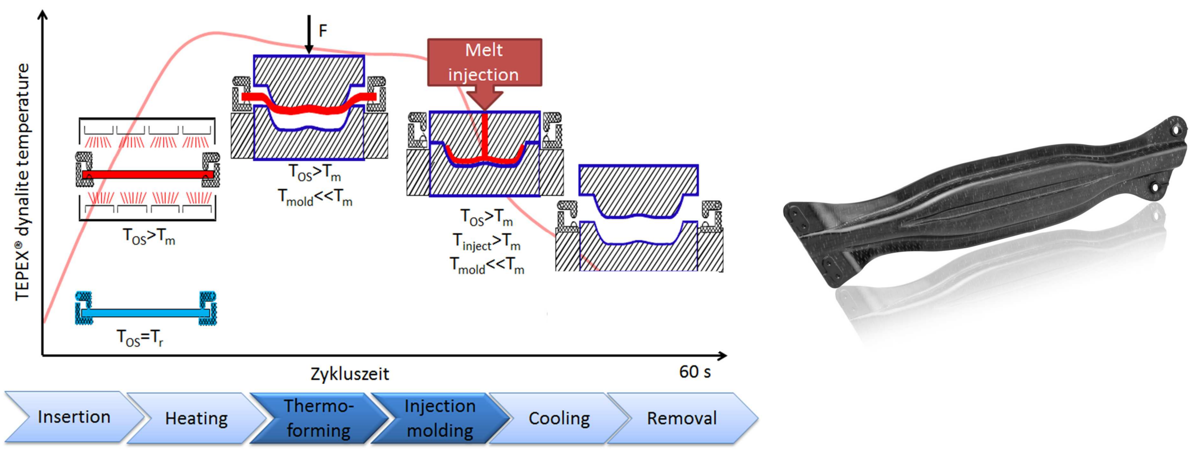

Figure 4. Left: Schematic TEPEX® dynalite SpriForm process. Right: Technical Demonstrator (Approximated car door crash beam)

The great freedom of design of injection molding processes offers a wide range of possibilities. For example, rips can be inserted into a profile as stiffeners. This may lead to significantly improved stiffness or strength in structural components. Furthermore, sophisticated functional elements can be realized, such as fastening elements. Even decorative surfaces can be realized by special tooling techniques [2, 3], special temperature cycles [4] or decorative surface film layers that can be back-molded in the tooling.

4 The mechanical behavior of thermoplastic continuous fiber reinforced plastics

Thermoplastic continuous fiber reinforced materials, in particular TEPEX® dynalite organosheets are often composed of the thermoplastic matrix and a woven textile consisting of reinforcing fibers. This woven fabric contains filaments in warp and weft. The direction of warp and weft are orthotropic, thus there is a 90° angle in between. In the most cases, there are equal fiber contents in both textile directions. The different fabrics are stacked over each other as multiple layers, so the organosheet thickness results depending on the number of layers and the fiber volume content.

For more and more applications, FEA calculations are carried out in order to forecast the mechanical behavior of the finished part. Therefore, the precise knowledge of the materials mechanical behavior under load is essential. Contrary to the most common construction materials like e.g. the most metals, continuous fiber reinforced plastics show a significantly anisotropic behavior. Especially in fiber direction, the mechanical behavior is dominated by the fibers, with increasing differing angle, the polymer matrix gains influence.

For the estimation of the mechanical characteristics in this work, the laws of the classical laminate theory were consulted. For the calculation of a plain stress problem, that should be valid for the most organosheet applications, some simplifying assumptions can be made [5]:

- Only small deformations with linear elasticity
- Mechanical behavior dominated by fibers
- Thermal expansion is negligible
- Maxwell-Betti relation is valid: $\frac{E_1}{\nu_{21}} = \frac{E_2}{\nu_{12}}$

Now, the elastic behavior can be described easily by three independent numbers: Young's modulus $E_1 = E_2$ (due to the balanced woven fabric), shear modulus G_{12} and Poisson ratio $\nu_{12} = \nu_{21}$. All the mechanical characteristics have due to the thermoplastic content a deformation rate- and temperature dependent component, that will not be observed in this paper.

With the above mentioned formulations, the flexibility matrix is composed like shown in (1):

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = [S] \cdot [\sigma] = \begin{bmatrix} \bar{S}_{11} & \bar{S}_{12} & \bar{S}_{16} \\ \bar{S}_{21} & \bar{S}_{22} & \bar{S}_{26} \\ \bar{S}_{16} & \bar{S}_{26} & \bar{S}_{66} \end{bmatrix} \quad (1)$$

Based on this and with the fiber orientation angle α, the transformed flexibility matrix consists of the following components [8]:

$$
\begin{aligned}
\overline{S_{11}} &= \frac{\cos^4\alpha}{E_1} + \frac{\sin^4\alpha}{E_2} + \frac{1}{4}\cdot\left(\frac{1}{G_{12}} - 2\cdot\frac{\nu_{21}}{E_1}\right)\cdot\sin^2 2\alpha \\
\overline{S_{22}} &= \frac{\sin^4\alpha}{E_1} + \frac{\cos^4\alpha}{E_2} + \frac{1}{4}\cdot\left(\frac{1}{G_{12}} - 2\cdot\frac{\nu_{21}}{E_1}\right)\cdot\sin^2 2\alpha \\
\overline{S_{66}} &= \frac{\cos^2\alpha}{G_{21}} + \left(\frac{1}{E_1} + \frac{1}{E_2} + 2\cdot\frac{\nu_{21}}{E_1}\right)\cdot\sin^2 2\alpha \\
\overline{S_{12}} &= \frac{1}{4}\cdot\left(\frac{1}{E_1} + \frac{1}{E_2} - \frac{1}{G_{12}}\right)\sin^2 2\alpha - \frac{\nu_{21}}{E_1}\left(\sin^4\alpha + \cos^4\right) \\
\overline{S_{16}} &= -\left(\frac{2}{E_2} + 2\cdot\frac{\nu_{21}}{E_1} - \frac{1}{G_{12}}\right)\sin^3\alpha\cos\alpha + \left(\frac{2}{E_1} + 2\cdot\frac{\nu_{21}}{E_1} - \frac{1}{G_{12}}\right)\cos^3\alpha\sin\alpha \\
\overline{S_{26}} &= -\left(\frac{2}{E_2} + 2\cdot\frac{\nu_{21}}{E_1} - \frac{1}{G_{12}}\right)\cos^3\alpha\sin\alpha + \left(\frac{2}{E_1} + 2\cdot\frac{\nu_{21}}{E_1} - \frac{1}{G_{12}}\right)\sin^3\alpha\cos\alpha
\end{aligned} \tag{2}
$$

With experimentally established values, the Young's modulus can be calculated in dependency of the orientation angle. The characteristic numbers can be established be only a couple of simple tensile tests: E_1 and E_2 result from simple stress-strain tests in α=0° and 90°, ν_{21} and G_{12} can be calculated easily from the results of a transversal contraction measurement and a tensile test under an orientation angle of 45° [6, 7]
Figure 5 shows the Young's modulus exemplarily for a glass fiber reinforced polyamide 6 with a fiber volume content of 47% (TEPEX® dynalite 102-RG600(X)/47%).

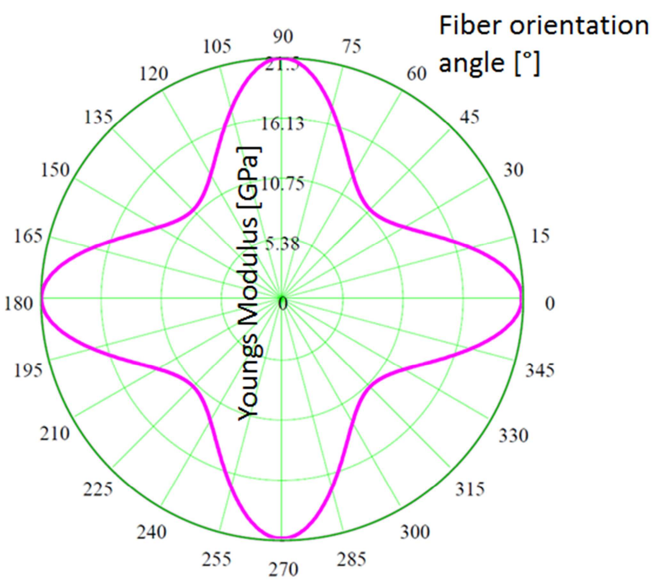

Figure 5. Calculated Young's modulus in dependency of orientation angle. Material: TEPEX® dynalite 102-RG600(X)/47%

The distinctive anisotropic behavior gets visible: While in warp and weft direction (α=0° and 90°) almost the maximum theoretical tensile modulus of the textile is reached, it decreases with increasing orientation angle; a minimum of stiffness is reached with α=45°, than it increases again up to the peak at α=90°.

For the verification of the analytic calculation results, some tensile tests with varied orientation angles in steps of 7.5° steps from 0° to 45° were conducted out. Figure 6 shows the results as stress-strain curves.

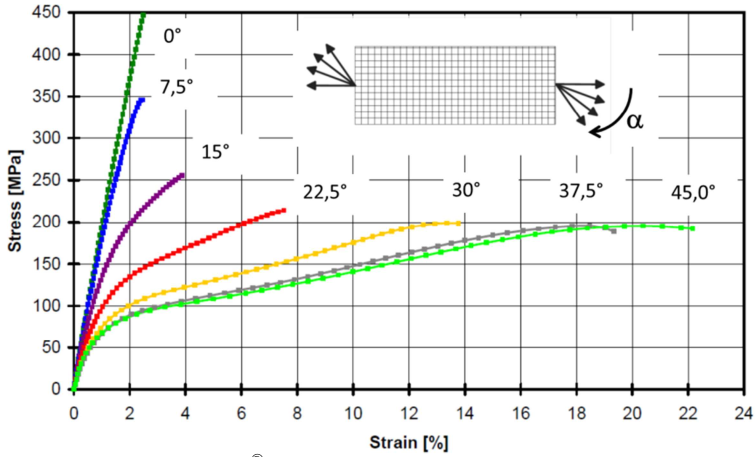

Figure 6. Tensile test results TEPEX® dynalite 102-RG600(X)/47% (Test according to ISO 527-4, specimen Type 3, test speed 2 mm/min)

If the measured Young's modulus is compared to the calculated values from Figure 5, a good correlation is found for each orientation angle (Figure 7).

For small angles, the almost linear, ideal elastic behavior gets visible. The specimens failed brittle only small strains. With increasing orientation angle, as well Young's modulus as tensile strength decrease, but the material fails more and more rigid and at significantly higher strains due to the gaining influence of the thermoplastic matrix. Due to this, the area beyond the curves, representing the energy absorption capacity increases. This is important for crash-relevant structural mechanical calculations.

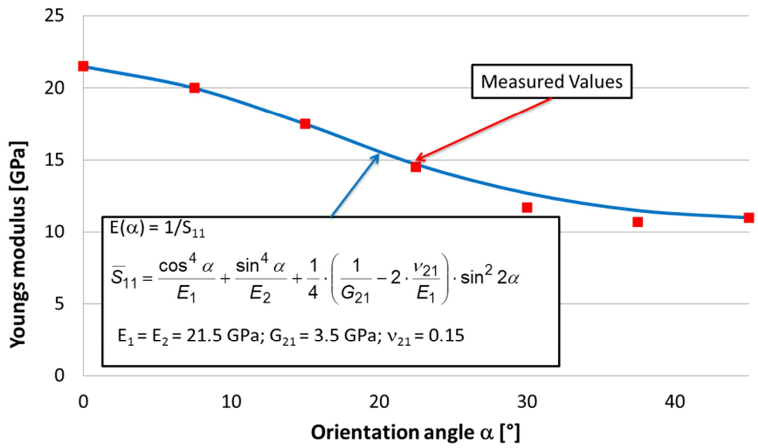

Figure 8. Correlation of calculated and measured Young's modulus. Material: TEPEX® dynalite 102-RG600(X)/47%

5 Summary

In this paper, the production of the structural construction material "organosheet", represented by the trading grade TEPEX® dynalite, manufactured by Bond-Laminates, is introduced. Besides the conventional thermoforming process of organosheets, a new hybrid technology called SpriForm is described. SpriForm combines the advantages of injection molding and thermoforming in mass series production suitable cycle times. The succesfull realization of the project was proved by means of different technical demonstrators, for example the technical demonstrator.

Due to the gaining relevance of numerical structure simulations (FEA), some material characteristics are established. One characteristic is the elastic behavior of the reinforced material represented by the Young's modulus. Therefore, experimental tests were conducted out and are correlated with analytical results from the classical laminate theory. For the investigated material, a very good correlation is found; the distinctive anisotropic behavior in dependency of the fiber orientation can be predicted analytically with a high accuracy.

In future investigations, on the one hand, the results have to be transduced to further materials (e.g. carbon fibers, different matrix plastics). On the other hand, furthermore the tensile strength will be in the focus of research in order to predict the failure behavior of continuous fiber reinforced thermoplastics. Especially valid for the viscous thermoplastics, temperature and deformation rate dependent behavior will be a further scope of work [9].

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