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Energy-efficient double belt press with integrated inductive heating system

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Abstract

At the Aachen Centre for Integrative Lightweight Production (AZL) of RWTH Aachen University a new double belt press with inductive heating and elastomer-coated pressure rollers has been developed and optimised within industrial AZL joint partner research projects. This machine system is patented by the AZL and available for industrial trials and also as commercial product in license. This new machine concept enables an efficient, continuous pressing process in a small installation space. The induction allows for a rapid heating of the steel belt material up to 300 °C and the elastomer pressure rollers enable surface contact during pressure application. The double belt press differs from conventional systems as it uses closed-loop controlled inductive heat input and high-temperature resistant elastomer-coated rollers for applying specific pressures up to 23 bar at maximum process temperatures up to 300 °C (current development for up to 400 °C). In extensive trials with several partners from the AZL partner network and external companies, the machine has proven to be efficient for consolidating thermoplastic composite laminates as well as for impregnating both thermoset and thermoplastic composite laminates.

1 Introduction

Fibre-reinforced plastics (FRP) are characterised, among other things, by the fact that the properties of the composite can be adapted to the respective requirements. The processing method can also be selected according to the application. As a result, FRP are used in many technical fields of application. These include, for example, the electrical, sports and automotive industries [1]. However, due to the high costs, FRPs have not yet achieved a breakthrough in many industrial sectors [2]. Due to the scarcity of natural raw materials and ecological challenges such as global climate change, there is a widespread shift in the energy and transport sector towards resource-saving and CO_2-neutral solutions. The use of FRP is increasing in this area and will play a major role in the future [3]. Important applications for the use of FRP are for example electrically driven vehicles and rotor blades for wind turbines. In addition to the weight savings, electric vehicles also benefit from new types of structural concepts that are freed from previous package restrictions [4]. Such high-performance applications require continuous fibre reinforcement [4]. In most cases, a thermoset matrix is used for continuous fibre reinforced composite parts. However, the importance of thermoplastic matrices is increasing. The decisive reason for this is, the possibility of welding and recycling of thermoplastics due to their meltability [5].

At the AZL a new double belt press (DBP) has been developed and is available for trials and the production of the FRP sheets with continuous fibre reinforcement and different matrices. The patented DBP is a proprietary development of the AZL and is more energy efficient than conventional DBPs due to inductive heating of the steel belts. Figure 1 shows the machine and its main specifications.

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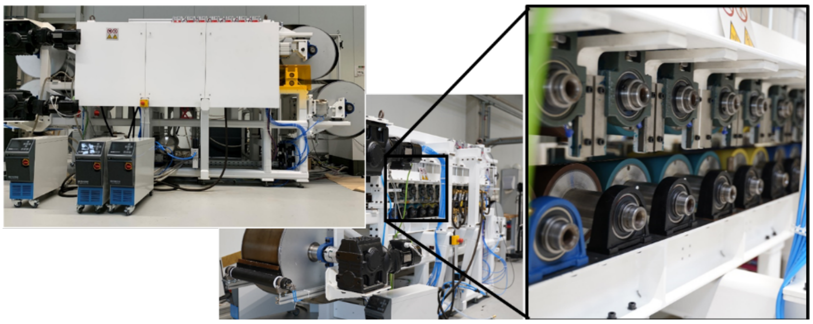


- **Inductive heating** of the steel belts
- Maximum temperature **300°C → current development for up to 400°C**
- Elastomer rollers to achieve a surface pressure
- Maximum pressure **23 bar**
- Different pressure profiles are possible
- Potential **energy savings > 50%** compared to the state of the art
- **Rapid thermal response** to changes in parameters
- **Steel belt width 350 mm**; scalable
- **Easy scalability** of the system to the application: speed, temperature, pressure distribution

Figure 1: Double belt press at the AZL with the main specifications

2 State of the Art

2.1 Press systems for organosheet production

Various presses are used to produce the fully consolidated composite sheets ("organosheets"), which can be divided into the groups discontinuous/static, semi-continuous and continuous on the basis of their mode of operation [3]. In *static systems*, heat input and output take place at the same position, which means that high cycle times are unavoidable. For larger material throughputs, one must resort to continuous or semi-continuous machine systems. In these systems, the material is moved so that areas with different temperatures can be run through. However, the advantage of reduced cycle times is accompanied by high system costs due to the increased system complexity [7]. Interval hot presses are the most important in practice. Compared to *continuous systems*, such as the DBP, the investment costs are lower and profiles can also be produced in addition to flat semi-finished products [2]. Together with the interval hot press, the DBP technology is the most important system concept for the production of organosheets [4]. The inductively heated DBP that was developed at the AZL is a very cost-effective alternative to established double belt press systems, due to its comparably small size and especially the energy-efficient inductive heating system. Compared to commercially available DBP systems with thermal oil-heating, the inductive heating system of the DBP has a potential energy saving of > 50 %, due to the high energy efficiency of induction heating, often times reaching a degree of efficiency of > 90 % [6].

2.2 Double belt press systems

DBP have been established process methods for large series production in the industry for many years. They are suitable for the production of flat FRP components. Their advantages are generally high reproducibility and production performance with tight tolerances [8]. They are relevant for large-scale production due to the highly automatable process and low cycle times. A distinction is made between either a *continuous* or *semi-continuous* design. Depending on the material combination or further processing individual processes have different advantages [9]. Both thermoplastic and thermoset FRP can be produced on a DBP. In the area of thermoset FRP, prepregs, i.e. pre-impregnated semi-finished products, are produced on DBP. The semi-finished products are soft and sticky after processing [1]. In the area of thermoplastic FRP, consolidated sheets are produced. These manufactured sheets are commonly referred to as organosheets [10].

DBP are differentiated into *isochoric* and *isobaric* working systems. Isochoric press systems operate at constant volume. The pressure and temperature build-up is achieved by means of rollers pressurised with compressed air and a heating plate. The working pressure results from the amount of material fed. Material fluctuations during feeding lead to intolerable pressure changes. They are more commonly used in industry than isobaric DBP [8]. Isobaric DBP work with a constant surface pressure. The pressing is done e.g. by pressure pads with oil or air up to max. 100 bar. Handling with liquid heating medium can lead to more difficult handling [2].

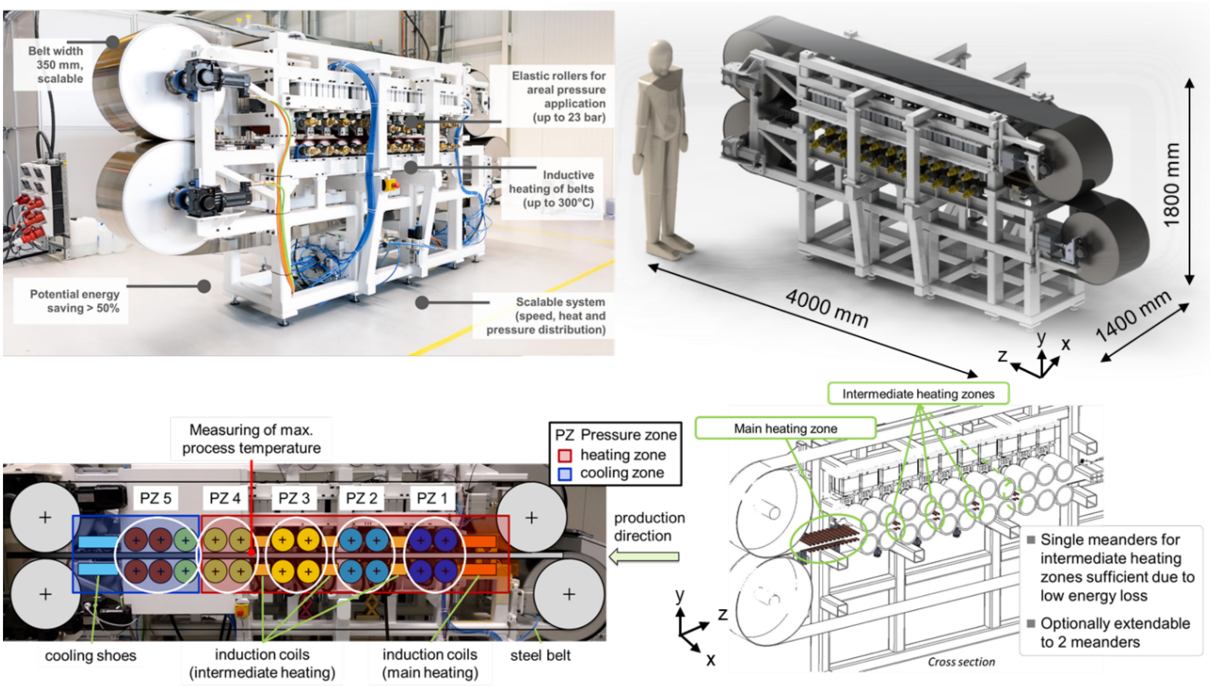


Figure 2: Dimensions and functionalities of the double belt press at the AZL

The DBP of the AZL has a completely new heating and pressure concept (Figure 2): Two separate induction circuits with 40 kW maximum power each ensure very low energy consumption for inductive heating of the steel belts compared to conventional machines, as the heat is only introduced where it is needed - in the steel belt material. For trials with process temperatures of up to 300 °C, only 50 % of the 2 x 40 kW maximum power was needed at a process speed of 300 mm/min. Whereas with conventional machines the heat is transferred to the entire machine and thus also continuously dissipated, the efficient approach of the AZL machine can reduce energy consumption by more than 50 % compared to state of the art DBP systems with steel belts. This not only reduces operating costs but also lowers the environmental footprint of the production process. Another positive aspect of the inductive heating is that the temperature of the steel belt can be changed within a few seconds. Changeover operations with different process parameters are thus completed in the range of minutes.

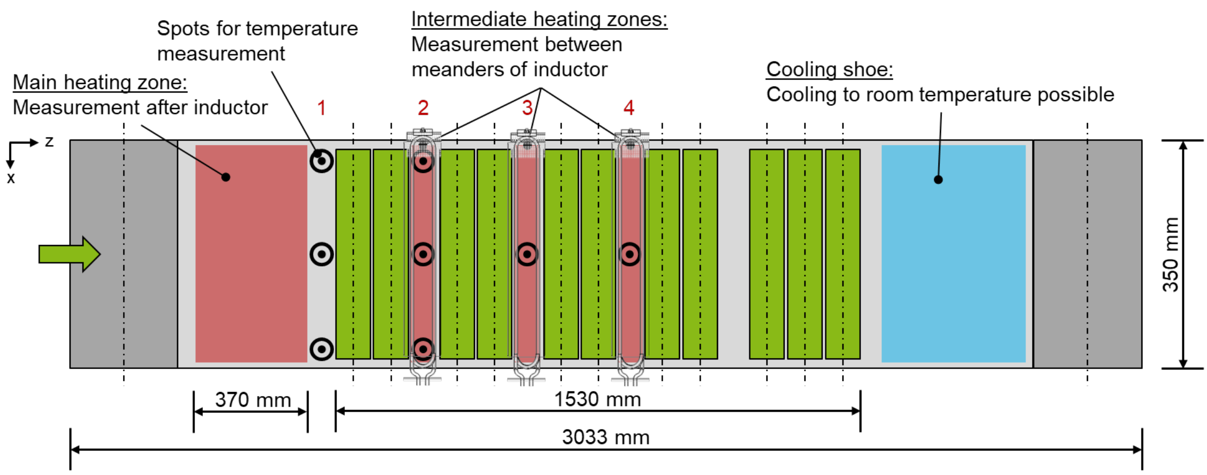
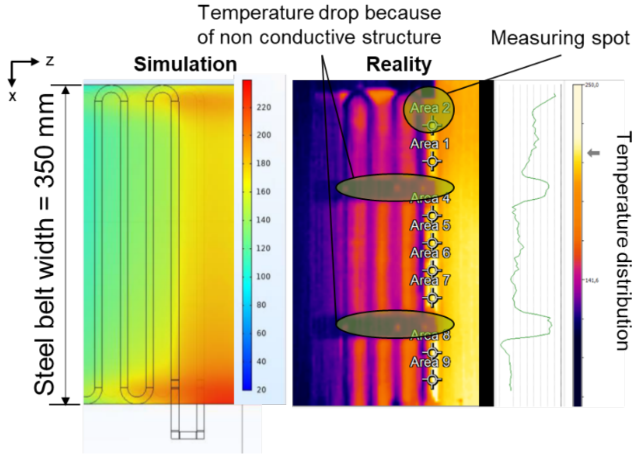


Figure 3: Pyrometer integration

The induction heating is controlled by a closed-loop temperature control system, which compares the steel belt temperature to the entered process temperature and changes the induction generator power accordingly. The steel belt temperature is measured with Micro-EPSILON CTM-3SF33-C3 pyrometers, as seen in Figure 3. Pyrometers evaluate electromagnetic radiation at one measurement point and are stationary built-in into the machine system. The implemented pyrometers are designed for the measurement of metals and have a high compatibility towards electromagnetic fields, which is essential for exact measurements in the near field of induction coils.



Measuring spot	Temperature
Area 1	203,5 °C
Area 2	205,5 °C
Area 4	206,4 °C
Area 5	203,8 °C
Area 6	204,5 °C
Area 7	203,1 °C
Area 8	207,1 °C
Area 9	206,6 °C

- Thermal imaging camera (Optris PI 160)
- Belt speed: 0.8 m/min
- Induction generator power: 28 kW

$\Delta T_{Optimized}$ +/- 2 °C

Figure 4: Measuring of temperature distribution with thermal imaging camera

Figure 4 shows the homogeneity of the temperature distribution, measured after the main heating zone. The induction coil design was optimised in an iterative process supported by simulations and prototype testing to provide a homogenous temperature distribution across the steel belt width, with a temperature deviation of +/- 2 °C, which is even smaller than the simulated temperature deviation.

Additionally, to the inductive heating, it has also a unique concept for the *pressure application*. The areal contact of the elastomer rollers in combination with the applied pressure also ensures very high surface qualities. The pressure profile can be individually adapted to the material properties. In the current machine set-up, five pressure zones (PZ) can be individually controlled and thus the pressure can be adjusted to suit the temperature, speed and material.

The elastomer coated rollers of the five different PZ have different shore hardness, to get an optimised pressure profile by relatively constant pressure area length. Figure 5 shows the roller contact zone in relation to the cylinder pressure for each PZ. The diagram on the left shows how the cylinder pressure from the pneumatic cylinders at the two ends of each roller is converted to the specific pressure that is applied to the steel belts. The roller contact zone was measured using Fujifilm Prescale LLW pressure foil which is capable of visualising the pressure distribution for 5-25 bar. It was used by feeding it into the DBP at AZL with no pressure and then applying the pressure in a static process.

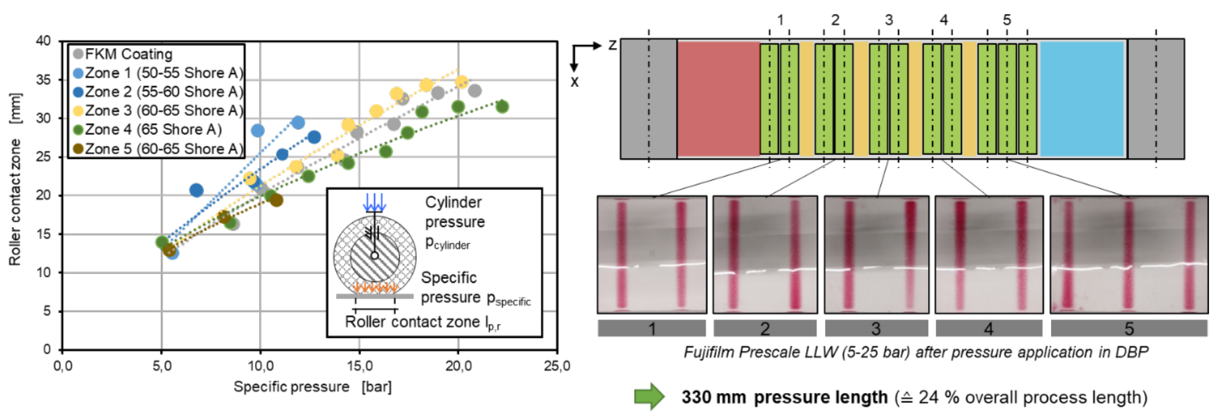


Figure 5: Pressure roller characteristics

The roller contact zone begins at around 12 mm for low cylinder pressures (1 bar) and goes up to 35 mm at $p_{cylinder}$ = 10 bar, which equals $p_{specific}$ = 23 bar. In the following, only the specific pressure will be used. In total, this results in an overall maximum pressure length of 330 mm, which equals 24 % of the overall process length.

3 Experimentation and results

3.1 Experimentation setup for the evaluation of temperature measurement

To evaluate the measurement deviation of the temperature measured with the pyrometers to the real process temperatures, several tests were carried out. The process parameters were set to a process speed of 0.3 m/min with maximum process temperatures reaching 240 °C. These values lie in the range of standard process temperatures used with the DBP system before, e.g. impregnation of glass-fibre wovens, and therefore were chosen for carrying out the tests. Temperature data was collected at the following points:

- Measurement of the steel belt temperature with in-built pyrometers (see Figure 3)
- Measurement of the material facing side of the steel belt with thermocouples (see Figure 6)
- Measurement of the temperature conducted through the material by placing thermocouples between two glass-fibre wovens (see Figure 6)

The *thermocouples* evaluate a voltage, that is produced by the welding of two dissimilar metals and correlates with the outer temperature. Three thermocouples are distributed across the width of the steel belt. For these trials, ThermaGmbH LT-1-2000-K-TF/TF40-0 type K thermocouples were used, which are able to measure temperatures of up to 300 °C. Figure 6 shows the equipment used for temperature measurements during the trials and their application to the machine system.

Figure 6: Equipment used for temperature measurements during trials

The resulting temperature data of the pyrometers and thermocouples was compared to show the accuracy of the temperature measurement system currently installed.

3.2 Results of temperature measurements

For the evaluation of the temperature measurement, three measurements were done for each measuring point. Figure 7 shows the temperature graph of each thermocouple against the temperatures measured with the pyrometers. The positions of the thermocouples are shown in Figure 6. Position 1 (Pos. 1) resembles the temperature of the thermocouple attached on the left side in process direction, position 2 (Pos. 2) the middle and position 3 (Pos. 3) the right side. The temperature graphs (Figure 7) show a steady rise in the heating zones, with four temperature peaks resembling each heating zone. Between each heating zone, two temperature drops can be detected, caused by the heat transfer from the steel belt into the pressure roller pairs. The temperatures measured with the pyrometers (marked with a cross) only show a slight deviation to the temperatures measured with the thermocouples, ranging from ~ 3–15 °C.

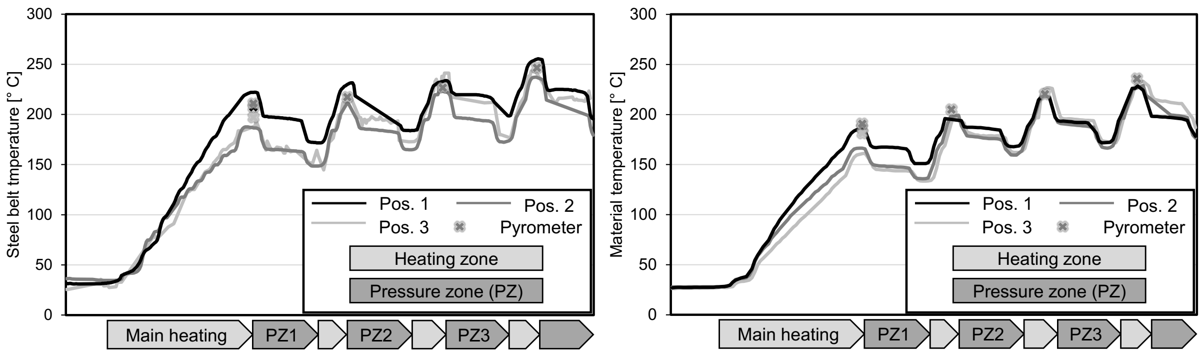


Figure 7: Temperature deviation

These deviations are most likely caused by two main factors. First, the measuring point of the pyrometers slightly deviate from the measuring point of the thermocouples, resulting in a temperature deviation. The process time at which the thermocouples are directly under the pyrometers was calculated, but an uncertainty remains in the exact determination of the measuring point. Another factor is the measuring uncertainty of the signal amplifier for the thermocouples, which is stated as 2–6 °C by the manufacturer.

3.3 Experimentation setup for the impregnation of glass-fibre wovens

For the investigation of film impregnation with the inductively heating DBP, the fabric G-WEAVE 600T from Chomarat, Le Cheylard, France, is used for both polymers investigated. This is a glass fibre fabric with a 2/2 twill weave, which has a weight per unit area of 600 g/m². The processed roving has a yarn count of 1200 tex and is provided with a sizing suitable for thermoplastic matrices. In order to carry out the test series successfully, precisely defined test conditions that are uniform for each polymer were specified in advance to reach an optimal comparability of the samples. Both, the applied pressure and the process temperature were identified as relevant process variables and defined with the help of a literature search. The process speed was set to 0.3 m/min for all polymers. Tests included PP (TU04YB by Profol Greiz GmbH, Greiz, Germany) and rPET (ECO-R-PET FILM TYPE 199 by Folienwerk Wolfen GmbH, Bitterfeld-Wolfen, Germany) (20 % recycled content) as polymers.

With regard to the process temperature, a maximum process temperature was defined for the intermediate heating zones, which is reached after the third and last zone. For the selection of this temperature, various values from the literature were used [2, 11–14]. Based on that, the maximum temperature for PP is set to be 220 °C and for rPET 300 °C. During the investigations, also two lower temperatures with steps of 20 °C have been investigated for each material.

With regard to the process pressure, a general pressure profile was defined for the five PZ. Similar to the investigation of the process temperature, three different pressure profiles are investigated for each polymer. In the following the pressure profile will be characterised using the maximum specific pressure ($p_{spec,max}$ at PZ 3 & 4).

A low pressure is required in PZ 1 (p_{spec} = 5.5 bar for each pressure profile), as this is where the macro impregnation mainly takes place. Too high a pressure here can lead to undesirable fibre shifts. The pressure gradient for the following micro-impregnation acts in two ways. On the one hand, it serves as a drive for the flow of the matrix. On the other hand, a high gradient also causes a narrowing of the flow paths due to compressed fibre bundles. Thus, a medium pressure is useful in PZ 2 (6.7 bar → 9.6 bar → 11.1 bar) as a compromise between these opposing effects. Subsequently, the consolidation is to be advanced. Here, it is particularly important to prevent air pockets by pushing out laterally. Likewise, the restoring forces of the GF fabric must be counteracted to avoid deconsolidation [11]. Accordingly, a high pressure must be selected for PZ 3 and 4 (13.8 bar → 15.8 bar → 18.3 bar). In PZ 5 (5.4 bar for each pressure profile), solidification begins, i.e. the consolidation of the organosheet. Heat is no longer added to the composite, but is removed from it. Here it is necessary to maintain a certain pressure to avoid deconsolidation and inclusions and thus to obtain a pore-free semi-finished product [7]. Since the very soft heat conduction silicone cannot withstand high loads, a low pressure is used in PZ 5. Figure 8 shows the impregnated organosheets after the processing in the DBP.

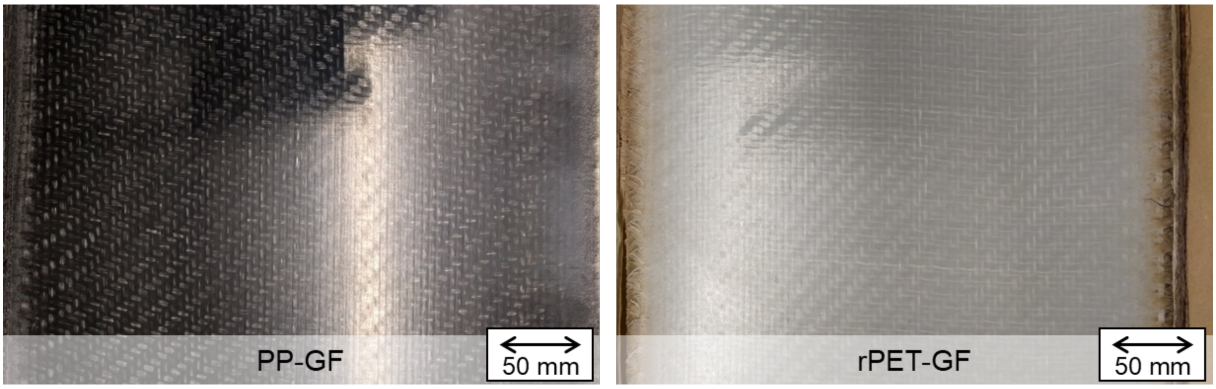


Figure 8: Photoghraphs of the impregnated organosheets after the impregnation in the DBP

The fibre volume content (FVC) for the experiments was selected to be about 45 %. The desired FVC is achieved by a corresponding layer structure of the used films and the glass fibre fabric. The film thickness and fibre area weight was chosen in such a way that an alternating layer structure with a total of seven layers could be used to reach the desired FVC. This resulted in a thickness of the organosheets of 1.3 mm. The specimen were evalutated with micrographs.

3.4 Results of the impregnation of glass-fibre wovens

In the following, the results of the two different polymers that were investigated for the impregnation of glass fibre woven in the DBP of the AZL are compared with each other. Figure 9 shows exemplary micrographs from the experiments with the highest investigated temperature ($T_{max,pp}$ = 220 °C, $T_{max,rPET}$ = 300 °C) for each polymer and the highest pressure profile ($p_{spec,max}$ = 18.3 bar). The micrographs underline the results that were generated with the three point bending tests and were chosen as a representative section for the whole laminate, regarding the length-, width- and thickness direction. PP and rPET show good impregnation with a low amount of voids.

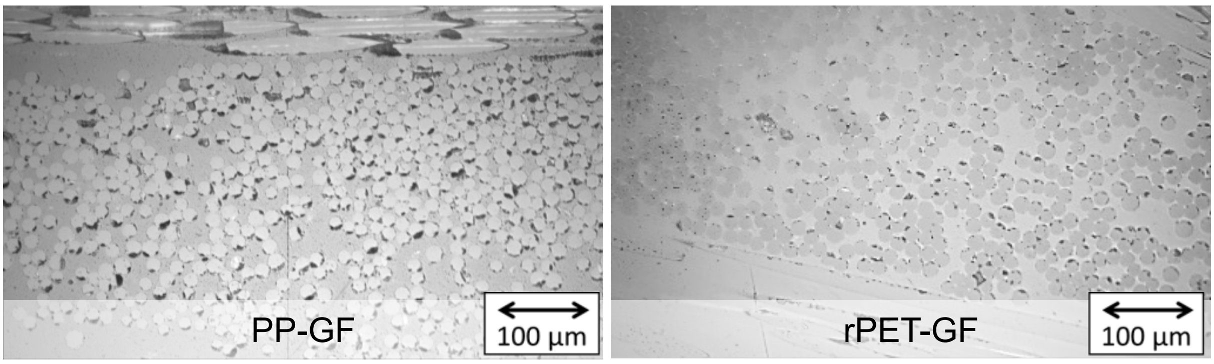


Figure 9: Micrographs of that were produced with PP and rPET at $T_{max,pp}$ = 220 °C $T_{max,rPET}$ = 300 °C and $p_{spec,max}$ = 18.3 bar

Most of the dark spots in both micrographs lie within the circular cross section of the fibres. These are fibre head breakouts, which can occur due to the grinding during sample preparation. Normally, these fibre head breakouts occur when the fibre matrix adhesion is not optimal or the young’s modulus of the polymer is low. As this stage of the research was initially a feasibility study, the fibre matrix adhesion and young’s modulus of the polymer were not quanitified, but are expected to play the main role for the shown fibre head breakouts.

3.5 Experimentation setup for the consolidation of tape laminates

For the evaluation of the post-consolidation of thermoplastic tape with the DBP, the consolidation was compared to the tape placement with the UltraFast machine of the AZL [15]. Each specimen consisted of two PP-GF tapes with a width of 25 mm, a length of 150 mm and a FVC of 70 %, that were joined together. The specimen were evaluated with micrographs from the cross sections to investigate the joint between two tapes (interlaminar) and the impregnation quality within the tapes (intralaminar). For the consolidation in the DBP, the tapes were manually placed on top of each other before the consolidation in the machine. A constant specific pressure of 5.4 bar and a maximum temperature of 200 °C was used. The process speed was set to 500 mm/min. For reference, two tapes were layed on top of each other in the tape laying process with the UltraFast with a nip point temperature of 200 °C. The process speed for the tape laying was set to 500 mm/s.

The microscopy images were evaluated by analysing the number and size of voids. A distinction can be made between voids within the polymer (macro-impregnation) and voids between fibres and polymer (micro-impregnation). In the tape laying process, voids within the polymer are usually observed especially in the interlaminar area and indicate insufficient consolidation. Voids between fibres and polymer result from faulty impregnation of the tape and cannot be compensated for in the taping process. With the DBP, both macro-impregnation and micro-impregnation can be improved, as shown in chapter 3.6.

3.6 Results of the consolidation of tape laminates

The evaluation of the post-consolidation with the DBP was done by comparing the resulting micrographs from GF-PP tapes that were consolidated with the DBP with those from tapes that were consolidated with the UltraFast tape laying machine. Figure 10 shows two exemplary micrographs of specimen that were consolidated with the DBP and with the UltraFast.

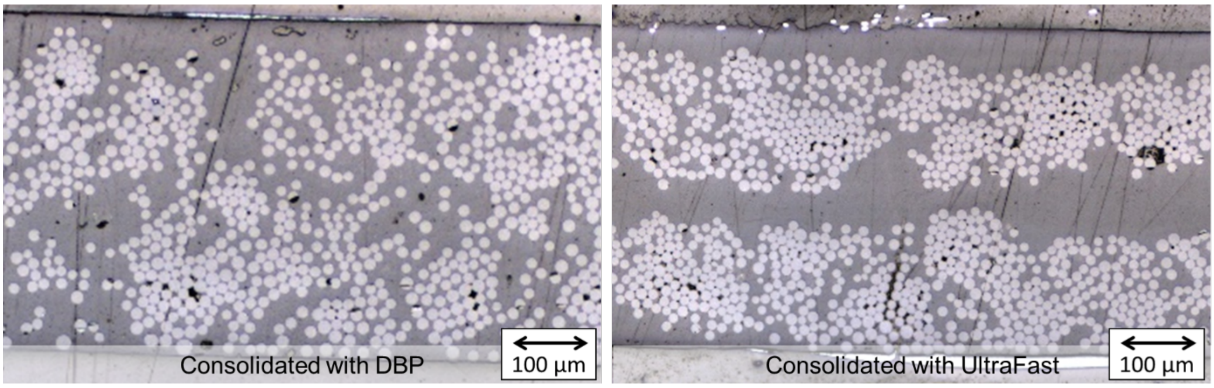


Figure 10: Micrographs of two PP-GF tapes consolidated with the DBP (left) and the UltraFast (right)

On the right micrograph the typical result for the tape laying process can be seen. The tapes are fully consolidated but there is a clear interlaminar layer without any fibre reinforcement. This interlaminar layer is erased by the consolidation with the DBP (left). The tapes are completely bonded together so that no interlaminar layer is visible and the fibre reinforcement is evenly distributed over the entire thickness of the composite. This significantly increases the strength of the laminate, especially against shear stress. In addition to the improvement in interlaminar strength, an improvement in the intralaminar impregnation quality can also be observed. The voids within a tape can be significantly reduced, which illustrates that the quality of the tape can also be increased by post-consolidation in the DBP. Several experiments with industrial partners have also shown that the impregnation and also the surface quality can be even further increased with a higher specific pressure, as during the displayed experiments only 10 % of the maximum possible pressure was used.

4 Conclusions

The comparison of the temperatures measured with the in-built pyrometers against the temperatures measured with the thermocouples quantified the measuring accuracy of the current machine system. The measuring deviations of ~ 3–15 °C, most likely caused by uncertainty in the measuring point and accuracy of the thermocouple measurement, showed that the current system is able to measure the process temperatures with high accuracy.

The *impregnation* of glass fibre fabrics showed that the highest investigated temperature (220 °C for PP and 300 °C for rPET) and the highest pressure profile ($p_{spec,max}$ = 18.3 bar) led to the highest quality. It could be shown that properties similar to commercially available FRP can be achieved using foil impregnation on the DBP of the AZL. The next step is to investigate and increase the fibre matrix adhesion by optimising the combination of the polymer and the fibre sizing. Further investigations will also include rollers that allow for higher temperatures up to 400 °C. With that adjustment, it will be also possible to process polymers with high melting temperatures like PEEK, PEAK and PC. Those investigations will be evaluated with extensive mechanical tests as well as micrographs. The results will be shown in future publications.

The results of the consolidation with the DBP show, that the consolidation of laminates that are manufactured in the tape laying process can be increased significantly. Not only the interlaminar strength of laminates, that are manufactured in the tape laying process can be increased. Several experiments have also shown, that tape qualities can be improved when it is post-processed in the DBP. This includes not only a better surface quality, but also a significant increase in impregnation quality for tapes consolidated with the DBP at AZL.

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