MECHANICAL PROPERTIES OF UNIDIRECTIONAL CONTINUOUS CARBON FIBER REINFORCED SHEET MOLDING COMPOUNDS

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Abstract

The integration of unidirectional carbon fiber fabrics in the sheet molding compound (SMC) technology offers a novel approach to manufacture carbon fiber prepregs in an economic way. Within this work, unidirectional carbon fiber SMC based on an unsaturated polyester-polyurethane hybrid (UPPH) resin system were manufactured with an adapted process and compression molded to sheets. For the mechanical characterization tensile and compression tests were implemented. Mechanical characterization shows that the presented manufacturing route for unidirectional carbon fiber reinforced sheets leads to a material with comparable elastic moduli in tension and compression as well as tensile strength comparable to epoxy based prepreg materials with the advantage of a more economic manufacturing process.

1. Introduction

Major drawbacks of unidirectional fiber reinforced thermosets are the time- and cost-consuming manufacturing and processing routes which have only limited potential for automatisation. The manufacturing and processing route is generally divided into three steps. The first step consists in the infiltration of dry fiber fabrics by a resin system to get a preimpregnated semi-finished product (prepreg). The second step contains the handling of the prepreg materials from the manufacturing to the processing site. The third step involves the stacking of different layers to a laminate in a tool and the final shape-defining process [1]. There are two major problems considering the whole manufacturing and processing route. First, the storage and shipping of the prepreg materials from the manufacturer to the processing site needs a permanent cooling to prevent further curing [2]. Second, the most common final shape-defining processing route is based on autoclave technology. This technology comes with a high capital-investment, causes high processing costs and long processing times.

The growing demand for fuel efficient and hence light vehicles and aircrafts led to a remarkable in-

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terest of unidirectional fiber-reinforced polymeric composites. These composites convince with high fiber contents and outstanding material properties. Technologies and materials successfully integrated in aerospace industry are promising, but the considered combination of prepreg and autoclave technology is inappropriate for mass production and thus, not interesting from an economic point of view. To overcome the drawbacks mentioned above and to rise economical potential of prepreg materials, an adaption of the resin system and processing route is indispensable. In this regard, out-of-autoclave methods gained acceptance over the past decade [3]. The vacuum-bag curing technique is a promising technique to produce autoclave-quality parts [4]. Since vacuum-bag techniques are based on lower processing pressures, there is less potential to compensate for errors and imperfections such as absorbed moisture or entrapped air as shown by Karcher et al. [5]. This study also highlights that compression molding of unidirectional fiber reinforced prepregs leads to satisfying results as for final void content, mechanical properties and costs. They also introduced a novel technology to manufacture unidirectional carbon fiber reinforced prepregs based on a sheet molding compound process. The sheet molding compound (SMC) process is a well established process to manufacture semi-structural components in the automotive field [6–8]. This technology offers the possibility to manufacture structures at a very high productivity combined with good part reproducibility, cost efficiency, surface quality and the possibility to manufacture parts with complex geometries due to a high bulk material flow capability [9]. However, as sheet molding compounds are normally based on precut long fibers, strength and stiffness of final parts are limited due to finite fiber length and anisotropy resulting from flow phenoma during compression molding. In contrast, unidirectional fiber reinforcements offer high load bearing capacities. As shown by Karcher et al. compression molding based on unidirectional carbon fiber prepregs is a promising path in the prepreg processing technology [5]. Within this study unidicretional carbon fiber prepregs were processed, which base on a novel hybrid resin system. It provides a chemically stable and highly viscous B-stage ideal for cutting, preforming and handling of the prepregs prior to molding. This system is also able to chemically connect to the resin system of a flowable SMC. Thus, a functionalization by local metal inserts and three-dimensional shapes like ribs are achievable by co-molding with SMC. A new approach focuses on the combination of discontinuously reinforced structures based on SMC with continuous unidirectional carbon fiber prepregs. The integration of such prepregs aims to obtain better load-bearing capacities at highly loaded areas. As a first step, continuously-discontinuously (CoDiCo) fiber reinforced laminate sheets have been processed by combining layers of chopped glass fiber and unidirectional carbon fiber sheet molding compounds during compression molding. The results indicate that compared to solely discontinuously reinforced sheet molding compounds, the CoDiCo laminates show an increase in global strength and stiffness, with the mechanical properties expectedly depending on layer architecture [10]. To further investigate hybrid continuously-discontinuously fiber reinforced SMC, the material properties of the individual components have to be determined. Thus, this study aims to investigate the applicability of the new resin system as well as obtained mechanical properties of unidirectional carbon fiber SMC processed by prepreg compression molding.

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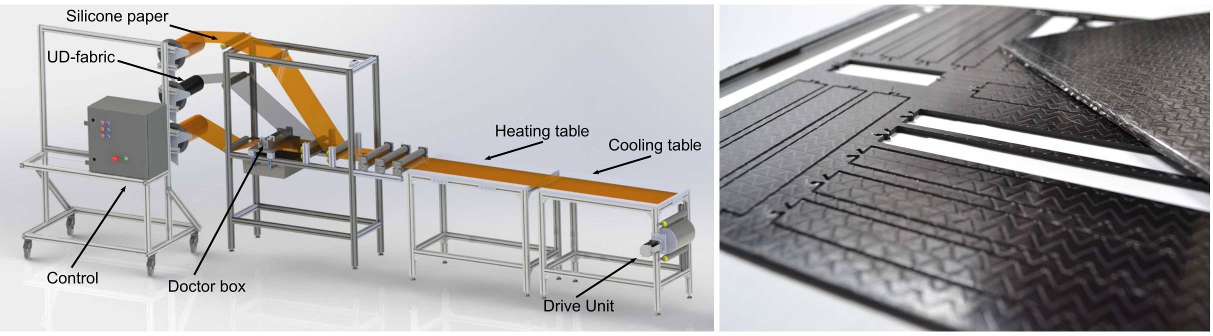
2. Materials and Methods

2.1. Materials and Processing

The unidirectional carbon fiber SMC sheets were manufactured with a lab-scale impregnation line (Figure 1 (a)), built at the Fraunhofer Institute for Chemical Technology (ICT) in Pfinztal, Germany. The material is based on a carbon fiber (CF) non-crimp-fabric (NCF) type UD300 by Zoltek [11] and on an unsaturated polyester-polyurethane hybrid (UPPH) resin system type Daron 41 by Aliancys [12]. The sheets feature a width of 300 mm, a surface weight of 500 g/m^2 and a theoretical fiber content of 47.5 vol.-% at a theoretical density of 1.45 g/cm^3. The impregnation line is equipped with a heating table (80 °C) to impregnate the NCF and to accelerate the B-stage reaction. The following cooling table (18 °C) prevents the material from further chemical cross-linking [5]. There is no need for maturation and the impregnated NCF can directly be further processed.

2.2. Compression Molding

Right after the impregnation the carbon fiber reinforced semi-finished sheets were cut into plies, stacked and compression molded. The molding process was realized with a down stroke press from Dieffenbacher (type COMPRESS PLUS DCP-G 3600/3200 AS). The closing speed was set to 1 mm/s. The final pressure reached 120 bar and the molding time was 90 s at 150°C. The dimensions of the molded plates were 800mm x 250 mm. Depending on number of semi-finished sheets stacked before molding the molded plates have a nominal thickness of either 1 or 2 mm (Fig.1 (b)).



(a) Adapted impregnation line to fabricate unidirectionally continuous carbon fiber reinforced SMC

(b) Molded unidirectionally carbon fiber reinforced SMC sheets with nominal thickness of 2 mm, specimen were extracted by water-jet cutting

Figure 1. Adapted impregnation line and molded unidirectionally carbon fiber reinforced SMC

2.3. Characterization

2.3.1. Thermogravimetric Analysis

To determine fiber content of molded unidirectionally carbon fiber reinforced SMC sheets, thermogravimetrical analysis were carried out. Therefore, three different sheets with a thickness of 2 mm were considered. For each sheet six samples were taken into account.

2.3.2. Tensile Test

The quasi-static tensile tests were performed with a ZwickRoell ZMART.PRO 200 kN universal testing machine. The testing was done according to DIN EN ISO 527-5 with slightly modified sample geometry to determine properties perpendicular to the fibers (230 x 25 x 2 mm^3) The specimen for mechanical testing were obtained by water-jet cutting. All specimen were provided with end tabs. Longitudinal strains were measured with an extensometer. The elastic modulus in tension E_t was calculated by linear regression with stresses measured at $\varepsilon_1 = 0.05\%$ and $\varepsilon_2 = 0.25\%$.Tensile strength σ_m and strain at break ε_b were determined from resulting stress-strain curves.

2.3.3. Compression Test

Compression tests were performed according to DIN EN ISO 14126 on a ZMART.PRO 100kN universal testing machine equipped with a Hydraulic Composites Compression Fixture (HCCF) clamping unit. Tests were performed with specimen (110 mm x 10 mm x 2 mm) extracted in fiber direction (0°) and

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perpendicular to the fibers (90°) by water-jet cutting. The measurement length was 12 mm and deformations were detected by two clip-on sensors, one at each side of the specimen to control bending of the specimen. Testing velocity was 1 mm/min and modulus of elasticity in compression E_c was calculated via linear regression between $\varepsilon_1 = 0.05\%$ and $\varepsilon_2 = 0.25\%$. Compressive strength σ_{cM} and strain at break ε_{cM} were determined from resulting stress-strain curves.

3. Results

3.1. Thermogravimetric Analysis

Mean value and standard deviation of determined fiber weight content for all measured samples were 64.2 ± 2.77 wt.%. This value equals a fiber volume content of 51.9 vol.% and a density of 1.48 g/cm^3.

3.2. Tensile Test

The elastic modulus in tension equals 120 GPa in fiber direction and 8.2 GPa perpendicular to the fiber direction. The material showed a tensile strength of 1647.8 MPa in fiber direction and 42.7 MPa perpendicular to the fibers. Strain at fracture equals 1.35% and 0.5% respectively. Tensile properties of unidirectional carbon fiber SMC are listed in table 1.

Table 1. Tensile properties of unidirectional carbon fiber SMC

Specimen Orientation (°)	Number of tested specimen (-)	E_t (GPa)	σ_m (MPa)	ε_b (%)
0	5	120 ± 5	1647.8 ± 312.6	1.35 ± 0.14
90	5	8.2 ± 0.7	42.7 ± 2.8	0.49 ± 0.06

3.3. Compression Test

The elastic modulus in compression equals 104.9 GPa in fiber direction and 7.8 GPa perpendicular to the fiber direction. The material showed a tensile strength of 584 MPa in fiber direction and 171.2 MPa perpendicular to the fibers. Strain at break equals 0.63% and 3.2% respectively. Compression properties of unidirectional carbon fiber SMC are listed in table 2.

Table 2. Compression properties of unidirectional carbon fiber SMC

Specimen Orientation (°)	Number of tested specimen (-)	E_c (GPa)	σ_{cM} (MPa)	ε_{cM} (%)
0	7	104.92 ± 6.9	548 ± 38.95	0.59 ± 0.04
90	6	7.82 ± 0.62	171.21 ± 5.82	3.22 ± 0.47

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4. Discussion

To evaluate processibility and mechanical properties, the material processed and tested within this study is compared to other alternative thermoset prepreg materials.

It could be shown that the processing route described within this study enables manufacturing of unidirectional fiber reinforced thermosets in a much faster way compared to standard autoclave, vacuum-bag or oven curing technologies. First, time saving is based on the possibility to further process the prepregs directly after impregnation without the need of maturing due to the adapted impregnation line. Second, the application of a compression molding process allows to reduce time for the shape-defining processing step. Whereas autoclave-based processing routes need to include long curing cycles of several hours [13], the above described processing route based on compression molding with a press time of only 90 s. Consequently, the adapted processing route does minimize processing time and cost. To evaluate the quality of processed material with the processing route described above, the theoretical elastic modulus in tension and tensile strength were calculated according to equation 1 and 2 [14] with v_f and $v_m = (1 - v_f)$ the fiber and matrix volume content and E_f and E_m the elastic modulus in tension for fiber and matrix respectively. σ_f and σ_m show the tensile strength in tension for fiber and matrix respectively. To be able to consider equation 2, fiber and matrix must show the same strain at break.

$$E_{th} = v_f * E_f + v_m * E_m \tag{1}$$

$$\sigma_{th} = v_f * \sigma_f + v_m * \sigma_m \tag{2}$$

Considering the realized fiber volume content of 51.9 vol.%, the elastic moduli in tension of $E_f = 242$ GPa [11] and $E_m = 3.1$ GPa [12], the theoretical elastic modulus in tension E_{th} equals 127 GPa, the theoretical tensile strength (σ_{th}) is 2183.9 MPa ($\sigma_f = 4137$ MPa [11] and $\sigma_m = 90$ MPa [12]). The experimentally determined elastic modulus in tension and tensile strength are 10 % respectively 21 % lower than the theoretical values. Regarding this slightly lower values it has to be considered that the theoretical strength and moduli neglect any fiber misalignment or fiber damage. In reality stresses are not equally distributed to all fibers in the composite leading to a lower real tensile strength. As there is only a small difference between theoretical and real mechanical properties, the described processing route is suitable to manufacture unidirectional prepreg materials of high quality.

To evaluate the performance of the novel material, mechanical properties of some comparable alternative materials are taken into account (Table 3).

Table 3. Characteristics of selected alternative materials for comparison of mechanical properties

material	Reference	prepreg	fiber content (vol.%)	density ($\frac{g}{cm^3}$)	process	resin type
1	Zoltek, PANEX35 [15]	Zoltek UD300	55	1.53	not specified	epoxy
2	Karcher et al. 1 [16]	Zoltek UD300	55	1.53	compression molding	epoxy
3	Karcher et al. 2 [16]	Zoltek UD300	43	1.45	compression molding	epoxy
4	Trauth et al. [this study]	Zoltek UD300	52	1.48	compression molding	UPPH

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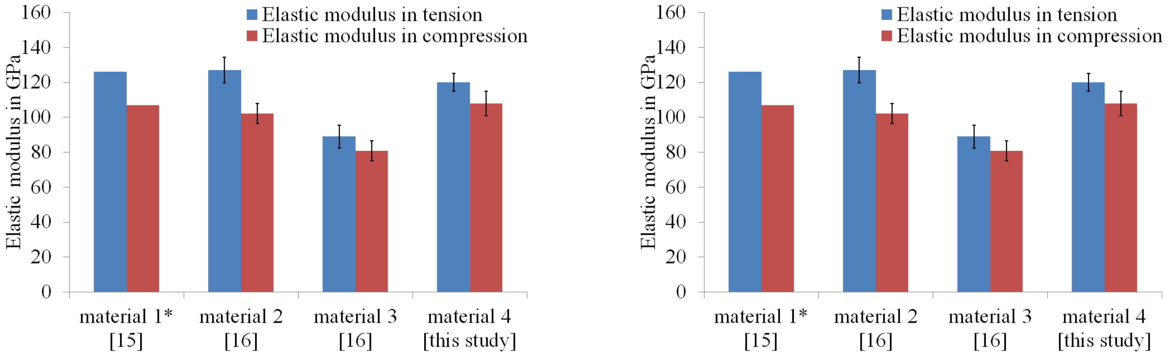
For all materials, tensile properties were determined according to DIN EN ISO 527. Compressive properties are based on DIN EN ISO 14126 for material 2 to 4. Compressive properties for material 1 were determined according to ASTM D694 and ASTM D695 respectively. Figure 2 shows the elastic moduli (a) and strength (b) of considered materials for tensile and compressive loads.
The elastic modulus in tension for the material processed within this study (material 4) is a slightly lower compared to the moduli obtained by material 1 and 2. As shown by Karcher et al. the elastic modulus in tension strongly depends on fiber volume content (material 2 and 3). This explains the slightly lower modulus of material 4 compared to material 1 and 2. As far as elastic modulus in compression is considered, material 4 shows a higher value than material 1 and 2 even if the fiber volume content is lower. For the material based on the novel hybrid resin system (material 4) the highest tensile strength was measured, even though the fiber volume content is not as high as for material 1 and 3. However, as the specimens fail very abruptly, starting region of failure can not clearly be identified. It has to be assumed that some samples first failed in the end tab region leading to a high standard deviation of measured values. Material 4 shows also a also higher compressive strength as the materials based on epoxy resin realized by Karcher et al. (material 2 and 3). This result underlines the applicability of the novel resin system to get a very high fiber-matrix adhesion. The compressive strength of material 1 is higher as for the materials obtained by prepreg compression molding. To evaluate this results is has to be mentioned that a compression test according to ASTM D694/695 provides a supporting jig for thin specimen. This supporting jig could be the reason for the higher compressive strength.



(a) Elastic moduli in tension and compression in fiber direction

(b) Tensile and compressive strength in fiber direction

Figure 2. Elastic moduli in tension and compression (a) and tensile and compressive strength (b) in fiber direction for investigated and alternative materials

To evaluate the applicability of different resin systems for the prepreg compression molding technology in greater detail, figure 3 shows elastic modulus in tension and compression (a) and tensile and compressive strength (b) perpendicular to the fiber direction (90°). These values reflect directly the resin properties as the fibers do not have any load-bearing properties in this direction. Considering elastic moduli in tension and compression (Fig. 3 (a)) there is no significant difference between the epoxy and UPPH based materials, but tensile and compressive strength (Fig. 3 (b)) are higher for the novel resin system as for the material processed by Karcher et al. This underlines once again the applicability of the presented novel resin system for high-quality unidirectionally carbon fiber reinforced thermosets.

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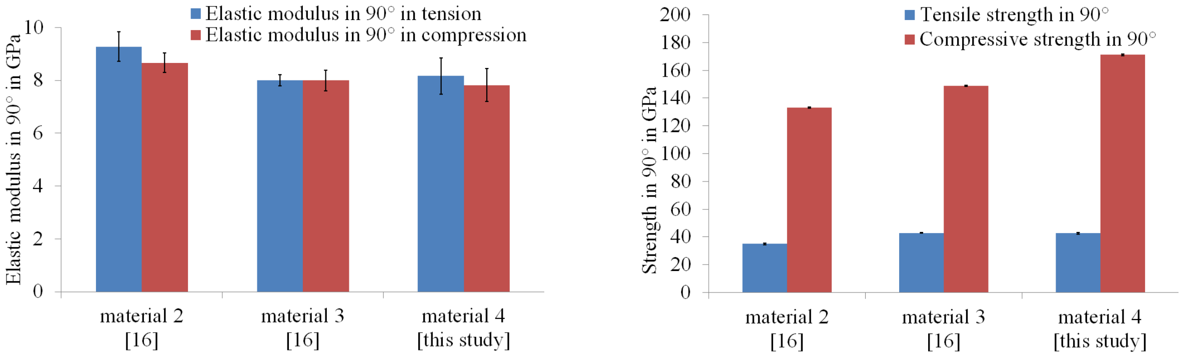
* no standard deviation listed



(a) Elastic moduli in tension and compression perpendicular to the fiber direction

(b) Tensile and compressive strength perpendicular to the fiber direction

Figure 3. Elastic moduli in tension and compression (a) and tensile and compressive strength (b) perpendicular to the fiber direction for investigated and alternative materials

5. Conclusion

Mechanical characterization of UPPH based unidirectionally carbon fiber reinforced thermosets shows, that the processing route described within this paper is suitable to process unidirectional prepregs in an economic way. Obtained mechanical properties can be compared to alternative materials based on epoxy resins. As a next step, to increase productivity, a standard SMC impregnation line will be equipped with heating and cooling unites to fasten up processing of unidirectional SMC prepregs. Furthermore, as the hybrid resin system is able to chemically connect to the resin system of a flowable SMC, the focus lays on a local continuous reinforcement of discontinuous chopped fiber SMC components. The integration of such unidirectional reinforcements will aim to obtain better load-bearing capacities at highly loaded areas.

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