Lower Pressure in the RTM-Process

Glass Mats Improve the Impregnation Properties in CRP Processing

Non-woven fabrics of carbon fibers include a large potential for lightweight construction at the price of challenging impregnation properties. To reduce cycle times when producing components of carbon fiber-reinforced plastics (CFRP), processors can benefit from the high permeability of glass fiber mats.

Previously used at small numbers in super sports cars, the automotive sector is increasingly employing CFRP components for energy efficient compact cars, at large series. As a result of the rise in numbers of items produced, the cost model is changing. This affects all technical aspects of production. Neglecting the special factors such as prestige and brand image, fiber composite materials are considered uncompetitive at present [1].

The two factors boosting the cost of CRP component production are excessive cycle times and excessive investment required for production equipment. To reduce cycle times, highly reactive resin systems are employed. With reaction speeds of epoxy resins mainly determined by mold temperatures, the RTM process is increasingly used at high temperatures. The trend can be observed at some automotive suppliers in Germany. High mold temperatures reduce the time that is necessary to process the matrix, which reduces cycle time. This fast impregnation requires high injection pressure. This increases the investment cost for equipment.

In order to utilize the lightweight potentials of CFRP materials in large series, production costs have to be reduced

Reducing Injection Pressure

To solve this conflict of goals, several different approaches aimed at reducing injection pressures are under investigation. Respective gating concepts are able to reduce the impregnation path. Some process variants make use of high permeability in parallel direction to the fiber during injection, by having the preform overflow, with subsequent impregnation in orthogonal direction to the fiber surface [2–4]. In expert literature, reports can be found concerning an increase in permeability by using layers to support the flow [5, 6]. Even though it is a known fact that they have been used in the serial production of automotive components, little information is available on flow supporting layers as to the improvement of their filling times in regard to their potential for lightweight construction. Barely any experimental data is at hand to show the relation between reduction in filling time and permeability of the fiber material, but could help adapt the fiber materials' efficiency and improve the robustness of the fiber impregnation.

This article will describe the experimental characterizations of four different layer structures, with glass mats intro- »

Layer structure		1	2	3	4
Thickness of the top layer	[mm]	1.0	0.67	0.34	0.0
Thickness of the middle glass layer	[mm]	0.0	0.66	1.32	2.0
Thickness of the bottom layer	[mm]	1.0	0.67	0.34	0.0
Weight per unit area	[g/m²]	6x306	2x306 / 2x215 / 2x306	1x306 / 4x215 / 1x306	6x215

Table 1. Layer structures investigated

Layer structure		1	2	3	4
K saturated	[10^{-10} m²]	0.311	3.17	7.39	8.77
Relative standard deviation saturated	[%]	9.1	18.0	9.2	18.0
K unsaturated	[10^{-10} m²]	0.281	2.00	4.67	5.44
Relative standard deviation unsaturated	[%]	15.5	24.3	16.8	14.4

Table 2. Saturated and unsaturated K values

Layer structure		1	2	3	4
Tensile modulus	[MPa]	50,162 ± 2,593	35,703 ± 984	25,799 ± 1114	9,497 ± 363
Tensile stiffness	[MPa]	945 ± 114	609 ± 27	374 ± 28	135 ± 7
Flexural modulus	[MPa]	44,604 ± 3,152	39,674 ± 3,225	37,568 ± 3,873	9,943 ± 1,479
Flexural strength	[MPa]	987 ± 42	829 ± 31	737 ± 64	258 ± 10

Table 3. Overview of the mechanical characteristics determined

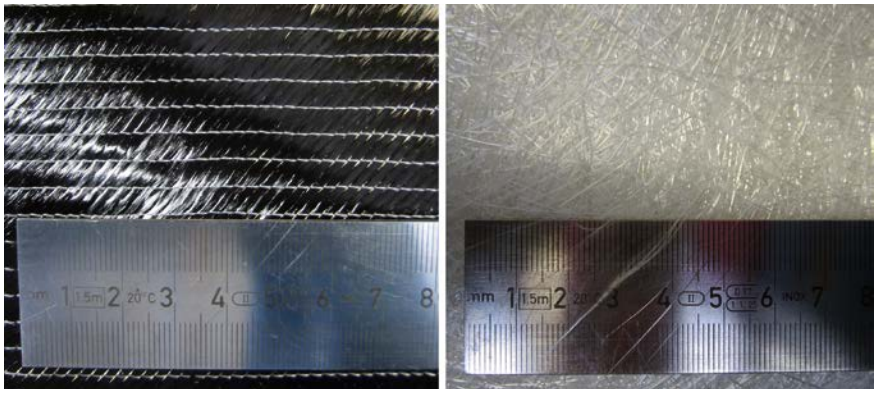

Fig. 1. As a reinforcing layer, a biaxial non-woven carbon fiber mat (left) is applied, while a random glass fiber mat (right) layer serves to support the flow

duced step by step to replace one of the flow supporting layers in the symmetrical plane. The relation between the resulting mechanical properties and the fiber material's permeability serves as the criterion of evaluation here. Permeability serves to indicate processability.

As a matrix material, an amine curing epoxy system (type: Epikote 05475 with hardener Epikure 05443, manufacturer: Momentive, Columbus, Ohio/USA) is used. Two different semi-finished products are employed. The flow supporting layer consists of a random glass fiber mat with an average fiber length of 49 mm and a weight per unit area of 215 g/m². A biaxial non-woven carbon fiber mat (type: C300BX, manufacturer: Hacotech, Hamburg) serves as a reinforcing layer. Its weight per unit area is 306 g/m². Four different layer structures are designed from these two materials (**Table 1**). **Figure 1** presents the materials employed. Each layer is 0.33 mm thick.

The RTM mold employed features a central gating and a cavity height of 2 mm (**Fig. 2**). The tool is closed by a hydraulic locking mechanism (type: Cannon 75 t, manufacturer: Cannon Solutions UK Ltd., Manchester, Great Britain). Injection pressure is applied by means of a pressure pot injection unit (type: 11DT010 - pressure pot, manufacturer: Dekumed GmbH & Co. KG, Bernau, Germany).

Each preform is built up from manually pre-cut single layers (carbon/glass) without using a binding agent. The complete layer structure is eventually cut to the dimensions of the RTM cavity. To prevent effects that might hinder flow at the gating in normal direction, a 32 mm diameter hole is introduced into the fiber material at the central gating. The preform is placed into the mold heated to 60.5 °C, and the mold is then closed at 750 kN clamping force. After that, pressure is evacuated from the mold down to a value below 4 mbar. The temperature of the fiber material is adjusted to that of the mold prior to injection.

The operator manually mixes resin and hardener for approx. 1 min. After mixing, the resin system is introduced into the pressure pot unit and a 6 bar injection pressure is built up. Opening the inlet while, at the same time, maintaining the vacuum at the outlet starts isothermal injection. The injection period is finished when the resin system emerges via the outlet. As soon as the first air bubbles emerge, the outlet pipe is locked and a dwell pressure of 2 bar maintained.

Measuring Permeabilities

Due to the annular outlet, the filling times measured during injection may vary. This is why the permeabilities of the four layer structures are tested in K_x-direction and compared to each other in a one-dimensional test stand. The test method is based on that employed in the comparative study [7]. The experimental set-up is described in [8]. Injection pressure as well as the temperature of the measuring oil are measured. The viscosity of the measuring oil (sunflower oil) is 53.3 mPas at 22.5 °C. The fiber volume content is calculated from the measured preform mass.

To evaluate the unsaturated measurement, the points in time are optically measured at defined distances in the test stand. As a result, the flow front position is known at several points in time and with their pressure difference. Evaluation is based on the „Squared Flow Front Approach" according to [8]. To calculate per-

meability K, one assumes constant boundary conditions (injection pressure, temperature) during the measurements.

Saturated permeability is additionally measured on each specimen at five different pressure levels. Volume flow is determined in a gravimetric measuring process. The known pressure difference Δp, the volume flow and the geometry of the test set-up serve as the basis to calculate permeability:

$$Q = -\frac{K_x}{\eta * A * (1-\varphi)} \frac{\Delta p}{\Delta x}$$

with: Q = volume flow
K_x = permeability in x-direction
η = viscosity
A = flow-through cross-section
Δx = sensor distance

The photomicrographs taken of polished sections show no increased porosities, even though the resin system was not degassed after manual mixing. After the tempering process, the plates did not deform. The test specimens are plane.

The unsaturated permeability corresponds to the case of RTM injection application and should therefore be used, generally, as a measuring variable. **Table 2** shows the permeability values (K) of the four layer structures in a comparison. What is striking is the significant deviation between saturated and unsaturated values in structures 2 to 4. The unsaturated values are lower, because the flow front in the glass layer extends much faster than in the carbon layer. This is why it is impossible to determine the front correctly by optical means. This corresponds to the article by Luce et al. [9] reporting deviations from Darcy's law in multi-layer structures. Due to this uncertainty in the determination of unsaturated permeability, saturated permeability is employed as a measure to determine the improvement in impregnation properties.

Reduction in Injection Time

In order to measure flow-improving behaviors, the four layer structures are compared to each other concerning filling times and measured permeabilities.

As compared to the mere carbon structure (structure 1), filling time is 77.2 % shorter for structure 2, for structure 3, it is 83.8 %, while filling time for the glass mat structure is reduced by 95 %. Some of the specimen mats used in structure 1 could not be completely impregnated up to their corners which is why the measured values do not represent reliable results.

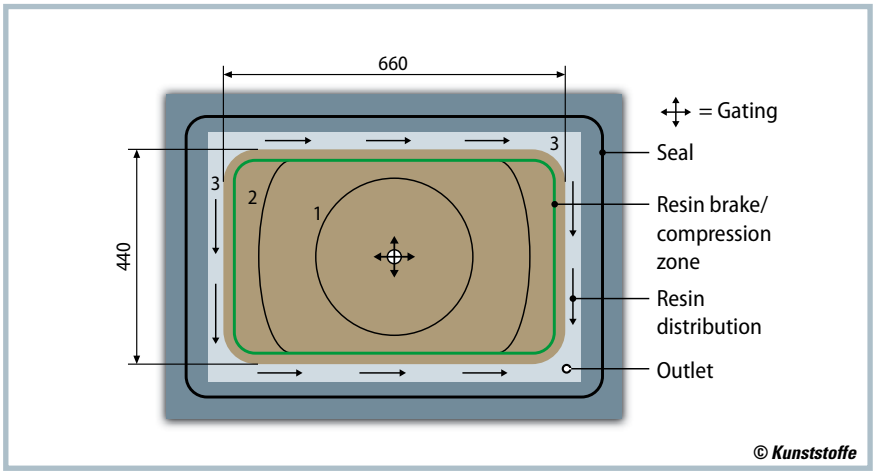

Fig. 2. Schematic presentation of the test mold with central gating and annular outlet. 1) Radial extension of the resin front; 2) the flow brake restricts resin flow on the narrow side, thus enabling filling of the rectangle within the compression zone; 3) the component is filled in the compression zone. After component filling, a rinsing phase follows

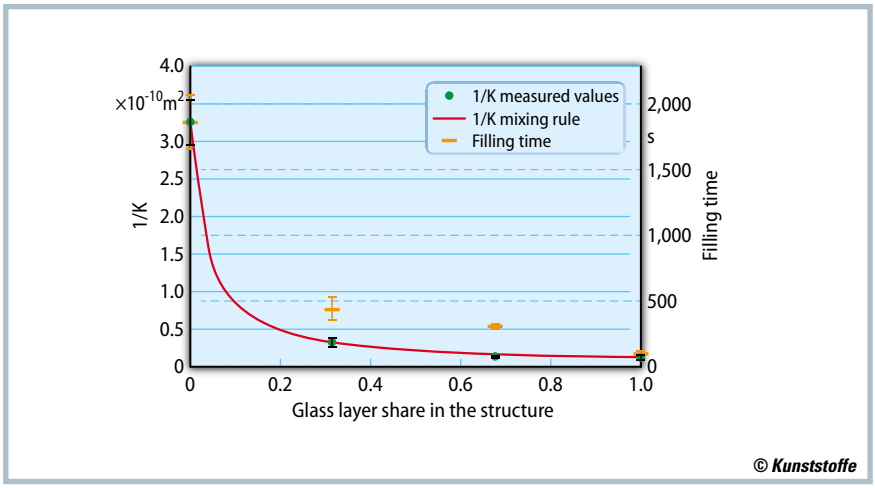

Fig. 3. Comparison of filling times to index 1/K

To align RTM trials and permeability measurements, Darcy's equation is solved for the one-dimensional case after filling. **Figure 3** presents the filling times and measured K values as index 1/K. On the basis of the K values of the mere glass structure and of the carbon structure, permeabilities were calculated by means of the mixing rule [9] based on wall thickness. In terms of quality, the RTM tests show a good correspondence with the permeability measurements.

Effect on Mechanical Characteristics

So as to achieve the maximum possible characteristic values, all components are submitted to posterior annealing in an oven. The annealing cycle rises gradually at 4 K/min, from 70 to 90 °C, followed by eight hours of holding phase, with subsequent gradual cooling, at 4 K/min again, down to room temperature. Five specimens are taken from each of the plates, to be investigated in tensile and bending tests at 0/90° orientation. The tensile properties are tested according to German Industrial Standard DIN EN ISO 527-4, bending properties are investigated according to DIN EN ISO 14125 class IV.

For a comparison of the mechanical characteristics of the four structures, see **Table 3**. In line with the carbon share diminished in tensile direction, the tensile modulus decreases linearly. The flexural modulus also decreases as the carbon share is diminished. The gradient of reduction is smaller. This is due to the Steiner share, because the flow-supporting layer was introduced into the neutral »

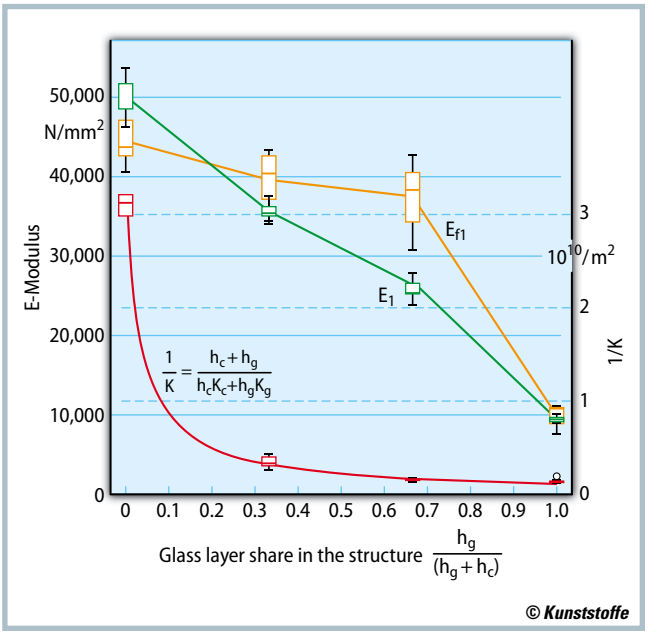

Fig. 4. Relation between 1/K and E-moduli

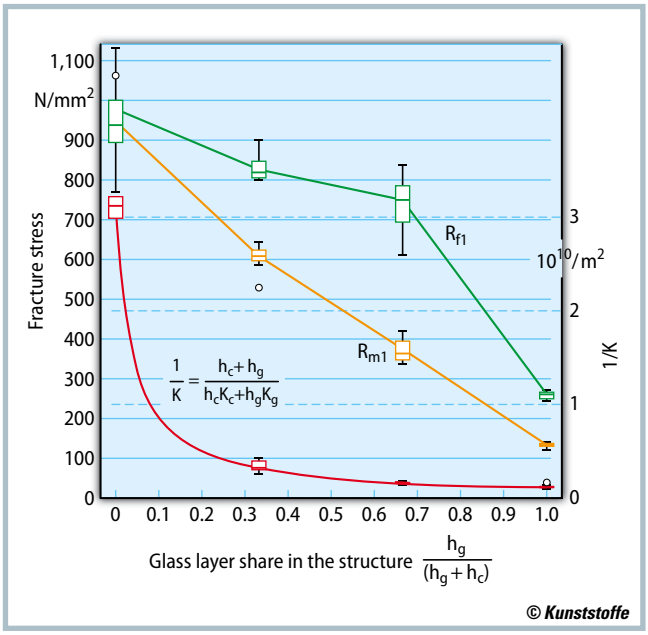

Fig. 5. Relation between 1/K and stiffnesses

fiber. The stiffness values determined behave in analogy to the modules.

Figures 4 and 5 show the relation between mechanical characteristics and improvement of filling time, represented by the 1/K value. Subject to the requirements posed to the respective component, the maximum possible share of glass layer becomes visible in this presentation.

Even low shares of a glass mat improve impregnation properties significantly. The mechanical characteristic values are diminished. Scattering of the mechanical characteristic values is increased as the share of glass rises (**Figs. 4 and 5**). The exact cause is not determined unambiguously. An interrelation between increased scattering and higher interlaminar shear stress was not tested experimentally. Prior to using the component in a product, this aspect needs to be considered in detail. Calculation according to the mixing rule for saturated permeability behaves similar to the filling times for the component, in terms of quality (**Fig. 3**).

The presentations in **Figures 4 and 5** help determine the deterioration in mechanical characteristics related to the reduction in filling time as a function of the glass share. For the lay-out of the flow-improving layer, the present material system shows a good agreement with the mixing rule based on wall-thickness. For the material combinations under consideration, the composite properties can be calculated according to the classical laminate theory, and the improvement of filling time can be calculated with the mixing rule. Thus, on this basis, the engineer can find an optimum corresponding to the respective component requirements.

Impact on Production Costs

The lower share of carbon fibers directly reduces the expenses involved, while the lower cost of production and shorter production times, respectively, reduce costs in an indirect way. For example, the material costs involved in structure 2 are 28% below those of structure 1. If multiplying material costs by filling time, the costs of structure 2 are 83.5% lower than those of structure 1.

In this case, pressure was maintained constant during injection, and so the reduced time of injection reflects the cost benefit. If injection is controlled by melt flow, the pressure generated in the mold is reduced, according to Darcy. With injection time preset, the clamping force necessary for the locking mechanism can be reduced in this way, which reduces the investment cost required for production. ■

The Authors

Dipl.-Ing. Wolfgang Raffelt has worked as an external research associate at the Chair of Carbon Composites at the Technical University of Munich, Germany (TUM) since 2014.

Dipl.-Ing. Daniel Häffelin has been a research associate at the Chair of Carbon Composites at the Technical University of Munich (TUM) since 2010.

Prof. Dr.-Ing. Klaus Drechsler has been head of the Chair of Carbon Composites at the Technical University of Munich (TUM) since 2009.

Service

References & Digital Version

You can find the list of references and a PDF file of the article at *www.kunststoffe-international.com/886057*

German Version

Read the German version of the article in our magazine *Kunststoffe* or at *www.kunststoffe.de*