GLASS FIBER MULTILAYER CONSTRUCTION FOR TEXTILE REINFORCED INJECTION MOLDED STRUCTURES

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ABSTRACT

Plastic components can be locally reinforced in a load-appropriate manner by integrating textile reinforcement structures into injection molds. However, thermoplastic prepregs are expensive because they are subjected to costly preliminary impregnating processes, so they have hardly gained general acceptance. Also, in the injection molding process a strong matrix-matrix bonding of the prepreg matrix with the injected melt is required in terms of short injection times. This is a critical fact due to residual stresses resulting from shrinkage effects during melt solidification. A new kind of non-crimp fabric in a multilayer design, based on OLU-Preg®-technology (SKM GmbH, Germany), is considered particularly advantageous, whose outer fiber layer impregnation will be completed in the injection molding process. Apart from lower manufacturing costs of this kind of prepreg, the impregnation process with the injected melt leads to an anchoring between the textile structure and thermoplastic melt as observed in in-mould decoration processes.

Index Terms: Injection moulding, melt impregnation, sandwich structure, non-crimp fabric

1. INTRODUCTION

Textile-reinforced thermoplastic components can be produced efficiently using press or injection moulding technologies. Injection moulding technology allows the integration of thermoplastic prepregs into the mould cavities, in which the prepregs are being back-injected in order to shape stiffening structures such as ribs or other complex geometries. However, thermoplastic prepregs are still characterised by considerable material costs since the preceding impregnation is a technologically complex process. Moreover, in injection moulding it is necessary to create a good connection to the injected plastic. Due to ensuing shrinkage and the resulting residual stresses this becomes an important factor during the process [1-3].

By using partially impregnated textile structures a higher bonding strength can be achieved, due to the fact that the impregnation of the outer fibre layers leads to an anchoring between the textile structure and thermoplastic melt as observed in in-mould decoration processes [4]. The melt impregnation, which means the encapsulation of every single fiber by the molten polymer, takes place within the injection process. This proves to be problematic due to the high viscosity of thermoplastic melts. Especially the micro impregnation of each roving bundle is of vital interest. Due to small flow gaps, high pressure gradients are necessary to keep the melt flow running. Also, the early freezing of the flow front forms a challenge, since a considerable heat transfer from the polymer melt into the cold cavity walls and fibres takes place.

The impregnation process of textile fibre bundles with a thermoplastic melt was first investigated for the production of long fibre reinforced thermoplastic pellets or tapes by using the common method of pulling unidirectional glass fibre bundles over several pins within a polypropylene or polyamide melt pool [5, 6]. An advantageous melt impregnation assessment technique is the determination of mechanical properties of the composite, which are related to the degree of melt impregnation and avoid time-consuming preparing of polished photomicrographs [7]. The impregnation of the fibre bundles during injection moulding is preferably carried out in the direction of thickness due to the increasing melt pressure along the flow distance. However, in doing so the number of the embedded single fibre layers is limited. Basic investigations on the embedding of fibre bundles into the injection moulding process and their resulting connection strength in the plastic have shown that only a few of the single fibre layers can be impregnated [8].

In this study the fibre bundle pull-out test was used and adopted on process related test specimen for indirect mechanical measurement of fibre bundle melt impregnation in injection moulding process. With the results of the fibre bundle pull-out test a novel textile glass fibre structure with multiple layers based on non-crimp fabrics was used which allows the impregnation of the outer fibre layers during the injection moulding process [9].

2. MELT IMPREGNATION ASSESSMENT TECHNIQUE

The direct melt impregnation of textile structures in injection moulding process has been investigated for determining a critical count of fibre filament layers which can be impregnated. The impregnation quality was verified via a fibre bundle pull-out test and optical by polished micrographs.

The common single fibre or fibre bundle pull-out test allows the pull of pure fibres out of a block of resin. To maintain the typical injection moulding process for impregnation of the fibre bundles the original test set-up needs to be adapted to the process. For partial insert moulding of the roving, which is necessary to have a free end for pull out, it has to lead through the closed and sealed mould, which is critical due to the brittleness of glass fibres. To avoid fibre fractures, the test set-up was modified in such a way, that the whole test specimen was integrated in the cavity. A geometrical form of a T-beam was chosen, whereas the notch between the cross beam and the lengthwise beam caused a crack during load increase and led to separation into a pulled-out roving and remaining polymer block (Figure 1, left and middle). The curve of measured load over displacement has a typical characteristic for both single fibre and fibre bundle pull-out tests (Figure 1, right). With load build-up the displacement starts linear in the phase of elastic material behaviour. With crack initiation and transition in ductile material behaviour, displacement increases nonlinear to maximal load, which leads to sudden debonding of the fibre or fibre bundle.

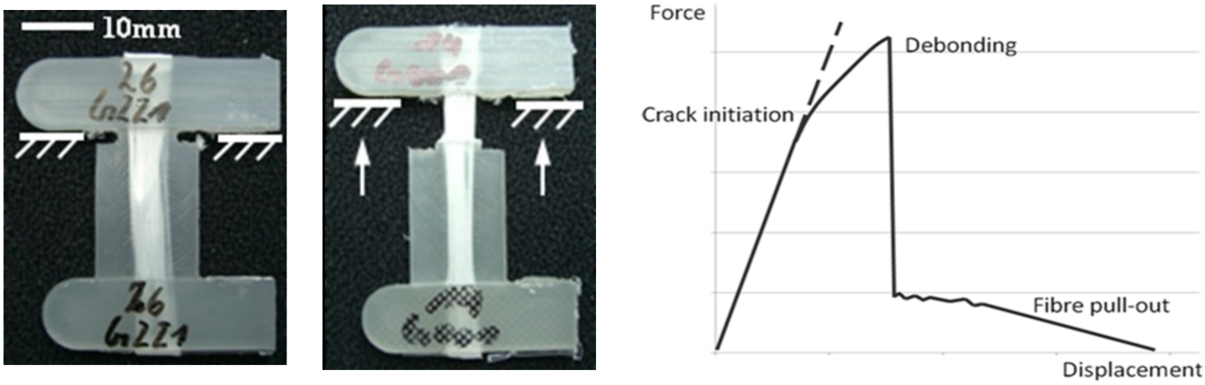


Figure 1: Injection moulded samples for fibre bundle pull-out test (left and middle) and typical load-displacement curve for fibre bundle pull-out test (right)

Several commercially available E-glass fibre rovings with 2,400 tex, 1,200 tex and 600 tex were used for impregnation tests. Besides the variation of yarn count the differentiation in spreading width was considered. The fibre diameter of all types was 16-17 µm. The sizing type for all rovings was a silane/silicone sizing with concentration between 0.4 and 0.64 %w/w which was determined by IR-Spectroscopy and Thermogravimetric Analysis. A high fluidity Polypropylene Homopolymer was used for melt impregnation of the rovings. The polymer was measured with a zero shear rate viscosity of 220 Pa*s at 190 °C and 85 Pa*s at 230 °C with. A maleic anhydride modifier (PP-g-MAH) was added to the polymer with 2% w/w to improve the fibre-matrix adhesion.

Higher tex numbers lead to an almost linear increase of the calculated debond load, since an increasing spread of the rovings leads to an increased circumferential surface. Once a complete impregnation is achieved, the debond load cannot longer increase regardless of further spreading. However, this can only be observed for rovings with a maximum density of 600 tex (Figure 2). These results allow the definition of a critical fiber bundle spreading width, which is necessary for a complete impregnation within the boundary conditions of the injection moulding process. It is reached, when a further spread of the fiber bundle has no increase in tensile load. Assuming the fiber bundle geometry with a rectangular cross section, the critical spreading width also leads to a maximum of fiber layers, lying upon another, which the polymer melt can impregnate. The critical number of fiber layers for the melt impregnation was estimated which an average value of about 8. For rovings with the yarn count of 1,200 tex a minimum spreading width of 4 mm and for 2,400 tex a spreading width of 6 mm is necessary. These results could be verified by the polished photomicrographs, which were taken from the cross section of the embedded rovings (Figure 3). The poor impregnated rovings shows a boundary area with impregnated fibres while the inner fibres remain unimpregnated and therefore without reinforcement effect. With better spreading the number of impregnated fibre layers stays constantly while the inner unimpregnated area becomes smaller.

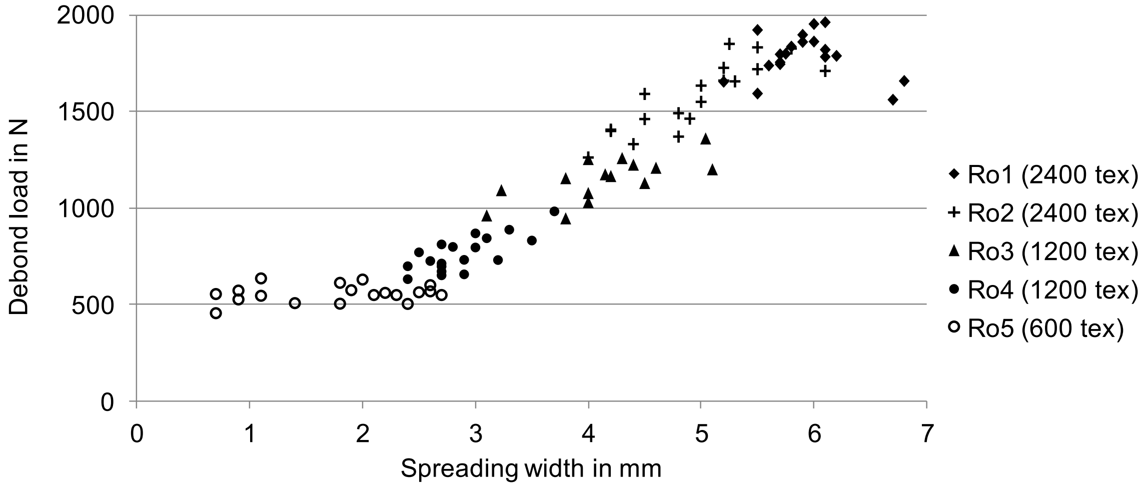


Figure 2: Debond load depending on the fibre bundle spreading width and yarn count

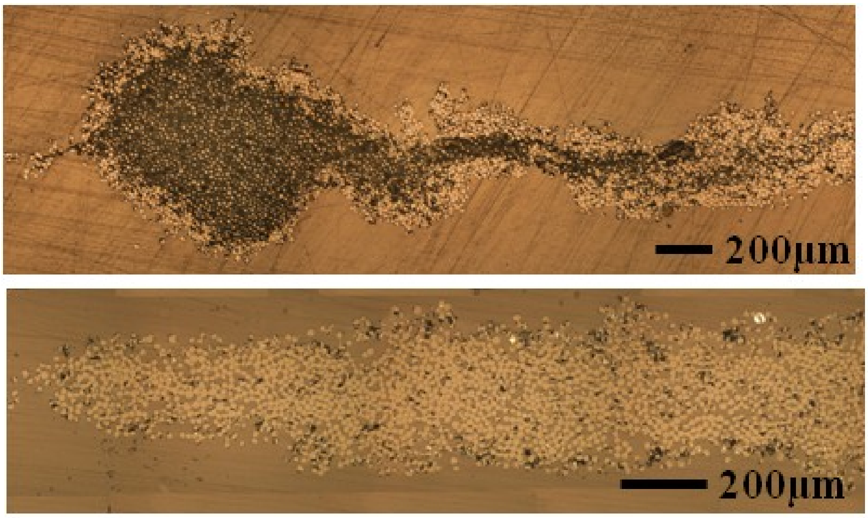


Figure 3: Photomicrographs of melt impregnated 2,400 tex glass roving; above: poor impregnation through low spreading width; below: well impregnated roving with high spreading width

3. INJECTION MOULDING WITH MULTI-LAYER NON-CRIMP FABRICS

Due to the process related fixing of the reinforcement onto the mould wall in the cavity, the integration of textile reinforcement structures into the injection moulded parts has to take place close to the surface. Hence, critical shear stresses between the plastic core and the textile reinforcing layer can be minimised as the largest shrinkage of the plastic melt can be found in the core area of the plastic part. Injection moulded sandwich structures are predestined for a symmetrical design that prevents distortion. For this purpose, flat components with textile reinforced surface layers and a central plastic layer should be used.

Ensuring an optimal connection of the surface layers to the injected plastic, it is ideal to use textile designs with structurally intrinsic flow channels for impregnation with the melt. This results in a micro anchoring. In comparison to a pure adhesive bond, it leads to notably higher bond strengths between the matrix of the textile reinforcement and the injection moulding plastic. Accordingly, the required textile reinforcement structure must have an appropriate partial impregnation, so that the external fibre layer is not yet fully impregnated during pre-consolidation.

The determined critical spreading width in the fibre bundle pull-out test was used for manufacturing load and process adapted textile reinforcements for the injection moulded structures. For this, a multi-layer non-crimp fibre structure was chosen as starting material, which had been produced through OLU-Preg®-Technology at SKL Schwergewebekonfektion Lichtenstein GmbH, Oberlungwitz, Germany. The textile design consists of an alternating layering of unidirectional fibre layers and nonwoven layers made of polypropylene. Here in the basic design, the individual glass fibre layers are connected to a nonwoven layer at a 0° and 90° angle by means of a PP stitch-bonding (Figure 4, left). Through a pressing process with temperature and pressure exposure the PP-nonwoven was transferred into the molten state and, as a matrix, impregnated the unidirectional glass fibre layers. By omitting one of the outer PP-layers during consolidation a textile reinforcement structure could be produced which has multi axial glass fabric layers that are open at one side. For a direct comparison of the sole adhesive bond in injection moulding an alternative was produced that had PP surface layers on both sides. Figure 4, on the right, shows the stacking sequence used for the following consolidation and injection moulding process.

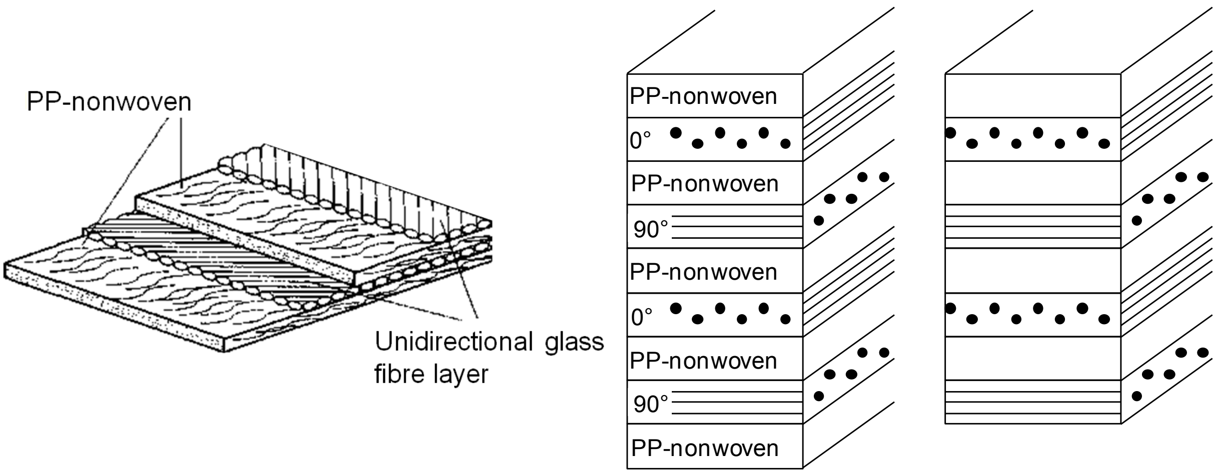
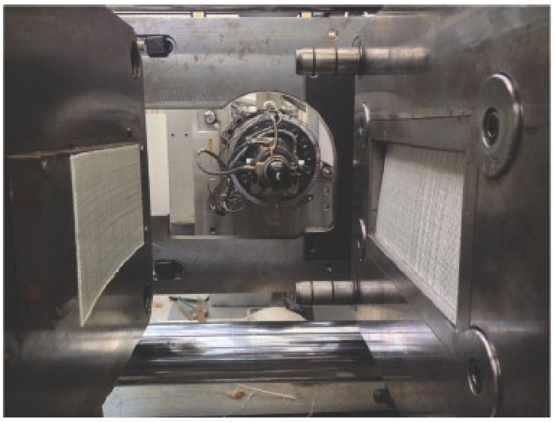


Figure 4: Textile structure of the OLU-Preg® (left) and stacking sequence (right)

According to the experience gained from the embedding of fibre bundles into the injection moulding tests, glass fibre rovings with a density of 300 tex were used for the individual reinforcement layers of the OLU-Preg®. This was done in order to minimise the number of filament layers of the laid rovings and to ensure good impregnation.

The textile starting material, cut into blanks of 700x350mm², was first heated in a heat contact oven for 120 s to approx. 230°C, at a pressure of approx. 5 bar. This was to melt the matrix components in OLU-Preg®. Afterwards, after a quick shift into a press, the pressurised impregnation and consolidation of the reinforcement materials took place. The pressing happened at room temperature and with a pressure of 90 kN for 5 min in order to ensure pressurised cooling almost down to room temperature.

The consolidated OLU-Preg®-reinforcement materials, cut into blanks of 250x100mm², were positioned on the mould walls in a panel-shaped cavity. They were then laterally injected with a bolt-on-aggregate through a hot runner. The positioning on the mould walls was carried out by placing two reinforcement inserts on the mould wall as surface layers with their open fibre layers facing inwards, which then formed a sandwich structure (Fig. 5).



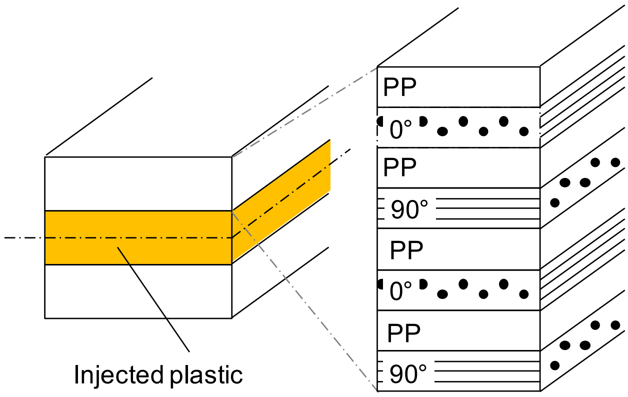


Figure 5: Injection mould with integrated reinforcement layers (left) and resulting sandwich structure (right)

The injected melt impregnated the surface layers and formed the micro-form fitting. Due to the symmetrical structure a non-distorted sandwich panel was created. The cavity was set to 3 mm, which matched the resulting thickness of the panels. The low-viscosity polypropylene-homopolymer HP500V, supplied by Lyondellbasell, again was used as the core material. For better wetting of the glass fibres it also had been modified with the MAH-grafted PP containing 2% by mass. The injection moulding plastic was used in two forms: unreinforced, as well as reinforced with an additional 40% by mass of short glass fibres.

For a good connection to the injected plastic, the surface layers were preheated through a dynamic close-to-cavity fluid heater in the closed mould. As a result of the close fit of the surface layers to the cavity walls, good thermal transfer could be ensured. Preheating up to 150 °C took 150 s, during which an injection delay took place within the injection moulding cycle. Immediately afterwards the plastic was injected and the settings were switched to cooling and packing phase. Altogether the injection moulding cycle took approx. 220 s (Fig. 6).

4. CHARACTERISATION OF INJECTION-MOULDED SANDWICH PANELS

The consolidated semi-finished products made from the multi-layer reinforcement OLU-Preg® were first characterised in terms of their mechanical properties in the tensile test according to DIN EN ISO 527-4. Table 1 summarises the characteristics as well as the values determined in the tensile test for the two variants of surface layers: glass fibre inlays (Variant A) and PP-nonwoven (Variant B).

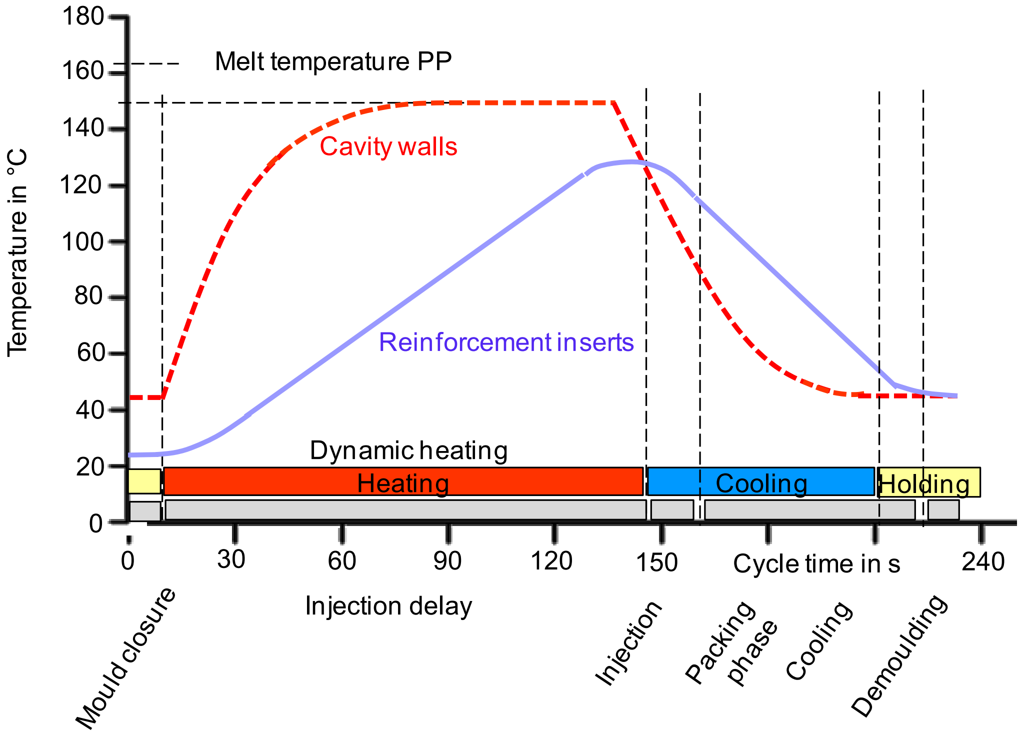


Figure 6: Injection moulding cycle with dynamic fluid heating of the reinforcement inserts

Table 1: Parameters of the consolidated semi-finished reinforcements

	OLU-Preg® Variant A	OLU-Preg® Variant B
layer stackup	PP-0°-PP-90°-PP-0°-PP-90°	PP-0°-PP-90°-PP-0°-PP-90°-PP
area density in g/m²	1100	1175
Thickness in mm	0.8	0.9
fibre volume ratio in %	45	40
modulus of elasticity in MPa	14900	13900
tensile strength in MPa	295	300

The sandwich panels that were produced during injection moulding were then tested for their bending stiffness in the 3-point bending test according to 3-DIN EN ISO 178. The variants that had a surface layer containing glass fibre inlays (Variant A) achieved significantly higher bending stiffness than the variants containing PP-nonwoven surface layers (Variant B). The reason for this is the anchoring between the injected plastic and the reinforcing surface layer, which lead to a better connection in comparison to the pure adhesive bond between the matrix of the surface layers and the injection moulding plastic (Fig. 7).

Generally, a significant increase in bending stiffness could be observed in contrast to the pure injection moulded panels without reinforcing surface layers. This was also noted for the short fibre reinforced panels. Here, the difference between the pure short fibre reinforced panels and short fibre reinforced panels with textile reinforced surface layers results from the higher fibre volume ratio as well as from the continuous fibre orientations of the unidirectional multi-layer reinforcement that are appropriate to the load. Despite higher melt viscosity also the short fibre melt achieved better connection properties with variant A, which results from the micro-from fit during impregnation of the external fibres.

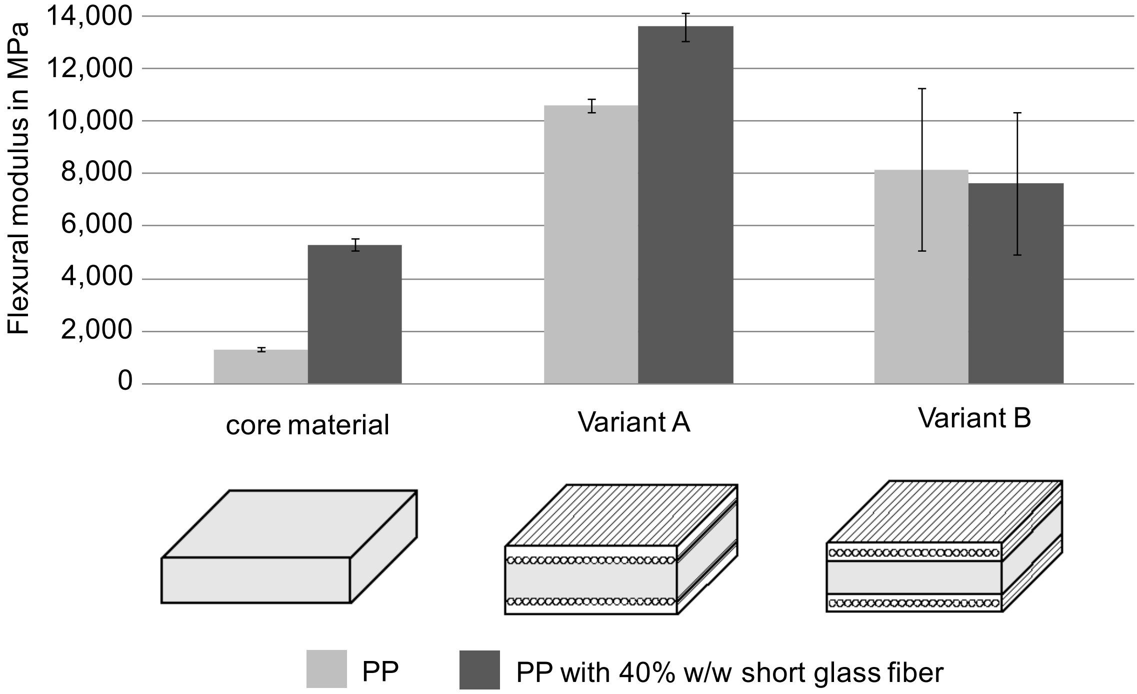


Figure 7: Determined bending stiffness of the sandwich panels with textile reinforced surface layers

5. CONCLUSION

The thermoplastic melt impregnation of textile reinforcements within the injection moulding process is an essential requirement to obtain good mechanical properties. Therefore the fibre bundle pull-out test is a suitable near-to-process test method to determine the impregnation quality of the used fibre and polymer materials. Subject to the existing material and process parameters a critical number of fibre layers could be determined, which could be impregnated through the polymer melt. This fundamental investigations and given results helps to develop process and load adapted textile structures for the local reinforcement of thermoplastic injection moulded parts.

Based on the results of the fibre bundle pull-out test a multi-layer non-crimp fibre structure was chosen with variation of the outer layer construction of the textile reinforcement which connects to the injected melt. Sandwich plates were produced and characterized by 3-Point-Bending test. The glass fibre layers are final impregnated in the injection moulding process and improves significantly the bond strength and therefore bending stiffness of the sandwich construction.

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