Sheet Molding Compound with highly aligned fiber reinforcement: An experimental investigation

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Abstract. This paper presents a method for aligning chopped glass fibers during SMC production on an SMC-line, using a vibrating gate to obtain a preferential fiber orientation in the semi-finished material. The vibrating gate consisted of multiple blades with varying height and relative distance, resulting in multiple slit configurations. Processing parameters of this test setup were varied in an experimental study to determine the effects on the resulting fiber orientation. Digital image analysis was used to quantify the degree of fiber orientation in the semi-finished material, and in the molded SMC plates produced thereof. In addition to that, tensile strength and modulus were characterized in dependance of load direction following DIN EN ISO 527. Material anisotropy was also characterized with a non-destructive test method using tensile discs. It was found that the chosen process approach was suitable to achieve a preferential fiber orientation, with the blade distance being the most influential parameter on fiber alignment. Highest fiber alignment results were achieved with a configuration with 5 mm relative distance between blades: (a) A fiber fraction of 45% was achieved within 0° ± 20°, (b) in the 0° orientation, tensile strength was doubled, and modulus was increased by 55% compared to a reference SMC with random fiber distribution.

Introduction

Sheet Molding Compound (SMC) is one of the most commonly used fiber reinforced composite materials, seeing application in the automotive, transportation, and construction industries, among others [1, 3]. SMC combines a thermosetting matrix system, usually based on unsaturated polyester, with a discontinuous fiber reinforcement in the form of chopped fiber glass [4, 14, 20]. Fibers have a random in-plane orientation within the semi-finished material, resulting in planar-isotropic material properties, which are usually also retained in the finished part molded thereof [8, 18]. The discontinuous fiber reinforcement in SMC allows for material flow during compression molding, enabling fast and efficient production of parts of a relatively high geometric complexity [8, 14]. SMC is also a very versatile class of materials: By variation of type and content of resin, fiber and filler, a wide range of material properties can be achieved, ranging from cost efficient or flame-resistant SMCs to high performance materials with a high content of glass or carbon fibers, to name just a few examples [1, 17]. In applications with clearly defined load paths, a preferential orientation of the reinforcement fibers in the SMC along those paths might be beneficial for overall part performance. With an increasing fraction of fibers contributing to the load transfer, superior weight specific strength and stiffness might be achieved, somewhat reducing the performance gap between SMC and composites with highly aligned, continuous fiber reinforcement [9, 15]. Assuming that the flowability of SMC could also be retained while achieving this targeted fiber alignment, this would make for an interesting new material variant for complex, high production volume parts with defined load paths such as suspension or control arms in vehicles, to give some examples. A preferential fiber orientation in SMC might theoretically be achieved either during the initial production of the semi-finished material, or through excessive material flow in the compression molding step [15]. With a sufficiently long flow path, fibers might have enough time and space for reorientation during mold filling as a result of the interaction with the surrounding flowing matrix. This process is, however, difficult to predict and control, especially with complex part geometries. It is therefore preferable to incorporate pre-aligned fibers in the semi-finished material itself.

While there are multiple fiber aligning methods for discontinuous fibers described in scientific literature, to our knowledge none of them have been applied in SMC production so far. One general approach involves flow-induced fiber alignment during transportation in a fluid suspension [19, 25]. This method is commonly used in the production of composites from recycled, discontinuous carbon fibers [7, 10–12, 23, 24]. Alternatively, fiber alignment might be achieved by carding. This method is commonly used in the textile industry, and is sometimes applied in composites production as an intermediate process step for obtaining nonwovens, e.g. from recycled carbon fibers [2, 13, 16]. A straightforward method for obtaining aligned fibers involves a vibrating gate. This gate comprises of a frame, in which multiple parallel blades are installed at a defined distance between one another. The fibers are dropped onto the gate and are forced into a certain orientation upon passing through it. The vibration of the gate prevents the fibers from piling up on top of it [5, 6, 16]. The authors of [5] were able to produce an organo-sheet with aligned reinforcement from discontinuous carbon fibers using the vibrating gate method. Specimens produced were benchmarked against continuously reinforced tapes with otherwise identical fiber content (fiber volume fraction: 20%) and matrix system. Young's modulus of the discontinuously reinforced specimens reached approx. 40 GPa, which corresponds to 90 % of the modulus of the reference material.

Gan et al. [6] describe a test setup that appears to be well suited for adaptation to the SMC process chain. The authors use several gates in serial configuration. Distance between blades and respective heights are varied between individual levels to gradually increase fiber alignment and to prevent fibers from piling up on top of the blades. Vibrating motors are used to further prevent fiber buildup. The experimental setup is decoupled from the surrounding equipment with dampeners. Fibers that pass through the alignment module are dropped on a conveyor belt. It was found that the distance between the alignment module and the conveyor belt should be minimized to prevent unwanted misalignment of the fibers during the remaining drop distance. According to the authors, their setup is suitable for covering a large output surface area at a high fiber throughput. It was found that approx. 55% of the fibers were aligned within ±5° of the processing direction. In this work, a similar method to the one described in [6] is adapted to an SMC line for the production of a semi-finished material with a high degree of fiber alignment. Materials were produced under variation of multiple processing parameters. Fiber orientation and resulting material properties were characterized using optical methods and mechanical testing.

Experimental

In this work, a modified SMC line of the type HM-LB-17 by Schmidt & Heinzmann GmbH & Co. KG was used. The HM-LB-17 is a lab scale line, with a maximum production width of 800 mm. The experimental setup for the fiber alignment was positioned directly below the glass fiber cutting unit. The guiding sheet metal housing for the chopped glass fibers was removed for this study. An approximate space of 850 mm x 1300 mm x 500 mm was available for the experimental setup in between the cutting unit and the lower carrier film. Line speed was set to 2.6 m/min for all experiments. Fig. 1 shows the experimental setup, as it was installed in the SMC line. The frame of the gate consisted of aluminum profiles. The blades were cut from sheet metal, thickness was 0.8 mm. The blades were aligned in processing direction of the SMC line. This corresponds with the 0° orientation. The vibration motor was fixed directly to the frame. The setup was fixed to the SMC line with rubber dampening elements.

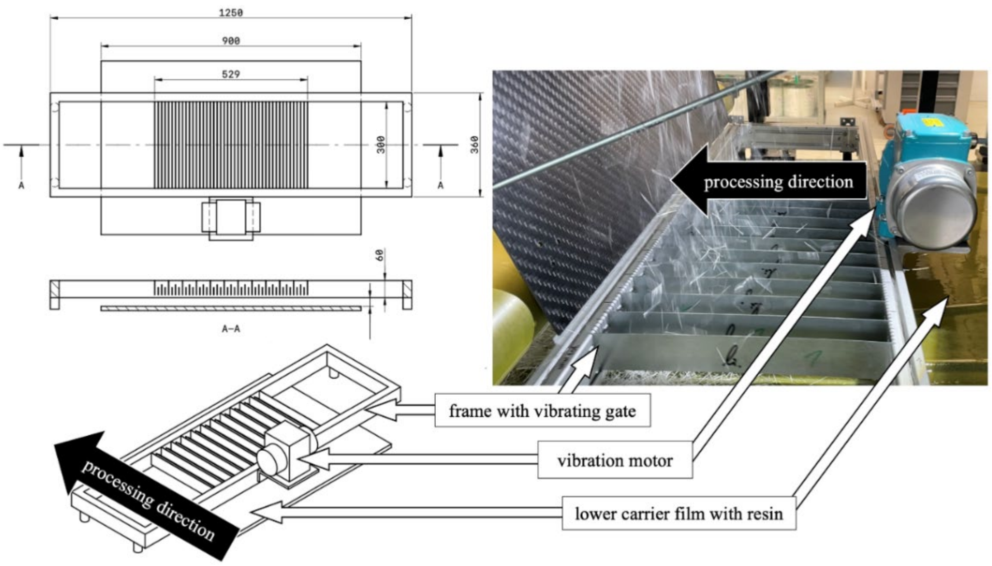
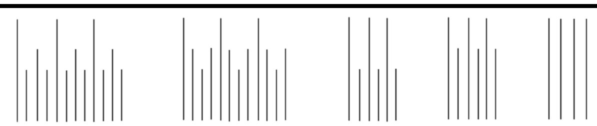


Figure 1 – Schematic of the vibrating gate experimental setup, and installation in SMC line

Experimental parameters for material production are summarized in Table 1. The first set of experiments was performed only with dry fibers, omitting the resin paste, to pre-select a subset of suitable processing parameters for material production. For the dry fiber tests, the full range of parameter combinations was investigated. The gate configuration describes the arrangement of blades of varying length used in the setup. It was found that the gate configuration did not have a significant effect on the quality of the fiber alignment. It did, however, influence fiber buildup on top of the gate, i.e., a configuration with multiple blade heights was usually better suited for preventing fiber bridging and buildup on top of the gate. Fiber buildup was always considered as a failure of the experiment, and the respective parameter set was omitted from further testing.

Table 1 – Experimental parameters with corresponding variations used

experimental parameters	variations used
gate configuration	 A B C D E
blade distance [mm]	5; 11; 17; 23
dampener type	small (Dk); medium (Dm); large (Dg)
AC frequency [Hz]	20; 30; 40; 50
motor orientation	Ms: perpendicular to the processing direction Mp: parallel to the processing direction

The same was also found for the dampener type, vibration frequency and motor orientation. No significant influence on resulting fiber alignment was identified for any of those parameters. Only the distance between the blades exhibited a significant effect on fiber alignment. Following the dry fiber tests, four gate configurations, as well as a reference conventional SMC without fiber alignment were selected for full testing. The specimen nomenclature is shown in Fig. 2.

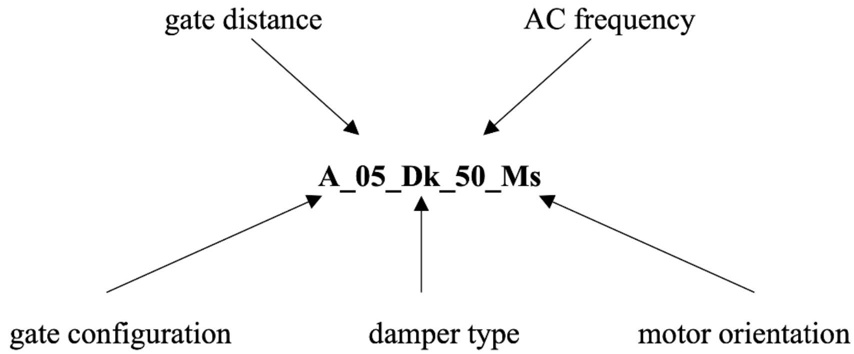


Figure 2 – Specimen nomenclature

A thermoset matrix based on vinyl ester was used in the production of the semi-finished material. The formulation is shown in Table 2, components are listed in order of mixing. In its molded state, the resin is slightly translucent when no fillers are used, enabling visual inspection of fiber orientation in the plates. Mixing was performed directly before the trial run to prevent premature thickening of the resin on the SMC line. The resin formulation was identical for all material charges produced in this study. The nominal glass fiber weight fraction was 40% for all materials produced, with the chopped fibers having a length of approx. 25.4 mm. As fiber reinforcement, an assembled glass roving of the type MultiStar 272 4800 tex (Johns Manville) was used. Fiber type was also fixed for all experiments. After production, the semi-finished materials were stored in a climate chamber for approx. seven days at 20 °C.

Table 2 – Vinyl ester SMC formulation

Material	Function	Supplier
Daron 8180	vinyl ester resin	AOC
UOP-L	water binding agent	Obermeier
BYK 9085	release agent and flow aid	BYK
pBQ	inhibitor	Sigma Aldrich
Peroxan BEC	initiator	Pergan
Lupranat M20R	thickener	BASF

For compression molding trials, a hydraulic upper piston press with parallelism control of the type DYL 630/500 (Dieffenbacher) was used. Square plates with a side length of 455 mm were produced with an SMC compression molding tool. Press force was 1200 kN, which corresponds to approx. 60 bar cavity pressure relative to the projected cavity surface. Cure duration was 300 s at a mean mold temperature of 150 °C. Mold closing speed was 1 mm/s upon contact with the SMC charge. Initial charge dimensions were 400 mm x 400 mm, resulting in a mold coverage of approx. 77%. The initial stack consisted of 3 SMC layers, resulting in a plate thickness of approx. 2.3 mm and a plate weight of approx. 750 g. Individual layers were stacked while retaining the same 0° orientation in between layers, and always placed in the center of the mold, consistently in the same orientation to make sure that any flow induced fiber orientation effects were identical among all specimen types processed.

Specimens were extracted from the molded plates via water jet cutting. Five tensile specimens oriented in processing direction (0° direction) and five tensile specimens perpendicular to it (90° direction) were extracted from the plates (150 mm x 25 mm). In addition, a tensile disc specimen [22] and five round 25 mm diameter specimens for thermogravimetric analysis were also extracted.

Material anisotropy was characterized using a method developed in [22]. Circular disc specimens with a diameter of 170 mm were used for this purpose. These tensile discs were mounted into a universal testing machine (Zwick Roell Zmart.Pro) with a clamping length of 122 mm. The specimens are loaded up to a maximum elongation of ε=0.3%. Tröster et al. [22] showed that for long fiber reinforced thermoplastic material this was well within the elastic region of the material. For the SMC investigated in this work, it can be assumed that this is also the case based on stress-strain curves of tensile testing experiments following DIN EN ISO 527. The force-elongation curves were recorded. A pseudo-Young's modulus (E^*) was determined from the measured stress-strain-curves between ε=0.05% and ε=0.25%. The length of the clamped area of the specimen was used in the calculation of the specimen cross section. Measurements were repeated after rotating the specimen in 10° increments, until a total of 180° of the disc is covered. Tröster [22] proved in his work that the purely elastic loading of the discs had no influence on subsequent measurements.

In addition to the tensile disc specimens, conventional quasistatic tensile tests based on DIN EN ISO 527 were also performed with a second set of specimens. Specimen dimensions were 150 mm x 25 mm. Testing was done in a universal testing machine of the type Inspekt table 50.

Fiber orientation of the dry fiber bed and within the molded plates were characterized in a visual evaluation, respectively. A camera was fixed on the SMC line, filming the dry fiber bed right before the material enters the impregnation zone of the SMC line. Additionally, images of the molded plates were also taken. Digital image evaluation was performed in Fiji/ImageJ. The plugin Directionality [21] was used to analyze the fiber alignment. This software was used to analyze the fiber length fraction within a given angular segment using a Fourier power spectrum analysis. The generated histogram of the fiber length fractions is approximated by a Gaussian function and statistically evaluated. For any given specimen type, a minimum of five pictures were evaluated.

Results and discussion

In Fig. 3 the fiber length fraction within an angle of ±20°of the 0° orientation is displayed for all materials tested, with five specimens investigated per variant. Results are shown for both the dry fiber bed tests, as well as for the molded plates with the same fiber alignment setup parameters. Additionally, the results of those experiments are compared to a reference SMC variant without any targeted fiber alignment. The reference material exhibits the overall lowest fiber length fraction in the given angular segment. A mean fiber length fraction of 31.7% was measured for the dry fiber bed experiment. Every other configuration using a gate showed a significantly higher fiber alignment in the dry fiber bed experiment. The main influence on fiber alignment is seemingly the distance between the blades. With decreasing distance, the fiber length fraction increases. This is consistent with the findings of Gan et al. [6]. The configuration with a blade distance of 17 mm (C_17_Dm_50_Ms) reached a mean fiber length fraction of 44.6 % in the dry fiber bed experiment. The two configurations with a 11 mm blade distance (D_11_Dk_40_Ms and A_11_Dm_30_Ms) reached, on average, 48.8%, and 50.0%, respectively. The configuration with a blade distance of 5 mm (A_05_Dk_50_Ms) reached a mean fiber length fraction of 55.7%. A clear trend can be seen when comparing the mean values. Standard deviation for all measurements was relatively small, indicating that the fiber alignment process was overall quite robust.

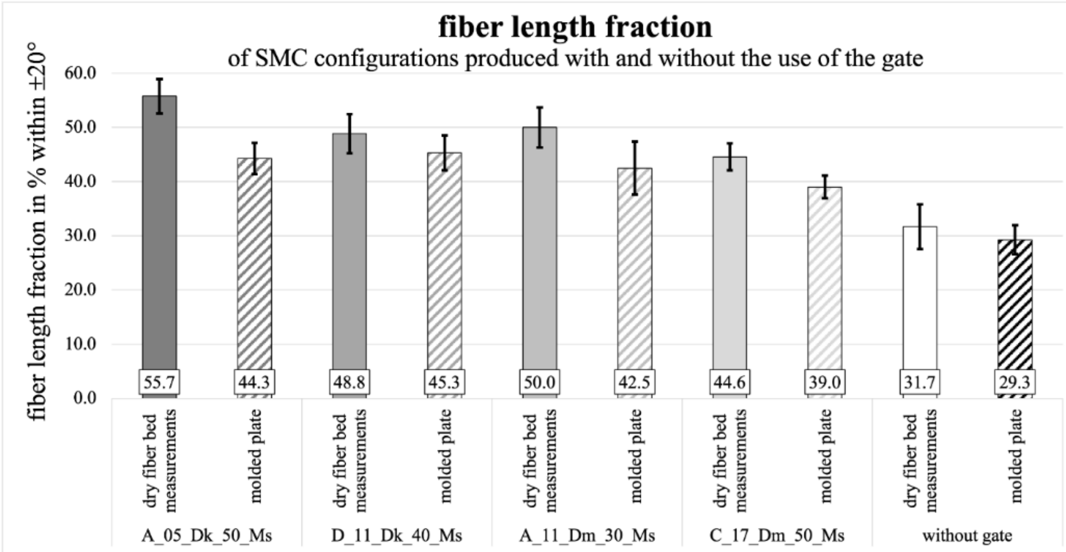


Figure 3 – Fiber length fraction within ±20° of the 0° direction for each experimental configuration

For the molded plates, the reference material reached a mean fiber length fraction of 29.3% within ±20° of the 0° orientation. The 17 mm distance configuration (C_17_Dm_50_Ms) reached a mean fraction of 39.0%. The 11 mm distance configurations (D_11_Dk_40_Ms and A_11_Dm_30_Ms) reached 45.3% and 42.5%, respectively. The 5 mm distance configuration (A_05_Dk_50_Ms) reached 44.3%, which is in the same range as the 11 mm configurations, showing no significant difference. While the general trend of an increasing fiber alignment effect with decreasing blade distance is also visible for the molded plates, it is seemingly less pronounced at very low blade distances compared to the dry fiber bed experiments, as indicated by the plateauing mean fiber length fractions. It is also of note, that the mean fiber length fractions are also consistently lower than those of the corresponding dry fiber bed experiments for every single molded plate type. This is likely due to fiber reorientation effects during SMC production within the impregnation zone, as the fibers are sheared between the chain belts of the SMC line, and potentially during molding, when some degree of flow-induced fiber alignment might have occurred.

In Fig. 4, left, the resulting curves of the mechanical anisotropy characterization experiments following the methodology of Tröster [22] are shown. The orientation-dependent E^* profiles of all five SMC configurations tested are displayed. The E^* curves of all configurations were normalized using the respective configuration-specific maximum value of E^*.

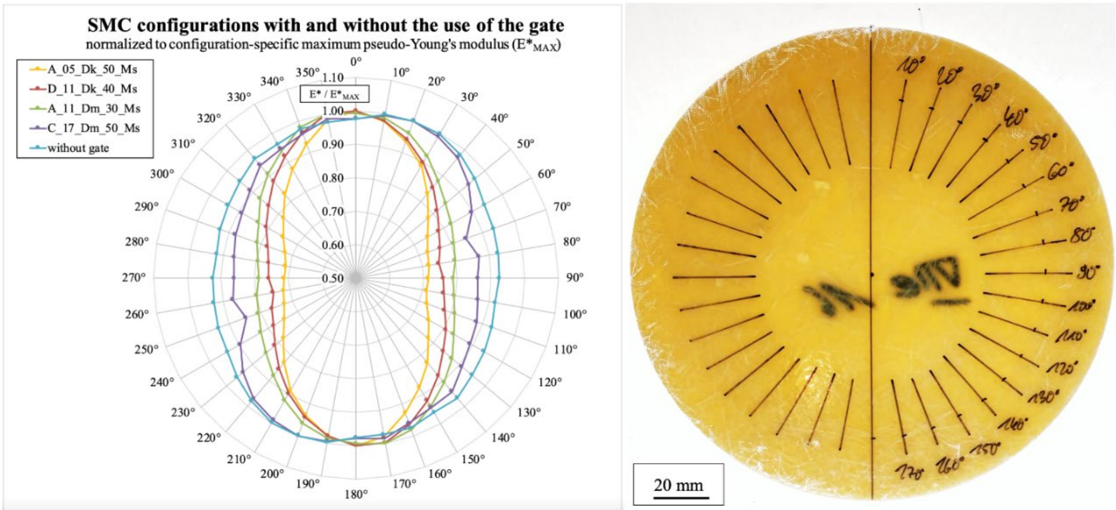


Figure 4 – Left: normalized pseudo Young's (E) modulus in dependence of loading angle and specimen type; right: circular disc specimen for mechanical material anisotropy determination*

For the reference material without any targeted fiber alignment, the E^* curve is nearly circular. The maximum value of E^*/E^*_{max} can be found at approx. 20°, indicating that there might be a slight preferential alignment in that direction. There is, however, only minimal orientation-dependent deviation of E^*, with E^*/E^*_{max} never dropping below 0.9 for this material type. The reference material therefore seems to be nearly isotropic. In sharp contrast, the normalized E^* curve of the specimen type with 5 mm spacing between blades (A_05_Dk_50_Ms) exhibits an ellipsoid profile. The maximum value of E^*/E^*_{max} was obtained in the 0° direction, while the minimum value is reached in the 90° direction. The other configurations investigated also show an ellipsoid curve shape, ranging somewhere between the two edge cases previously discussed. The maximum value for E^*/E^*_{max} was also reached in the 0° direction for all configurations with a targeted fiber alignment, independent of blade spacing, while the minimum value is always found in the 90° direction. However, the ellipsoid shape in these configurations is somewhat less pronounced. In general, it can be stated that, the smaller the distance between the blades of the fiber alignment gate, the more ellipsoid the orientation-dependent E^* shape becomes, indicating that the material anisotropy increases. The location of the maximum and minimum values for E^* at 0° and 90°, respectively, indicates that, the fibers are preferentially oriented into the 0° direction.

To quantify the degree of fiber orientation, an anisotropy factor was calculated with E^*_{min} / E^*_{max} for all configurations. The reference material has a mean anisotropy factor of 0.9 across three specimens. The variant C_17_Dm_50_Ms has a mean anisotropy factor of 0.83. The variants D_11_Dk_40_Ms and A_11_Dm_30_Ms reached 0.74 and 0.78, respectively. The variant A_05_Dk_50_Ms has a mean anisotropy factor of 0.71. The results of the mechanical anisotropy characterization seem to match the visual evaluation results. In general, the results of the SMC anisotropy evaluation seem to be in good agreement with the findings of Tröster, who performed his investigations on long fiber reinforced thermoplastic materials [22]. The author also encountered elliptical profiles of the normalized E^* curves and was able to correlate those to the degree of anisotropy of the fiber orientation.

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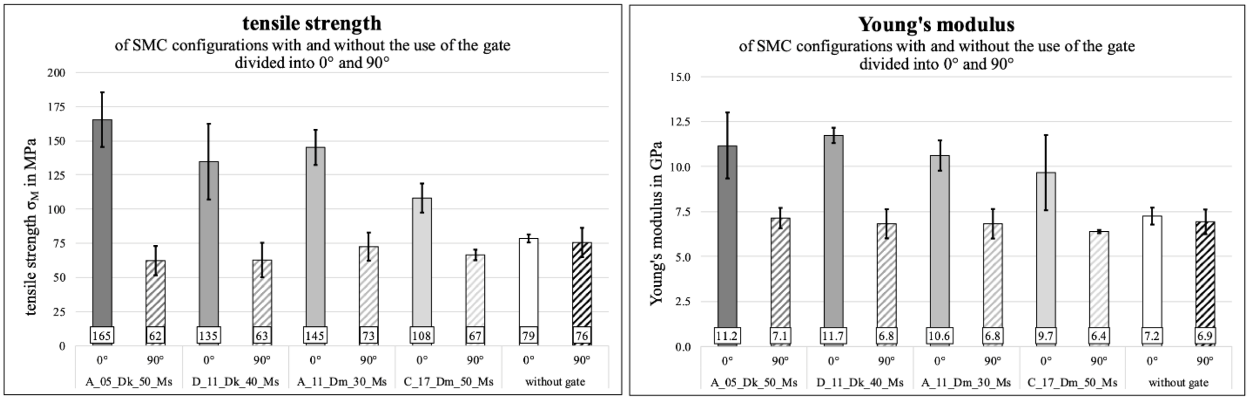

Figure 5 – Left: mean tensile strength in 0° and 90°; right: mean Young's modulus in 0° and 90°

Fig. 5 (left) shows the mean tensile strength of each configuration in dependance of the load direction. For each variant, five specimens were tested. The reference material reached 79 MPa in 0°, and 76 MPa in 90° direction, with no statistically significant difference between those two, indicating that the material is planar isotropic. All other configurations exhibit a significant difference in strength between 0° and 90° load direction. The 17 mm blade spacing configuration (C_17_Dm_50_Ms) reached a mean tensile strength of 108 MPa in 0°, and 67 MPa in 90° orientation. For D_11_Dk_40_Ms, tensile strength was 135 MPa and 63 MPa in 0° and 90°, respectively. The other 11 mm spacing variant A_11_Dm_30_Ms performed similarly, wit 145 MPa and 73 MPa mean tensile strength in 0° and 90°, respectively. Highest strength was achieved for A_05_Dk_50_Ms in 0° direction, with 165 MPa, while in 90°, only 62 MPa were measured, on average. Standard deviation was, in general, in the normal range for SMC, indicating that there was no negative influence on process robustness with the fiber alignment setup integrated into the process chain. A clear anisotropy was found for all material variants with the fiber gate setup, showing a significant increase in 0°, and a corresponding drop in 90°. Based on fiber content determination measurements via thermogravimetric analysis, the reference material has an average fiber wight fraction of approx. 29.6 %, while the other material variants were, on average, closer to 35 %. The scatter of measured fiber mass was relatively large. While the difference between the different material variants was not statistically significant overall, the seemingly lower average fiber content in the reference material might be a possible reason for the relatively low mean tensile strength of the reference material. The target fiber weight fraction of 40% was not matched for any of the material variants.

Fig. 5 (right) shows the mean Young's modulus of each configuration in dependance of the load direction. The reference material reached 7.2 GPa in 0°, and 6.9 GPa in 90° orientation, once again showing isotropic material behavior. The other materials showed a significant difference between 0° and 90°. C_17_Dm_50_Ms reached 9.7 GPa and 6.4 GPa, respectively. D_11_Dk_40_Ms reached 11.7 GPa and 6.8 GPa, while A_11_Dm_30_Ms reached 10.6 GPa and 6.8 GPa, respectively. Finally, A_05_Dk_50_Ms reached 11.2 GPa in 0° and 7.1 GPa in 90°. The difference between the 11 mm and 5 mm spacing variants is not significant in neither load direction. The increase in stiffness from the reference material seems to be not as pronounced as the corresponding increase in strength, and the scattering of measured data seems to be also slightly higher. This seems to match the findings of Gan et al. [6], who also saw a difference between strength and stiffness gain for their aligned materials. The tensile testing results seem to fit well with the circular disc and visual characterization results.

Conclusions

In this work, semi-finished SMC with a preferential fiber orientation was successfully produced, using a vibrating gate for fiber alignment during material production on the SMC line. Multiple configurations of the fiber alignment setup were investigated. It was found that the spacing between the blades of the gate had the biggest impact on the resulting fiber alignment within the SMC, with smaller spacing resulting in a bigger fraction of fibers being oriented in processing direction. Best results were obtained with a 5 mm spacing between blades, with approx. 56 % of fibers being oriented within ±20° of the production direction. Other process parameters, mainly related to the vibration of the experimental setup, were found to be important for the avoidance of fiber buildup on the gate, while otherwise not exhibiting any significant influence on the fiber alignment.

The material produced showed significant anisotropy throughout both visual and mechanical characterization, with one material reaching an anisotropy factor E^*_{min} / E^*_{max} of 0.71. In 0° orientation, this material variant reached 165 MPa in strength, and 11.2 GPa in stiffness under tensile load, which is remarkable for a mean glass fiber weight fraction of approx. 35%. A material with such a preferential fiber alignment is potentially of great interest for certain applications with clearly defined load paths.

References

[1] AVK - Industrievereinigung Verstärkte Kunststoffe e. V., Ed. 2013. Handbuch Faserverbundkunststoffe/Composites. Springer Fachmedien Wiesbaden, Wiesbaden.

[2] Barnett, P. R. and Ghossein, H. K. 2021. A Review of Recent Developments in Composites Made of Recycled Carbon Fiber Textiles. Textiles 1, 3, 433-465. https://doi.org/10.3390/textiles1030023

[3] Beuth Verlag GmbH. 2005. DIN EN 14598-1, Berlin. DOI=10.31030/9598327.

[4] Diestel, O. and Hausding, J. 2011. Vorimprägnierte textile Halbzeuge (Prepregs). In Textile Werkstoffe für den Leichtbau, C. Cherif, Ed. Springer, Berlin, 381-399. https://doi.org/10.1007/978-3-642-17992-1_11

[5] Dommes, H. 2010. Vom Faserabfall zum hochwertigen Leichtbau-Halbzeug: CFK-Organofolie. Lightweight Design 3, 5, 23-27. https://doi.org/10.1007/BF03223621

[6] Gan, K. W., Ho, Y. W., Ow, Z. Y., Israr, H. A., and Wong, K. J. 2019. Aligned discontinuous carbon fibre tows in hybrid composites and their tensile behaviour: An experimental study. Journal of Composite Materials 53, 26-27, 3893-3907. https://doi.org/10.1177/0021998319849697

[7] Harper, L. T., Turner, T. A., Martin, J., and Warrior, N. A. 2009. Fiber Alignment in Directed Carbon Fiber Preforms. Journal of Composite Materials 43, 1, 57-74. https://doi.org/10.1177/0021998308098151

[8] Henning, F., Drechsler, K., and Chatzigeorgiou, L. 2020. Faserverstärkte Kunststoffe. In Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung, F. Henning and E. Moeller, Eds. Hanser, München, 335-379. https://doi.org/10.3139/9783446459847.014

[9] Henning, F. and Moeller, E., Eds. 2020. Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung. Hanser, München. https://doi.org/10.3139/9783446459847.fm

[10] Liu, Z., Turner, T. A., Wong, K. H., and Pickering, S. J. 2021. Development of high performance recycled carbon fibre composites with an advanced hydrodynamic fibre alignment process. Journal of Cleaner Production 278, 123785. https://doi.org/10.1016/j.jclepro.2020.123785

[11] Liu, Z., Wong, K., Thimsuvan, T., Turner, T., and Pickering, S. 2015. Effect of fibre length and suspension concentration on alignment quality of discontinuous recycled carbon fibre. In 20th International Conference on Composite Materials, ICCM 2015.

[12] Longana, M. L., Ong, N., Yu, H., and Potter, K. D. 2016. Multiple closed loop recycling of carbon fibre composites with the HiPerDiF (High Performance Discontinuous Fibre) method. Composite Structures 153, 271-277. https://doi.org/10.1016/j.compstruct.2016.06.018

[13] Manis, F., Stegschuster, G., Wölling, J., and Schlichter, S. 2021. Influences on Textile and Mechanical Properties of Recycled Carbon Fiber Nonwovens Produced by Carding. Journal of Composites Science 5, 8, 209. https://doi.org/10.3390/jcs5080209

[14] Orgéas, L. and Dumont, P. J. J. 2012. Sheet Molding Compounds. In Wiley Encyclopedia of Composites. Wiley, 1-36. DOI=10.1002/9781118097298.weoc222. https://doi.org/10.1002/9781118097298.weoc222

[15] Papthanasiou, T. D. 2022. Flow-Induced Alignment in Composite Materials. Woodhead Publishing Series in Composites Science and Engineering Ser. Elsevier Science & Technology, San Diego.

[16] Plinke, B., Dix, B., Andrä, H., Schneider, M., and WKI, F. 2017. MDF Faserorientierung.

[17] 2022. Saechtling Kunststoff-Handbuch. Hanser, München.

[18] Schürmann, H. 2005. Konstruieren mit Faser-Kunststoff-Verbunden. VDI. Springer, Berlin https://doi.org/10.1007/b137636

[19] Such, M., Ward, C., and Potter, K. 2014. Aligned discontinuous fibre composites: a short history. J. Multifunct. Compos 2, 3, 155-168. https://doi.org/10.12783/issn.2168-4286/2/3/4/Such

[20] Teschner, R. 2019. Glasfasern. Springer Berlin Heidelberg, Berlin, Heidelberg.

[21] Tinevez, J.-Y. 2018. Directionality plugin for ImageJ. https://imagej.net/plugins/directionality. Accessed 30 April 2024.

[22] Tröster, S. 2003. Materialentwicklung und-charakterisierung für thermoplastische Faserverbundwerkstoffe im Direktverfahren, Universität Stuttgart.

[23] Woidasky, J. 2020. Recyclingfähigkeit und End-of-Life-Konzept im Leichtbau. In Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung, F. Henning and E. Moeller, Eds. Hanser, München, 1141-1160. https://doi.org/10.3139/9783446459847.041

[24] Wong, K. H., Turner, T. A., Pickering, S. J., and Warrior, N. A. 2009. The potential for fibre alignment in the manufacture of polymer composites from recycled carbon fibre. SAE International journal of Aerospace 2, 2009-01-3237, 225-231. https://doi.org/10.4271/2009-01-3237

[25] Yu, H., Potter, K. D., and Wisnom, M. R. 2014. A novel manufacturing method for aligned discontinuous fibre composites (High Performance-Discontinuous Fibre method). Composites Part A: Applied Science and Manufacturing 65, 175-185. https://doi.org/10.1016/j.compositesa.2014.06.005