PROCESS COMBINATIONS AS A KEY FOR PRODUCING LIGHTWEIGHT AND HIGH-DUTY COMPOSITE STRUCTURES BASED ON THERMOPLASTIC MATERIALS

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Abstract

This paper presents a number of approaches aimed at producing lightweight and high-duty fibre composite structures. The approaches are based on state-of-the art fibre-reinforced material systems and manufacturing processes of polymer technology. The process strategies described combine established materials and processes in a well-aimed way, in order to generate mechanically loaded integral constructions in an integrative production process.

1 Introduction

When they were introduced in the eighties, thermoplastic high-performance fibre composite materials did not immediately make their way into large-scale production [1]. Today, however, they are used in many applications. This shows how engineers were able to open up innovative ranges of products and applications by enhancing and developing prepregs tailored to the process, as well as design guidelines and new processing techniques. The variety of processes available today for the economic large-scale production of components based on thermoplastic fibre composite plastics is not sufficient, though. This paper shows how combining established techniques of plastics processing makes it possible to produce the most diverse types of designs, e.g. planar fibre composites, hybrid composite structures or hollow composite structures. Injection moulding technology serves as a basis for the conceivable process combinations. To enable one-shot integrative production, the individual manufacturing processes are integrated into the injection mould. This strategy is described by the „in-mould“ term.

2 Suitable materials

The option of combining different types of fibre and matrix systems to each other entails a variety of fibre composite plastics that cover a wide rang of properties. The fibres determine the composite materials’ reinforcing effect. Apart from length, they differ in terms of material properties (of e.g. glass, carbon, aramid) as well as their orientation, architecture and their content. As a matrix, the user may select thermosetting, elastomeric or thermoplastic systems, which differ significantly with respect of their molecular structure, and thus to their material properties. Fibre-reinforced elastomers are mainly used for reversibly deformable products (e.g. car wheels, damping elements), whereas the two other matrix elements can mainly be found in rigid components. [2] provides a detailed comparison of the benefits included in fibre composite plastics on a thermoset basis to the benefits offered by composites based on thermoplastics. Evidently, the material characteristics directly affect the restrictions in terms of processing. For instance, if compared to a non-cross-linked thermoset matrix, the viscosity of a thermoplastic matrix is high, which makes it difficult to soak the dry fibres, and this means a particular challenge during impregnation. In addition, the inherent differences in solidification behaviour lead to differences in processing times. For the case of a thermoplastic matrix system, cycle times are thus shorter than those of a reference system based on a thermosetting material, and this eventually improves efficiency.

3 Suitable procedures

In polymer processing, a variety of techniques is available to form and finish plastics materials. In recent years, there has been a trend towards increasingly complex manufacturing units and techniques designed to produce in one plant, and in one single mould, components or prepregs of demanding shapes or comprised of several plastics materials [3]. As examples, see multi-component injection moulding, coextrusion or in-mould welding [4]. Based on German Industrial Standard DIN 8580, the authors briefly present the basic processes of moulding and finishing, cleverly combined in various types of special processes, to thus enable the production of high-duty and integral fibre structures.

3.1 Primary Shaping

The term primary shaping comprises all manufacturing processes that use a die or mould to make a solid component or prepreg, e.g. when thermoplastic materials are submitted to injection moulding. Generally speaking, its short cycle times make the injection moulding process suitable for the economic large-scale production of components. The parts do not usually require secondary finishing. Injection moulding can be applied to functionalize or stiffen fibre composite structures, as is done in e.g. hybrid technology. The process of injection moulding, as well as the mould itself, allows for further manufacturing processes to be integrated. These processes will be subject to further consideration in the following.

3.2 Forming

Forming of thermoplastic materials means the non-cutting process of forming. This mainly refers to prepregs, but also moulded parts, see VDI guideline 2008 part 1, published by the German Association of Engineers. While the thermoforming of non-reinforced thermoplastic prepregs, the compression moulding of flowable long fibre reinforced prepregs, and the forming of metal materials permits for parts to be stretched or compressed, this is impossible with non-flowable thermoplastic fibre composite prepregs due to their reinforcing continuous fibres included. Three-dimensional shaping is basically done by relatively shifting the reinforcing fibres. To form fibre composite prepregs on a thermoplastic basis, several processes are available, such as the stamp forming, the diaphragm forming or the rubber pad press forming [2]. This paper is due to show how forming can be linked to other manufacturing processes.

3.3 Impregnation

The mechanical properties of fibre composite plastics are highly dependant on their impregnation properties. The reinforcing structures of fibre composite plastics based on thermoset materials are usually impregnated during forming, i.e. by e.g. so-called RTM, resin transfer moulding, whereas most thermoplastic fibre composite plastics have so long been impregnated prior to actual forming, that is during prepreg generation. This is due to the fact that dry fibres are hard to wet completely. If compared to component production by using prepregs - which are also named “organosheets” in the case of continuous fibre reinforcement - direct impregnation cuts the process chain.

3.4 Joining

Following the definition according to German Industrial Standard DIN 8593, the term joining, if used for issues of production engineering, means the solid link of at least two components. Joints can either be form-fit, force-fit or substance-to-substance. One of the techniques of substance-to-substance joining is plastics welding, which is suitable only for thermoplastics, because the cross-linked macromolecules of thermosets and elastomers do not have the mobility required for welding. During welding, the surfaces are heated up to a point above melt temperature, and joined under pressure, in order to achieve the best possible homogeneity in the joint. A wide range of welding techniques is available, such as hot gas welding, hot plate welding, or welding by primary shaping. In order to generate high-duty material composites, welding can serve to join e.g. formed or primary shaped structures to each other.

3.5 Cutting

In the field of production engineering, the term comprises the methods that are suitable to change the form of a workpiece, by eliminating the cohesion in a certain spot. In some cases, planar fibre composite prepregs need to be cut. This may be necessary before or after forming, in order to confection the prepreg for forming, or else to separate the component from scrap. Some of the methods suitable for cutting fibre composite prepregs are laser cutting, water jet cutting and shearing.

4 Experimental Procedures

The experiments looked into four processes to show how the beneficial combination of different types of manufacturing processes can generate integral and high-duty fibre composite structures. Table 1 presents an overview of the manufacturing processes included in the four highly integrative processes. In some of the cases, it is even possible, in general, to integrate more manufacturing processes, which can be seen in brackets. What is more, the individual processes will be described in an outline.

	Primary shaping (injection moulding,...)	**Forming** (stamp forming, fluid pressure,...)	**Impregnation**	**Joining** (infrared welding, joining by primary shaping,...)	**Cutting** (blade cutting, shearing,...)
In-Mould Forming	**x**	**x**		**x**	**x**
FIT-Hybrid	**x**	**x**		**x**	**(x)**
Twin-O-Sheet	**(x)**	**x**		**x**	**(x)**
In-Mould Impregnation	**(x)**	**x**	**x**	**(x)**	**(x)**

Table 1. Survey of the different options of process combinations, subject to investigation at the Institute of Polymer Technology; (x) means the process stage can be integrated into the process, in principle.

4.1 In-Mould Forming

During In-Mould Forming (IMF) the pre-heated fibre composite prepreg on a thermoplastic basis is placed into the injection mould and formed when the injection mould is closed. Two short-wave infrared radiators (IRE 380L type, 2 kW each, Fa. Optron) heated the prepregs. For the tests, the injection mould was tempered to 100 °C. A pinch-off edge separates the excess material of the prepreg at the end of the closing path. Substance-to-substance onmoulding and joining of the formed component to the primary shaped rib structure in the same production cycle finally completes the one-shot hybrid component [2], see fig. 1. For the experiments, a PA66 47 Vol.-% GF (type: 101-RG600(4), 2 mm, TEPEX® dynalite, supplier: Bond Laminates) was used for the prepreg, and a PA66 GF30 (type: AKV 30 H2.0, Durethan® by LANXESS) was injection moulded.

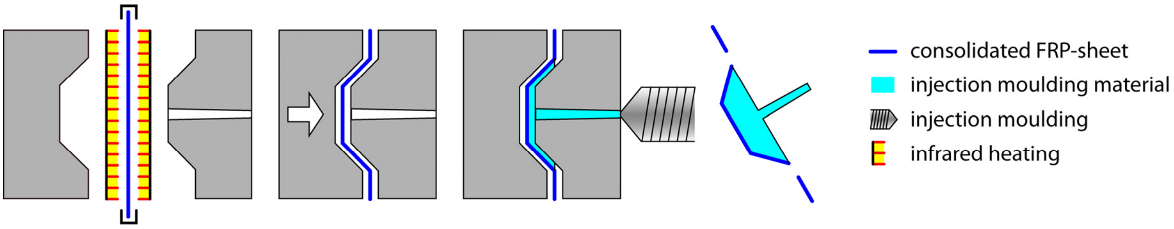

Figure 1. Schematic presentation of the In-Mould Forming process

4.2 FIT-Hybrid

The FIT-Hybrid process serves to manufacture fibre composite structures with hollow profiles. Other than the In-Mould Forming technique, this method employs fluid pressure to form continuous fibre reinforced thermoplastics. Two consolidated sheets are first pre-heated to forming temperature. Then a polymer melt with a compatible matrix is injected in between the two sheets. Subject to the volume of the pre-filled melt, either a blow-out or an inflation process is available. In the blow-out process, the melt volume is so high the external sheets are formed completely by the embossing pressure caused by the embossing stroke. In a subsequent step, fluid injection can then blow-out part of the melted core into an overflow chamber see fig. 2.

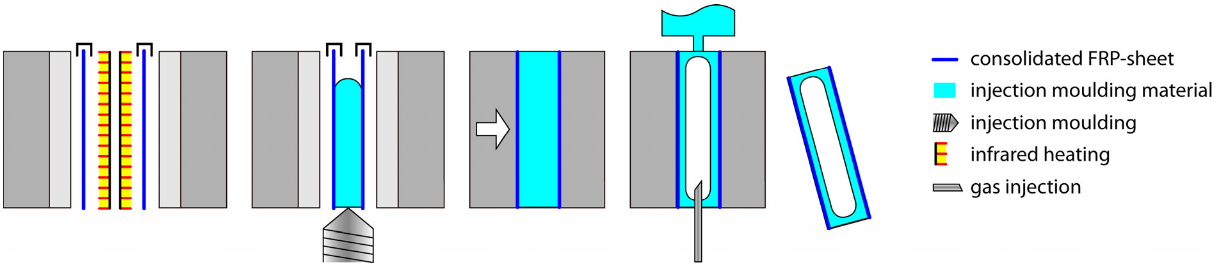

Figure 2. Schematic presentation of the FIT-Hybrid process (blow-out variant)

Applying the inflation variant, less material is pre-filled into the mould. The consolidated sheets are therefore formed only in part by the embossing move of the injection mould. Fluid injection is applied to inflate the melt inside the cavity, which produces the final geometry, see also [7]. Model test specimens were made of a PP 47 Vol.-% GF (type: 104-RG600(4), 1 mm, TEPEX® dynalite, supplier: Bond Laminates) as a prepreg material. As injection moulding material, a polypropylene (type APPC 1100N by APPC, marketed by A. Schulman) was used.

4.3 Twin-O-Sheet

The Twin-O-Sheet (TOS) process serves to produce hollow large-volume composite structures from continuous fibre reinforced thermoplastics. As soon as the thermoplastic matrix of the prepregs has reached its processing temperature, a fluid is introduced. This fluid causes overpressure, which then forms the prepregs, see fig. 3.

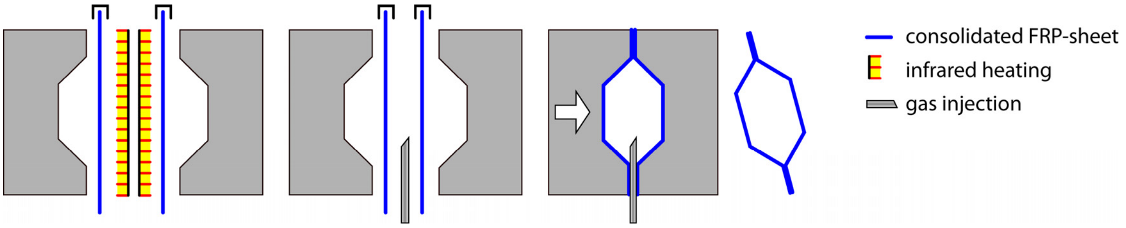

Figure 3. Schematic presentation of the Twin-O-Sheet process

To prevent the fluid from exhausting via the prepregs' areas, the prepregs must be modified in terms of material, to make them sufficiently fluid-proof. Moreover, clever process management must isolate the prepregs from each other. Other than the FIT-Hybrid process, with melt acting as a diaphragm, the TOS process can form the continuous fibre reinforced thermoplastics without injecting a melt, thanks to their tightness to fluids.

4.4 In-Mould Impregnation

The In-Mould Impregnation (IMI) process is designed to include into the forming process the impregnation of the reinforcing fibres with a thermoplastic matrix. In this process, the dry reinforcing prepreg is placed in between the two mould halves. By closing the movable half of the mould, or by using a robot, the prepreg is then draped inside the cavity at room temperature. Electrical contact can then be applied to heat the carbon fibre prepreg. The carbon fibres act as resistance heater here. When the plasticized polymer melt is finally injected, it has to withstand only little filling resistance, which prevents damage to the prepreg. An embossing frame seals the cavity from the environment. An embossing stroke first distributes the melt in lateral direction. Then it penetrates the dry heated reinforcing structure in through-thickness direction, thus causing impregnation of the fibres. After the air was eliminated from the carbon fibre fabric, and after the consolidation phase is completed, the current source can finally be disconnected and therefore the heating be switched off. Due to the high heat conductivity of the carbon fibres, the thermoplastic matrix of the high performance fibre composite part solidifies within seconds, thus permitting for demoulding, see fig. 4.

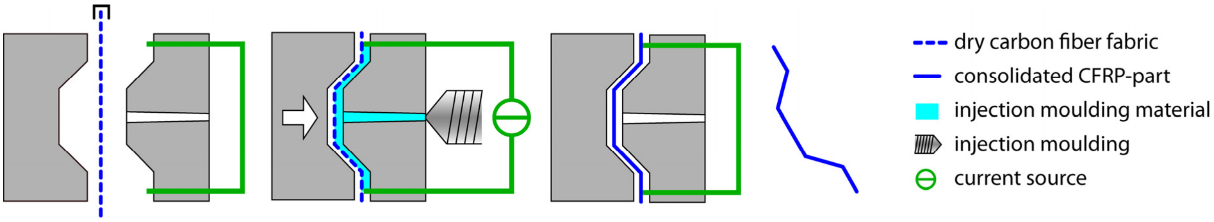

Figure 4. Schematic presentation of the In-Mould Impregnation process

For the first trials, the scientists applied a PA6 by Lanxess. As a reinforcing fibre, Panex® 35, a carbon fibre offered by Zoltek, was applied, which had been processed into non-crimped fabrics by LIBA Maschinenfabrik GmbH.

5 Results

The following chapters will present selected findings obtained for the processes mentioned. These findings are due to show how some manufacturing techniques can be integrated into a process.

5.1 In-Mould Forming

To attain a substance-to-substance bond between the primary shaped rib structure and the formed fibre composite structure, pressure and temperature are necessary. The injection pressure of the injection moulding machine is sufficient for this purpose. To fulfil the thermal conditions required to weld compatible matrix systems, the contact temperature between formed and primary shaped component must be above or equal to the melt temperature. This is the case with In-Mould Forming, which can be seen in fig. 5, right. The chart shows the temperatures measured both at the surface, as well as in the centre of the fabric-reinforced thermoplastic (see fig. 5, left) over the entire cycle of In-Mould Forming. What is striking is a temperature peak at the side of the ribs that occurs during forming. The course of temperature at the rib side thus differs from the temperature course at the mould side, which suddenly decreases at contact with the injection mould tempered to 100 °C. When the prepreg is formed and reconsolidated, melt is discharged at the area of the rib root that constitutes the geometrical connection between the formed prepreg and the primary shaped rib. The plastic melt leaves the melted core of the heated prepreg, thus showing that its temperature is above the material-specific range of melt temperature. The temperature of this squeezed plastic melt is also higher than that in the rib-sided surface of the formed prepreg. It is thus responsible for the first temperature peak in the rib-sided thermocouple.

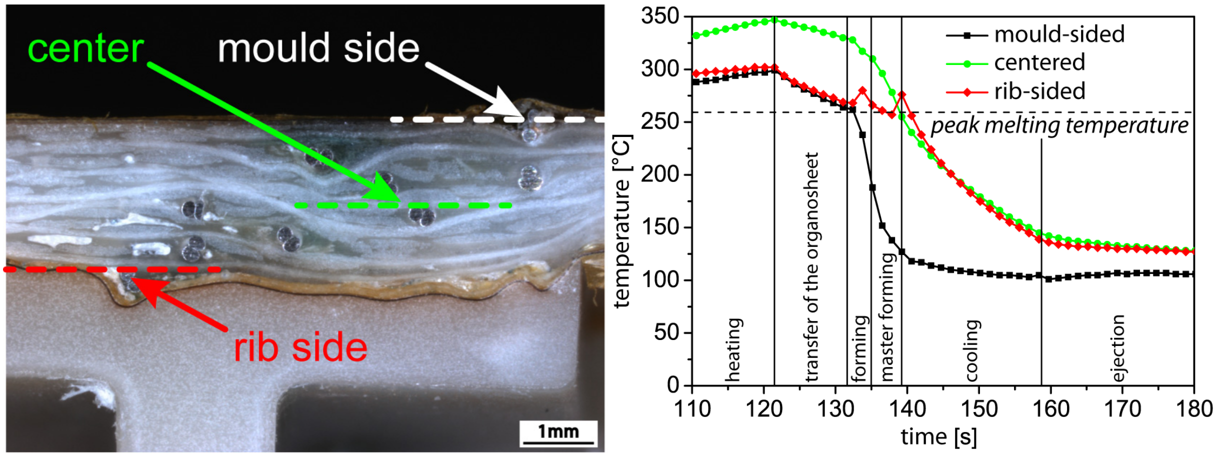

Figure 5. Example of joining inside the mould: In-Mould Forming
(prepreg material: PA66 47 Vol.% GF, injection material: PA66 GF30)
left: Thermocouple positions inside the rib test specimen
right: Prepreg temperatures measured during In-Mould Forming

While the temperatures measured at the centre of the prepreg and at the side of the mould decrease as cycle time proceeds, another peak in temperature shows in the rib-sided thermocouple at the end of the injection phase. This second peak occurs when the plastic melt of the injection moulded rib reaches the prepreg. At the same time, it thus represents the temperature of contact between organosheet and injection moulded plastic melt. While this contact temperature is above the melt peak temperature, the In-Mould Forming process fulfils the thermal conditions required for substance-to-substance welding of primary shaped and formed structures. Consequently, integrative production by In-Mould Forming can utilize the residual heat from initial heating to generate a substance-to-substance bond. No further heating is thus required. For more information, please refer to [2].

Cutting can also be an integral part of the In-Mould Forming process. This is visible in fig. 6, which shows a pinch-off edge integrated in the injection mould.

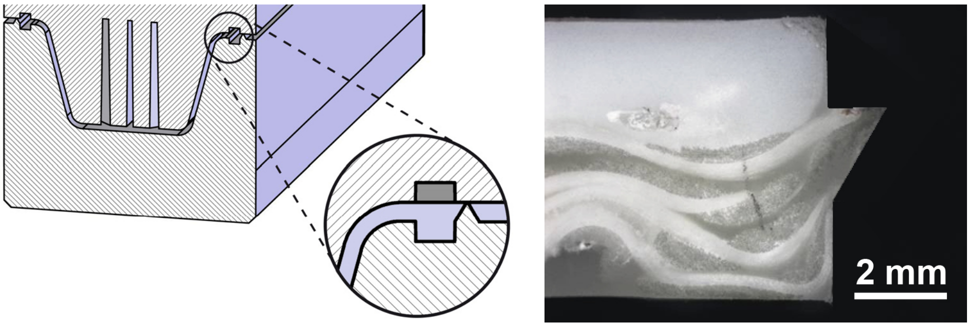

Figure 6. Example of cutting as an integral part of the mould: In-Mould Forming
left: Pinch-off edge integrated in the injection mould
right: cut-off fibre composite structure

5.2 FIT-Hybrid

First, model test specimens were submitted to systematic examinations in order to investigate the FIT-Hybrid process. The results thus obtained could then be transferred to a complex formed high-duty rear seatback. The outer diameters achievable in the model test specimens, i.e. 30 mm, were scaled by a factor higher than 1.5 for the rear seatback, and could be produced in a process-safe manner too. The hollow pipes of the rear seatback are formed on one side, and have a conical quadrangular form with a pronounced rounding, see fig. 7.

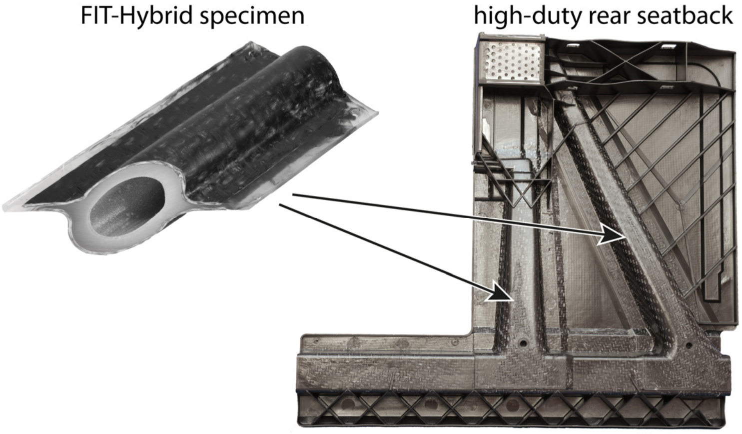

Figure 7. FIT-Hybrid technology transferred to a complex formed rear seatback made in an integrative process; Materials used: glass fibre reinforced polypropylene, for more information, refer to [7]

Inserted as a strand or injection moulded, the plastic melt has a barrier function aimed at maintaining the gas pressure inside the hollow structure. The residual wall thicknesses of the FIT-Hybrid pipes largely follow the same rules that apply to conventional gas-assist injection moulding. Subject to the respective processing parameters, residual wall thicknesses in the model test specimens are between 4.00 and 4.26 mm. As diameters are stepped up, residual wall thicknesses increase correspondingly. More information is available at [8].

5.3 Twin-O-Sheet

Other than the FIT-Hybrid process, the Twin-O-Sheet technique is designed to increase lightweight potentials by entirely dispensing with the injection moulding of a plastic melt. Engineers expect this technique to enable the production of large-volume hollow structures without a residual wall thickness. To achieve this aim, fibre composite prepregs are specially modified so as not to be penetrated by the fluid used for inflation. Preliminary tests have shown that the process is feasible.

5.4 In-Mould Impregnation

Measurements have shown that the dry carbon fibre prepreg can achieve the melt temperatures of thermoplastics within second, if heated by a current source, thanks to its electric resistance. Figure 8, left, shows the cross-section of a flat plate in through-thickness direction. The quality of impregnation achieved in the first trials can be seen here. It becomes clear from the microscopic image that the fibres could be impregnated completely, and this is proof for the feasibility of this new approach to impregnation for thermoplastic matrix materials. Moreover, process optimization will eliminate the outer layer with its large amount of matrix, and further increase fibre volume content.

Figure 8, right, presents an SEM image of a cryogenically induced fracture of a flat test specimen. Coupling between fibre and matrix is obviously very good, which, apart from the high degree of impregnation, is another prerequisite for utmost mechanical stiffness.

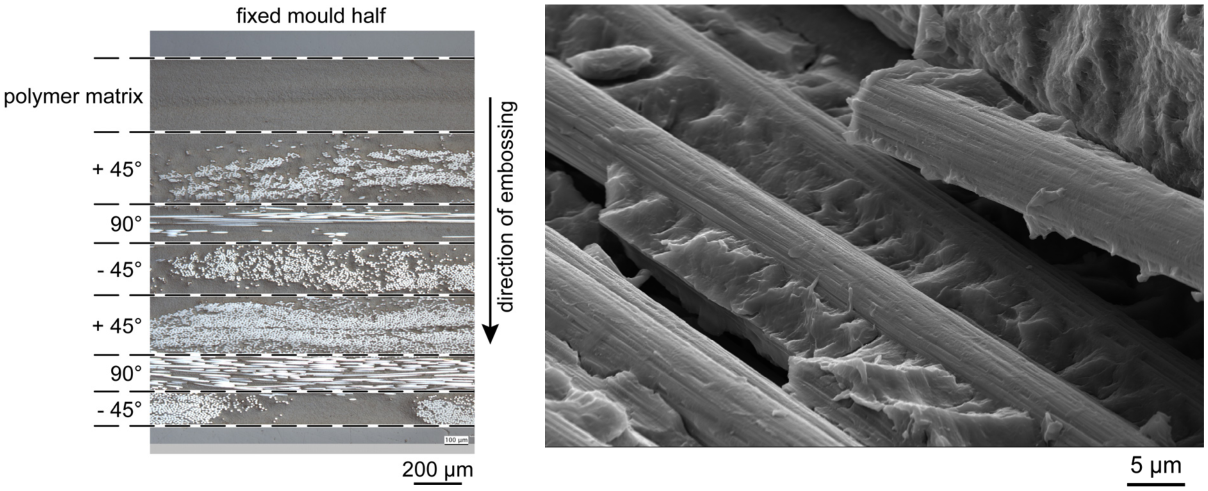

Figure 8. In-Mould Impregnation being one example of impregnation inside the mould
left: Microscopic image of the specimen cross-section in through-thickness direction (incident light, DIC)
right: SEM image of a cryogenically induced fracture

6 Summary and outlook

This paper has presented an outline of various options available to make individual processes a part of one integrative process. In most cases, users will obtain one-shot integral structures out of reduced process chains. Future research will be aimed at combining processes designed for the economic production of functionalized and entirely consolidated prepregs. This is due to enable the production of, e.g. prepregs with integrated electric circuits, or with class-A surfaces, which can then be processed into intelligent, three-dimensional and high-duty structures.

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