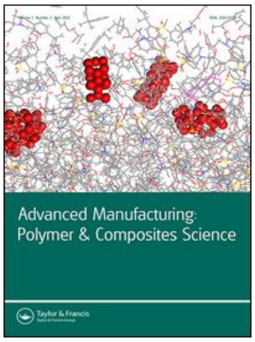


Taylor & Francis
Taylor & Francis Group

Advanced Manufacturing: Polymer & Composites Science

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/yadm20

Increasing the performance of continuous compression moulding by local pressure adaption

Florian Piott, Andreas Krämer, André Lück, Leo Hoffmann, Peter Mitschang & Dietmar Drummer

To cite this article: Florian Piott, Andreas Krämer, André Lück, Leo Hoffmann, Peter Mitschang & Dietmar Drummer (2021): Increasing the performance of continuous compression moulding by local pressure adaption, Advanced Manufacturing: Polymer & Composites Science, DOI: 10.1080/20550340.2021.1888209

To link to this article: https://doi.org/10.1080/20550340.2021.1888209

Published online: 08 Mar 2021.

ADVANCED MANUFACTURING: POLYMER & COMPOSITES SCIENCE
https://doi.org/10.1080/20550340.2021.1888209

Increasing the performance of continuous compression moulding by local pressure adaption

Florian Piott[a], Andreas Krämer[b], André Lück[a], Leo Hoffmann[a], Peter Mitschang[b], and Dietmar Drummer[a,c]

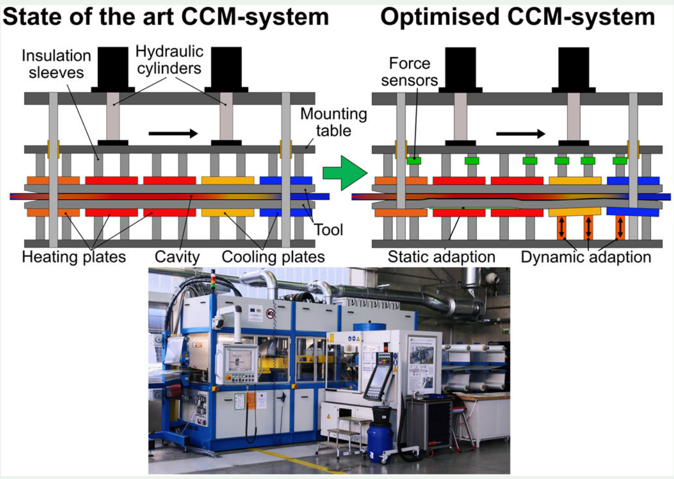
[a]Neue Materialien Fürth GmbH, Fürth, Germany; [b]Institut für Verbundwerkstoffe GmbH, Kaiserslautern, Germany; [c]Lehrstuhl für Kunststofftechnik, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

ABSTRACT

Continuous compression moulding (CCM) is an efficient process for manufacturing endless fibre-reinforced thermoplastic composites, so called organic sheets. The semi-finished products are fully impregnated and consolidated and can be thermoformed into complex 3D-geometries. Applications benefit from excellent weight-specific features as well as functional integration. Nevertheless, limited production speed and lower than acceptable manufacturing quality are still a challenge, especially with the use of high shrinkage polymers. Hence, porosities and defects due to pressure drops inside the laminate during impregnation and solidification can cause degradation in material properties. With the integration of an active adaptive pressing tool and an inline pressure measurement system, the process can be optimised towards guided impregnation and improved pressure distribution. A calculation method based on the B-factor method by Mayer has been adapted for the CCM process in order to enhance the tool design. Both, production speed as well as organic sheet quality can be improved with the optimised processing system presented in the following work.

KEYWORDS
Continuous compression moulding; organic sheet; impregnation; solidification

GRAPHICAL ABSTRACT



Introduction

Continuous fibre-reinforced polymer composites (FRPC) offer high potential for lightweight design and benefit from excellent weight-specific features [1]. Through the use of thermoplastic matrices flat semi-finished products, so called organic sheets, can be reheated and converted into complex 3D-geometries by a thermoforming process in short cycle times for large scale production [2]. In combination with established manufacturing processes, such as injection moulding, foaming or joining, the potential range of thermoplastic FRPC is further expanded [3]. The availability of different fibre-based reinforcement structures and a wide selection of polymer matrices results in a variety of organic sheets that is attracting more and more industries to their potential [4–6].

One challenge in the establishment of thermoplastic FRPC structures is the development of efficient manufacturing processes. While composites based on thermosetting polymers have already saturated the market for large part size applications

CONTACT Florian Piott florian.piott@nmfgmbh.de

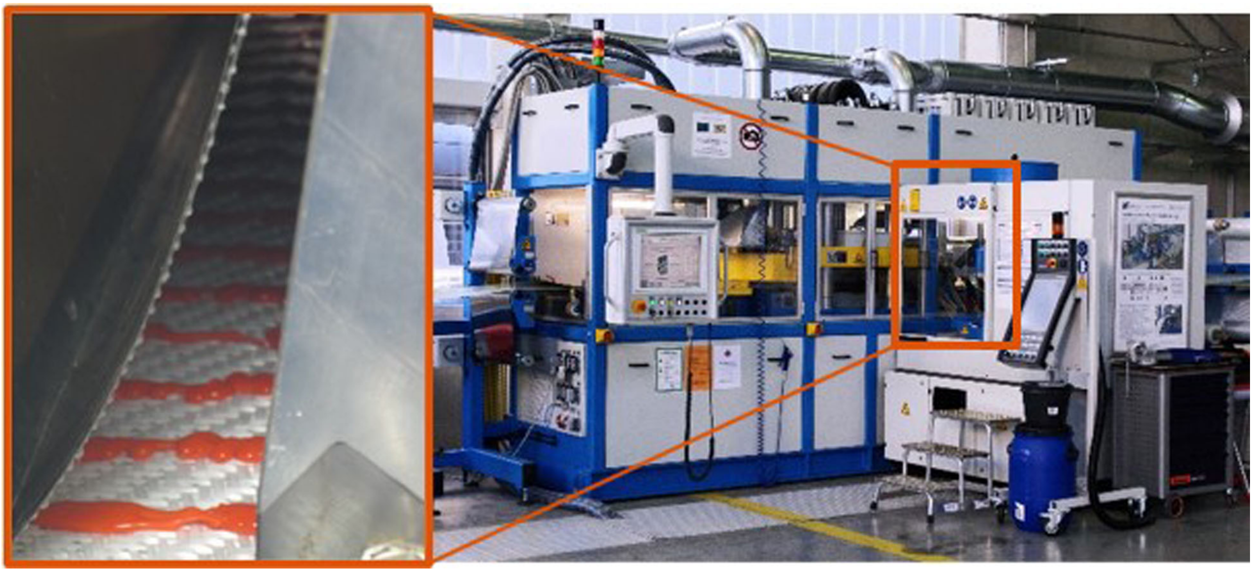


Figure 1. Direct-melt CCM-technology at Neue Materialien Fürth, Germany (left: entry of the molten polymer by a hot runner system).

such as boat hulls, aircraft structures or wind turbine blades [7,8], there have been increasing efforts in recent years to promote the use of thermoplastic matrices. The dimensions of the producible components depend on the available size of corresponding semi-finished sheets. With regard to the mechanical properties, it is often important to maintain the continuous fibre structure along the complete load path of the component. For this reason, several small organic sheets cannot be combined for larger FRPC applications. The required sheet dimensions must at least correspond to the components total surface area. Thus, the maximum part size which can be realised depends on the dimensions of the semi-finished materials (organic sheets) available on the market.

The continuous compression moulding technology (CCM) is an economically and technically efficient process for manufacturing organic sheets [9]. The main advantages of this technique are the flexibility due to a high temperature range up to 450 °C and low investment costs compared to other continuous processing technologies. However, there are different ways of producing organic sheets with a CCM-system. Common ways for series production are film-stacking layups and the processing of powder prepregs [10]. An alternative method is the direct melt process, a unique feature of the CCM-machine at Neue Materialien Fürth, Germany (Figure 1). The integration of a plasticising unit and a balanced extrusion tool just in front of the pressing unit enables the system to apply thermoplastic melt directly out of the granules onto the dry textile. With this system countless variations and modifications of the matrix polymer can be realised in combination with a low amount of material waste. In addition, the thermoplastic resin does not have to be pre-processed into a polymer foil or milled into powder form.

While the current state of the art allows a sheet width of approximately one meter, the market is experiencing an increasing demand for semi-finished products with a higher width due to the demand for larger endless fibre reinforced thermoplastic composite parts. The challenge in the production of wide laminates is the impregnation of fibre strands lying perpendicular to the process direction with the highly viscous polymer. In contrast the impregnation of fibres oriented in process direction (0° direction) is sufficiently achieved by the current CCM technology. In order to produce a completely impregnated semi-finished product with low porosity, the rapid and selective displacement of enclosed air from the inner layer structure to the open tool edges must be ensured. Besides the need for wider semi-finished products, full market penetration is hindered due to the high price compared to other light weight solutions. This is mainly caused by the costs for the dry textile and the limited output of the manufacturing process. The decisive factor for the production speed is the time required for impregnating the reinforcement structure with the highly viscous thermoplastic matrix. In summary, the main aim must be to increase the impregnation capacity of the plant in order to produce larger widths with a higher material output.

State of the art and objectives

Figure 2 shows a schematic illustration of a state of the art CCM pressing unit. A raw material layup (textile and polymer) is pulled step by step through a flat pressing tool and gets heated while a defined hydraulic pressure is applied. When the polymer reaches its melting temperature, impregnation of the textile starts. After impregnation the saturated filaments are cooled down by a fluid-controlled temperature distribution in the cooling zones and the consolidated laminate is solidified under pressure. After reaching the demoulding temperature of the thermoplastic matrix, the organic sheet leaves the tool and can be separated from the release metal sheets. To ensure constant thermal conditions inside the flat tool, different heating and cooling plates are separated from each other and insulation sleeves reduce the heat flow to the mounting table.

In a standard CCM-system with flat tools, the impregnation mainly takes place in thickness direction, so called transversal impregnation. Due to the quick flow of the polymer melt around the fibre bundles, so called macro-impregnation, the inner yarn air displacement can only take place in direction of the reinforcing filaments. That is why the distance of the perpendicular air displacement increases with growing production width, while the distance of the longitudinal displacement of enclosed air remains constant (Figure 3 left). As a consequence, by increasing the manufacturing speed the perpendicular air displacement is often not completed, which results in a higher porosity of the FRPC [11]. An optimisation potential would be a convex curved flow front (Figure 3 right). With a specific adaption of the tool geometry, the macro flow front of the melt can be controlled to a boomerang-shape and the impregnation can be accelerated by a mixture of axial and transversal flow behaviour around the fibre bundles [11,12].

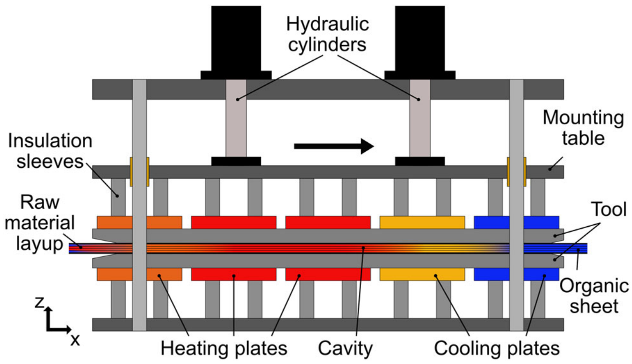


Figure 2. Schematic illustration of a standard CCM-system.

A further challenge in the CCM-process arises from the pressure distribution inside the laminate. The flat tool is likely to tilt due to varying thermal elongation effects in the support structure, which in turn may cause significant variations in the pressure distribution as visualised in Figure 4. On top of that, the specific volume of the polymer varies due to the change of the physical states induced by the heating and cooling process. In relation to the

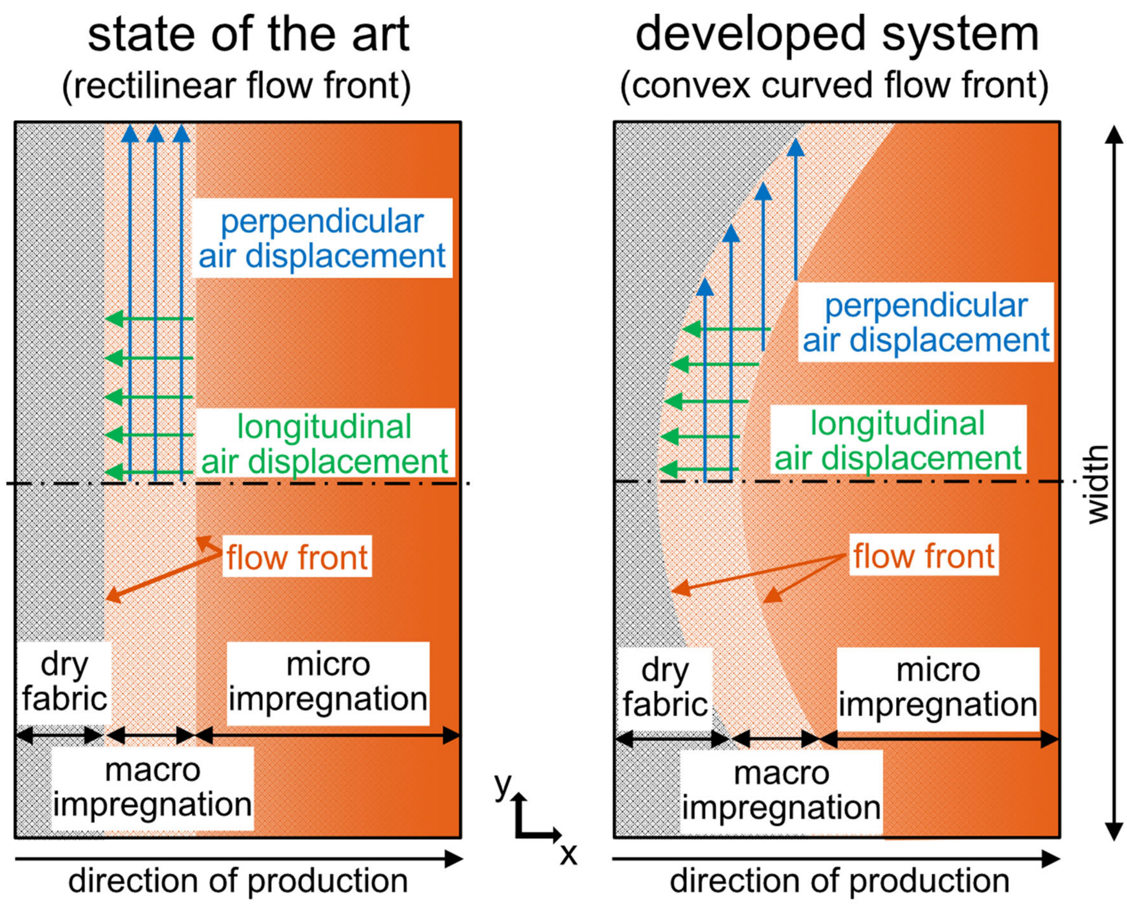


Figure 3. Rectilinear (left) and convex curved (right) flow front and longitudinal vs. perpendicular air displacement of the CCM-process.

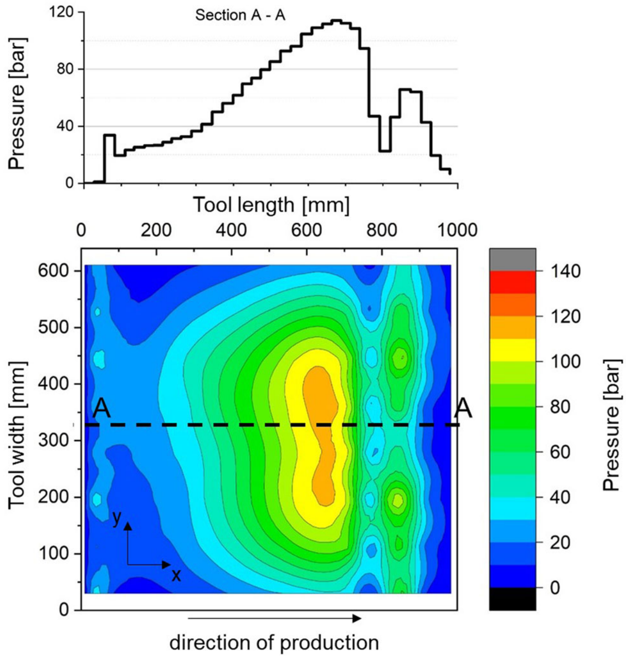


Figure 4. Pressure distribution in a standard CCM-process.

laminate quality the most critical pressure losses occur during the cooling phase, when especially semi crystalline thermoplastic resins reach their maximum shrinkage behaviour at recrystallisation temperature. At this point the specific volume decreases rapidly and the flat tool is not able to apply pressure onto the laminate, which results in optical defects or vacuoles and therefore in reduced material performance of the organic sheet.

At present, a standard CCM-machine offers no possibility to measure the pressure distribution inside the laminate. Influencing the local flow front behaviour is also not available on current systems and the state of the art has no possibility to avoid the pressure losses during the cooling phase. An inline pressure measurement system would have many advantages for analysing and optimising the process. In addition, the operator or even the system itself could react on inaccuracies or pressure drops during manufacturing long before the organic sheet is visible and so the efficiency and quality could be ensured. Actually, there are no pressure recording systems established because it is not possible to measure directly inside the laminate due to the release metal sheets which separate the organic sheet from the hot tool. Depending on the polymer to be processed, the temperatures can reach more than 400 °C. Most pressure sensors can't handle these high temperatures. In order to increase production speed while maintaining a high level of impregnation quality, the aim of this work is to realise a convex curved macroscopic flow front as illustrated in Figure 3 (right). For this to achieve, reshaping the mould surface by a specific bending, which affects

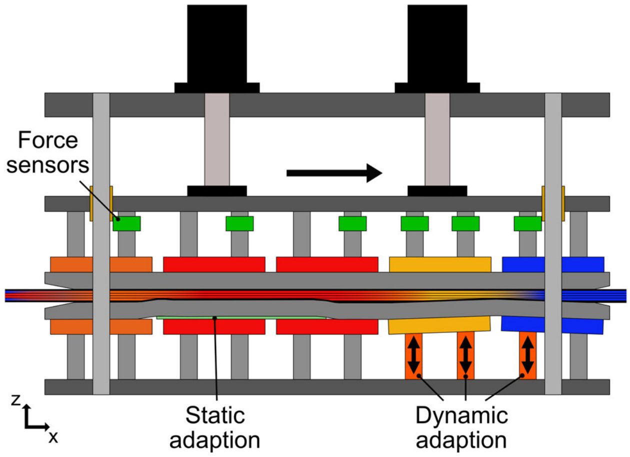


Figure 5. Schematic illustration of an optimised CCM-system with local pressure adaption.

the pressure distribution in the material being processed is proposed.

For this purpose, the aim of this research is to evaluate a local pressure adaption inside the CCM-tool by a mechanical deformation system. As a result, the flat tool could get partially bended slightly. By measuring the predominating local pressure level, it would be possible to adjust the necessary extension of the tool. In a collaborative research work, Neue Materialien Fürth GmbH (NMF) together with the Institut für Verbundwerkstoffe GmbH (IVW) and Teubert Maschinenbau GmbH developed an inline force measurement system for the CCM-machine available at NMF lab, which is schematically depicted in Figure 5. For this purpose, numerous force sensors were integrated in the upper pressing unit. Even though it is not possible to capture the real process pressure, local force differences can be detected sensitively and so it is possible to react immediately to pressure deviations. A static adaption of 0.3 mm thick sheets between the heating plates and the hot mould bends the tool surface and effects the flow front during impregnation. By choosing a triangular shape, a convex curved flow front will be obtained and the perpendicular air displacement will be improved. In addition, the system allows to elongate different sleeves by a defined thermal elongation at certain cooling zones. Pressure drops during solidification especially with the use of high shrinking polymers can therefore be reduced. Hence, the dynamic adaption is able to bend the flat tool sensitively and to compensate for the shrinkage behaviour of several semi crystalline thermoplastics individually.

Analytical calculation

The pressure distribution in the processed material needs to be adapted in order to realize a convex curved macroscopic flow front. The necessary tool

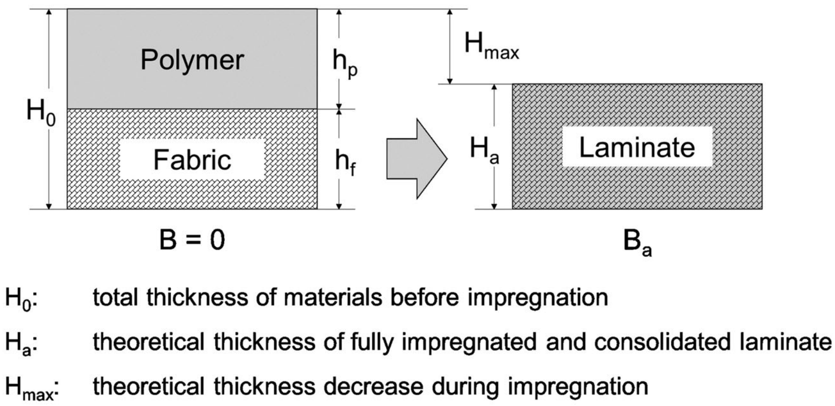


Figure 6. Transition from polymer and fabric to laminate in the extended B-factor model.

modification can be determined empirically in test series. Alternatively, the process can be modelled to predict the necessary tool adaptation and to reduce the number of test series. For this purpose, a process model based on the so-called B-factor model was developed. The B-factor is a dimensionless constant that summarizes the process parameters pressure P, time t as well as the viscosity η and represents the impregnation performance of a process (Equation (1)) [13–15].

$$B = b \cdot P = \int_{t_0}^{t_a} \frac{1}{\eta_0(T(t))} dt \cdot P \tag{1}$$

By including the viscosity in the calculation, the process temperature is implicitly considered in addition to the above-mentioned parameters. Originally, the B-factor model was developed by Mayer to transfer existing parameter sets of one type of a plant to other plants with the aim of achieving the same composite quality. By combining the B-factor model with the spring damper model according to Kelvin Voigt, the impregnation and consolidation behaviour during thermoplastic processing can be characterised by the decrease in laminate thickness. In this extended B-factor model, the thermoplastic impregnation is represented as the creep of a viscoelastic material under a constant pressure load. The model assumes that at the beginning of the impregnation both phases of the later composite material are present separately. During impregnation, the two phases merge into each other until a final thickness H_a according to the selected laminate structure is achieved (Figure 6) [13,15,16].

Equation (2) describes the relationship between the individual variables.

$$\Delta H = H_{max} \cdot \exp(-k_s \cdot B) \tag{2}$$

The equation shows that the thickness decrease during impregnation is represented by an exponentially decreasing function. The variable k_s, defined as saturation permeability, depends on the fibre structure used as well as on the selected process pressure and influences the slope of the exponential function during modelling. In order to describe the impregnation behaviour of the selected material combination in the model, k_s has to be determined in tests beforehand. For this purpose, the decrease in thickness is recorded for different parameter sets ($T = 200\,°C$, $p = 10$ and 20 bar) and a corresponding k_s value is derived (Figure 7 shows the thickness progression for $T = 200\,°C$ and $p = 20$ bar).

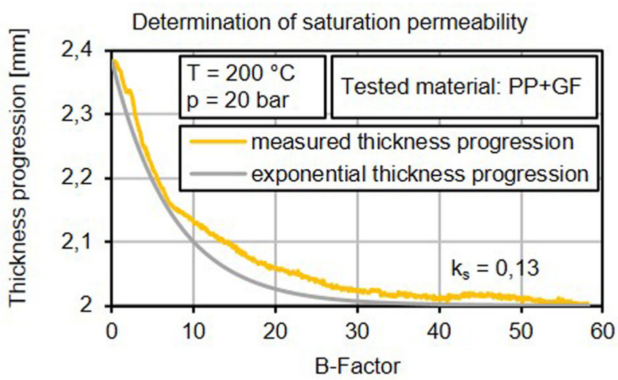


Figure 7. Determination of saturation permeability k_s.

If the saturation permeability for different process pressures is known, the model is able to generate corresponding thickness curves for different process conditions based on the system parameters (feeding rate, effective pressing time, heating plate temperature). The following assumptions are made for the calculation:

- The specified process temperatures correspond to the laminate temperatures. Consequently, an immediate heating of the laminate to the set temperature is assumed. If the heating behaviour of the material is known, it would be possible to take this into account in order to increase the accuracy of the model.
- Due to the principle of the CCM machine, the process pressure in the transfer phase of the material decreases to 0 bar. It is assumed that there is no deconsolidation and no change in the degree of impregnation in this phase and so the material thickness remains constant.

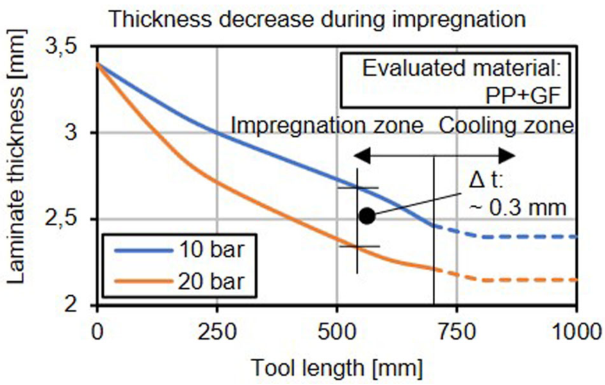


Figure 8. Thickness curves for 10 and 20 bar at 200 °C.

- In the transition area from heating to cooling zone, the process pressure decreases as shown in Figure 4. This process is not taken into account in the model because the model is designed for the impregnation and consolidation phase. In order to maintain the process pressure at the transition point in the phase of solidification, a corresponding tool adaptation can be calculated according to the specific shrinkage behaviour of the polymer.

Figure 8 shows the modelled thickness curves for a process pressure of 10 and 20 bar at a processing temperature of 200 °C for PP and GF fabric.

The generated curves show that according to the model calculation the thickness profile of the laminate relative to the tool length decreases faster at a processing pressure of 20 bar compared to 10 bar at a constant process temperature. Assuming that no polymer loss occurs, a reduction of the laminate thickness in the impregnation phase is only achieved by the polymer penetrating into the flow channels between the fibre filaments. Therefore, it is implied that impregnation proceeds faster in time at a higher processing pressure. In this case, this results in a difference in height of up to 0.3 mm in relation to the laminate thickness with the same temperature and pressure exposure time. Consequently, for a pressure profile that decreases from a pressure of 20 bar in the tool centre to a lower pressure of 10 bar at the tool edges, a geometric adaption of the tool cavity of 0.3 mm would be necessary. The local differences in thickness can thus be used to derive a theoretical contour line of the tool with the aim of achieving a fast impregnation in the tool centre and a subsequent expansion of the impregnation front to the tool edges. This influence on the impregnation front is also intended to promote appropriate air transport out of the laminate. In order to use the model for new material combinations, so that unknown tool geometries can be derived without experimental evaluation, it is necessary to validate the model statements in real tests.

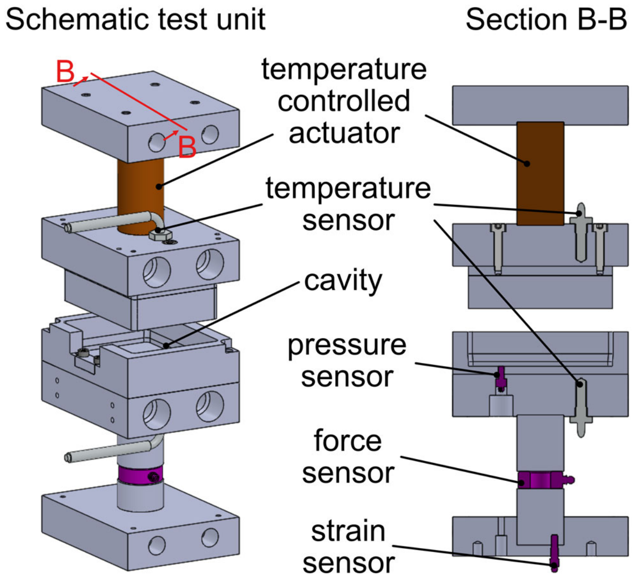


Figure 9. Single cell test unit and force sensors.

Materials and experimental methods

To develop a local adaption system under high loads and to measure the accumulating pressure at temperatures reach more than 400 °C is a challenging task. For the development of a new system a small test bench has been engineered. The complex workings of the CCM machine have been reduced to a single cell unit of similar geometric design to test it under controlled boundary conditions. Different tests concerning the elongation behaviour of temperature-controlled actuator and finding the optimum load sensor have been carried out. In a second step the gathered information has been transferred to the NMF lab-machine and an optimised laminate fabrication has been evaluated.

To capture and control the variation of defined loads, the single cell test unit has been installed on a universal testing machine (AllroundLine Z100, ZwickRoell GmbH & Co. KG, Germany) with a calibrated force and stroke measurement system. Using a defined thermal elongation, the upper insulation sleeve can be elongated which causes an increase in load to the pre-stressed unit (Figure 9). Different types of force sensors detect the local load at different positions: A piezoelectric strain sensor (type 9247 A, Kistler AG, Switzerland) based inside the cooled mounting table is able to detect strain in the mounting table. A second force sensor (type 9031 A, Kistler AG, Switzerland) in the centre position under the lower non-heated sleeve measures the force in direct force flow. A third sensor (type 6157 C, Kistler AG, Switzerland) is able to capture the applied cavity pressure in direct contact to the release metal sheet of the compressed material.

Impregnating, consolidating and solidifying organic sheets is a complex process, which depends

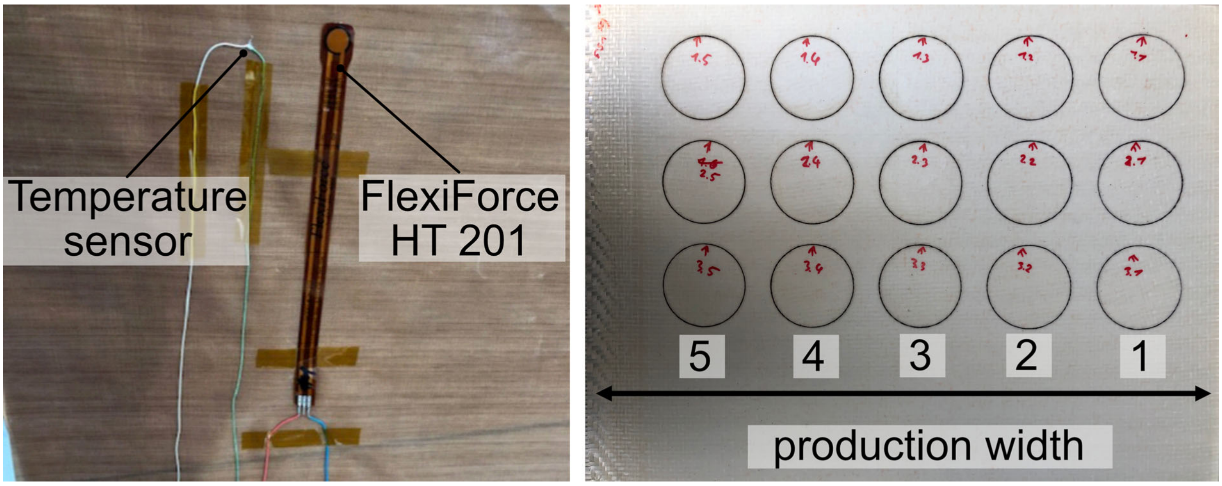


Figure 10. left: Integrated sensors to measure temperature and pressure inline; right: cut outs for density measurement.

on temperature, pressure and time. Hence, the single cell test unit operates with a small cavity and it is possible to add flat stack layups inside a small tool to readjust different material behaviours. Two cartridge heaters on each side of the cavity can apply temperatures up to 450 °C. In addition, a small gap at the side edge allows to measure the local pressure with a thin pressure sensor (FlexiForce™ standard model HT201, Tekscan, USA). Different defined forces (5−30 kN) at different temperature levels of the cavity (20−200 °C) have been applied with the universal testing machine and the measured signals have been recorded with an external data logger.

In the actual CCM-process, as previously described, a raw material layup using two layers of glass-fibre 2-2 twill fabric (GW124-580K2, P-D Glasseiden GmbH Oschatz, Germany) and a middle layer of extruded semi-crystalline polypropylene homopolymer (BJ100HP, Borealis Polyolefine GmbH, Austria) was guided between two layers of release metal sheets. The fabric features a surface weight of 576 grams per square meter (gsm) and a width of 650 mm. Furthermore, 19 cubic centimetres (ccm) of molten thermoplastic polypropylene was extruded by a temperature of 220 °C through sixteen nozzles of a hot runner system. The whole setup was pulled step by step through the tool with a feeding rate of 25 mm at each cycle by a forwarding mechanism. The five temperatures zones of the tool were set to 170, 220, 220, 160, 80 °C from inlet to outlet side, while each zone was tempered constant over the tool width. An average laminate pressure of 20 bar specific was applied. To register the real laminate pressure and temperatures while processing FlexiForce™ sensors (standard model HT201, Tekscan, USA) and a thermocouple type K have been attached in the centre position of the laminate under the two fabric plies while an external amplifier converted the signals and a data logger recorded the measured values (Figure 10 left).

To generate a relation between physical adaption, measured signals and manufactured quality of the laminate, thickness and density measurements have been performed with the laminate after processing in the CCM-system. For this purpose, test specimen with a diameter of 80 mm has been cut out by laser at five positions over the tool width (Figure 10 right). After separation, the density ρ_{FRPC} of all samples has been measured according to DIN EN ISO 1183-1 with a slightly modified relation so that absorbed water of the unimpregnated textile has been respected (Equation (3)). Therefore, the weight of each test specimen has been measured before $m_{S,b}$ and after immersing in test fluid $m_{S,a}$. Together with the density of the fluid $\rho(T)_{IL}$ and the weight of the test samples immersed in fluid $m_{S,IL}$ the actual density can be determined.

$$\rho_{FRPC} = \frac{m_{S,\ b} \cdot \rho(T)_{IL}}{m_{S,b} - (m_{S,IL} - (m_{S,a} - m_{S,b}))} \tag{3}$$

The surface weight of the samples has been determined by calculating the sample area A_S and measuring the weight. Due to the fact, that the amount of polymer in the finished organic sheet differs because of melt losses on the sides of the tool, the target density of an impregnated laminate $\rho_{FRPCimp}$ changes over the production width. Under the assumption that the surface weight of the reinforcement M_{GF} is nearly constant in the cut test samples, the density for a complete impregnated sample can be calculated with Equation (4). ρ_{GF} and ρ_M represent the density of the polymer respective of the reinforcement. With this value the grade of impregnation I_{imp} can be calculated with Equation (5).

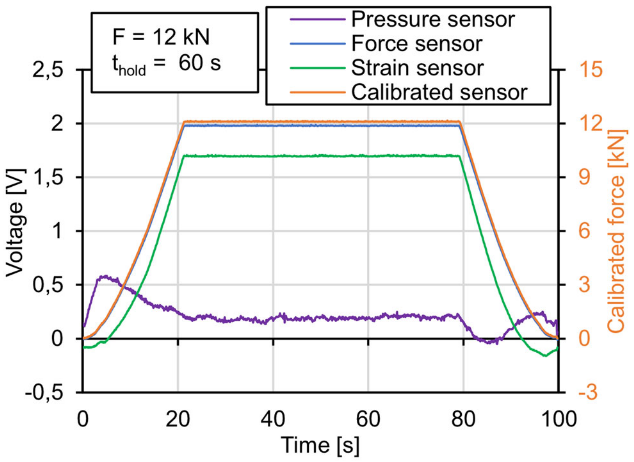


Figure 11. Comparison of the signals of the different sensors in the single unit test cell.

$$\rho_{FRPCimp} = \frac{m_{s,b}}{V_{GF} + V_P} = \frac{m_{s,b}/A_s}{\frac{M_{GF}}{\rho_{GF}} + \frac{(m_{s,b}/A_s) - M_{GF}}{\rho_P}} \quad (4)$$

$$I_{imp} = \frac{\rho_{FRPC}}{\rho_{FRPCimp}} \quad (5)$$

Equipment design and calibration

To develop the inline pressure measurement system, tests with the single cell test unit were performed. After holding a vertical force constant for 60 s, the setup was unloaded. Figure 11 shows the voltage signals of the three integrated sensors and the force of the calibrated force sensor of the universal testing machine. It can be seen, that the force sensor measures nearly the same as the calibrated sensor of the testing machine. The output signal of the strain sensor differs especially at loading and unloading. However, the pressure sensor could not achieve a good measuring result at all.

Due to the measurement results of the single unit test cell, it was decided to integrate Kistler Type 9031 A force sensors into the CCM-system at NMF laboratory.

In further experiments, the dynamic adaption with the temperature-controlled actuators was also evaluated with the test cell. Therefore, a defined force of 10 kN was loaded on the single unit test cell and the tool distance kept constant. By increasing the temperature of the actuator, the measured force rises. Figure 12 shows the increase in the force with different tool temperatures. It can be seen, that the force rises linearly with the increase in the actuator temperature, which is advantageous for automatic control. With an increase in temperature of 100 °C the resulting force in the test unit increases approximately 4 kN.

For the CCM-machine at the NMF laboratory it was decided to integrate the dynamic adaption

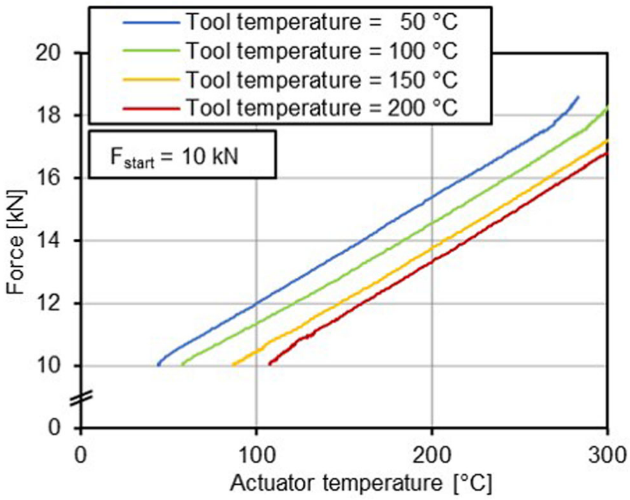


Figure 12. Force increase due to activating the temperature-controlled actuator.

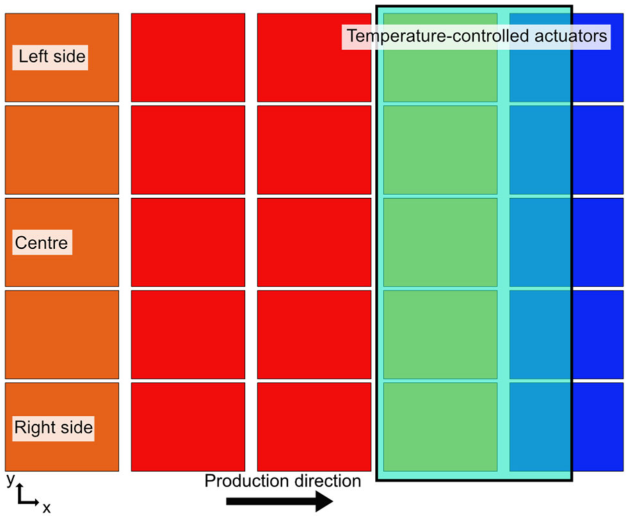


Figure 13. Schematic illustration of the temperature-controlled actuators in the high shrinkage section of the CCM pressing unit.

system over the whole width of the cooling zones, as shown in the schematic picture in Figure 13.

For a thermal separation it was decided to put the dynamic adaption on one side of the pressing unit and the force sensors on the other side. To capture the impact of the temperature-controlled actuators on the laminate pressure, nine force sensors were integrated directly in the high shrinkage section of the CCM-system, respectively in the centre and on the sides of the tool. Three more sensors were mounted in the centre of the heating zones for characterising the impregnation behaviour. Figure 14 shows the position of all force sensors. Due to the usage of the existing heating and cooling plates, the mounting situation does not allow the calculation of the real pressure in the cavity. However, the sensitivity of the measurement system enables a very good relative comparison.

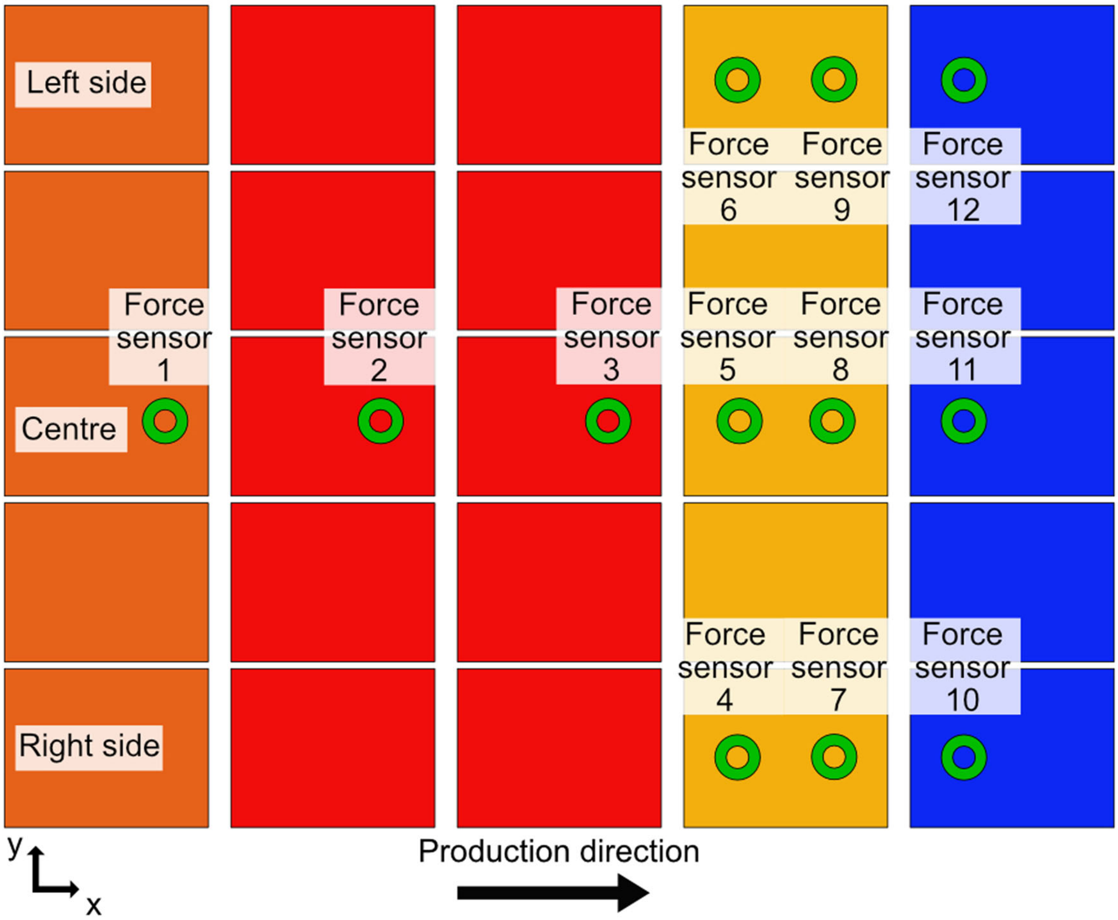


Figure 14. Schematic distribution of the 12 force sensors in the CCM-system in the upper pressing unit.

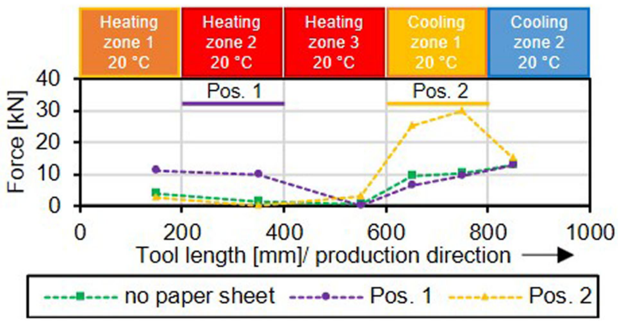


Figure 15. Force distribution in the middle of the tool in dependence of the paper sheet position.

To prove the sensitivity of the system, tests with a $210 \times 297\,mm^2$ sized paper sheet (DIN A4) were performed. This sheet with a thickness of 0.1 mm was placed at different positions of the cold tool and then a total force of 1200 kN was applied. The resulting force in the centre of the tool is shown in Figure 15. It can be seen, that even in the empty tool, the force is not the same over the tool length. This can be explained with small tolerances in the manufacturing process of the pressing unit and the mounting situation of the different force sensors. Nevertheless, with integrating the paper sheet at two exemplary positions (1 and 2), an increase in force of the closest sensors is clearly measurable.

Figure 16 shows a comparison of the interlaminar pressure measurement with the developed inline force measurement. Both curves demonstrate the same process in the centre of the tool. The oscillating characteristic of the interlaminar sensor measurement arises from the semi-continuous process. It can be seen, that the trends, especially in the cooling area, are quite similar. The differences can be explained by inaccuracies of both systems. The signal of the thin pressure sensors is very temperature and time dependent and the measured forces depend on the mounting situation. Nevertheless, the results demonstrate that the developed system is a well working method to get more detailed information about the process values in real time. The pressure drop due to the shrinkage behaviour of the thermoplastic polymer and thermal elongation effects of the pressing unit at about 800 mm tool length can be detected by both measurement systems sensitively.

Results

To evaluate the static and dynamic adaption systems under real manufacturing conditions further tests were performed. Therefore, two different shim geometries were cut out of an aluminium sheet with a

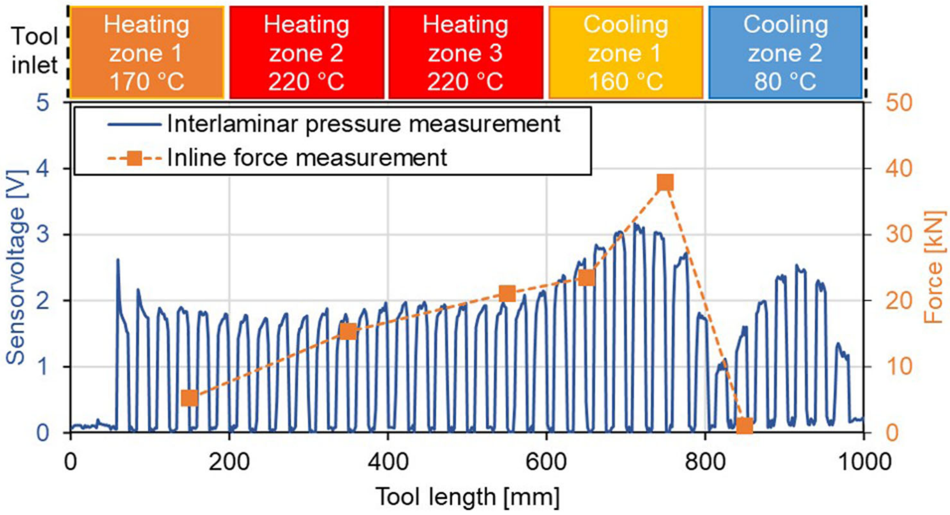


Figure 16. Comparison of interlaminar pressure and inline force measurement.

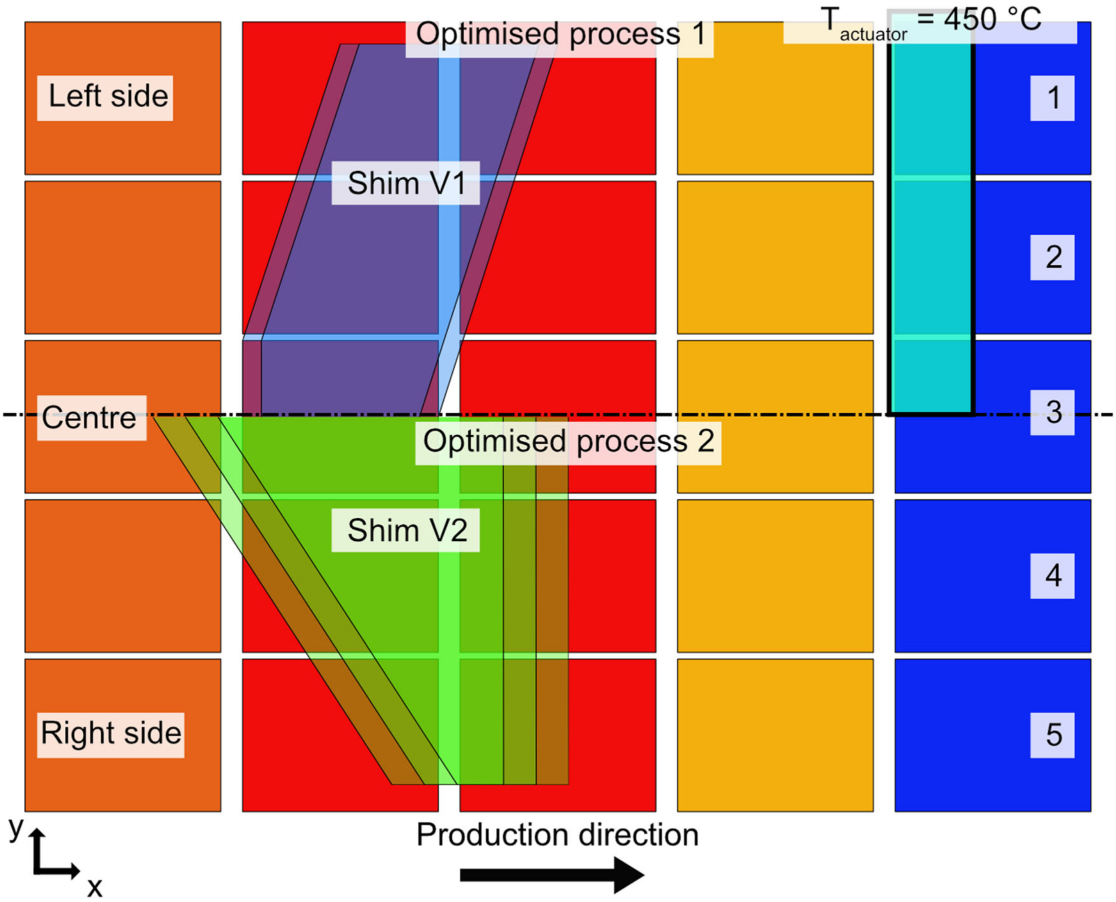


Figure 17. Schematic optimised process setup 1 and 2.

thickness of 0.1 mm and placed between the heating plates and the tool, as shown in Figure 17.

Shim V1 consists of two layers and shim V2 has three layers with an absolute thickness of 0.2 mm respectively 0.3 mm. Furthermore, in the optimised setup 1 the dynamic adaption system was activated to compensate the pressure drop due to the polymer shrinkage behaviour and the press unit elongation, as already presented in Figure 16.

With the developed system tests were performed to prove the functionality of the optimised CCM-machine. Figure 18 shows the pressure distribution measured with the inline force measurement system. The measured forces of a standard laminate production are compared to the two shim-optimised processes. The process parameters (temperature distribution, pressing time, hydraulic pressure, etc.) remain the same for both trials. The only difference

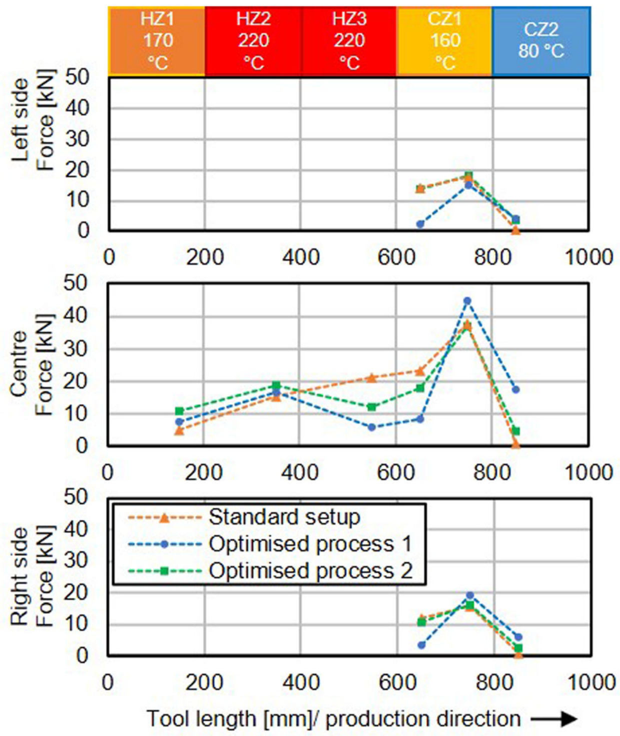


Figure 18. Inline force measurement of different test setups.

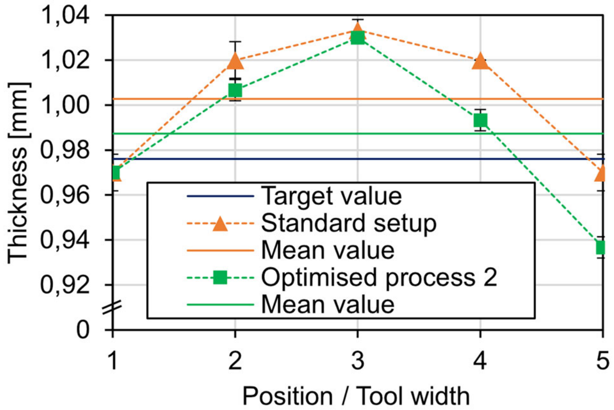


Figure 19. Comparison of the laminate thickness.

is the static and dynamic adaption of the pressing unit. In the heating zones in the centre of the tool the force of the optimised systems is higher due to the integrated shims. Thereby the resulting force of the optimised setup 2 appears higher because of the thicker shim. Subsequently the force drops under the level of the standard process. This is caused by the faster impregnation and so the lower thickness of the laminate in the optimised setups as well as the geometry of the static adaption systems. The difference between the forces at 850 mm tool length can be explained by the activation of the temperature-controlled actuators in this zone in setup 1. The pressure loss due to the shrinkage behaviour of the polymer can be reduced with the dynamic adaption system. Due to material losses at the sides of the tool, the force turns out to be lower than in the centre.

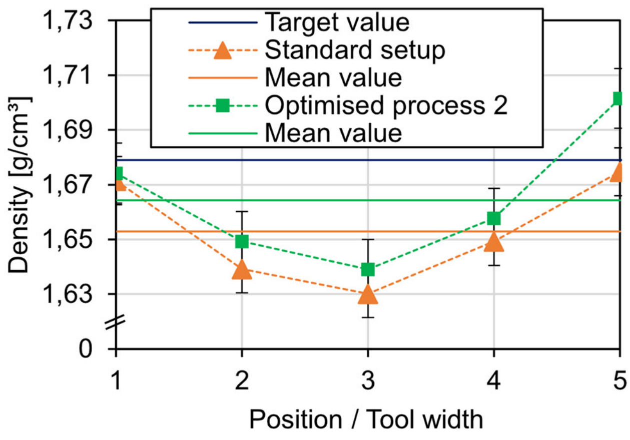


Figure 20. Comparison of the laminate density.

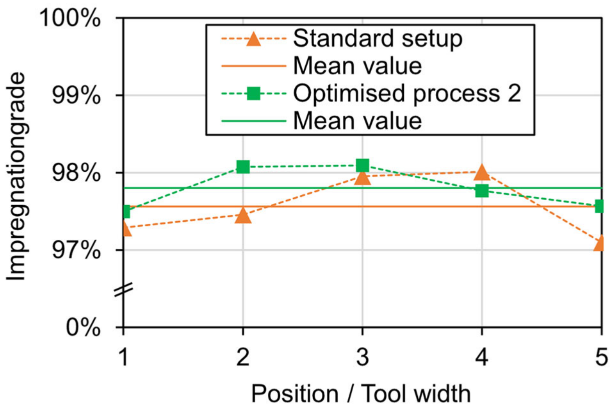


Figure 21. Comparison of laminate impregnation grade.

Figure 19 shows the measurement results of the laminate thickness, Figure 20 the measuring results of the density and Figure 21 the impregnation grade at different positions as well as the average values of all positions on the organic sheet after production. Both laminates were processed with the same layup and process parameters. The only difference is the integrated shim in the optimised process setup 2. To ensure the same amount of polymer a film stacking setup with two polypropylene BJ100HP film layers and two layers of the already described glass fibre fabric was used. The process parameters were defined in a way that the laminate will have an incomplete impregnation using the standard setup. This results in a very short pressing time of only 3 s with a material feed of 25 mm. Incomplete impregnation is recognized when the average thickness values are higher than the calculated target values and the average density is lower than analytically determined. However, the measurements clearly show that with the optimised process technology the thickness is lower and the density higher as with standard processing. Under the assumption of a constant surface weight of the reinforcement, the impregnation grade at each position can be calculated. The mean value of the impregnation grade of the optimised process is thereby slightly higher than

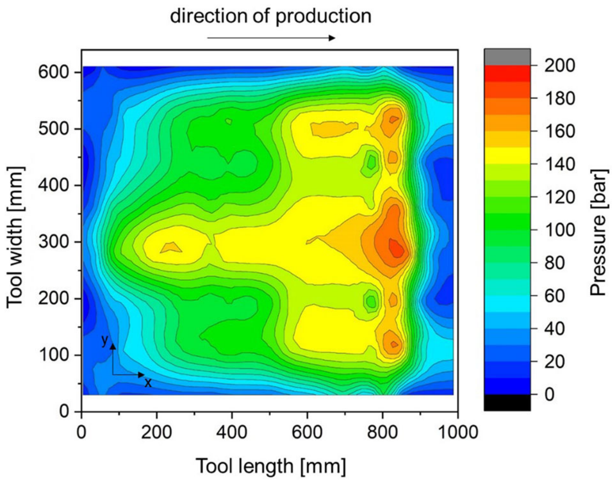


Figure 22. Pressure distribution in the CCM tool with shim adaption.

in the standard process. The result shows a faster impregnation with the integrated shim.

Figure 22 shows the influence of the shim adaption on the measurement of the cavity pressure during laminate production with a total amount of eight FlexiForce^{TM} HT 201 sensors over the tool width. Compared to the conventional tool (Figure 4), the pressure level already increases in the centre of the tool at about 50 mm tool length (approx. 400 mm for conventional setup). In relation to the tool width, a higher-pressure level is evident in the centre of the tool, which drops as desired towards the tool edges. In addition, the pressure loss in the transition zone from heating to cooling zone can be prevented by the tool adaptation. Therefore, a metal shim can be used to directly influence the pressure conditions in the tool during the impregnation and consolidation process.

Discussion

The evaluated results show the first findings of the new developed CCM-machine technology. In a first step the B-factor model by Mayer has been expanded and evaluated to forecast the necessary three-dimensional adaption of the press geometry. By respecting the predominating process conditions sufficiently, it is possible to predict the required height differences for increasing the local pressure inside the tool quite well. Thus, the experimental effort to identify an optimum tool surface will be minimized. To raise the accuracy of the model further parameters like the influence of local temperature variations due to losses at the tool edge should be respected also. Nevertheless, it would be desirable to implement a process calculation tool inside the machine controller to adjust new material combinations in future online. However, this forecast provides a simple way to define an optimised geometry for efficient local pressure distribution inside very large CCM-tools.

The single cell test unit and its tested equipment identify a load sensor ring as the best solution to measure local forces inside the total system. Resulting from its vertical position in direct force flow, the ring is able to quantify the set clamping force very accurately. But with this method it is not possible to convert the measured forces into the effective area of the cavity to obtain the local pressure values. Otherwise, it is possible to increase the clamping force of the preloaded test unit by temperature-controlled actuators. Within a preload of 10 kN the clamping force can be doubled independently of the cavity temperature. Furthermore, the evaluated extension behaviour is linear to temperature, so that a temperature control represents a very good possibility to adjust the local laminate pressure rapidly.

The knowledge of the single cell test unit can easily be transferred to larger CCM-machines. As a consequence of the realised tests, it is possible to install the dynamic adaption system into the clamping unit and therefore to deform a large-scale press tool to a three-dimensional shape. Similarly, it is verified that force sensors are able to identify a local bend of the tool surface sensitively and in relation to detect local force increases. While processing, this CCM-technology is able to increase the pressure inside the laminate in defined areas. The adaption can be either done statically by shimming or dynamically by thermal expansion. If only one material combination will be processed, the static adaption is sufficient. When different material combinations with varying thicknesses are processed, the dynamic adaption is a more flexible solution. A comparison between internal laminate pressure and the force measurement shows a good correlation, so it would be possible to use an automated adaptive system for increasing the performance of the CCM-technology.

The driven CCM-tests correspond with evaluated adaptive pressure system of the single cell test unit and organic sheets can be manufactured more efficiently. A defined convex curved macroscopic flow front can be achieved by adding triangular shaped shims in essential thickness to the pressing unit. With the additional knowledge of its specific saturation permeability, the necessary pressure values can be adjusted locally while processing. So, the micro impregnation can be accelerated and the processing speed increased. The verified laminates show a slight improvement in thickness (0.99 to 0.98 mm) and density (1.652 to 1.661 g/cm^3) and as a result a higher degree of impregnation (97.6% to 97.9%)

compared to a standard processed material. Furthermore, the pressure drop caused by the specific shrinkage behaviour of the polymer while solidification can be minimised.

Conclusions

The results of this study clearly demonstrate the potential of increasing the performance of CCM by local pressure adaption. The targeted convex curved macroscopic flow front by local deformation of the flat pressing surface can be used for an increased impregnation speed and subsequently for a faster processing. In addition, it is possible to compensate the polymer shrinkage behaviour of highly semi-crystalline thermoplastic matrices during cooling. The integrated force measurement sensors, which enable a process monitoring and control, generates detailed process knowledge, so that the production rate can be improved both qualitatively and quantitatively. It is also possible to optimise the control loop of the machine and therefore ensure a continuous production at a high level.

On the other hand, there are still open questions with the developed technology. To assess the real influence of a convex curved flow front of different combinations a deeper analysis of the inner material characteristics is necessary. Therefore, a deeper understanding of the correlation between the used shim design and the obtained impregnation progress has to be implemented. Another focus should be applied on the pressure adaption during solidification. To achieve the full potential of the process, more detailed characterisation tests like mechanical testing or microscopy need to be carried out with the manufactured laminates. Finally, a wider variation of layups and optimised pressure measurements inside the laminate itself would be very helpful to push this technique to its optimum.

Nomenclature

CCM	Continuous compression moulding
FRPC	Fibre reinforced polymer composite
IVW	Institut für Verbundwerkstoffe GmbH
NMF	Neue Materialien Fürth GmbH
A_s	Area of sample
ρ_{FRPC}	Calculated density of FRPC test specimen
$\rho_{FRPCimp}$	Density of fully impregnated sample
ρ_{IL}	Density of test fluid
ρ_P	Density of polymer
ρ_{GF}	Density of glass fibre
I_{Imp}	Grade of impregnation
$m_{S,a}$	Weight of test specimen after immersing in test fluid
$m_{S,b}$	Weight of test specimen before immersing in test fluid
$m_{S,IL}$	Weight of test specimen in test fluid
M_{GF}	Surface weight of glass fibre
V_{GF}	Volume of glass fibres
V_P	Volume of polymer

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The project "IMAPRESS – Increasing the Impregnation Performance of the Semi-Continuous Compression Molding Process by Adaptive Pressing Tools for the Future Production of 50" Organo Sheets" was funded by the Federal Ministry of Economic Affairs and Energy on the basis of a decision by the German Bundestag (funding reference ZF4052318RU7). Parts of this scientific paper have been also presented at the ITHEC 2020 (www.ithec.com).

ORCID

Peter Mitschang http://orcid.org/0000-0003-2650-6678

References

[1] Neitzel M, Mitschang P. Handbuch Verbundwerkstoffe. Werkstoffe, Verarbeitung, Anwendung, München: Hanser Verlag, 2004.
[2] Ehrenstein G. Faserverbund-Kunststoffe: Werkstoffe - Verarbeitung - Eigenschaften. 2. Aufl. München: Carl Hanser Verlag, 2006.
[3] Müller T, Al-Sheyyab A, Kühnert ISE. Grossserientauglich. Plastverarbeiter. 2007;58(11):30–32.
[4] Stock A, Egger P. Organobleche verlassen das Hochpreissegement. Compos World. 2011;12–15.
[5] Renn M, Müller T, Hoffmann L, et al. Hochbelastbare Faserverbundbauteile großserientauglich hergestellt. Lightweightdesign. 2011;4(2):38–43.
[6] Malek T. Leichter als Stahl. Kunststoffe. 2010;100(3):80–84.
[7] Hollaway CA. Advanced fibre-reinforced polymer (FRP) composite materials for sustainable energy technologies. In Advanced fibre-reinforced polymer (frp) composites for structural applications. Cambridge: Woodhead Publishing Limited; 2013. pp. 737–779.
[8] Baker A, Callus P, Georgiadis J, et al. An affordable methodology for replacing metallic aircraft panels with advanced composites. Compos Part A. Appl Sci Manuf. 2002;33(5):687–696.
[9] Teubert Maschinenbau GmbH, Technologien für Partikelschäume und Leichtbau. Blumberg: Teubert, 2018.
[10] Mitschang P, Blinzler M, Wöginger A. Process Technologies for Continuous Fibre Reinforced Thermoplastics with Novel Polymerblends. Compos Sci Technol. 2003;63(14):2099–2110.
[11] Christmann M, Mitschang P. Innovative temperature distribution influences the impregnation quality. 15th European Conference on Composite Materials, Venice, Italy; 2020.

[12] Christmann M, Medina L, Mitschang P. Effect of inhomogeneous temperature distribution on the impregnation process of the contiuous compression molding technology. J Thermoplast Compos Mater. 2017;30(9):1285–1302.
[13] Mayer C. Prozeßanalyse und Modellbildung bei der Herstellung gewebeverstärkter, thermoplastischer Halbzeuge. TU Kaiserslautern; 1999.
[14] Gennaro R, Maffezzoli A, Greco A, et al. Experimental measurement of transversal micro and macro permeability during compression molding of PP/Glass composites. Polym Compos. 2014;35(1):105–132.
[15] Mitschang P, Christmann M, Moser L. Joining of high performance thermoplastic composites. Processing and Fabrication of Advanced Materials XIX, 2011.
[16] Christmann M, Mitschang P, Medina L. Impregnation performance of non-isobaric processes. 20th International Conference on Composite Materials, Kopenhagen, Denmark; 2015.