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Carbon Composite Sheet Werkstoffe für Automotiv-Strukturbauteile aus neuartiger Presstechnologie

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0-WASTE: Carbon Composite Sheet Werkstoffe für Automotiv-Strukturbauteile aus neuartiger Presstechnologie

TEIL I – PRODUCT AND TECHNOLOGY DEVELOPMENT

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1 Introduction

Product design, manufacture, repair and recycling are concepts that have evolved since the early days of the production history of humans. Today, they require complicated knowledge and cost intensive processes. Despite great advances in tools and techniques of product development and support, the central idea is still the same: determining a certain set of needs and developing a product that satisfies those needs.

Nowadays, adaptable product lifecycle management (PLM) software tools support the designers and product developers to respond quickly to change from business or market disruptions and summarizes all activities and data during the product development. Both the concepts behind the software tools and the user friendliness of these tools are continuously further developed.

The awareness of sustainable development has increased in the last decades. The consideration of the environmental impacts of the whole product system with its life cycle (raw material & manufacturing, transports, consumer use, disposal & recycling) have led to more interest in the development of methods to better understand and address these impacts. With the purpose to fulfil these demands systematically, the method of life cycle assessment (LCA) has evolved on the basis of the ISO 14000 standards family.

Numerous concepts, methods and diagnostic software tools have been developed and are frequently applied for various products. In addition to the various methodological aspects of LCA, proper data about the entire product chain is needed. Both the generation and the collection of appropriate and reliable data and the management of such data demand serious considerations. In spite of all of these uncertainties, a systematic and quantitative LCA analysis provides more insight into the product and process development of specific materials and may offer at least an estimation towards realistic environmental impacts.

The increasing environmental awareness of the society together with the middle and long-term shortage of natural resources (materials and energy) leads to the engineer's challenge and even the immediate necessity to develop and manufacture industrial and consumer products in a sustainable design process. The challenge is to design components to consume as little material as possible incorporating profound recycling strategies, but in the same time to meet the load and safety requirements (Neitzel et al., 2014; Yang et al., 2012).

The research project 0-WASTE addresses this challenge by developing a beyond state-of-the-art design and manufacturing technology of discontinuous carbon fiber reinforced composites**.** The goals thereby were to reduce the waste of carbon fiber composites and to propose recycling strategies in the production of structural automotive components (here transmission cross beam) exploiting the full light-weight potential. Besides the engineering approach, also the environmental performance was considered with LCA.

The approach focuses on an advanced, one-shot carbon fiber sheet molding compound (C-SMC) compression molding technology, which enables the industrial manufacture in an automated and cost efficient way. A multilayered hybrid material architecture (“sandwich” structure) enables the multistage use of industrial recyclates for varying quality requirements with virtually zero waste generation. Virgin material is only used where necessary, tailor-made to the specific application. Furthermore, it allows for local reinforcement with UD tapes (unidirectional carbon fiber prepreg) and functionalities with metallic inserts for a reliable manufacture of the structural automotive components with a low variability of product performance. Although it may sound metallic to the experienced engineer, the components feature all advantages of the carbon fiber composite technology to exploit their full lightweight potential.

LCA is used to provide a systematic framework that helps to identify, quantify, interpret and evaluate the environmental impacts of a product, function or service in an orderly way. “It is a diagnostic tool which can be used to compare existing products or services with each other or with a standard, which may indicate promising areas for improvement in existing products and which may aid in the design of new products” (European commission, 2006). As a development tool for the future, LCA needs to meet the requirements of eco-design for a successful product development. There is still a debate how LCA can be implemented in a PLM solution. Our view is that product lifecycle management can be integrated with the life cycle assessment functions. This combination may yield an improved product development process while simultaneously consider ecological and environmental issues.

Hence, the project report consists of two parts.

While in the first part of this report the product development process is described from an engineering point of view, a detailed and systematic LCA supported by various software tools is described and discussed in the second part of the report.

2 Project Description

2.1 Motivation and Objectives

High performance composites like prepregs are conventionally used in low-volume and structurally demanding applications in the aerospace and aviation industry. Prepreg components, impregnated with thermosetting resins, are manufactured in various curing processes under pressure and temperature (Figure 1). The strength-to-weight ratio presented by these materials is exceptional, but they are not suitable for realizing complex, three-dimensional structures with sharp edges and radii. Furthermore, a cost efficient manufacture is not possible due to the slow lay-up processes which excludes this technology for automotive mass applications (cycle times in the range of hours to days). Sheet Molding Compounds (SMC) and Bulk Molding Compounds (BMC) meet the criterions of low costs and fast production, e.g. in the automotive industry. However, the disadvantage of this material class are their lower mechanical properties because of lower fiber volume fractions (usually glass fibers) (Aubry, 2001).

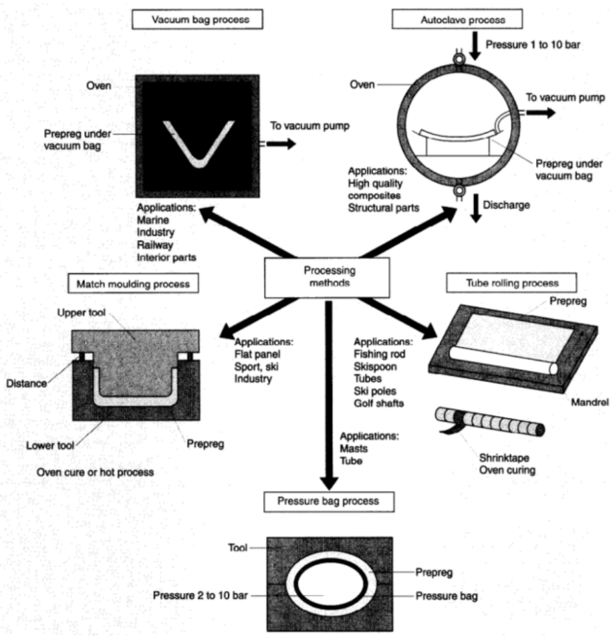

Figure 1: Summary and representation of manufacture methods of prepregs (Marsh, 2002).

C-SMC (Carbon Fiber Sheet Molding Compound) (Potter, 1986; Marsh, 2002) combines the properties of high performance prepregs with the cheaper and easier manufacturing possibilities of SMCs. They usually feature high carbon fiber fractions of 40 vol% or above and quasi-isotropic properties (Kaczmarczyk and Langschwager, 2013). C-SMC materials consist either of chopped prepreg platelets or discontinuous carbon fibers dispersed in a resin, which are usually randomly oriented to form the SMC semi-finished part. C-SMC is delivered in rolls. It is sufficient flexible and adhesive, can be easily cut into preforms and transferred into a mold of a press. The preforms are finished in a single-stage compression and curing process under heat and pressure and molded into a 2D or 3D shape. Depending on the part the applied pressure varies between 50 bar and 200 bar with tool temperatures ranging from 120 °C until

160 °C. Cycle times of 2 min to 5 min can be realized. As a consequence, such materials feature a good performance-to-costs ratio and it is possible to realize complex geometries due to the good flow properties of C-SMC.

A variety of C-SMC and prepreg materials (impregnated with duroplasts or thermoplastics) are commercially available on the market. In our research activities we use HexMC® materials (EP1134314; US20070036963), a commercial grade of Hexcel. These materials contain carbon fibers between 50 vol % and 65 vol %. The manufacture technology was developed for fiber reinforced composites with thermoplastic matrix by The Boeing Company (US8709319). This method uses fiber platelets (flakes) of varying geometries which are randomly distributed in a mold and compression molded under processing temperature. Optional thermoplastic resin can be added (Figure 2).

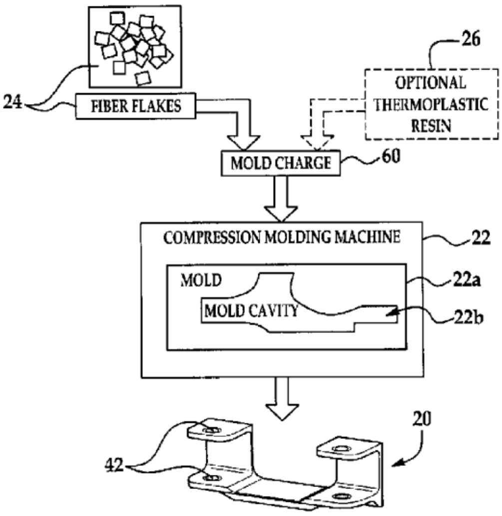

Figure 2: Compression moulding method for fibre reinforced thermoplastics (US8709319).

This process should be modified for C-SMC materials to allow for a special hybrid material architecture for the multistage use of industrial recyclates and local tape reinforcements in the 0-WASTE research project. The objectives were to reduce the waste of carbon fiber composites, to propose recycling strategies in the production of structural automotive components (here **transmission cross beam**) and to achieve weight savings by about 30 % to 40 % in comparison to the industrial standard version in aluminum. Further, a fully automated press technology and process-optimized tool were investigated and developed to achieve a cost efficient industrial production method.

The proposed methodology needs to assert itself against other state-of-the-art process technologies for automotive applications with the potential of mass production: Resin Transfer Molding (RTM), Wet Molding, Prepreg pressing, Compression Resin Transfer Molding (C-RTM) and Organosheet Hybrids. However, despite their excellent mechanical properties they cannot achieve the high degree of geometrical complexity as the C-SMC compression molding technology.

2.2 Project Summary

The research project with a duration of two years and three months (27 months) was funded through the FTI-Inititative „Energieforschungsprogramm 3. Ausschreibung". The consortium consisted of one university partner and three industry partners. The university partner (JKU iPPE) was leading the consortium under the technical direction of Univ.-Prof. Dr. Zoltán Major. It has to be highlighted that the competencies of the industry partners cover the total value chain of the fiber composite manufacture and application from the material supplier (Hexcel), over the tool maker (Alpex) to the polymer processing (Engel) and finally to the end product. This industry consortium is rounded off by the expertise of the university partner in the field of mechanical characterization and simulation (JKU iPPE under the direction of Univ.-Prof. Dr. Zoltán Major). By means of the production-based LCA it was possible to assess the ecological sustainability of the 0-WASTE concept (a. Univ.-Prof. Dr. Heinz Prammer of the Institute of Corporate and Regional Environmental Management, JKU Linz). Through this integrative combination of technological and virtual development methodologies, the full potential of the material system and the manufacture process together with the recyclability could be exploited. The advantages regarding the environmental impacts of the C-SMC transmission cross beam compared to the aluminum version is analyzed in more detail in the LCA study of the report (Part II).

The research project was divided into 4 work packages and an additional management and dissemination part. Each work package was tailored in such manner that it was providing insight into the life cycle management of the newly developed technology and reveal potential recycling opportunities for the end product. The practically oriented results were academically complemented with the simulation and design capabilities of the university partner. A multiscale simulation approach was developed to model the process-induced mesostructure and thus the material behavior. The R&D activities focused on experimental and numerical investigations performed on both material samples as well as on components (with special subcomponents) and resulted in a concept ready for industrial implementation. The combination of process and structural simulation, as well as the complexity of the material behavior pose many research questions, addressed by 1 PhD, 4 MSc and 1 BSc theses. In addition, due to the unique industry cooperation and the final C-SMC component the academic partner established an international research network with partners from Italy, Spain, the USA and Taiwan. The project consortium and the schematic representation of collaboration is illustrated in Figure 3.

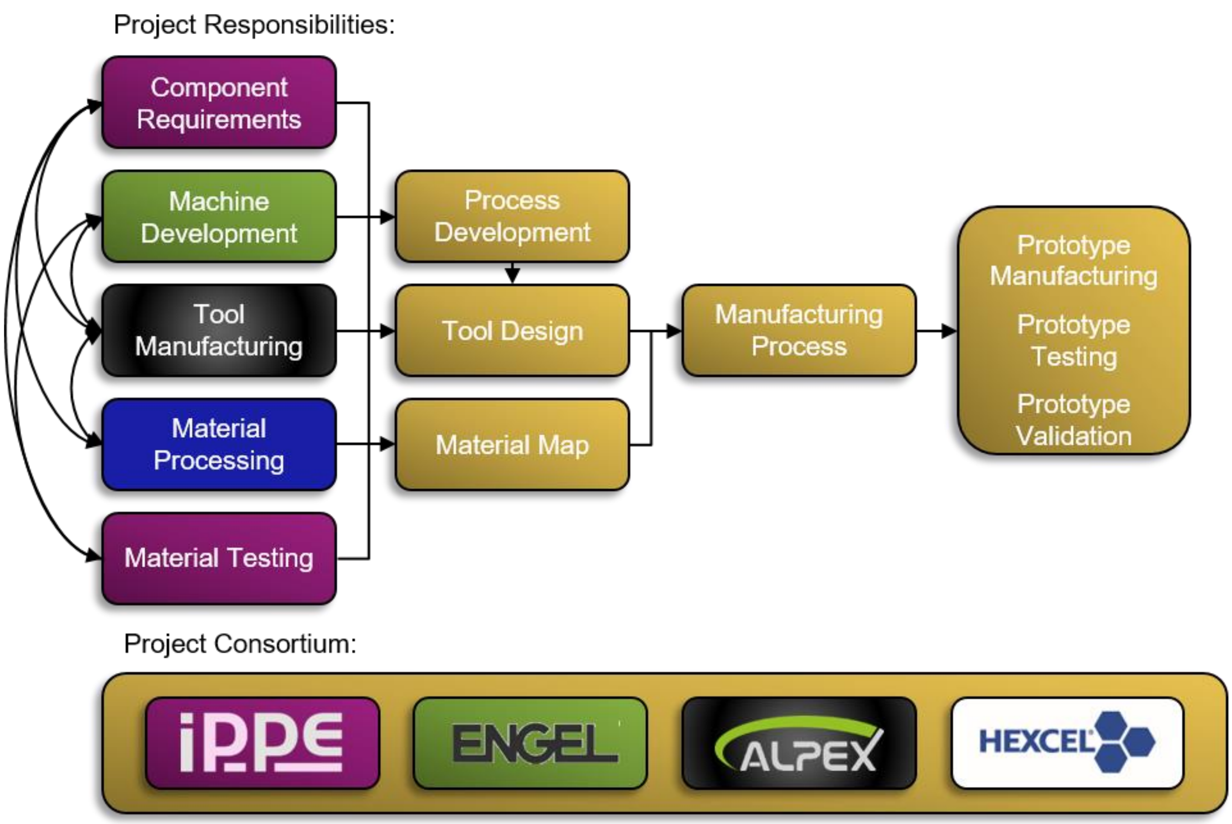

Figure 3: Project consortium and schematic representation of collaboration, colours correspond to the logos.

The approach (Figure 4) focuses on an advanced, one-shot C-SMC compression molding technology to achieve an industrial manufacture of structural lightweight automotive components in an automated and cost efficient way. The transmission cross beam represents a practically oriented C-SMC automotive component to validate the 0-WASTE development concept on the laboratory scale. A multilayered hybrid material structure enables the multistage use of industrial recyclates for varying quality requirements with virtually zero waste generation. Prepreg platelet based C-SMC materials are of special interest in this project because they can be made from prepreg scrap and enhancing thus the recycling capabilities of the proposed manufacturing technology. Furthermore, it allows for local reinforcement with UD tapes (unidirectional continuous carbon fiber prepreg), controlled platelet orientation and functionalities with metallic inserts for a reliable manufacture of the structural automotive components with a low uncertainty of product performance.

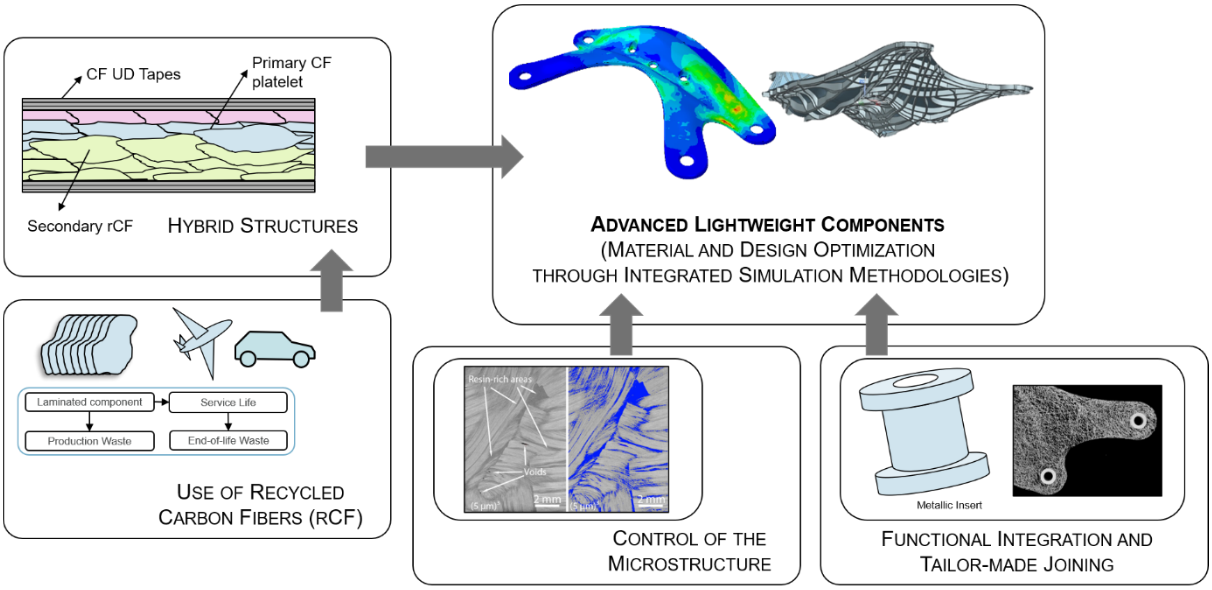

Figure 4: 0-WASTE concept to reduce carbon fiber waste in the production of structural lightweight automotive components.

2.3 Research Approach

2.3.1 Product Development and Design Process

The transmission cross beam has to fulfil loading requirements and performance specifications of a leading OEM. As a design and feasibility study the bionics motivated topology facilitates a hybrid material architecture of virgin and recycled materials to maintain the processability and the mechanical performance compared to virgin C-SMC. The bionic “manta ray” structure with its freeform shape provides an approach to avoid stress concentrations for superior fatigue strength instead of conventional rib designs. Furthermore, local reinforcement with UD tapes and functionalization with metallic inserts can be used for a reliable manufacture of the automotive components with a low uncertainty of product performance.

To understand the complex material behavior and to work out design guidelines for the final tool of the transmission cross beam, first subcomponents (hat profiles and thickness profile plates) were manufactured with special tools. The hat profile served as simplification of the 3D geometry and the main loading mode of bending of the transmission cross beam. This subcomponent was used to derive the dependence of the mechanical properties on the process conditions and different material systems. With the thickness profile plate it was possible to gain insight into inherent defects arising through thickness jumps in the geometry and through different process conditions.

The **virtual prototype** was **designed** with the software toll Siemens NX (Siemens PLM). Design decisions were based on **simulation support** with other software tools, Abaqus (Simulia, Dassault Systèmes), LS-Dyna (Livermore Software Technology Corporation) and Digimat (e-Xstream engineering) (see Figure 5). The CAD concepts were developed in an iterative optimization loop according to the real-world loading and design space requirements. The first step was to create a validated material model to predict the stiffness and failure behavior accurately. The material models were calibrated based on the experimental material tests on the coupon level and the subcomponent tests on the component level. Then, structural simulations and **topology optimization** runs with the Finite Element Method (FEM) were performed for the various design iterations. In that manner, an optimum design for the transmission cross member geometry was created. It must be emphasized here, however, that the designed geometry represents a “concept study” and it was not intended for use in practical applications. The main emphasis was placed on a bionics motivated smooth curvature geometry, which can accentuate the specific advantages of the C-SMC materials. Furthermore, inputs of the industry partners with their expertise in tooling, manufacture machines and materials were continually integrated to achieve the best possible tool geometry. Further improvements can consist of the application of global reinforcing elements (UD tapes, ribs) and the local reinforcement of the junction points around metallic inserts.

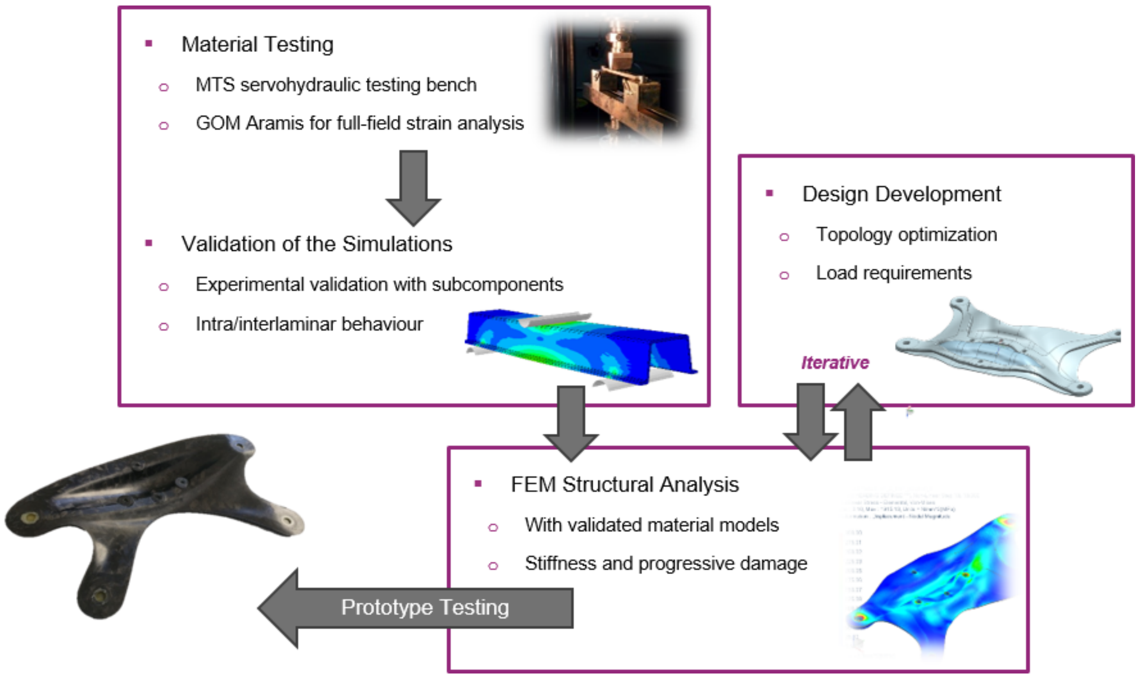

Figure 5: CAD product development with simulation support.

2.3.2 Material Characterization and Simulation

The composition and the C-SMC material flow during the compression process result in a complex mesostructure with inherent defects, like voids, resin pockets and fiber waviness, and alignment of the fibers with the flow direction. This mesostructure determines the macroscopic material behavior (Feraboli et al., 2010; Kravchenko et al., 2018, 2019; Li and Pimenta, 2019) and thus the mechanical performance of C-SMC component. The stochasticity of the mesostructure and the non-representative size of the test coupons (Hill, 1963; van Mier, 1997) lead to high scattering in the material tests, which makes the experimental determination of suitable material properties for the simulation models difficult. For this reason, a **multiscale approach** (Figure 6) was employed to calculate the macroscopic material properties based on micromechanical models. A further advantage of the multiscale material modelling are time and cost savings in the design process, since material parameters with an estimation of the influence of defects and layer structure are available at an early stage and experimental testing can be reduced.

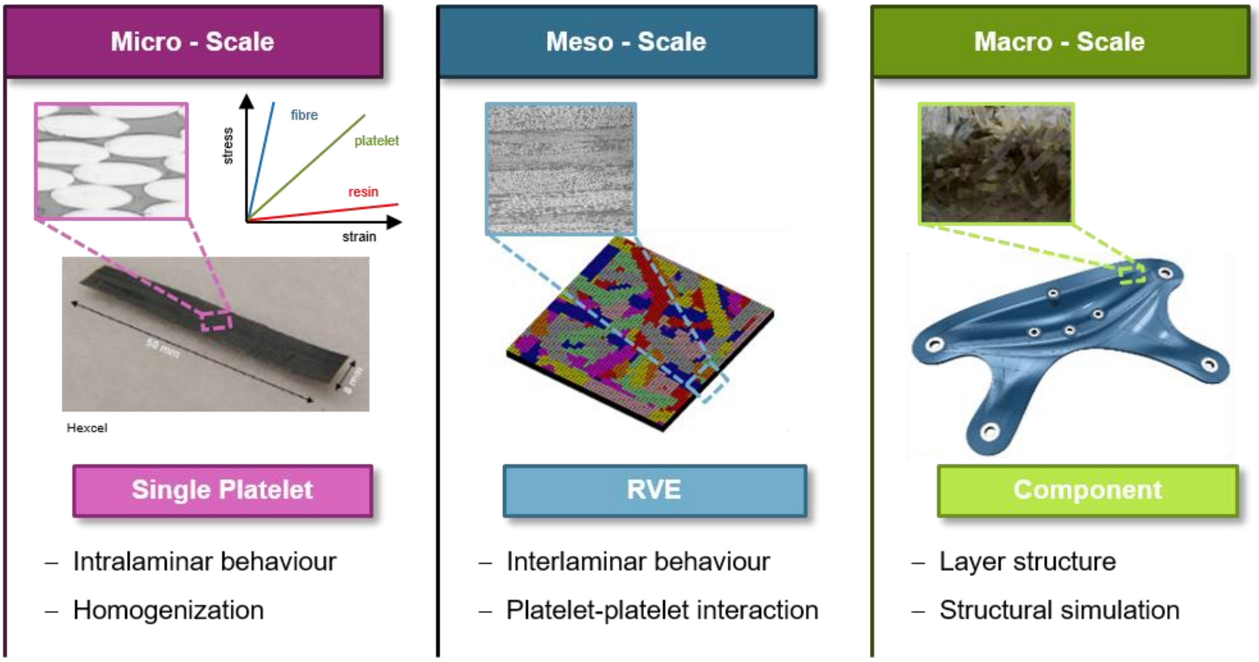

Figure 6: Multiscale simulation approach for the simulation of the SMC material behavior.

On the microscale the individual fibers of one platelet are distinguishable from the surrounding resin. Knowing the mechanical properties of the fibers and the resin material the homogenized intralaminar behavior of a single platelet can be calculated with micromechanical models. Representative Volume Elements (RVE) are then generated to model the mesostructure of the material and full-scale FEM simulations are run to study the material behavior. The mesostructure models are generated with the material modeling software Digimat by sequentially placing platelets of determined size with a random location and specified orientation and stacking them in a voxel mesh. The interlaminar interaction between the platelets, inherent defects and the effects of preferential fiber orientations can be considered on the mesoscale. Defects are modelled isotropic with failure initiation at a threshold level of von Mises stresses. X-ray computed tomography (XCT) scans were conducted to create realistic RVEs (Figure 7). The multiscale approach represents an adequate tool for virtual material characterization by means of the RVE simulations, which is not possible with standardized experiments due to the countless parameter possibilities of the mesostructure and the limited specimen size.

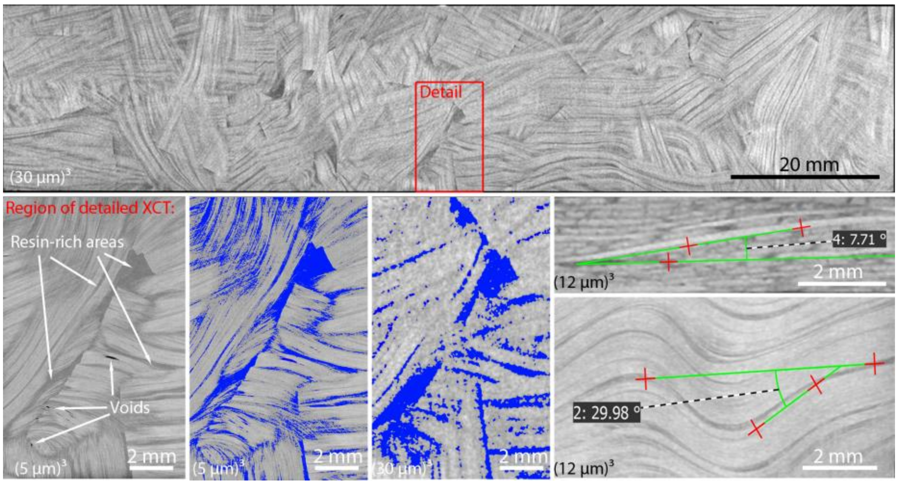

Figure 7: XCT measurements of a tensile coupon specimen at (30 µm)³, (12 µm)³ and (5 µm)³ resolution respectively, showing voids, resin-rich areas with corresponding segmentations (blue) and fiber waviness.

The results of the RVE calculations are finally used to calibrate the material models for the structural simulations on the macroscale to predict the elastic behavior and the failure of the components. The macroscopic material behavior can be considered as quasi-isotropic, because of the in-plane random orientation of the platelets. The elastic response is reproduced well with this simple approach. However, the failure initiation and the progressive damage depend on the local fiber orientation. Especially the spatial change of the local fiber orientation is important to describe the damage tolerant material behavior of C-SMC. Hence, a second approach with locally assigned stochastic fiber orientation was developed to model the underlying mesostructure in the structural simulations. It was based on the laminate analogy model proposed by (Feraboli et al., 2010) and extended to model failure. Anisotropic failure criteria after Tsai-Wu, Hashin and Puck with progressive damage accumulation (Maimí et al., 2007; Lapczyk and Hurtado, 2007) were used. XCT scans of the subcomponents and the transmission cross beam showed a random fiber orientation after the compression molding process and confirmed the use of the proposed simulation approaches.

The simulations were carried out with increasing complexity in three steps (Figure 8). First, the mechanical parameters for the macroscopic material models were determined by means of the standardized tests on the coupon level and the virtual characterization with the multiscale approach. Digital image correlation methods were used in the experiments to obtain the full-field strain patterns. Second, quasi-static 3- and 4-point bending tests of the hat profiles were carried out for the validation of the simulation models on the component level. In that way already validated material models were used for the design of the transmission cross beam.

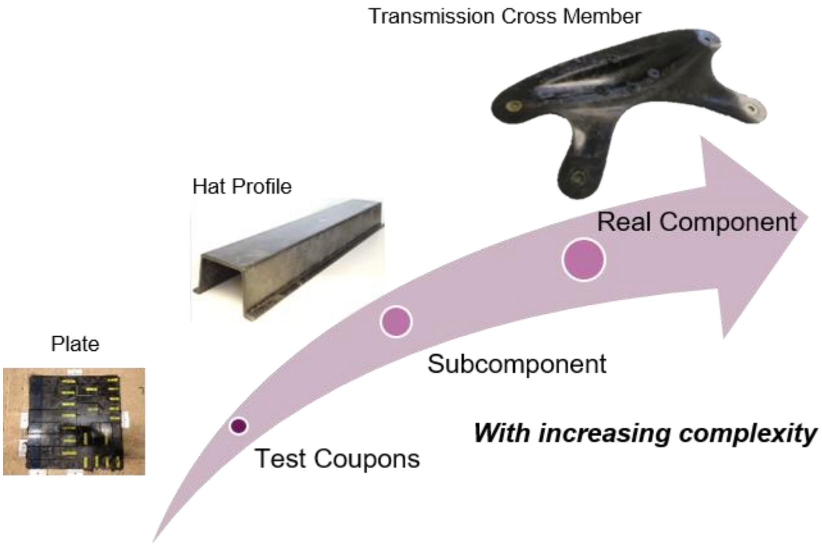

Figure 8: Increasing complexity of material characterization.

2.3.3 Manufacture and Process Development

The technical feasibility of the 0-WASTE concept was examined and assessed based on **5 different materials**. The materials are shown in Figure 9 and are shortly introduced below. All materials were provided by Hexcel, with the carbon fibers always being preimpregnated with the same epoxy resin, Hexcels HexPly® M77. This resin cures in two minutes at 150 °C and is therefore especially suitable for automotive applications, where short production cycle times are needed.

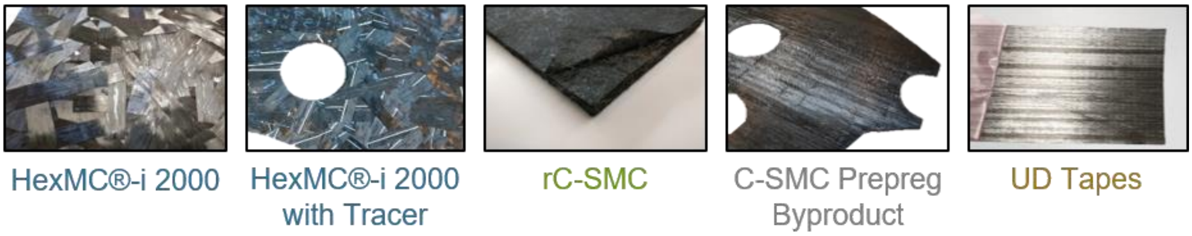

Figure 9: Materials used in the project.

Discontinuous Carbon Fiber Composites used in this Project

- **HexMC®-i 2000, primary C-SMC**
  This material is a Prepreg Platelet Sheet Molding Compound (C-SMC) and a commercial grade of Hexcel. It serves as reference material in the project. Carbon fiber prepreg is slit and chopped into discontinuous, rectangular platelets (50 mm x 8 mm), which are randomly distributed to form the Sheet Molding Compound (SMC) semi-finished part.

- **HexMC®-i 2000, with glass fibers as tracers**
  Special glass fiber tracers were added to the HexMC®-i 2000 platelets to analyse the process reliability and product quality. These tracers can be better differentiated than carbon fiber to epoxy resin in the XCT scans due to the bigger density difference. In that way, it could be assessed if the fibers maintain a random orientation under different flow conditions.
- **rC-SMC, secondary C-SMC with recycled carbon fibers**
  It consists of recycled carbon fibers of the company Carbon Conversions Inc. (Lake City, SC, USA), which were impregnated with epoxy resin on a prepreg line of Hexcel. The recycled fibers exhibit an unordered structure, similar to conventional glass fiber mats.
- **C-SMC Prepreg Byproduct, secondary C-SMC made of industrial UD prepreg scrap**
  It was obtained from UD prepreg scrap of the industrial series production at Hexcel. The UD material was used to produce prepreg stacks for BMW AG (München, Germany). The prepreg mats were cut in 50 mm distances to form a C-SMC material with platelets.

In addition, to exploit the advantages of continuous fiber reinforced materials, UD tapes were also applied and combined with the discontinuous fiber materials.

Continuous Carbon Fiber Composites

- **UD tapes, out of primary carbon fiber prepreg**
  UD Tapes consist of unidirectional continuous carbon fiber prepreg with the same constituents as HexMC®-i 2000 for the local reinforcement of the structural components.

C-SMC plates were manufactured for the characterization of the intra- and interlaminar behavior of the materials on the coupon level. A preliminary test series was carried out in a next step to produce the subcomponents (hat profile and thickness profile plate). By means of these test tools experience with the press technology was gathered at an early stage. Moreover, the simulations could be validated before the production of the costly transmission cross beam tool. The sensitivity of the process parameters on the mechanical properties was analyzed with a statistical design of experiment study (2^3- Factorial Design). **XCT scans** provided further information about the product quality concerning material defects.

On the basis of the preliminary tests the optimum process parameters and material configurations could be derived for the manufacturing of the transmission cross beam. A **fully automated** compression molding **technology** and a **process-optimized tool** were developed. The tool concept (Figure 10) benefited from the investigations with the test tools in the areas of shear edge design, positioning elements, sealing and vacuum concept, temperature control as well as in the ejector and interlocking systems. The transmission cross beam features 8 aluminum inserts, which could be integrated in a one-shot process. No additional manufacturing steps were thus necessary to mount the inserts. ALPEX developed special hold-down devices with spring elements integrated into the moving mold side to seal the inserts and to prevent material flow into the insert holes. Positioning of the material stacks could be also secured in that way. Furthermore, ENGELs machine **v-duo** (Figure 10) provided ideal conditions for the development of a fully automated process. High closing speeds, clamping forces and active parallelism control enable an efficient series production of precise C-SMC components. The process parameters can be adapted with user defined profiles to optimize the SMC manufacture.

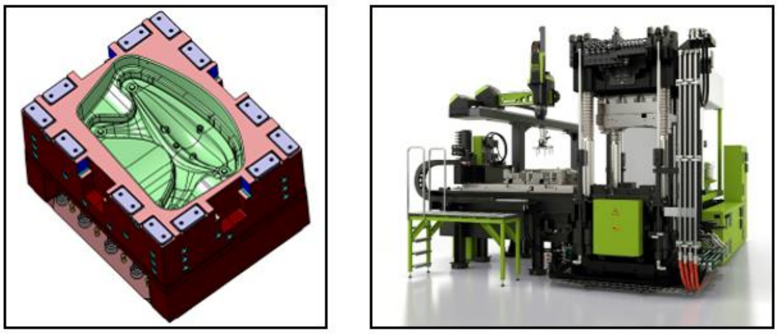

Figure 10: Left, ALPEX tool and right, ENGEL machine v-duo 700 for the production of the transmission cross beam.

The C-SMC **compression molding process** adapted in the project is shown in Figure 11.

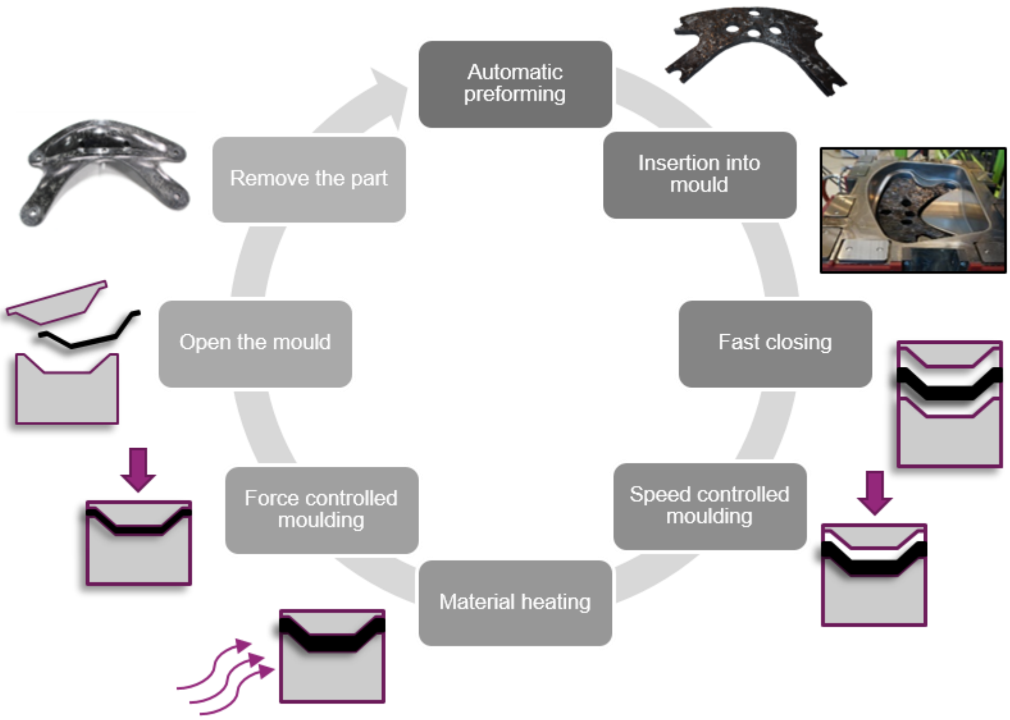

Figure 11: C-SMC compression molding process.

Net-shaped preforms are automatically cut from the SMC rolls and stacked to obtain a charge with a mass of 1270 g to 1300 g and a thickness of 16 mm. The charge together with the hard coat anodized aluminum inserts are then transferred into the heated mold at temperatures ranging from 130 °C until 150 °C. This can be handled automatically by a robot with a suitable end-of-arm tooling. As soon as the material is located inside the mold, the machine closes at maximum speed and the mold compacts the

C-SMC material in speed controlled mode until a set switch-over point. At this switch-over point the material is heated to processing temperature and integrated pressure sensors in the cavity ensure a specified compaction, here 8 bar. After material heating a force controlled molding and curing process takes place. The vacuum evacuation of the mold is important to fill the mold completely. After curing the finished part can be ejected. Contrary to the adapted process of C-SMC, there is no preheating time, but a prolonged speed controlled molding until near-complete cavity filling in the processing of conventional SMC materials.

3 Results and Discussion

3.1 Manufactured Prototypes

The manufactured transmission cross beams exhibited a weight of 1270 g to 1280 g, and are thus **considerably lighter than the industrial standard version in aluminum** with a mass of about 2490 g. The component was 8 mm thick with main dimensions of 520 mm x 340 mm x 100 mm. A clamping force of 5000 kN was necessary to fill the mold with a measured cavity pressure of 200 bar to 300 bar (Figure 12). **Cycle times of 135 s** could be achieved with optimized process parameters at 150 °C mold temperature under laboratory conditions. A cycle time study, with DSC measurements and mechanical component tests, was conducted to examine, if the minimum cycle time was sufficient for complete curing of the resin.

Transmission cross member

- Weight: 1270 g to 1280 g
- Cycle time: 135 s
- Mould temperature: 150 °C
- Clamping force: 5000 kN
- Cavity pressures: > 200 bar

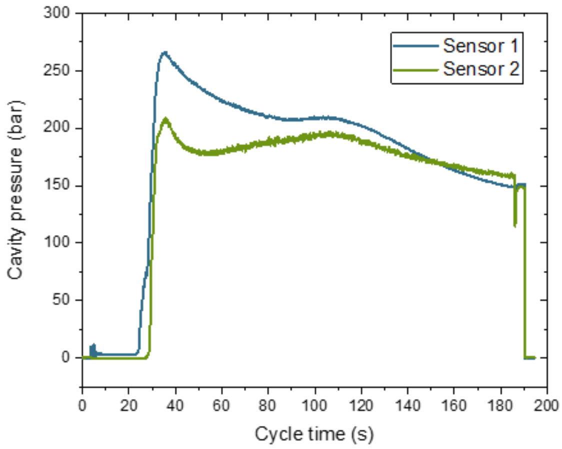

Figure 12: Optimized process parameters and the measured cavity pressure during the manufacture of the transmission cross beam.

The C-SMC **tool** was **optimized** based on a preliminary series of prototype manufacture. The implemented temperature control provided uniformly distributed surface temperature of the mold. The cavity was evacuated without difficulty with the chosen vacuum concept. The experiments showed that sufficient pressure was built up inside the cavity for complete filling with the shear edge design. The sealing concept did not collapse with cavity pressures up to 300 bar. Though post-processing was necessary due to slight flash of resin at the shear edge. This could be easily done by trimming with a knife. The special hold-down devices developed by ALPEX prevented material flow into the insert holes. This was necessary since the material stack had a thickness of 16 mm with a final thickness of only 8 mm after molding. The ejectors were located at the metal inserts in order to not leave marks on the part surface.

The net-shaped preforms were adapted so that the cavity pressure distribution was evenly balanced throughout the mold. Two different geometries were selected for further testing (Figure 13). The preform on the left side with weld lines was considered to be more suitable for automatic handling together with the metal inserts by a robot. Though weld lines result from the squeeze flow around the outer inserts when the two flow fronts collide. Weld lines are unfavorable for the mechanical performance, and a design need to makes sure that they form only in low stressed regions. A manufacture without weld lines can be realized with the preform on the right side.

Figure 13: C-SMC preforms for the transmission cross beam: Left, with weld lines; right, without weld lines.

With the process-optimized tool prototypes were manufactured to validate the 0-WASTE concept by means of the mechanical component tests. **Reference** prototypes were made of the commercial **C-SMC** material of Hexcel. In a systematic experimental study, **hybrid material** stacks were then used to investigate the feasibility and suitability of the different elements (recycled carbon fibers, prepreg scrap, UD tapes and controlled platelet orientation) forming the 0-WASTE hybrid material architecture. In total **4 different material configurations** with **9 subcategories** were produced (Figure 14).

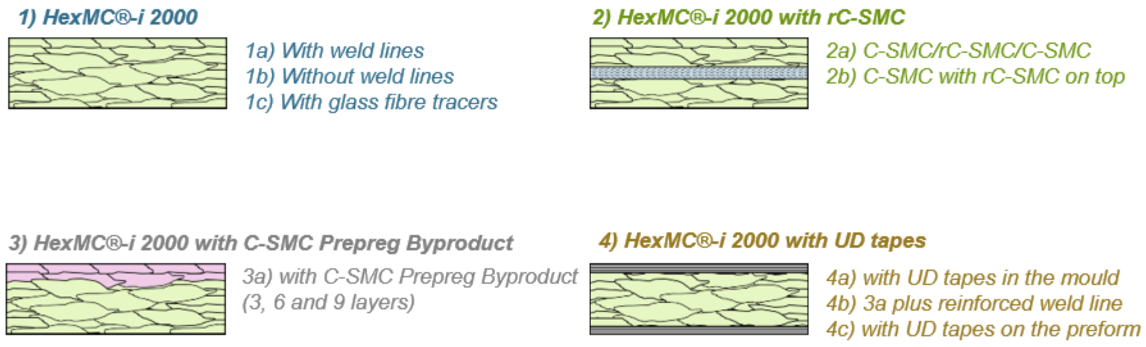

Figure 14: Material configurations for the manufacture of the transmission cross beam prototypes.

The reference material HexMC®-i 2000 was processed with both preform geometries and with glass fiber tracers **(1a-1c)**. For all the other material configurations the preform geometry with weld lines was used based on the better automation possibilities. The recycling material rC-SMC exhibits insufficient flow properties due to the unordered, entangled carbon fibers. However, it could be processed well as core material in a hybrid sandwich structure with HexMC®-i 2000 without changing the preform geometry **(2a).** Processing difficulties were encountered with rC-SMC as top layer **(2b)**, though these prototypes were mainly produced as demonstrators. The C-SMC Prepreg Byproduct made of industrial prepreg scrap cut each 50 mm showed good flow properties similar to the commercial reference C-SMC material. This simplifies the recycling of prepreg scrap and is suitable for industrial series production due to time and cost savings. It was mixed with HexMC®-i 2000 with 3, 6 and 9 layers **(3a)**. Due to the unidirectional fibers C-SMC Prepreg Byproduct could be used as reinforcement in main loading directions through controlled platelet orientation. The continuous UD tapes for local reinforcement were on the one hand inserted into the hot mold **(3a)**, plus weld line reinforcement **(3b)** and on the other hand added directly on the preform stack **(3c)**. (3a) and (3b) could be manufactured successfully. The bionic shape simplified the placing of the tapes. For (3c) the UD tapes were penetrated by the C-SMC material and could not be successfully molded.

XCT scans of the transmission cross beam made of HexMC®-i 2000 with glass fibers tracers (1c) showed, that the fibers maintain their random orientation also after compression molding. Preferential fiber orientations are only visible around the aluminum inserts. The weld lines are clearly distinguishable through the two colliding fiber fronts.

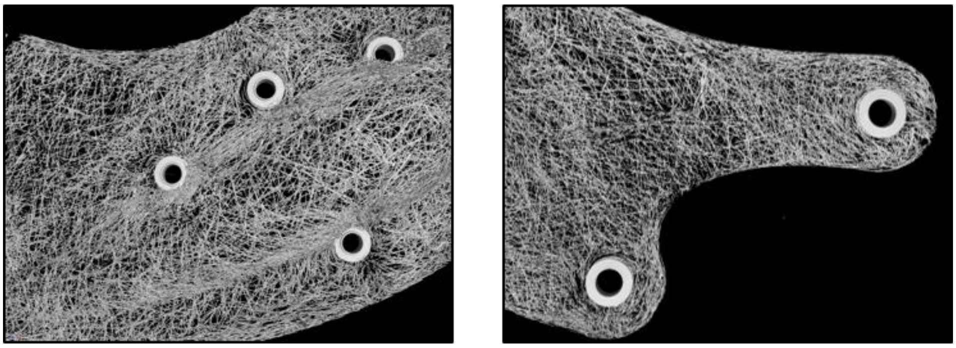

Figure 15: XCT scans of the transmission cross beam with glass fiber tracers.

The integrative approach followed in the project rendered possible the development and manufacture of a high-value, practically oriented C-SMC automotive component (here transmission cross beam, Figure 16 left). Our product was presented at various customer conferences and international exhibitions by the industry partners and discussed extensively due to the unique design and one-shot manufacture of multiple materials and functionalities (metallic inserts, primary and secondary C-SMC and tape materials). The developed compression molding technology can be used fully automated and the tool was process-optimized for the production of the transmission cross beam. It offers great potential to **reduce carbon fiber waste** with the multistage use of industrial recyclates in a **hybrid material architecture** (Figure 16 right) for varying quality requirements. Short **cycle times down to 135 seconds** were achieved under lab conditions, making the technology an interesting choice for automotive components as a **cost efficient large-scale production** method.

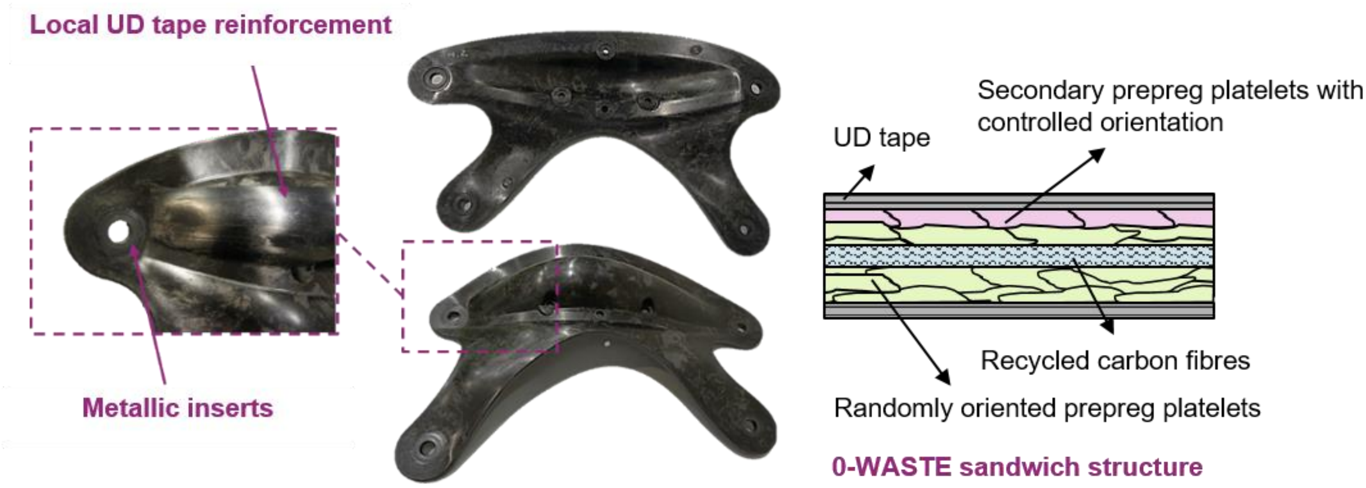

Figure 16: Manufactured transmission cross beam with 0-WASTE concept.

3.2 Prototype Testing and Concept Validation

To prove the suitability of the 0-WASTE concept for structural automotive components, the transmission cross beam prototypes were mechanically tested after **OEM requirements** on the laboratory scale. The component testing set-up (Figure 17) features the same outer fixation points like in the real vehicle body. A transmission dummy connected to the piston of the servo-hydraulic test bench (MTS damper tests system) introduces the load from the bottom. During testing the displacement is measured by the internal LVDT of the machine via the piston movement and the reaction force is captured by a load cell. The **component performance under monotonic, quasi-static loading** was investigated by means of the critical load case in –Z direction. **Cyclic tests** under service conditions were carried out in the critical +/-Z load case to assess the mechanical **fatigue life**.

Figure 17: Component testing set-up after OEM requirements.

The quasi-static component tests were conducted at a testing speed of 2 mm/min and room temperature. All material configurations (see Figure 14) were compared in a benchmark study and checked for the static fracture limit of 21 kN. The typical failure positions and force-deflection graph for a quasi-static component test of the transmission cross beam with weld lines are shown in Figure 18 on a selected example of a prototype made of HexMC®-i 2000 (configuration 1a). As expected, fracture occurred at the first weld line after reaching the maximum load. However, the damage was localized in the vicinity of the outer fixation point and it did not lead to ultimate failure. The component was able to bear additional loads at considerable deflection values. The test was stopped after the fracture at the third weld line.

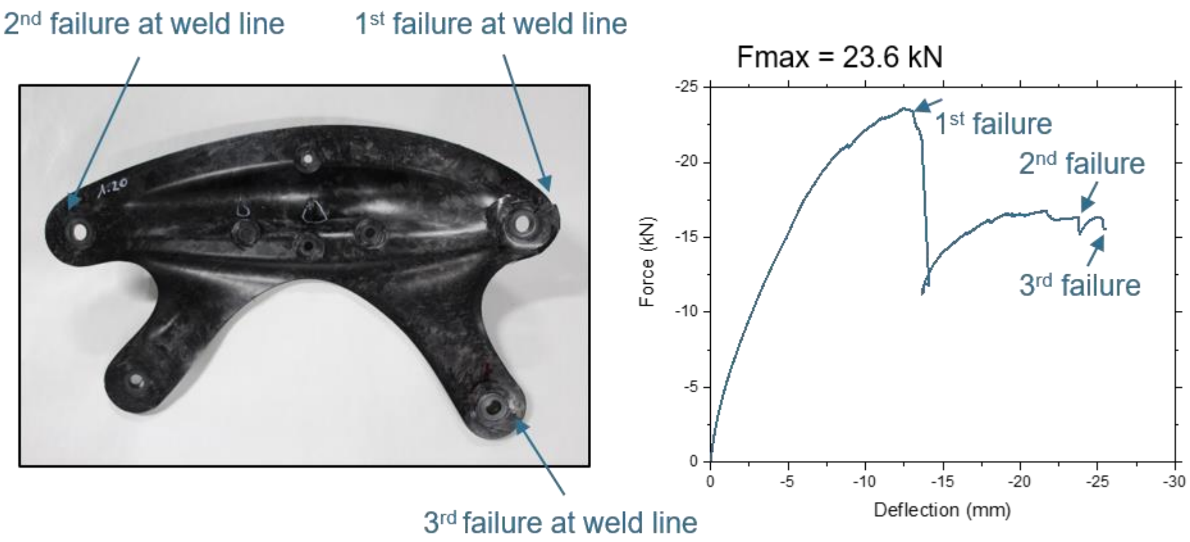

Figure 18: Left, failure positions and right, force-deflection graph for a quasi-static component test of the transmission cross beam made of HexMC®-i 2000 with weld lines.

The weld lines represent a weak point in the structure and determine the component strength. Furthermore, weld lines cause big scattering in terms of the component strength. Higher fracture loads with less scattering can be achieved using a preform design without weld lines (configuration 1b) in the component manufacture, see Figure 19. The cracks initiate thereby not at the outer, but at the inner inserts and grows across the component. Nevertheless, both preform designs fulfilled the load requirements.

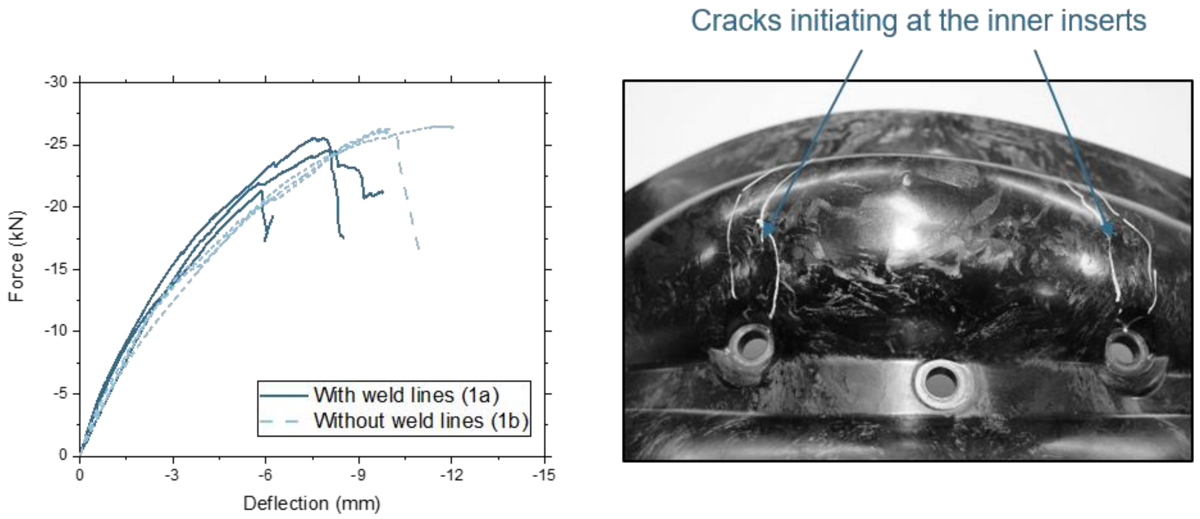

Figure 19: Left, comparison of the quasi-static component tests with (1a) and without weld lines (1b). Right, fracture pattern of a transmission cross beam without weld lines (1b).

All material configurations were compared in a **benchmark study**. The criteria of comparison were the linear component stiffness, the secant component stiffness and the fracture load (F_{max}), as depicted in Figure 20. The results were normalized to the data of the reference material configuration (1a). All material configurations fulfil the minimum static fracture limit of 21 kN with maximum values over 26 kN.

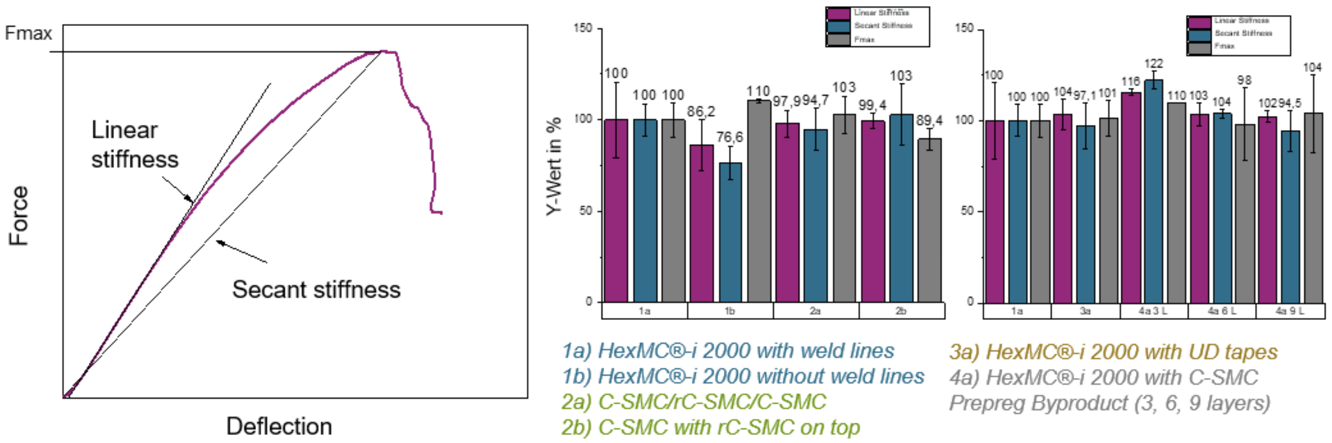

Figure 20: Left, criteria of comparison for the benchmark study. Right, results of the benchmark study normalized to the reference material configuration (1a).

With the usage of **recycled carbon fibers** (2a) and secondary C-SMC made of industrial UD **prepreg scrap** (4a) in a hybrid material architecture with primary C-SMC at least the same product performance could be achieved as with the primary reference material HexMC®-i 2000 (1a). That confirmed the 0-WASTE concept as a solution to reduce carbon fiber waste. The worse results of option (2b) with rC-SMC as top layer can be explained by processing difficulties, though they were mainly produced for demonstration purposes. The methods of **local reinforcement** with UD tapes (3a) and **controlled platelet orientation** (4a) yielded an improvement in stiffness and a **reduction of its standard deviation**

to half compared to the reference configuration (1a). The component strength could not be improved by these methods, since it is determined by the weld lines and exhibits high scattering (standard deviations of 10 % to 20 %). As mentioned above, the scattering can be reduced drastically when using a preform design without weld lines (1b). However, the preliminary tests by means of the hat profiles showed great potential of UD tapes to reduce the scattering of the strength.

Cyclic fatigue tests were performed at room temperature under sinusoidal load-control at a frequency of 5 Hz. The reference material configuration (1a) was tested under displacement and force controlled mode. A further configuration with UD prepreg scrap (4a) was tested under force controlled mode. A mean value of 0 mm and amplitude value of 0.5 mm were used in the displacement controlled mode, while a mean value of 0 kN and an amplitude of 5 kN were set in the load controlled mode. The secant and dynamic component stiffness were analyzed to assess the material damage under fatigue loading. The secant stiffness gives also evidence of cyclic creep behavior. After each 10 000 cycles a monotonic, quasi-static test in –Z direction was performed. Furthermore, a final monotonic, quasi-static test until fracture was conducted after completion of the fatigue test. In that further information about possible material damage could be obtained. Figure 21 shows the dynamic and monotonic component stiffness of a displacement controlled fatigue test for a selected example prototype of the reference configuration (1a). The secant component stiffness is evaluated in the tension (K_{s+}) and in the compression domain (K_{s-}).

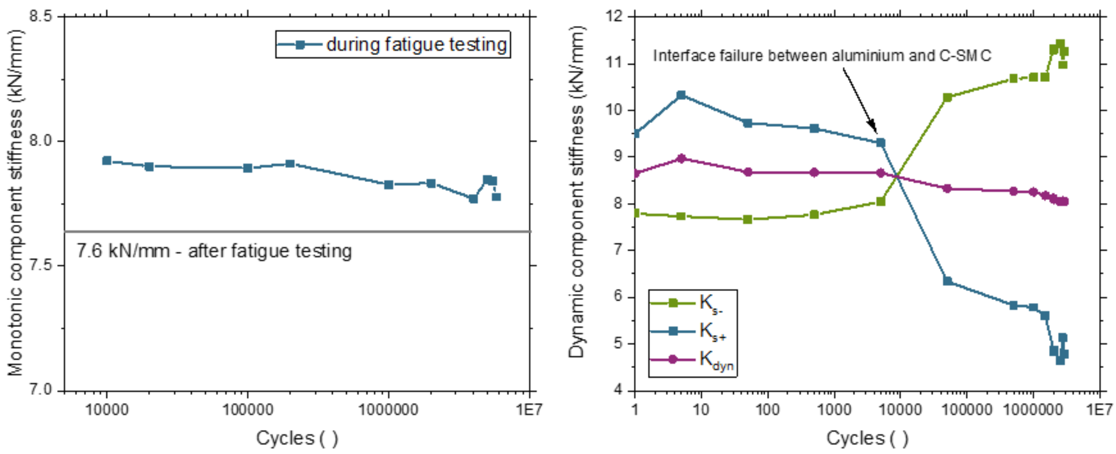

Figure 21: Displacement controlled fatigue test of a transmission cross beam made of HexMC®-i 2000 with weld lines (1a): Left, monotonic component stiffness during and after fatigue testing. Right, secant (K_{s-} and K_{s+}) and dynamic (K_{dyn}) component stiffness.

The tested transmission cross beams showed no visible damage of the C-SMC material after the cyclic fatigue tests (displacement controlled 3 Mio. cycles for (1a), force controlled 1 Mio. cycles for (1a) and 2 Mio. cycles for (4a)). Also the monotonic component tests (Figure 21 left) showed similar values to the pristine parts of the quasi-static benchmark study. The secant component stiffness falls (K_{s+}) and increases (K_{s-}) respectively considerably after 10 000 cycles for all configurations, but which involves only a slight reduction of the dynamic (K_{dyn}) component stiffness (Figure 21 right). This does not show a damage of the C-SMC material, but rather a **failure of the interface between the aluminum insert and the C-SMC material** causing creep behavior. Optical observation during displacement controlled loading confirm this assumption. This premature failure can be explained by increased stress concentrations in the vicinity of the outer inserts due to the **idealized component test set-up** with stiffer fixations. To capture the real compliance range of the service fixation in the car body and of the load introduction via the transmission, the set-up was optimized with parameterized Pareto Front analysis. The optimum fixations and transmission dummy (Figure 22) are spring elements, which model the stiffness in all 6 degrees of freedom in a realistic and service-close manner.

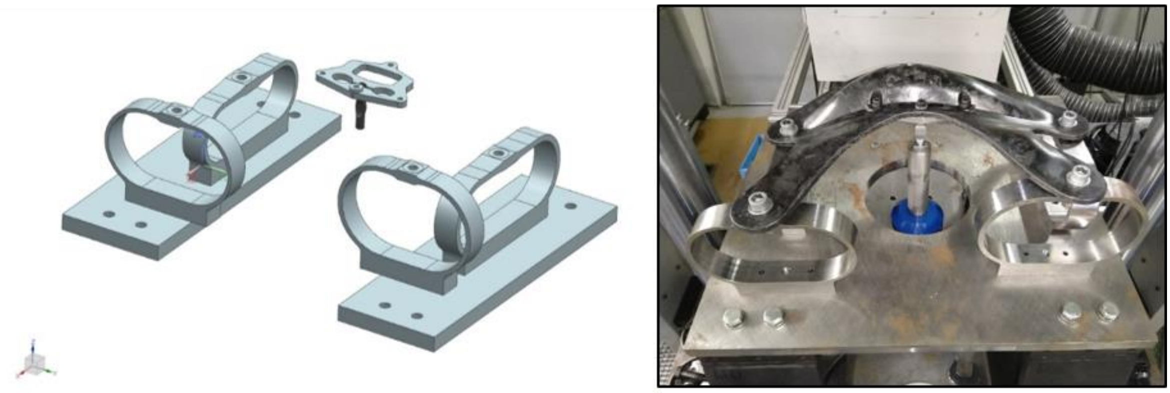

Figure 22: Optimized fixations and transmission dummy to model the real car body stiffness.

A prototype of the reference configuration (1a) was tested with the **optimized component test set-up** under displacement controlled mode with an average value of 0 mm and an amplitude value of 0.5 mm. Due to the reduction of stress concentrations at the outer inserts with this set-up **interface failure was prevented**. The dynamic component stiffness did not change after 5 Mio. cycles, contrary to the previous idealized set-up with a reduction of ~7 % after 3 Mio. cycles. The secant component stiffness fell ~7 %, compared to a reduction of ~50 % with the idealized set-up. Moreover, the monotonic component stiffness during fatigue testing changed barely and no damage was visible after optical inspection.

The performance specifications of a leading OEM regarding the stiffness and strength were **fulfilled under the required loading conditions**. The monotonic component tests showed that the fracture loads for the manufactured prototypes were well above the minimum limit (21 kN). **Cyclic fatigue tests** of the transmission cross member exhibited no damage of the C-SMC (C-SMC) material over a wide cycle number range**,** which supports the idea to use these materials for practical structural applications. On the basis of the experimental data the **interface** between aluminum **insert** and C-SMC material is considered to be **critical** for the components fatigue life. Therefore, in order to realize a C-SMC structural component of similar design for the industrial series production, the geometry must be adapted according to the specific application case to optimize the components fatigue life to prevent premature interface failure. With the **use of recycled materials** and **reinforcement methods** (UD tapes and controlled platelet orientation) at least the same product performance with only half the weight compared to the industrial standard version in aluminum were achieved.

4 Outlook and Recommendations

Although, lightweight (LW) design reveals high practical industrial and socio-ecological importance, the **only use** of lightweight design methods and materials is **not sufficient** enough to master the industrial and social challenges of the present and the future. LW must be efficiently **combined** with **function integration** over a wide structural length scales and over a wide complexity for demanding engineering components. The structure should increasingly consist of sensor functions and a thermomechanical balance control. To fulfil industrial cost requirements **flexible and cost efficient large-scale production methods** should be implemented for LW components. Furthermore, recycled high performance LW materials should be also considered for both demanding applications and for large series production.

The design methods for various components must correspond to these requirements. In addition to the conventional outer shape based topology optimization techniques, a simultaneous and combined optimization of the microstructure is needed. Layered structures reveal the advantage for tailored anisotropy and for combining lower and higher stiffness/strength layers in various locations of the structure. It was expected that the recycled materials (fiber/matrix system) reveal somewhat impaired processing and application properties. Hence, these materials may be placed in the core of the layered materials. The layered “sandwich” structures produced can yet fulfill high requirements regarding stiffness and strength. However, there is a lot of room for detailed microstructure optimization of these “recycled-sandwich” structures. The critical amount of a specific recycled single fibers or platelets can be calculated for various lay-ups and for specific applications needs.

Furthermore, in the project work the classical topology optimization was combined with a kind of bionics motivated geometry optimization. Further refinements of this technique would result in an even better LW ratio. Simultaneously, for a real industrial application of such C-SMC components in complex structures (car body), the local compliance and the joining strength should vigorously be considered in the component design.

A number of advancements have been achieved in the project work regarding the processing technology for C-SMC materials. Material specific behavior was learned in the numerous processing experiments performed in the project. C-SMC materials have the potential to equally fulfil structural-mechanical and processing requirements towards an efficient large-scale production and may therefore be turned into efficient/high-performance structures and products with beneficial production efforts and costs.

Hence, further improvements should focus on the development for a partially or full digitized/automatized production of such components. The critical issue is a fast and modular design of the complex forming tools required for the production. The intensive use of PLM software tools and the extension of the PLM concept to manufacturing process management (MPM) – such as process planning, process simulation, process line balancing might efficiently support this process. The development may also consist of the application of online sensors during the processing and the realization of a closed loop process control for improved quality assurance.

Furthermore, future works can be focused on extending the basic approach of the integrative simulation methodology to more complex geometries. The consequent link of the processing simulations with subsequent performance simulations would support both the improvement of the product quality in terms of service relevant properties like stiffness, strength and fatigue resistance and the realization of an efficient production.

The structure of the C-SMC materials inherently originates form the specific **processing conditions** (i.e., fiber orientation and quasi-layer formation of the platelets). Hence, it is of prime practical and theoretical importance **to predict** these **microstructure features**. The predicted microstructures should be validated by various characterization methods, i.e., conventional and in-situ SEM, computed tomography (CT), active thermography or laser acoustics. The systematic application of novel non-destructive testing and evaluation (NDTE) methods for C-SMC would also support production oriented **quality control (assessment), structural health monitoring and integrative simulations**. The harmonization of these data with inline process data and the application of a data based process analysis would even further contribute to the improvement of the C-SMC process.

Recently, the assessment of material or structure eco-balance has gained increased importance.

A preliminary LCA methodology was used in the project to provide a systematic framework that helps to identify, quantify, interpret and evaluate the environmental impacts of C-SMC product. The systematic application of LCA along with specific software tools helped for the project researchers to gain more technical and eco-specific insights into the processes with C-SMC materials. The collection of proper data has shown the complexity of the engineering processes from an eco-balance point of view.

Based on these results and considerations we are going the further develop the LCA of C-SMC components in our current project (CAR e-Bo, FFG No. 865213). Although, the quantitative LCA of a C-SMC battery box is not an objective of the CAR e-Bo project, using existing data we can provide an estimation.

We are working intensively in other research projects (LITY) on the applicability of PLM software tools for various complexity of fiber reinforced composite components. These PLM systems involve not only the conventional engineering product design data (CAD) but consists of processing and performance simulations of the specific components. This integrative modeling approach can be extended by the application and integration of LCA tools into PLM tools.

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