INFLUENCE OF INHOMOGENEOUS TOOL TEMPERATURE ON THE IMPREGNATION PRESSURE OF THE CONTINUOUS COMPRESSION MOLDING PROCESS

M. Christmann*, P. Mitschang
[1] Institut für Verbundwerkstoffe, GmbH, Kaiserslautern, Germany
* Corresponding author (marcel.christmann@ivw.uni-kl.de)

Keywords: *impregnation, thermoplastic, inhomogeneous, pressure, temperature*

1 Introduction

Due to their specific properties such as high toughness, fatigue resistance, chemical resistance, or nearly unlimited shelf life, the demand for continuous fiber reinforced thermoplastic polymer composites has steadily increased over the past years. This group of materials is used in a wide range of applications, e.g. in the aerospace or transportation industry. Thereby, the processing chain typically starts with the manufacturing of continuously reinforced semi-finished products, so-called organic sheets. Because of the long impregnation time, this first step significantly influences the efficiency of the whole process.

Considering economic terms, presently one of the most meaningful possibilities for the production of organic sheets is the use of a continuous compression molding (CCM) machine. However, for a further increase of the output, a fundamental knowledge of the process and the interlaminare situation during the impregnation and consolidation is necessary.

2 The Continuous Compression Molding Technology

The continuous compression molding process works on the basis of a semi-continuous press, which comprises the following four steps: Closing the mold, applying the pressure and temperature, opening the mold, and transporting the laminate for a desired distance. Once these four steps are completed, the cycle starts again (see Figure 1).

The press is equipped with an open-plan sheet die, which is divided into a heated and a cooled section. Thus, at the beginning of the process, the impregnation and consolidation takes place in the heated area of the pressing zone and the solidification takes place at the end of the pressing zone. Furthermore a modular heating and cooling system (see Figure 2) provides the flexibility for various temperature profiles in longitudinal and cross-direction of the pressing tool. [1 - 5]
The scope of the paper is to show the influence of different inhomogeneous tool temperatures on the interlaminare pressure during the continuous compression molding process of film stacking laminates. Further aim of the paper is the introduction of a model to predict the progress of impregnation during the CCM process.

3 Calibration of Sensor Equipment

The examination of the pressure distribution was done using FlexiForce® Sensors (model: HT201) of Texscan®, which offer a specified operating temperature range of -9 up to 204 °C. Because the measuring behavior of each sensor is individual and beyond, there is an influence of the temperature on the measured values (see Figure 3) of 0.15%/K, a calibration and modeling of the sensor behavior was necessary.

The calibration was carried out in an autoclave in order to apply homogeneous pressure to the sensors. Because of the operating principle, the sensors are only able to detect applied force loads and no pressure loads. Thus, a special calibration bag was used to convert pressure into force by allowing lateral expansion of the sensors (see Figure 4). The outer bag, made of PI film, keeps the compressed air from the sensors and is connected to the atmosphere. Inside the bag, the sensors are placed between another PI film and an aluminum plate. The foil covers the sensors and separates them from the outer bag. The aluminum plate serves as support and prevents bending and buckling of the bag because of the airflow inside the autoclave. In addition, there are two very thin glass fiber textiles in the bag which enable the transport of the air outside the bag.

During the calibration cycle, sensor values from 0 up to 20 bar at temperatures of 50, 100, 150 and 200 °C have been recorded. The generated data base was used to create a specific polynomial pressure function for each sensor (dependent of temperature and pressure). The visualization of one of these functions as a 3-dimensional diagram is given in Figure 5. Thereby the dots represent the data basis generated with the related sensor.

4 Investigation of Pressure Distribution

The investigation of the influence of an inhomogeneous temperature distribution on the pressure distribution during the impregnation was carried out using three different temperature profiles. Firstly, a homogeneous temperature profile with a defined temperature of 200 °C in the heating zone serves as a reference profile. Secondly, the inhomogeneous temperature profiles were selected with a biggest possible temperature gradient in cross direction of the tool. Thus, one profile was set to 170 °C at the edges and 200 °C at the center of the tool. The second inhomogeneous profile was defined with 200 °C at the edge and 170 °C at the center. The different temperatures have been defined, because polypropylene (PP) serves as matrix material, which has a melting point of 163 °C. Thus, the lower temperature is near the melting point, but already all elements of the polymer are liquid. The higher temperature represents a normal processing temperature for PP. The resulting temperature distributions on the tools' surface, which have been determined by a FE-simulation, are given in Figure 6, 7, and 8. Thereby each of the three profiles has the same temperature settings in the cooling zone of 90 °C after the transition region and 40 °C at the end of the tool. The pressure was set to 192 bar in the pressure cylinder, which should lead to a pressure of 15 bar across the tools surface.

For carrying out all measurements, the sensors have been put into another film bag. The lay-up is similar to the shown one in Figure 4. The sensors have been arranged with an equal distance in cross direction of the tool. The arrangement is given in Figure 9. Thereby, the size of the foil bag is chosen with the double length of the tool in order to avoid tilting of the tool during the pressing stage, even the foil bag has a thickness of only 0.4 mm including sensors. For the connection of the sensors with the measuring amplifier cables with PTFE insulation and a diameter of 0.65 mm have been used.

The pressure distribution can be effected by a large number of different effects. One effect, which is independent of the progress of impregnation, can be caused by the deformation of the tool under the inhomogeneous temperature load. Especially the transition region from the heated to the cooled zone is of major importance. Thus, in a first step the pressure distribution was investigated using two silicon films instead of a thermoplastic laminate. Each silicon film had a thickness of about 1.5 mm. The sensors have been inserted between these two silicon films so that no overload due to the sensor thickness could appear. Besides, the applied pressure is homogeneously transferred to the sensors. Figure 10 shows the result of the pressure value measurement using the silicon film and the isothermal temperature profiles (200 °C in the heating zone).

It can be seen that there is an inhomogeneous pressure distribution across the tool. The pressure is steadily increasing from the inlet to the outlet of the tool. This effect is superimposed of a pressure aggregation in the center of the tool. Both effects can be treated back to the off-center alignment of the pressure cylinder in longitudinal direction of the press and the bending of the tool under the applied load. Due to these properties, very high pressure values of about 40 to 50 bar are reached in some regions. The average pressure was determined to be 25 bar. Assumed, the pressure control of the press is acceptable, the big difference between the defined pressure and the measured pressure can be entailed by the thickening of the sensors or by the calibration of the sensors. Because the maximum pressure during the calibration was 20 bar, there is no reliable database for higher values. Thus, the predicted sensor values of the model can be inaccurate. Figure 11 illustrates the predicted sensor behavior for higher pressure values. Although there is some impreciseness because of the modeling of the sensors, there can't be found any distortion of the tool due to thermal stress, which significantly influences the pressure distribution.

As a second step of the investigation, organic sheets consisting of glass fiber textile (Hexcel HexForce® 01038) and polypropylene matrix material (Borealis

PP BJ100HP) have been manufactured using the three different temperature profiles. The sensors are again applied in the middle of the laminate which is consisting of four layers of reinforcement and four layers of matrix material.

The theoretical fiber volume content was set to 44 % which leads to a thickness of 2.14 mm. The used lay-up is shown in Figure 12.

The examination of the pressure distribution under isothermal conditions shows big differences in comparison to the examination using silicon film. The results are given in Figure 13. Thereby, a distinctive inhomogeneity in the pressure across the tools surface can be seen. Starting with low pressure values in the inlet area, there is a very intensive pressure aggregation in the middle of the cooling zone. In-between, in the transition region from hot to cold, a considerable lack of pressure becomes apparent. Especially the last effect is of major interest, because it could affect the quality of the laminate negatively.

There are different reasons which could affect the lack of pressure in the transition region. Although, the geometry of the tool was checked with the prior investigation using silicon film, the planarity was checked again using a straight edge made of graphite. One big advantage of this material is the very low thermal expansion, so that no deflection of the measurement instrument occurs during the contact with the hot tool. Finally, Figure 14 shows that there is no light gap in the transition region from hot to cold. Hence, no deformation could be found.

Another possible reason for the lack of pressure can be an error in measurement of the sensors due to quenching in the transition region. Thus, an abrupt cooling of the sensors was counterfeit with two water bath tempered at 20 °C and 90 °C. After a drop down in values for a split of second, only a small drop down of about 5 % was remaining, which can be treated back to the temperature dependent behavior of the sensors (see Figure 15).

As a last influencing factor, the shrinkage of the laminate was indicated. Because of the low thermal expansion of the glass fibers, the shrinkage of the laminate is mainly determined by the thermal expansion and the crystallization of the matrix material. In general, polypropylene has an average thermal expansion coefficient of about $1.5*10^{-4}$ [1/K]. The initial thickness of the applied PP material inside the laminate is 1.2 mm in total. Thus, the theoretically maximum cooling of 110 °C (200°C – 90 °C) would lead to a shrinkage of 0.02 mm. In a realistic point of view, this value will not be reached of two neighboring laminate points, because there is a smooth transition from hot to cold in the continuous tool. Furthermore, this smooth zone cannot be skipped by a transportation step, because during each step the laminate is pulled ahead for only 30 mm. The shrinkage because of the crystallization is specified with 1.7% in the data sheet. Thus, the thickness is reduced by about 0.02 mm which leads to a total shrinkage of 0.04 mm. Finally, the polymer shrinkage seems to be a realistic possibility, which could evoke the lack of pressure. A detailed investigation of the shrinkage during the cooling process is not part of this investigation.

In the next step, the pressure distribution using the two inhomogeneous temperature profiles was carried out. The results are given in Figure 16 and 17. In general, the pressure distribution is comparable to the isothermal settings, i.e. the pressure is steadily increasing from the inlet to the outlet and there is a lack of pressure in the transition region from hot to cold.

But in addition, it is clearly shown, that there is an influence of the temperature settings in cross direction of the tool on the pressure distribution. The pressure is increased in the region with the lower temperature, i.e. the pressure is more constant in cross direction of the tool when the edges are tempered to 170 °C (center 200 °C) (see Figure 16) and the pressure is more constant in longitudinal direction when the center is tempered to 170 °C (edge 200 °C) (see Figure 17). One possible reason for the found results can be a faster impregnation progress in the hotter region due to the lower viscosity of the polymer. Thus, the necessary impregnation force is reduced and the interlaminare pressure increases in the colder region.

6 Conclusions

The examination of the interlaminare pressure distribution of the continuous compression molding process has clearly shown that there is a significant influence of an inhomogeneous tool temperature.

Firstly, a lack of pressure was found in the transition region from hot to cold which was treated back to the shrinkage of the polymer during the cooling. Secondly, a non-uniform impregnation speed due to inhomogeneous viscosity leads to increasing pressure in the colder region of the tool. Beyond, an inhomogeneous pressure distribution evoked by the machine design was found too.

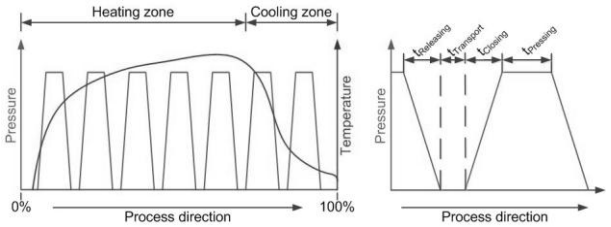

Fig. 1. Tool temperatures distribution.

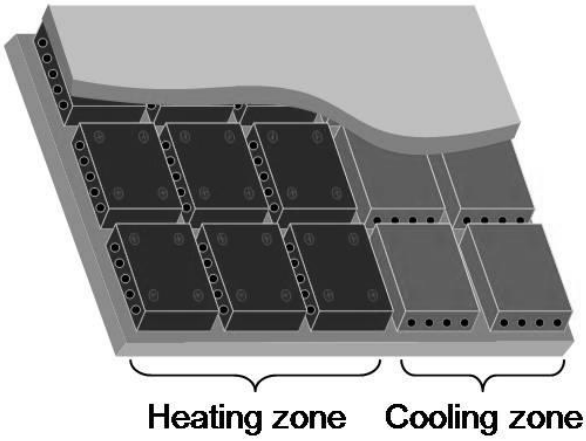

Fig. 2. Tool temperatures distribution.

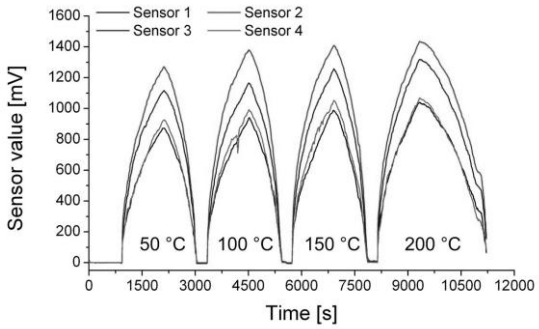

Fig. 3. Temperature dependent sensor behavior.

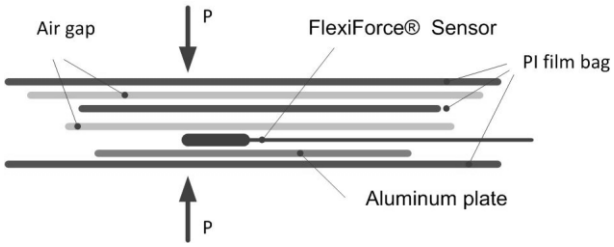

Fig.4. Schematic drawing of the lay-up of the used bag for calibrating the used sensors.

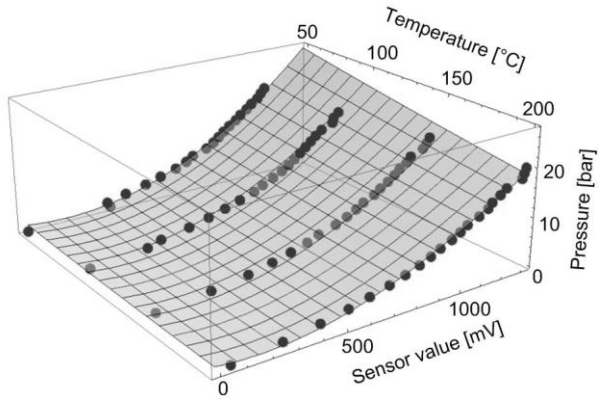

Fig. 5. Visualized data of modeling the sensor behavior as a function of temperature and pressure.

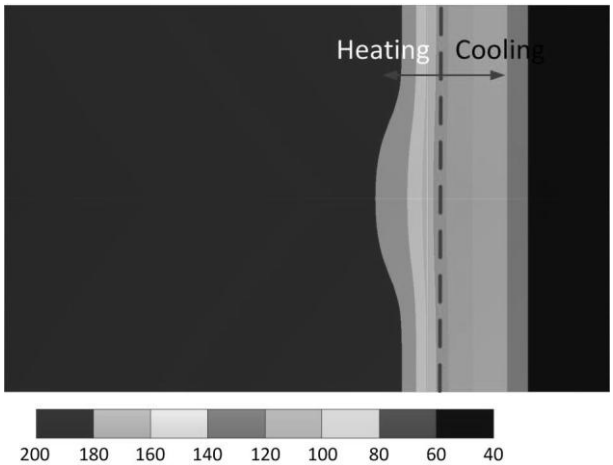

Fig. 6. Isothermal temperature profile (200 °C).

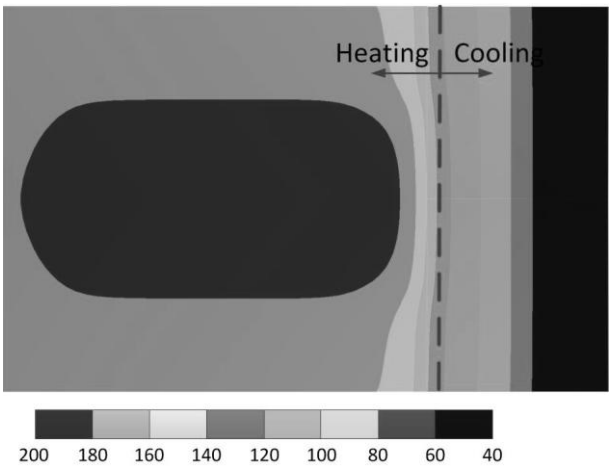

Fig. 7. Inhomogeneous temperature profile (edge 170 °C / center 200 °C).

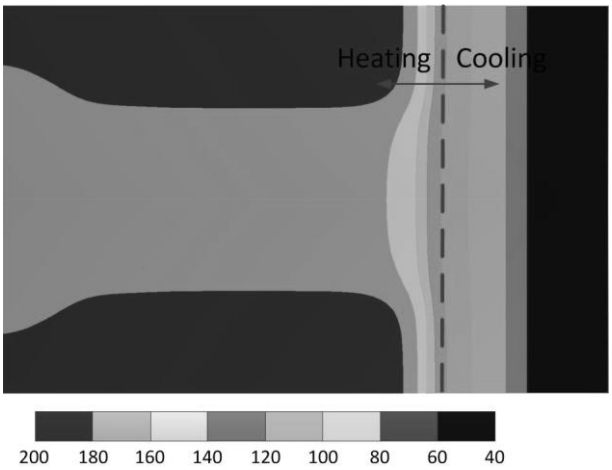

Fig. 8. Inhomogeneous temperature profile (edge 200 °C / center 170 °C).

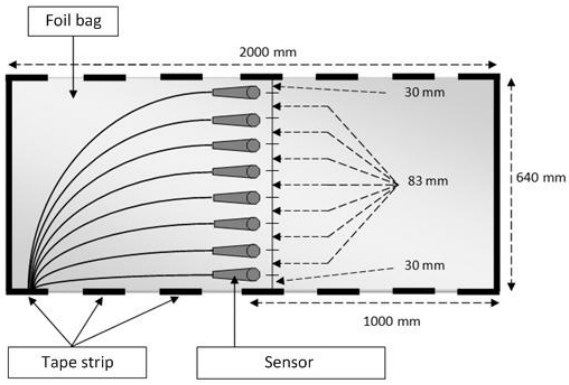

Fig. 9. Sensors added to the foil bag.

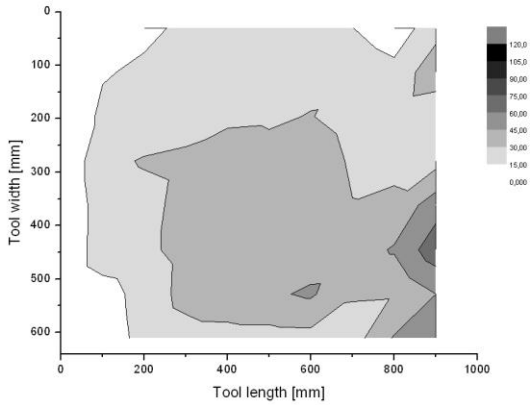

Fig. 10. Pressure distribution using silicon film and isothermal settings (200 °C).

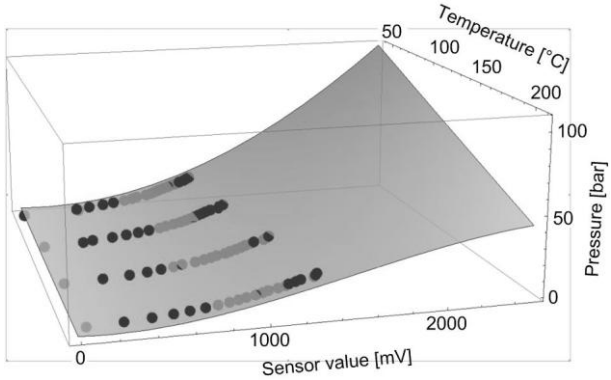

Fig. 11. Modeling of sensor behavior for pressures higher than 20 bar.

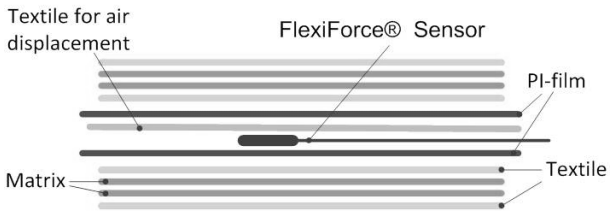

Fig. 12. Laminate lay-up with pressure sensors applied in the middle.

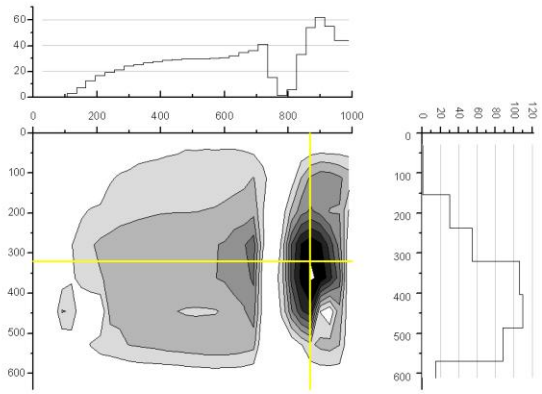

Fig. 13. Pressure distribution during the manufacturing process of a fiber/matrix laminate under isothermal settings (200 °C).

Fig. 14. Graphite straight edge on the tool surface in the transition area (200 °C).

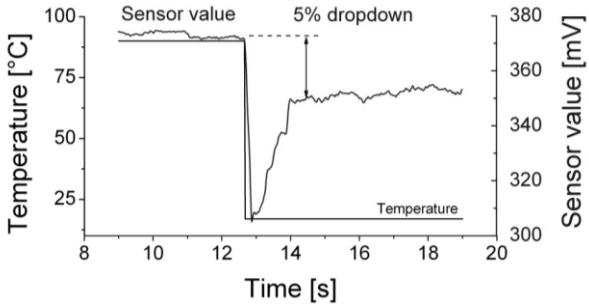

Fig. 15. Quenching of sensors.

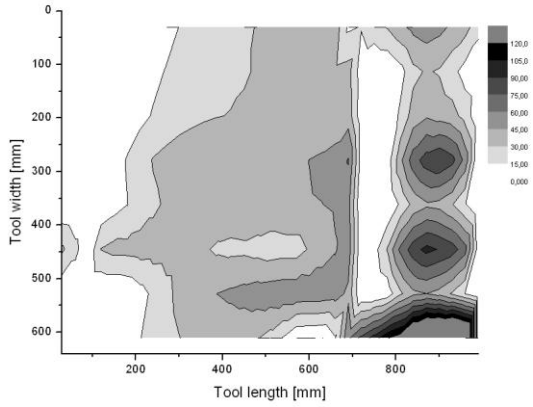

Fig. 16. Pressure distribution during the manufacturing process of a fiber/matrix laminate under inhomogeneous settings (edge 170 °C / center 200 °C).

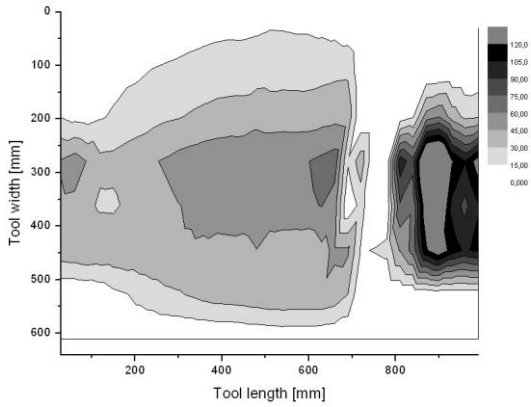

Fig. 17. Pressure distribution during the manufacturing process of a fiber/matrix laminate under inhomogeneous settings (edge 200 °C / center 170 °C).

Acknowledgment

The research presented in this paper were financially supported by the "Deutsche Forschungsgesellschaft" (DFG).

References

[1] Sp. Pantelakis, E. Baxevani, U. Spelz „An automated technique for manufacturing thermoplastic stringers in continuous length", *Composites Structures*, Vol. 26, pp. 115-121, 1993.

[2] M. Steeg "*Prozesstechnologie für Cyclic Butylene Terephthalate im Faser-Kunststoff-Verbund",* Schriftenreihe Institut für Verbundwerkstoffe GmbH, Kaiserslautern, 2010.

[3] P. Mitschang, M. Blinzler, A. Wöginger "Processing technologies for continuous fibre reinforced thermoplastics with novel polymer blends", *Composites Science and Technology*, Vol. 63, pp. 2099-2110, 2003.

[4] G. Gardiner „Aerospace-grade – Compression Molding", *High Performance Composites*, July 2010, pp. 34-40, 2010.

[5] S. Scholl, H. Schürmann „Continuous Profiles with Targeted Orientation", *Kunststoffe international*, Vol. 7, pp. 55-58, 2008.