Influence of Textile Reinforcement on Bending Properties and Impact Strength of SMC-components

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Abstract
In Europe, Sheet Molding Compound (SMC) has high market relevance in the field of glass fiber reinforced polymer composites with a market share of almost 20% in terms of mass. The material has a thermal expansion coefficient similar to steel and special grades show Class-A surface quality being thereby an appreciated material in the automotive industry. The mechanical properties of SMC components and thus its implementation in new application fields are mainly limited by the type of fiber and fiber length. The project "Preform-SMC" analyzed the combination of the standard SMC process (chopped long fibers) and the preform technology (textiles) in order to improve the overall performance of components. The studies revealed that the quality of the impregnation of the preform material is mainly determined by the density and thus the filler content of the SMC semi-finished product and the layer structure of the reinforcing fibers. Locally implemented reinforcing textiles improve, by implementing endless fibers among load paths, the mechanical properties. Depending on the fiber type and the layer structure e.g. impact strength and absorbed energy could at least be doubled.

Keywords: Sheet Molding Compound (SMC), In-situ-impregnation, Out-of-plane permeability, Impact strength, Bending properties, Continuous fiber reinforcement

1 Introduction

In course of steadily increasing energy prices, global warming and increasing scarcity of resources, composite materials are gaining importance. Based on the specific advantages of composite materials, parts can be designed individually and for specific requirements. Especially high-performance composites, which are commonly based on carbon fibers with long- and continuous filament reinforcement, provide a tremendous lightweight potential based on the pronounced anisotropic material behavior. Unfavorable for the use of such parts is a very high price of the carbon reinforcement fibers, which is at about 20–30 € / kg [1]. Additional costs for further processing from the filament fibers to non-crimp fabrics or fabrics limit the application fields to some industries, for example aerospace sector.

Contrary to continuous reinforced composites, Sheet Molding Compound (SMC) provides the opportunity of producing glass fiber reinforced parts by compression molding process at advantageous prices. With this process the mass production of parts with near-net-shape geometry and constant wall thickness as well as constant quality is possible. Therefore, SMC has high market relevance and is well established, as it-depending on the additives-can be used for numerous applications (e.g. in the automotive industry, the transport sector, or for cable cabinets). However, there are some limitations of use due to the length of reinforcement fibers, which are normally cut to a length of 0.5 or 1 inch.

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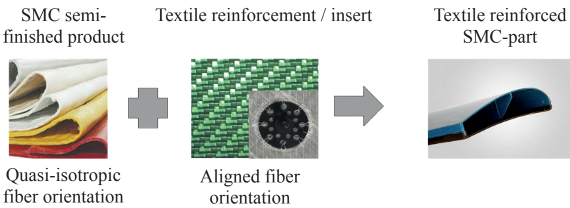


Figure 1: Project idea Preform-SMC.

SMC semi-finished product consists of a highly filled resin like e.g. unsaturated polyester resin or vinylester resin and glass fibers. To produce the SMC semi-finished product, a resin film of homogeneous thickness is applied to a styrene-proof carrier foil. On top of this resin film, glass fibers, which are evenly distributed and cut by a cutting unit, are arranged. A second carrier foil with a second resin film is placed on top of the glass fibers in order to achieve a symmetrical layer structure. Afterwards, this layer structure passes a tumbling area where the fibers are impregnated by SMC resin paste. Finally, the semi-finished SMC product is rolled up and sealed in a styrene-proof bag. After production, the material has to mature about 14 days. Within this time the viscosity rises and the material gets more and more homogeneous.

To expand the characteristic profile of SMC parts and their application field, e.g. as structural parts, within the project "Preform-SMC" a new and innovative composite material has been investigated. The hybrid material results from a combination of SMC and preforming technology. During a compression molding process, a dry reinforcement structure should be completely in-situ impregnated by SMC resin paste. Due to the implementation of continuous reinforcement fibers into SMC parts, the structure properties should be improved.

A further advantage of the new material is the reduction of the wall thickness and thus a reduction of the weight of SMC parts. Based on this process, the advantages of the parallel regulated press process (e.g. short cycle times, die-cut and near-net components) and the advantages of preforming technology (e.g. fiber-orientation along load paths, improvement of structural mechanics, locally adapted fiber volume content) are combined to enable new application fields for SMC parts, see Figure 1.

The impregnation of the dry inserted reinforcement textile by the SMC resin paste mainly takes place in

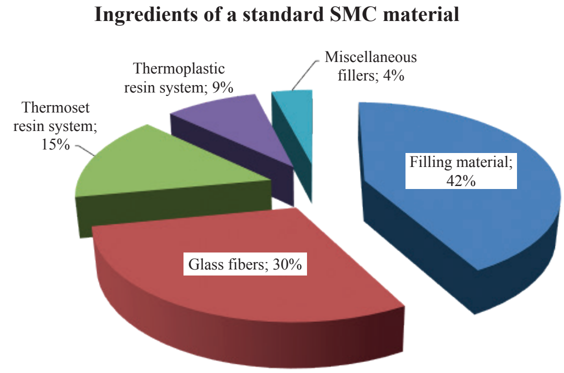


Figure 2: Ingredients of a standard SMC material [2].

through-the-thickness direction of the textile. The impregnability of the preform depends amongst others on the out-of-plane permeability of the textile, which is determined by its architecture (e.g. stitching parameters) [3]. Also the chemical composition of the SMC resin paste (resin type, fiber- or filler content, additives, etc.) plays a crucial role in the impregnation process and end part quality. If the SMC resin paste flows in the through-the-thickness direction of the reinforcing textile, the textile acts like a sieve and filters out the filling material of the SMC. This filtering process seals the flow paths within the textile and thus prevents matrix from flowing through the textile, so that there are non-impregnated areas in reinforcement textile.

To achieve a well impregnation of the reinforcement textile, the knowledge of the out-of-plane permeability and the selection of an appropriate SMC-semi finished product with low adapted filler content are indispensable.

2 Materials

Commonly, SMC semi-finished product consists of thermoset resin system (15%), based on e.g. unsaturated polyester resins, glass fibers (30%), thermoplastic resin (9%), filling material (42%), and miscellaneous fillers (4%), see Figure 2 [2].

In this study, different standard types of SMC semi-finished products available on the market (see Table 1) are considered. The SMC semi-finished products, which are based on an unsaturated polyester resin were chosen in cooperation with an industry partner and only differ in terms of filler content and consequently density.

Table 1: SMC materials considered in the study

Engineering constant		SMC A	SMC B	SMC C
Grammage	[g/m²]	3600	3600	3600
Fiber content by weight	[%]	30	30	30
Density	[g/cm³]	1.73	1.80	1.88
Young's modulus	[GPa]	10.0	11.0	11.5

As reinforcing textiles, different non-crimp fabrics (NCF) and fabrics were previously tested [3]. For this study two suitable reinforcing textiles with same fiber orientation (one reinforcing textile layer consists of 2 single layers with +45° and –45°), but differing in type of fiber, were used, see Table 2.

Table 2: Reinforcement textiles considered in this study

		Reinforcement textile 1	Reinforcement textile 2
Fiber type	-	GF	CF
Structure	-	+/–45°NCF	+/–45°NCF
Grammage	[g/m²]	620	540

By the investigation of the viscosity of the SMC prepreg materials and the permeability of the textiles, the most promising material combinations were examined.

3 Methods and Processes

3.1 *Permeability measurement*

The out-of-plane permeability was measured with a re-engineered measuring cell, see Figure 3, based on the cell of Stöven *et al* [4]. The measuring cell uses ultrasonic technology to detect the progress of the flow front of the measurement fluid, which is point-injected into the textile lay-up.

The time-of-flight of the ultrasound signal in the unsaturated and saturated part of the preform is different. Due to this it is possible to track the flow front while the measurement fluid infiltrates the fiber stack. The fiber volume content of the sample can be calculated by the number of layers, the areal weight, and the density of the fibers. The cavity height is constant for all measurements [5].

The through-the-thickness permeability (K) can be calculated using the Darcy equation (1) [6], which correlates the permeability with the viscosity of the impregnation fluid (η), the volume-averaged flow velocity (v), and the known pressure gradient in flow direction ($\frac{dP}{dr}$).

$$v = -\frac{K}{\eta} \cdot \frac{dP}{dr} \quad (1)$$

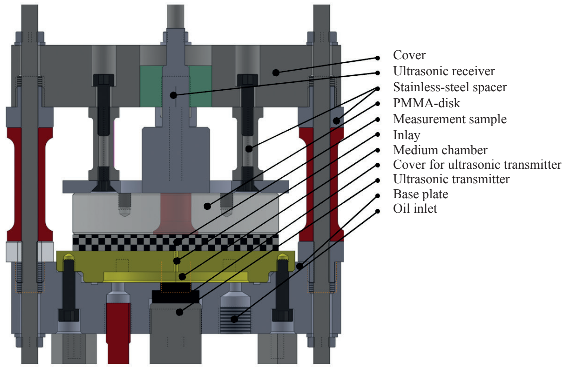


Figure 3: Cross-section of the out-of-plane measuring cell.

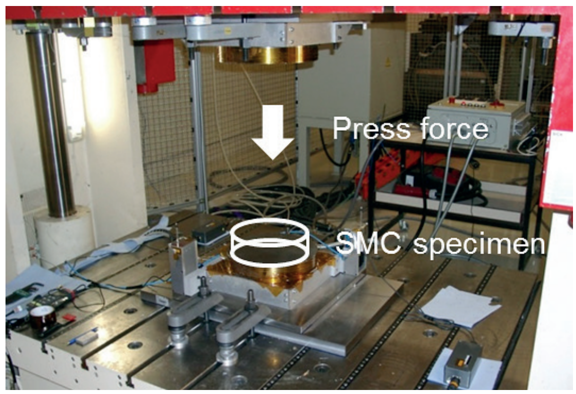


Figure 4: IVW press rheometer in an 800 tons parallel regulated press.

3.2 *Press rheometry*

To characterize the viscosity and the flow behavior of different SMC semi-finished products which only differ in density (see Table 1), press rheometry measurements were carried out on the IVW press rheometer, see Figure 4. For these trials, the material was first cut into circular shaped specimen with a diameter of 350 mm and stacked between two flat circular plates which were mounted on the press. The diameter of the used pressing plates is 344 mm and both the top and bottom plates could be heated to the required processing temperature. The press was closed with a constant closing speed of 1.5 mm/s. Due to the known constant pressing area, the pressing force could then be used to calculate a compression stress and a compaction in thickness-direction of the stack [7].

3.3 *SMC compression molding process*

SMC semi-finished product is processed by compression molding on parallel controlled press on tools with sealing edges to partly highly complex and relatively large parts (e.g. interior trim of local transport system). Therefore, prepreg material is cut with CNC-controlled cutting machines to the required dimensions and stacked to packages that are exactly positioned to the mold. Normally the pressure inside the mold is between 50–120 bars [8], the temperature of the mold is at about 130–160°C and the occupancy is usually between 40–60%. When closing the tool, the package is compressed and heated up. The increase of the temperature leads to decrease of the SMC resin paste viscosity. This change of viscosity enables the SMC material to flow and to fulfill the mold completely. The chopped short fibers with a length of 0.5 to 1 inch are carried along and distributed among the complete tool by the flow of the SMC resin paste. The temperature of the tool also initiates curing of the SMC material and enables thermoplastic shrinkage compensation. After the part is cured, it can be removed from the tool and reworked. The difference between the test series is the type of SMC prepreg material, number of reinforcement layers (one or two), and the layer structure.

3.4 *Preliminary impregnation tests*

To investigate the influence of the different filler contents on the impregnation quality, preliminary test series with the different SMC prepreg materials A, B, and C, see Table 1, were performed. The press conditions and the reinforcement textiles were equal for all tests, the only difference was the filler content of the SMC prepreg materials. For these trials a Satim laboratory press with a maximum press force of 1200 kN was used. The dimensions of the tool are 380 × 460 mm^2. Both the upper tool and the lower tool

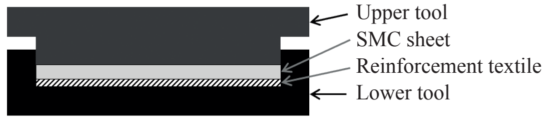


Figure 5: Insertion of reinforcement textile and SMC sheet.

Figure 6: 8000 kN parallel controlled component.

were heated to the required tooling temperature of at about 150°C. On one layer of reinforcement textile, which was inserted centrally on the bottom of the mold, a layer SMC-sheet was placed. This sequence prevented a premature curing of the SMC sheets, caused by the heat of the surface of the tool. Despite of the sequence, the SMC sheets heat up slowly. Within this heating time, the viscosity of the SMC sheets drops and a better impregnation of the reinforcement textile can be reached. If the SMC heats up to long, a curing process starts and the impregnation of the reinforcement textile is no longer possible. So the right timing for closing the press is very important. Following, the press was closed with a maximum pressure inside the cavity of 60 bars with a holding time between 180 and 240 seconds.

3.5 *Impregnation trials (even plate tool)*

In a next step, impregnation trials were carried out on a parallel regulated Dieffenbacher press with a maximum press force of 8000 kN. The dimensions of the tool are 543 × 543 mm^2, see Figure 6. As in the previous tests one layer of reinforcement textile was placed centrically on the bottom of the mold and on top of this layer SMC sheets were laid.

The main challenge of these trials is the impregnation of the dry inserted reinforcement textiles within a standardized pressing process without warping or breaking the textile inside the mold.

Further targets of the trials are a completely filled tool, whereby the thickness of the plate should be 2–3 mm, regarding valid test specifications [9], [10]. Subsequently, test specimens were cut for mechanical and rheological characterization.

3.6 *Micro section*

The impregnation quality of the different reinforced SMC samples was analyzed using a light microscope to determine the void content in the finished part. Therefore, small pieces (20 × 20 mm^2) of the different samples were embedded into EP-resin. After the resin cured, the samples were grounded and polished. With a magnification of 25 till 500, pictures of the samples were made to investigate void content inside reinforcement textile.

3.7 *Mechanical properties*

Bending properties were measured according to DIN 14125 on a Zwick universal testing machine. Specimen size was 64 mm × 15 mm, class of materials three.

Charpy impact resistance was tested according to DIN EN ISO 179 with unnotched specimens, type 2. Specimen size was 80 mm × 15 mm, span L = 20 × thickness of the specimen.

Puncture resistance was tested according to DIN EN ISO 6603-2 with a drop tower. Specimen size was 60 × 60 mm, testing energy 355 J, drop height of the impactor 0.8 m, diameter of the impactor 10.0 ± 0.1 mm. Within the trials the deformation and simultaneously the absorbed energy was recorded.

For a statistical basis, at least seven tests were made for every test configuration.

4 Results and Discussion

4.1 *Results of permeability measurement*

In different previous works the out-of-plane permeability of more than 150 different reinforcing materials including glass-fiber-, carbon fiber-(non) crimp fabrics and textiles was determined by different measuring cells [11]. These measurements showed

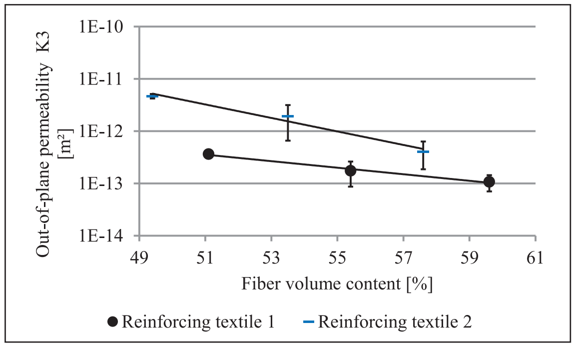


Figure 7: Results of out-of-plane permeability measurements.

that on the one hand the out-of-plane permeability of ±45°-NCF is much higher than of 0/90°-NCF. This is based on the stitching seam through the thickness of the single layers. This stitching seam acts like a flow channel and increases the out-of-plane permeability [11]. On the other hand the out-of-plane permeability of NCFs is much higher than of fabrics. The permeability through the thickness decreases with increasing fiber volume content. The permeability through the thickness of woven fabrics, e.g. with a 0/90° fiber orientation, is much lower than the permeability through the thickness of non-crimp fabrics.

Based on these results a ±45°CF-NCF and a ± 45°GF-NCF were chosen for further impregnation trials, see Figure 7.

4.2 *Results of material characterization using Press Rheometry*

Figure 8 shows the results of the press rheometry. Hereby the graph, which demonstrates the press force over the press time, is clearly split into three sections. At the first section (0–10 s) the press force rises and induces both a compaction of the sample and a full-area contact of the outer layers of the stack with the heated surface of the press rheometer. In the second area can be observed that the warming up of the materials decreases viscosity and the material starts to flow (10–30 s). Above 30 s, the curing reaction takes place increasing again the viscosity of the SMC. This leads to a higher needed press force while the material flows and fills-up the mold completely. It can be clearly seen that the SMC material with the highest filler content (SMC type C, section three, left line) requires the

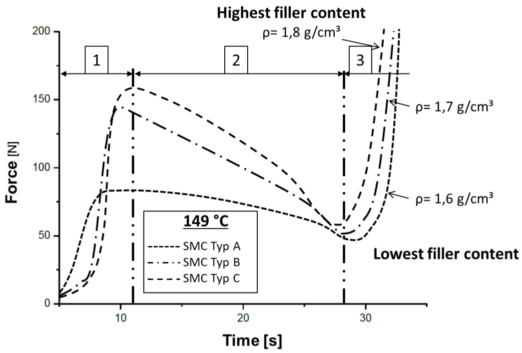


Figure 8: Results of press rheometry.

highest press forces to flow into the mold.

4.3 *Results of preliminary impregnation tests*

In a further step a comprehensive study was performed to characterize the impregnation quality of the selected dry textiles with the different standard SMC prepreg materials, which differ only in filler content and density, see Table 1. These tests showed that the filler content has a strong influence on the impregnation quality, Table 3. Hereby, dark sections show non-impregnated reinforcement textiles and light sections show impregnated areas. To enable a better view on the light optical microscope, images are colored in green.

This overview shows that with exactly same press conditions, the SMC prepreg material with the lowest filler content leads to the best impregnation results.

Due to an optimized combination of suitable reinforcement textiles (± 45°GF-or CF-NCF) with a high out-of-plane permeability and an SMC semi-finished product (Table 1, material A) with a relatively low processing viscosity of the resin paste and an optimized press process, a well impregnation of the textiles can be achieved.

4.4 *Results of impregnation trials (flat plate)*

Test specimen consisting of two different reinforcing textiles (1 and 2) and three different SMC semi-finished products (A, B, and C) were manufactured using different process parameters. In addition, the number of reinforcement textile layers in the samples was also varied. In some test series the reinforcing textile was positioned only on the lower surface of the samples while in some other test series the reinforcement was placed on both sides.

In this study more than 25 different material compositions were tested. Table 4 shows some example material configurations, where solid lines represent the placement location of the SMC sheets and dotted lines, placement location of the reinforcing textile layers.

Table 3: Impregnation results of different SMC prepreg materials

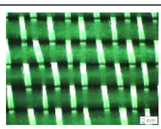
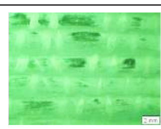
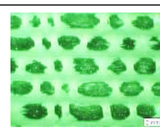
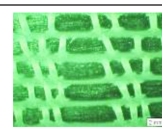
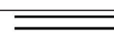
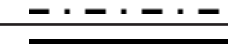
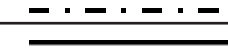
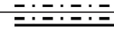
Uninfiltrated reinforcement textile	**Processing parameter: 148°C, 50 bar, 180 sec**		
	SMC 1	**SMC 2**	**SMC 3**
	 Lowest filler content, lowest density ρ = 1.6 g/cm³	 Middle filler content, middle density ρ = 1.7 g/cm³	 Highest filler content, highest density ρ = 1.8 g/cm³

Table 4: Excerpt of the composition of the manufactured composite plates

Used SMC prepreg material	**Used reinforcing textile**	**SMC tool assignment at the beginning of press cycle [%]**	**Reinforcing textile tool assignment at the beginning of press cycle [%]**	**Pressure inside the mold [bars]**	**Schematic sample structure**
A	1	approx. 100	approx. 100	30	
A	1	approx. 100	approx. 100	150	
C	1	approx. 100	approx. 100	150	
B	2	approx. 60	approx. 100	150	
A	2	approx. 100	approx. 100	150	
A	2	approx. 60	approx. 100	150	

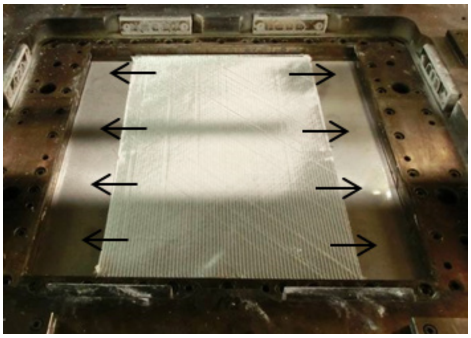


Figure 9: Tool assignment of glass fiber (approx. 65%).

Within the first press trials the optimum quantity of SMC semi-finished product to fill the mold completely was investigated. The parameters for these trials were: 30 bars pressure inside the mold, tool assignment nearly 100%, tool temperature at about 140°C, hold time 240 s. Thereafter, the pressure inside the tool was gradually increased from 30 to 150 bars in order to obtain a satisfactory impregnation of the reinforcement textile. With increasing pressure inside the mold, the impregnation quality of the reinforcement textile improved. The best impregnation quality was reached at 150 bars pressure inside the mold, so these parameters were used for the subsequent trials.

In a further optimization step to improve the impregnation the reinforcement textile and the SMC stack were placed in the heated tool and the press was closed for about 20 seconds with minimum press force before applying the end pressure of 150 bars. The raise of temperature inside the SMC semi-finished product decreased its viscosity, see Figure 8 section 2, and improved the impregnation of reinforcement textile by SMC resin-paste.

In a further step tool assignment of reinforcement textile and SMC semi-finished product was reduced to approximately 65% to see the influence of the flow of material inside the tool to the reinforcement textile, see Figure 9. On top of the GF-NCF (540 × 355 mm^2) one respectively two layers of SMC semi-finished product were placed and the mold was closed. After the optimized press cycle, the GF-NCF was completely impregnated and the mold was completely filled. Although the tool assignment was reduced, the dimensions of the reinforcement textile remained almost unchanged, see Figure 10. The width of the textile after the press process was 357 mm.

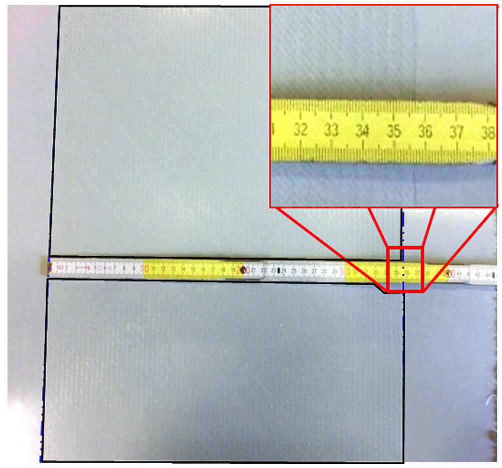


Figure 10: Reinforcement textile after press process (approx. 65%).

This is based on the symmetrical flow of the SMC semi-finished product in only one direction of the tool. If the SMC semi-finished product does not flow symmetrical in the mold, it drags the reinforcement material along the flow front. To prevent this, fixation e.g. clamps for the reinforcement textiles during press cycle is needed.

To complete the test series, samples using the double sided reinforcement configuration were made. For these specimens, one layer of textile reinforcement material, with a cutting size equal to 100% of the mold area, was first laid into the mold and a SMC prepreg cut to approximately 66% of the mold area was placed on top. This stack was then covered with a second layer of textile reinforcement, also cut to 100% of the mold area. When the mold closes, the SMC material flows, filling the cavity completely by simultaneously impregnating the textile reinforcement layers.

The studies showed that the best impregnation results were achieved with a SMC semi-finished product with low density (material A), GF-NCF with a layer structure of ±45° (reinforcing textile 1), and a high pressure inside the mold (150 bars). The trials also showed that SMC resin-paste could not flow through and impregnate several textile layers. .

4.5 *Results of light microscopy analysis*

The impregnation quality of the processed parts was investigated by light microscopy. The micro section

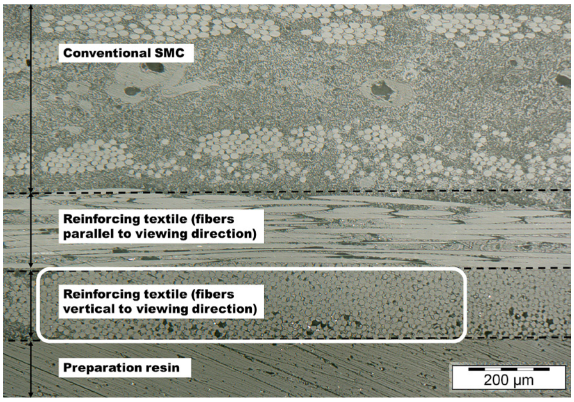


Figure 11: Microsection of test specimen with low filled SMC semi-finished product.

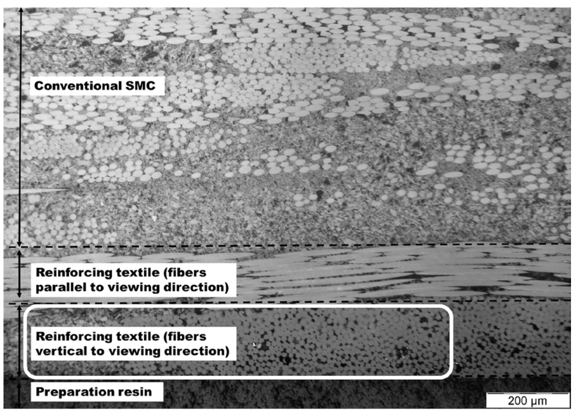


Figure 12: Microsection of test specimen with highly filled SMC semi-finished product.

pictures Figure 11 and Figure 12 show two specimen which were processed under exactly the same process conditions (tool temperature 140°C, press force 4500 kN, holding time 240 s) while the same type of reinforcement textile (±45°GF-NCF) was impregnated. The only difference is the density of the SMC semi-finished product. The impregnation direction of the dry inserted reinforcement textile was from the top to the bottom. The quality of the impregnation of the reinforcement textile was determined by the void content and showed significant differences. Moreover, the determination of the void content demonstrated that a highly filled SMC semi-finished product leads to three times as many voids (black spots) (9%, Figure 12) as a low filled SMC (3%, Figure 11).

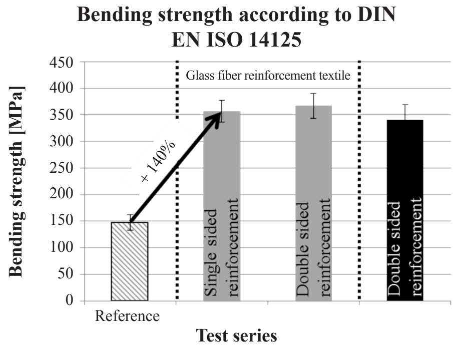


Figure 13: Bending strength according DIN EN ISO 14125.

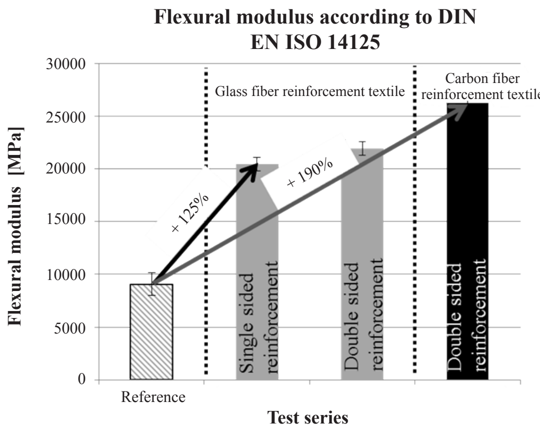


Figure 14: Flexural modulus according to DIN EN ISO 14125.

A verification of the impregnation quality of the textile reinforcement fibers with micro section showed the possibility to impregnate the reinforcement textile almost completely by SMC resin.

4.6 *Results of mechanical properties*

4.6.1 Bending test

In previous tests, bending properties of unreinforced material were tested (Reference = SMC type A, see Table 1). The results corresponded almost to the data of the manufacturer.

Figure 13 and Figure 14 show the results of bending strength and flexural modulus. The reinforcing textile was placed on the bottom of the test sample where tensile load appears. A single sided reinforcement of glass fibers leads to an increase of at about 140%

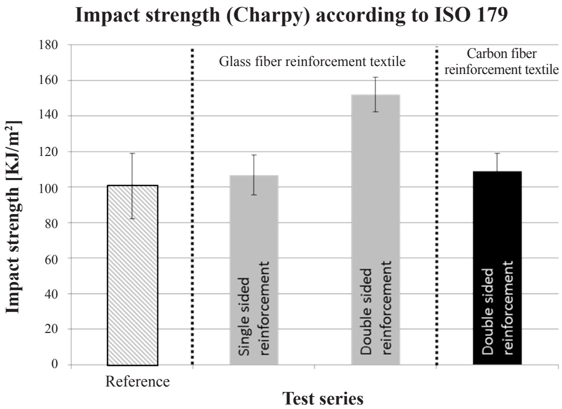


Figure 15: Impact strength according to ISO 179.

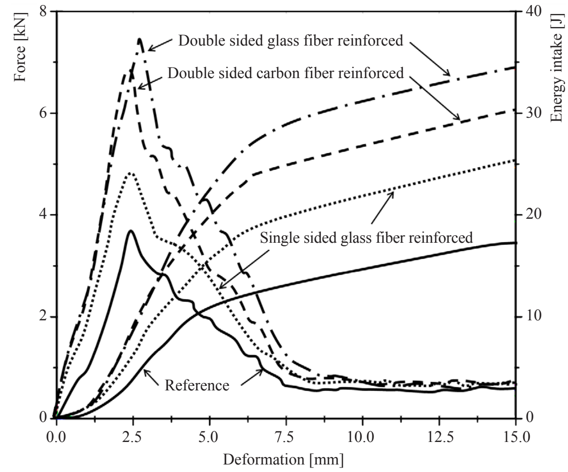


Figure 16: Maximum force and absorbed energy of reinforced and unreinforced samples.

regarding bending strength and at about 125% regarding flexural modulus. The insertion of a second layer on the opposite top of the sample could not increase the bending strength. This could be explained as these fibers are loaded on pressure and not on tension. The replacement of GF- by CF reinforcement fibers on both sides of the sample did not increase bending strength, while flexural modulus could be increased for further 190%. The increase of the bending strength is based on higher fiber volume content with simultaneous orientation of the reinforcing fibers in load path direction.

4.6.2 Impact strength test

At first the impact strength of the reference material was tested. The results [100 kJ/m^2] correspond very well to the data of the manufacturer. Figure 15 shows the results of the reinforced samples. With a single sided reinforcement, no matter if glass- or carbon-fiber, the impact strength could just be increased by 10%. Hereby the sample was tested in a way that tensile load appeared on the reinforcement fibers.

In further test series, samples with a second reinforcement layer out of glass-fibers were tested. Hereby, the impact strength could be increased to 155%. These results show that there is less influence of endless reinforcement to impact strength than to bending strength or bending stiffness.

4.6.3 Puncture resistance test

The value of the absorbed energy of a specimen states how much energy can be absorbed before the specimen collapses, i.e. breakthrough of the pin. Figure 16 shows the different energy absorption rates of unreinforced (Reference) and reinforced specimen.

At first the energy absorbing capability of the unreinforced SMC reference materials, see Table 1, was tested. Material B and C showed a maximum force of at about 4 kN and an energy intake of at about 20 J. For all the impregnation tests the reference material A was used, so these values are plotted in Figure 16. Hereby the maximum force is at about 3.5 kN and the energy intake capacity at circa 17 J. The implementation of a single layer of reinforcing textile within the samples increases the maximum force at least about 140% and the maximum absorbed energy at about 150%. By implementing a second layer of reinforcing structure (double sided reinforcement) maximum force can be increased to at least 7.5 kN and energy intake to 35 J. This causes an increase of maximum force of 215% and 205% regarding energy intake capacity.

The absorbed energy (E) can be calculated as the integration of the product of the current force ($F(l)$) and the associated deformation (dl), see equation (2).

$$E = \int_0^l F(l)\, dl \quad (2)$$

5 Conclusions

The project "Preform-SMC" proved the possibility to impregnate locally inserted dry textile reinforcement

Figure 17: Schmidt & Heinzmann SMC Line 600 at IVW Kaiserslautern.

structures within a conventional SMC press process and conventional SMC semi-finished product. The combination of the textile reinforcement with a conventional short fiber SMC material enables the production of complex component geometries with increased mechanical properties. This is based on the higher fiber volume content and the possibility to align the reinforcement fibers along load paths.

Based on the improved mechanical properties, the wall thickness of the components as also their weight can be reduced. Another advantage of the increased properties is the possibility of tapping into new application fields, e.g. for structural applications.

6 Outlook

As the possibility of impregnating the dry inserted preforms within a normal SMC press process was shown, further investigations with new developed SMC semi-finished products will start. These products will be manufactured with an industry-orientated SMC-line, which is available at IVW Kaiserslautern, see Figure 17. Within this SMC production line, SMC semi-finished products, also with continuous fiber reinforcement, according to specific requirements with a maximum transportation width of 600 mm, can be produced. An extraction unit allows the processing of different resin systems, e.g. EP, UP or VE. There is also a cutting unit, which enables the processing of glass or carbon fibers, see Figure 18, available.

Figure 18: Cutting result of the Cutter; left: mix consisting of Carbon fibers and Glass fibers, right: 50k Carbon fibers.

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