# INNOVATIVE TEMPERATURE DISTRIBUTION INFLUENCES THE IMPREGNATION QUALITY

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## Abstract
*During the investigation the influence of an inhomogeneous temperature distribution on the impregnation quality is examined. Therefore, organic sheets have been processed using different temperature settings. Afterwards the impregnation quality was evaluated by micrographs of polished cross sections, which have been taken at different positions. Furthermore, the results have been correlated to previous studies of the pressure distribution.*

## 1 Introduction
Due to their specific properties such as high toughness or excellent fatigue performance, the demand for fiber reinforced thermoplastic composites has steadily increased. These materials are used for many applications in different industries, e.g. as sole or ski reinforcements in sport industry, as bumper beams in the automotive industry or leading edges in aeronautic industry. Thereby, thermoplastic composites offer the advantage of short cycle times of the forming process due to the use of semi-finished products, so called organic sheets. Considering economic terms, presently one of the most meaningful possibilities for the production of these semi-finished products is the use of the continuous compression molding (CCM) technology [1, 2, 3]. However, for a further increase of the output, a fundamental knowledge of the impregnation and consolidation behavior during the process is necessary. The machine used for this examination provides the flexibility for various temperature profiles across the tools' surface. Thus, scope of the paper is to show the influence of an inhomogeneous tool temperature in cross-direction of the tool on the impregnation quality of the laminate.

## 2 The Continuous Compression Molding Technology
The continuous compression molding process is based on a static press in combination with a transport system, which results in an intermittently working unit. Thus, the process comprises the following four steps: Closing the mold, applying the pressure and temperature, opening the mold, and transporting the laminate for a desired distance. The inlet area of the die is heated in order to melt the matrix material and to impregnate the fibers. Afterwards, the laminate is solidified again in the cooled lead out area of the die. Thus, the laminate is exposed to a various temperature profile in longitudinal direction of the tool. Beyond, the CCM press of the IVW GmbH (producer: Xperion Aerospace GmbH, Immenstaad) is equipped with a modular heating and cooling system, which also enables various temperature profiles in cross-direction of the tool (see Figure 1).

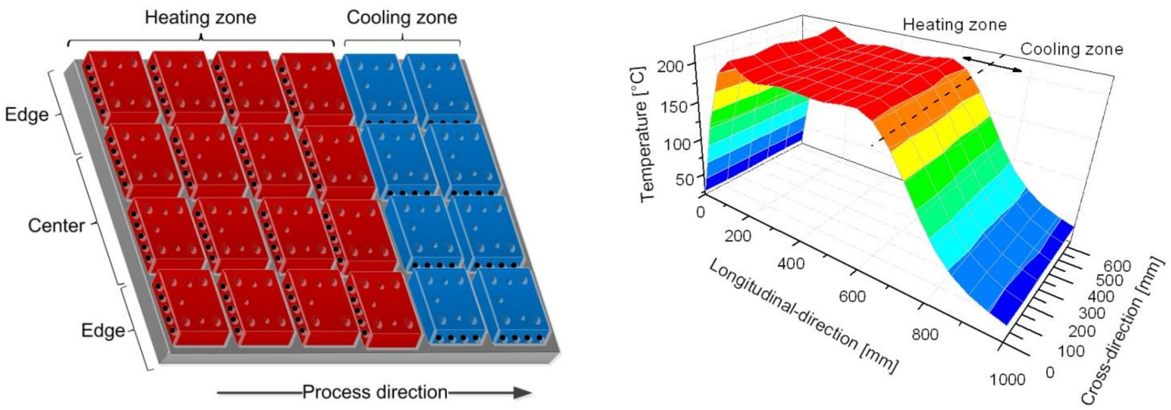


**Figure 1.** Various temperature profile of the CCM process

Because there is a correlation between the temperature and the viscosity for a thermoplastic polymer, the realization of an inhomogeneous temperature distribution in cross-direction of the tool should have significant effects on the interlaminare situation. This study will focus on the impregnation quality of the laminate due to inhomogeneous temperatures in cross-direction of the tool, whereas in a former investigation the influence on the pressure distribution was examined (see Figure 2) [4].

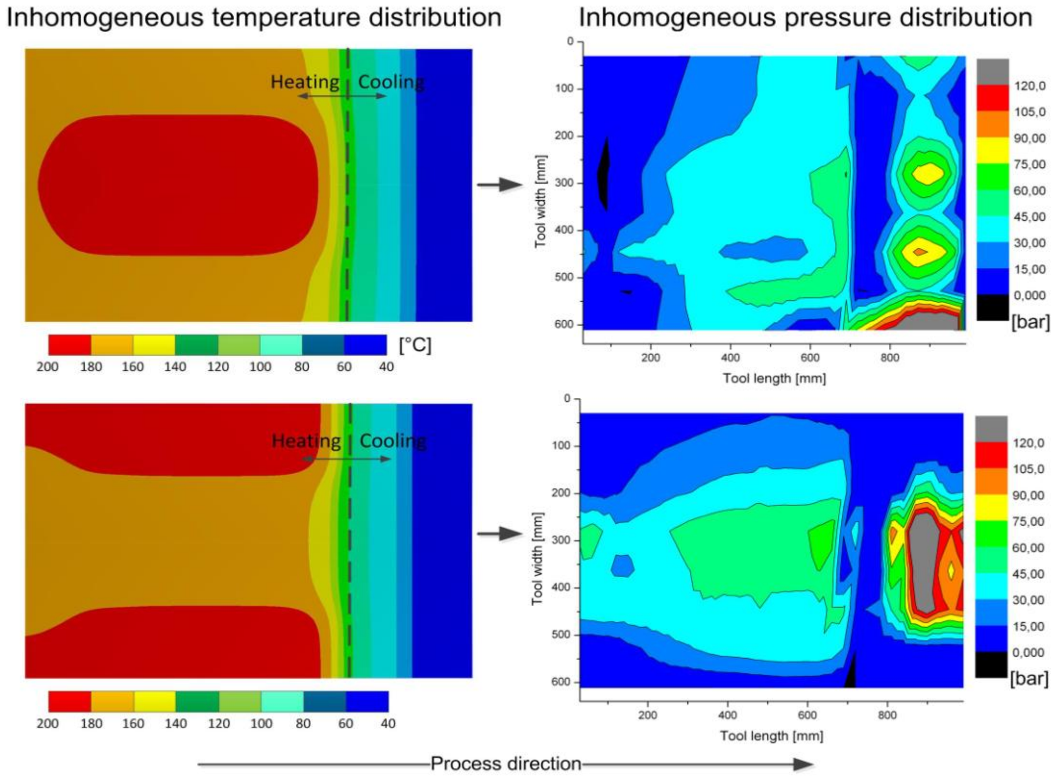


**Figure 2.** Pressure distribution due to inhomogeneous temperature distribution [4]

It could be shown, that there is a pressure aggregation in the middle and lead out of the tool, which could be attributed to the design of the machine. Furthermore, the investigation showed a lack of pressure in the transition region form the heating to the cooling zone. Finally, it could be shown, that the pressure increases in the colder regions of the tool, when an inhomogeneous temperature distribution in cross direction of the tool is used. This could be traced back to the non-uniform impregnation speed due to inhomogeneous matrix viscosity.

Starting point of the investigation are several organic sheets, which have been produced with the CCM-machine. As reference material commercially available reinforcement and matrix materials have been used. Glass fiber textile from Hexcel (HexForce® 1038) with an area weight of 600 g/m² was used as reinforcement material, because it offers the same number of yarns in warp and weft direction as well as a homogeneous weight distribution in both directions. Thus, the influence of different permeabilities in weft and warp direction is minimized, which might be important for the matrix flow front due to an inhomogeneous temperature distribution. Polypropylene from Borealis (PP bj100hp) with a film thickness of 300 µm and a melting point of 166 °C served as matrix material. A symmetric film-stacking lay-up with 4 layers of textile and 4 layers of matrix film was chosen (F = fiber; M = matrix; lay-up = [F,M,M,F]s). The theoretical fiber volume content was calculated to be 44% and a theoretical thickness of 2.14 mm was determined.
For the reference values, samples have been processed at different production speeds (2, 3, 4, 5, 6, 7, 10, 15, and 20 m/h) using homogeneous temperature settings of 190 °C in the heating zone. The pressure was set to 1.5 MPa (15 bar) first and based on these reference organic sheets a reasonable production speed for the later trials using the inhomogeneous temperature distribution were determined. Secondly, the cross section micrographs taken at each production speed in the center of the organic sheets serve as base for the evaluation of the laminate quality (see Figure 3).

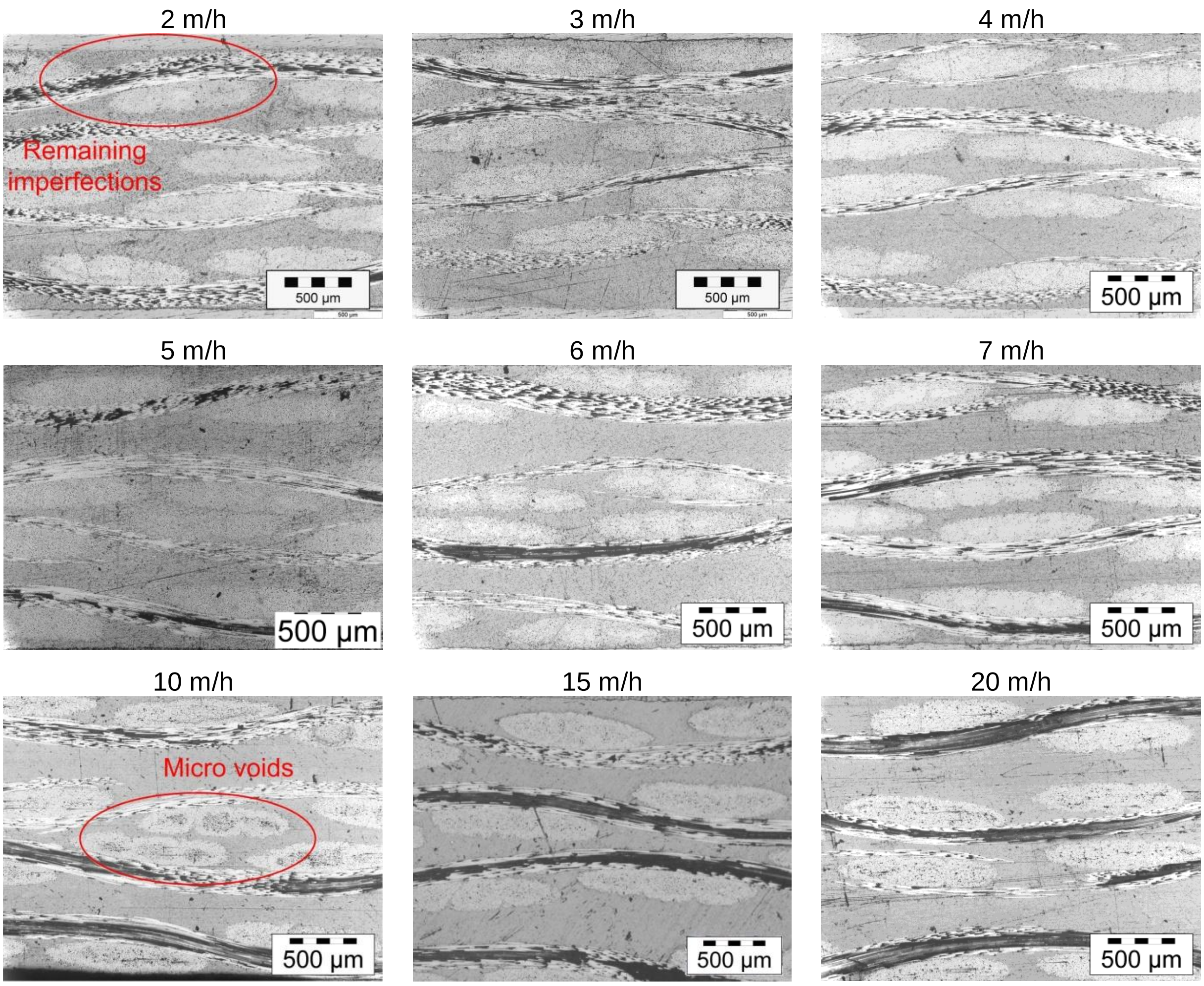


**Figure 3.** Impregnation quality of the GF/PP laminates processed at different process speeds

It was found, that a good micro impregnation quality for production speeds below approximately 5 m/h could be achieved. For higher speeds, the micro-impregnation is imperfect, whereas for lower speed the impregnation is determined and the fiber distribution gets more homogeneous. However, for each process speeds there are still some imperfections remaining, which might be attributed to the polishing process or to the process pressure (temperature is sufficient, because settings are 24 °C higher than the melding point of the polymer). In order to check if the pressure was too low, organic sheets have been processed with increased process pressure of 2 MPa (20 bar). Because the examination of this micrograph doesn't show a significant change in impregnation quality, the remaining imperfections might be the result of the polishing process.

## 3 Analysis of Impregnation Quality for Inhomogeneous Temperature Profiles

In order to evaluate the influence of inhomogeneous temperature profiles on the impregnation quality, samples have been processed using five different inhomogeneous temperature profiles. Therefore, the temperatures at the edges (see Figure 1) of the tool have been varied in the range of 170 °C to 210 °C with steps of 10 K. The temperature in the center of the tool was kept constant at 190 °C. In the further text, the temperature profiles will be named according to the used temperatures (170/190 °C; 180/190 °C; 190/190 °C; 200/190 °C; 210/190 °C). Three of these five inhomogeneous temperature profiles are given in Figure 4.

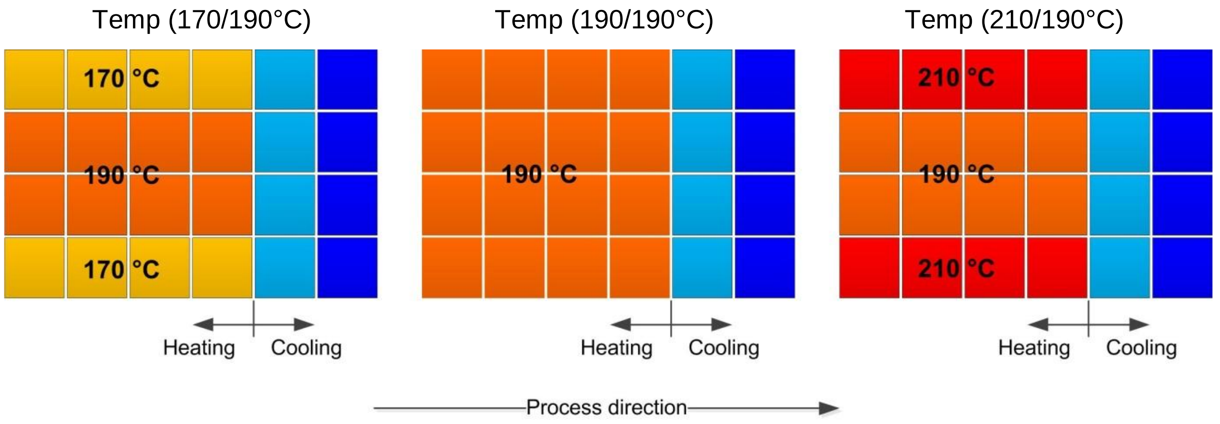


**Figure 4.** Inhomogeneous temperature settings

The impregnation quality was analyzed with cross section micrographs, which were taken at three different positions in cross-direction of the tool as well as for different states of impregnation for each inhomogeneous temperature profile (see Figure 5). Therefore, the process was stopped while the mold was opened and the laminate was pulled out of the tool in order to solidify. This approach enables to compare the impregnation quality to each other and to the reference values in order to determine a slowed or accelerated impregnation process. Due to the use of an air impermeable release paper, the deconsolidation of the laminate was minimized, because the air could only penetrate the laminate from the side. Nevertheless, the micrographs might show some deconsolidation effects due to deconsolidation. Furthermore, at each position two samples were taken in order to make micrographs in process direction (0° view) as well as transverse to the process direction (90° view) (see Figure 5). Because the examination of the reference quality samples has shown no increase in impregnation quality for process speeds below 5 m/h, it was decided to use this speed for the investigation of the inhomogeneous temperature profiles. The process pressure was set to 20 bar (2 MPa).

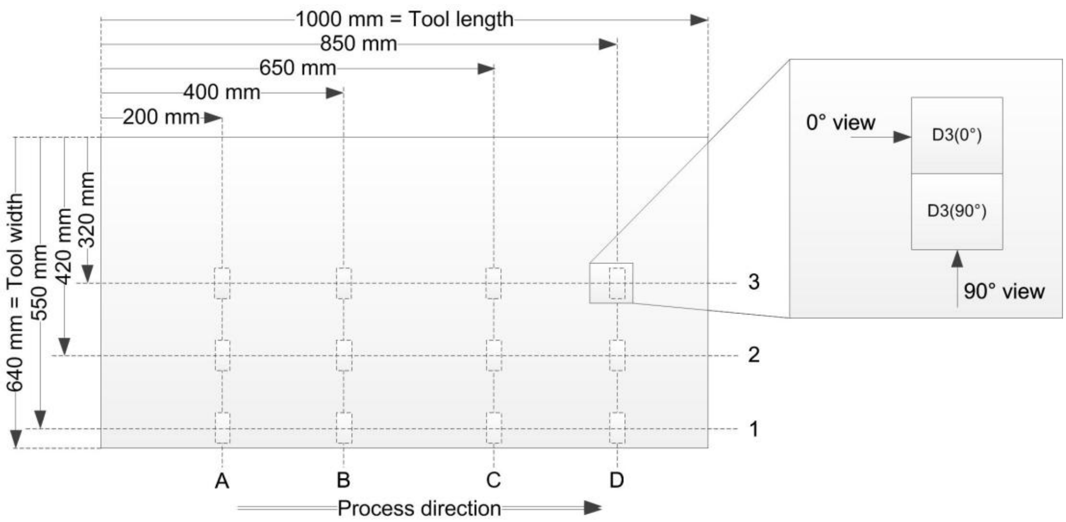


**Figure 5.** Cross section micrographs taken at different positions

During the examination of the organic sheets processed with inhomogeneous temperature profiles, some impregnation effects became apparent. The samples processed with 170 °C at the edges (170/190°C) only show a slight macro-impregnation at position A1(0°). Thus, the single layers don't adhere to each other, which makes it impossible to evaluate the impregnation progress for the used temperature profile at this position. Having a look at the samples processed with 180 °C at the edges (180/190°C), no effects on the impregnation quality can be seen at position A in 0° view (see Figure 6 samples A1(0°) and A3(0°)).

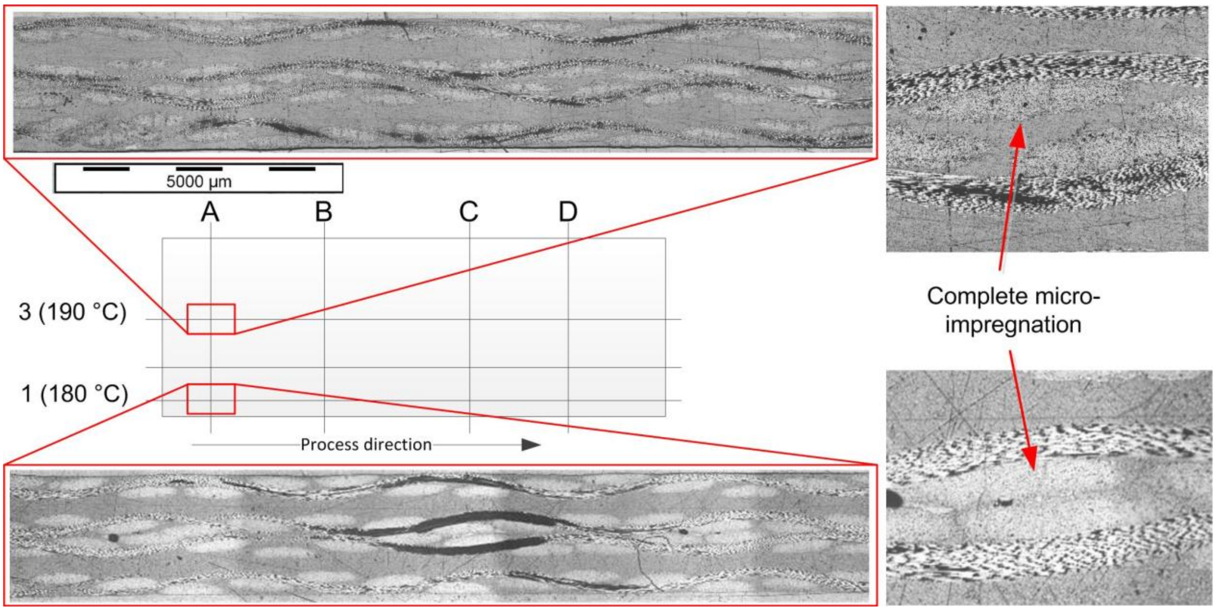


**Figure 6.** Impregnation quality of laminates produced with lower temperature at the edges (180/190°C – 0° view)

But when examining the micrographs taken in 90° view, big voids inside the fiber bundles of all sample became obvious at position A (see Figure 7 samples A1(90°) and A3(90°)). One possible reason for this difference between 0° view and 90° view could be that the displacement of the entrapped air inside the fiber bundles is dependent on the direction. Because there is a continuous increase of pressure in the inlet area, it is easier to displace the air in the opposite process direction (0°) than in cross direction (90°) of the tool. Furthermore, the displacement in cross direction is constricted by the high matrix viscosity at the edges.

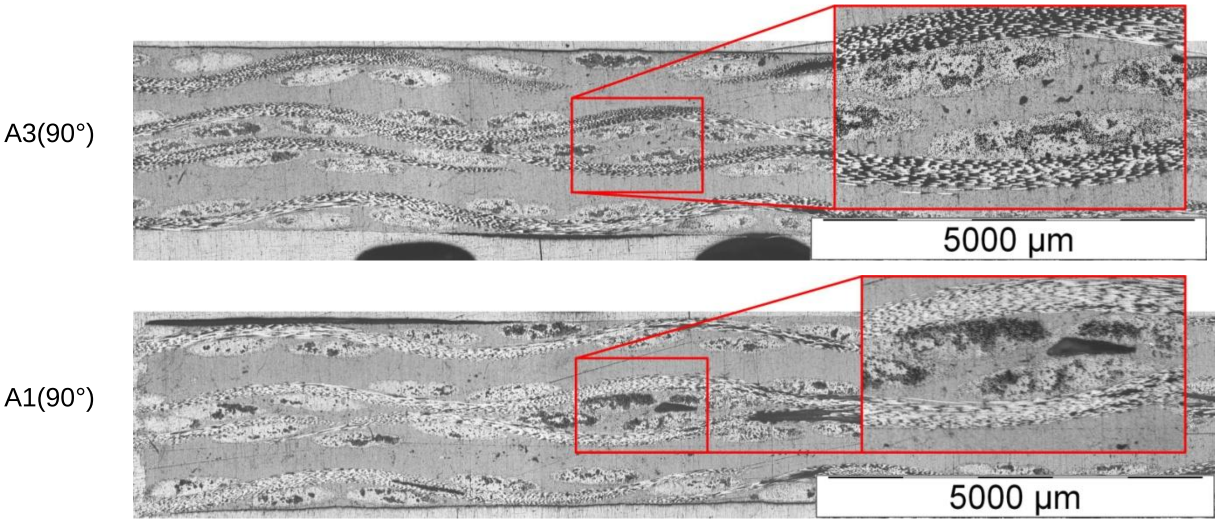


**Figure 7.** Impregnation quality of laminates produced at 180/190 °C - 90° view

In order to evaluate if the micro voids in 90° view at position A are affected by the inhomogeneous temperature distribution (180/190 °C), a comparison of the impregnation quality with samples processed with the homogeneous temperature profile (190/190 °C) was performed. Because these micrographs (see Figure 8) don't show micro voids in 90° view, the formerly found phenomenon can clearly be traced back to the inhomogeneous tool temperature.

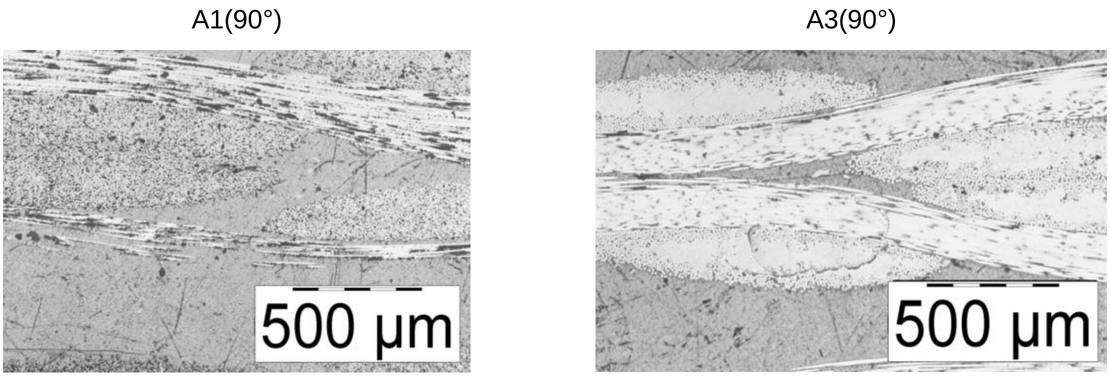


**Figure 8.** Cross section micrographs (190/190 °C)

The cross section examination of the laminates produced with higher temperatures at the edges also shows an influence of the temperature distribution. Samples taken at position B and C (210/190 °C) show a decrease in micro impregnation quality. This phenomenon is illustrated most effectively for the micrographs taken in 90° view (see Figure 9). A possible explanation might be the decreasing temperature at Position C. Because of this, the polymer starts to shrink, which might lead to decreasing pressure and increasing micro voids in the transition region from the heating to the cooling zone.

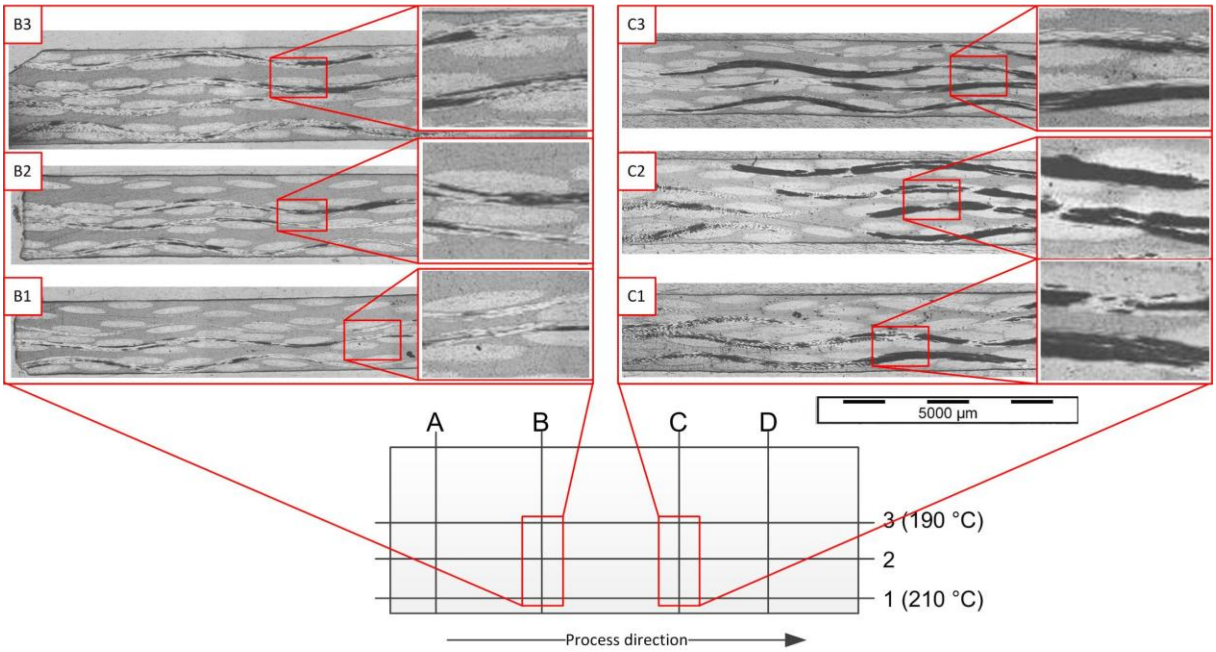


**Figure 9.** Comparison of impregnation quality for inhomogeneous temperature settings (210/190 °C - 90° view)

The further examination of the laminates produced with the inhomogeneous temperature profile (210/190 °C – 0° view) also showed that higher temperatures at the edges lead to a fully impregnated laminate in the center (see Figure 10). Beyond, the investigation revealed an aggregation of entrapped air in the lateral transition region from 210 °C to 190 °C.

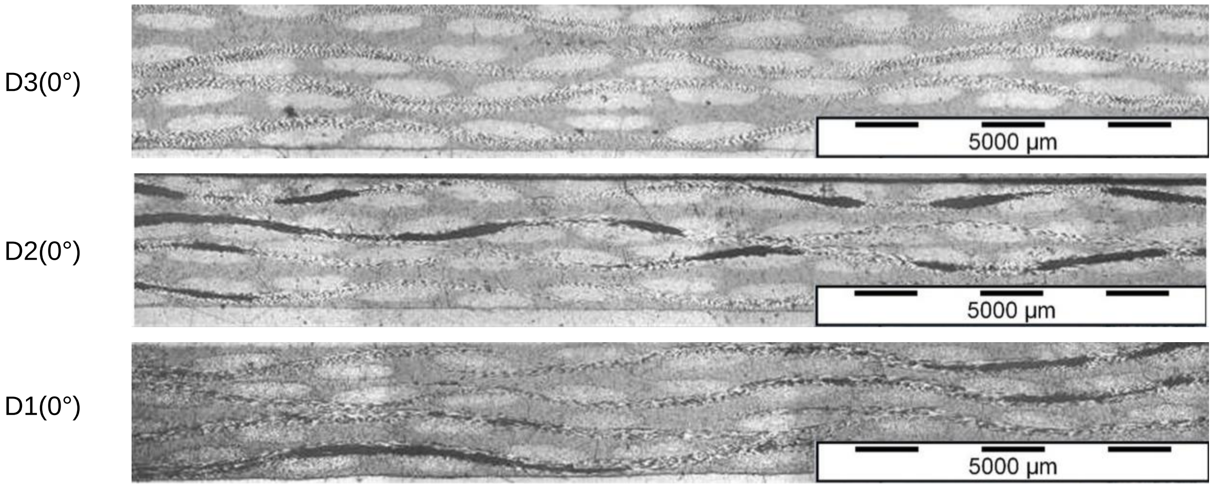


**Figure 10.** Increased impregnation quality in the laminate center (210/190 °C – 0° view)

Having a look at the laminate before and after entering the cooling zone (position C and D) for the same temperature profile, these phenomena mentioned are explained. The impregnation quality improves rapidly in the middle of the tool and reduced in the transition region from 210°C to 190°C. Thus, this effect can be attributed to the sideways displacement of the entrapped air in the middle of the tool, which is a result of the inhomogeneous pressure distribution respectively inhomogeneous tool temperature (see Figure 11). Finally, the cross section micrograph taken at position D3(0°) shows a fully impregnated laminate, although the high pressure was only applied for a short period of time in the cooling zone.

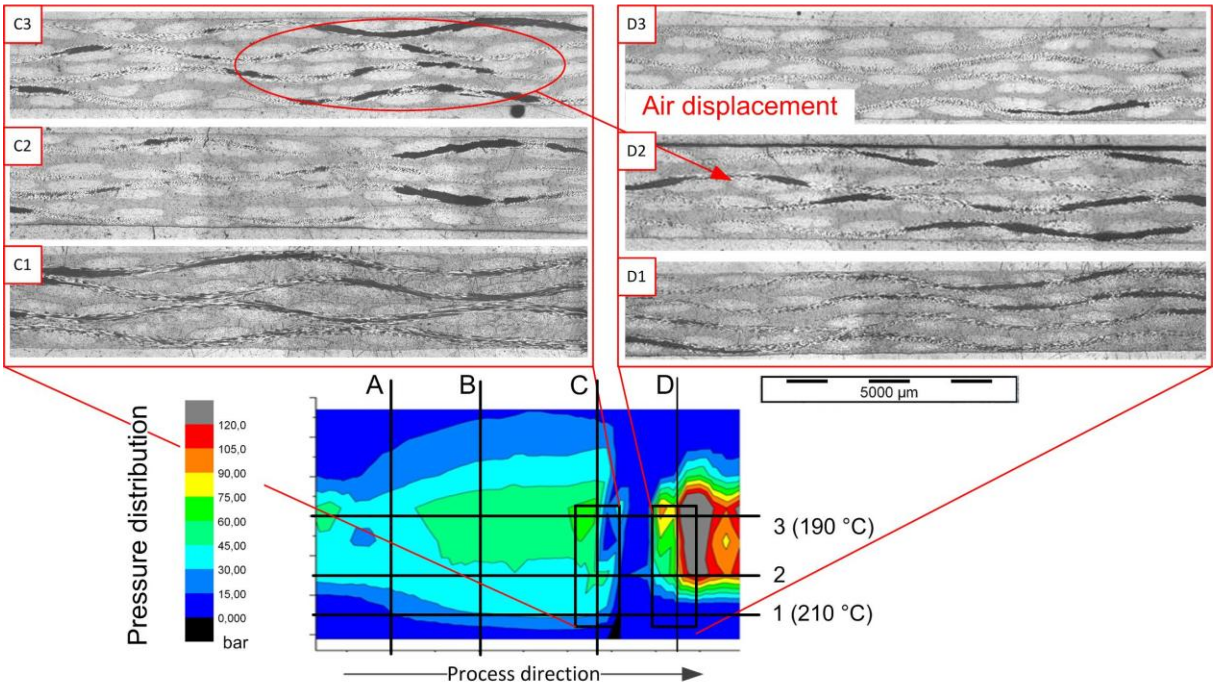


**Figure 11.** Air displacement due to inhomogeneous pressure distribution (210/190 °C – 0° view)

## 4 Conclusion

The investigation has shown that there is a significant influence of the temperature distribution on the impregnation quality of the laminate. Contrary to the expectations, a higher temperature does not automatically lead to a better impregnation quality. Moreover, it seems to be advantageous, if the temperature is increasing from the center to the edges of the tool, although this effect is superimposed by the problem of matrix squeezing at the edges. This temperature gradient simplifies the displacement of the entrapped air. Furthermore, it could be shown, that the applied process pressure is very important for the displacement of entrapped air. Areas with locally reduced pressure show an aggregation of entrapped air (e.g. transition region from heating to cooling zone). In contrast, if the applied pressure is locally very high, the impregnation quality of the laminate increases rapidly. Thus, for further improvement of the laminate quality and process output, the pressure distribution has to be optimized by adapting the tool geometry and by defining a proper temperature profile.

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