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SELF-SEALING TOOL CONCEPT FOR RTM-PROCESSES

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ABSTRACT

Due to their high weight-specific mechanical properties, fibre-reinforced plastics (FRP) are widely used in lightweight applications. In terms of cost and benefit optimising lightweight design, metal FRP hybrid materials exhibit a great potential because the expensive FRP can be used exclusively in highly stressed areas instead of manufacturing the entire component from FRP. With vacuum assisted resin transfer moulding (VARTM), complex FRP and hybrid components can be produced. In conventional manufacturing methods, the mould of the VARTM tool is sealed with silicone-based elements in order to prevent the relatively low-viscosity resin from leaking. A significant disadvantage of this sealing technique is a high wear caused by chemical, mechanical and thermal exposure. This results in additional maintenance costs and unproductive downtime for the inspection and replacement of sealing elements. Therefore, current research is focussed on innovative self-sealing tool-concepts that cure the resin close-to-contour without any sealing elements. To seal the cavity a highly accelerated curing of the resin is induced at the outer edge of the mould during the injection process. In the area to be sealed a cross section reduction of the cavity is combined with local heating and/or the use of a chemical catalyst. Due to the superimposed effects of flow front modification and the thermally and chemically stimulated curing of the matrix, a high flow resistance is generated which precisely stops the resin flow.

1 INTRODUCTION

Fibre-reinforced plastics (FRP) find wide use in several industry sectors for example in aerospace and defence, automotive and wind energy [1]. Besides the good properties of FRP, the improving technologies of manufacturing lead to a constant increase in demand. While FRP were processed traditionally by hand laminating, the use of autoclaves developed to an established process for high-end quality parts. Meanwhile injection processes such as resin transfer moulding (RTM) were developed to achieve both high qualities and lower manufacturing costs. Short, long and continuous fibres can be processed into structural, complex components using the RTM process. For this the dry fibre laminate is preformed and inserted into a cavity. Following the closure of cavity, the resin injection takes place. The tool is closed and sealed during the injection process until the resin has reached a certain degree of curing. Afterwards the part can be removed and fed into finishing processes.

The sealing of the mould is a special discipline of the tooling technology. Due to the relatively low viscosity and the high pressures during the injection of the resin the process sets high demands on the seal. In order to prevent leakage and ensure stable component quality a continuous inspection of the seal condition is necessary. The high clamping forces on the sealing and the contact with fibres of the preform cause mechanical wear. Furthermore, in areas with low draft angles the seal is exposed to high shear stress during closing the mould. In addition to the mechanical wear, the contact from the highly reactive resins along with the tool temperatures of up to 200 °C stresses the sealing material even further. Due to this, the sealing elements need to be exchanged after 10 to 30 production cycles that causes unproductive downtime of the tool [2].

As this issue does not only decrease the productivity of the production but also generates a lot of waste and inhibits the full automation of the process, the current research is focussed on the development of optimised sealing technologies.

1.1 State of the art

According to the state of the art, several techniques for sealing RTM tools have been investigated of which some find use in series production. Wang et al. use silicone cords for intrinsic manufacturing of metal-CFRP hybrid omega profiles by vacuum assisted RTM (VARTM) process [3]. The sealing has a rectangular cross section and is located in a groove surrounding the outer contour of the punch (figure 1). Due to the position of the punch the space for milling is limited and thus the upper mould is made in two parts. Furthermore, just in non-complex parts a silicone cord which is available as semi-finished product can be used. In complex tool structures sealings are particularly manufactured for the geometrical requirements by e.g. casting. Thus, an additional mould for producing the sealing is necessary. In addition to that, the sealing can withstand only a few production cycles until exchanging it.

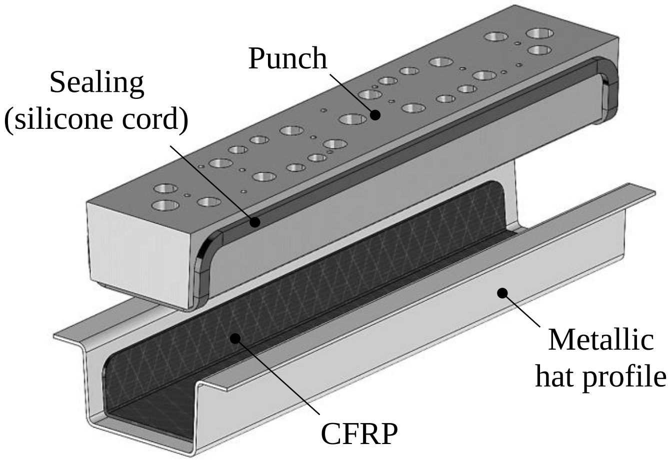

Figure 1: Example for sealing technique for intrinsic VARTM processes

The company *Murtfeldt Kunststoffe* uses high-performance thermoplastics as sealing material for high pressure RTM (HPRTM) processes [4]. It is claimed that sealings made out of their material can withstand several hundred process cycles at temperatures up to 200 °C and pressures up to 100 bar. It is characteristic that the sealing inserts are produced by machining from semi-finished products.

Fraunhofer ICT invented a process chain where the sealing is directly applied to the preform in order to decouple the maintenance-intensive components from the main tool [2]. By applying a fast curing polyurethane moulding compound to the surrounding edge of the preform, the sealing function is directly integrated. After insertion of the prepreg into the cavity the tool closes and the sealing area gets clamped between the halves of the mould. As a last step of the whole process chain the integrated sealing which remains at the produced part is removed. A similar approach is under investigation at *Karlsruhe Institute of Technology (KIT)* where functional elements are sealed with polyurethane foam during the injection process [5].

All in all every previously described sealing technology is based on surface pressure of polymer elements. Some concepts can decrease or even prevent the downtime of the tool for the exchange of sealing elements but therefore require additional work for postprocessing the part and generate a lot of production waste. This resulted in the idea of developing a contactless sealing technology, which is described below.

1.2 Innovative sealing concept

The innovative sealing concept is based on a mechanism that cures the resin as it comes in touch with the sealing area. Thus, the cured resin closes the cavity and inhibits the rest of the liquid matrix from flowing out. As a result an additional seal is not necessary anymore, so that the downtime of the RTM process for exchanging the sealing is eliminated and the amount of production waste heavily reduced.

To seal the cavity a highly accelerated curing of the resin is induced at the outer edge of the mould during the injection process. In the area to be sealed a cross section reduction of the cavity is combined with local heating and/or the use of a chemical catalyst. Due to the superimposed effects of flow front modification and thermal energy supply, the resin cures close-to-contour without additional sealing medium. The displacement of the cured resin due to the pressure gradient from inside to outside of the tool is prevented by form lock. This can be realised by high surface roughness or a specific contour of the heating element. This concept is universally applicable to many FRP processes and thus offers an enormous scaling potential.

For the sealing concept that is under investigation at the chair for automotive lightweight design (LiA) a rigid heating element and thermal insulation are installed in the upper mould. The heating element locally delivers a significantly higher temperature than the rest of the mould and is thermally insulated, as shown in figure 2. The thermal insulation protects the rest of the cavity from heating up excessively in order to maintain equal properties of the laminate.

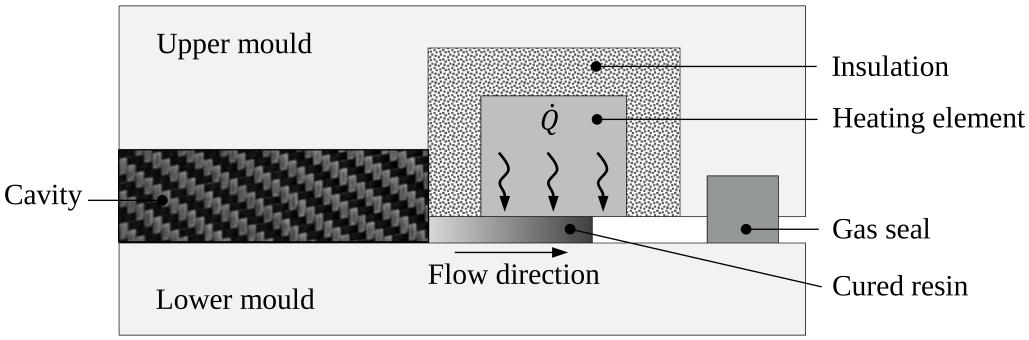

Figure 2: Sealing concept

Different forms of heating are conceivable in this concept. Examples are provided by the temperature control in the injection moulding process that is heated via induction, electric heating cartridges or conduction with hot water or oil. Often the tools are cooled analogous to heating with coolant flowing through channels [6].

2 EXPERIMENTAL INVESTIGATION

The experiments have been carried out in order to test the functionality of the sealing concept. In the first step the main effects of process and geometry parameters on different target values were investigated by a reduced design of experiment with just a few experimental steps for each variable. Further detailed investigations are necessary for parameterisation of the sealing and optimisation of its components.

2.1 Materials

The preform used for the experimental research consists of unidirectional carbon fibre layers (HPT 320 CO 24K) with an area weight of 320 g/m². Within one layer, bundles of fibres are held together by warp threads. In order to process the layers into a preform, the fibres are coated with a thermoplastic binder which weighs 14 g/m² additionally. The injected resin is a medium viscous epoxy (EPIKOTE 05475) in combination with an amine curing agent (EPIKURE 05443). This matrix system is developed for serial production in automotive industry with low initial viscosity and a fast curing reaction. For the intrinsic manufacturing of hybrid components a micro-alloyed steel plate (steel 1.0548) with a thickness of 1.5 mm is inserted. Its surface is sandblasted in order to increase the adhesive strength between the resin and steel. Other techniques of surface pre-treatment such as laser structuring are conceivable, too [7].

The laminate structure consists of six layers of CFRP that are aligned in x-direction (0°) with a total thickness of 2 mm. Furthermore, one layer of glass fibre is inserted as an interface between the CFRP and metal. This glass fibre (ForTex®Type SH35/1, area weight: 30 g/m²) prevents contact corrosion and causes a defined resin rich layer that is important for the adhesive strength of the hybrid laminate [8]. This layer design results in a relatively low fibre volume fraction of 55 %. The aim here was to increase the permeability of the laminate in order to increase the requirements on the seal with a higher resin flow.

2.2 Test setup

The new sealing concept is firstly tested on a RTM tool for flat plates in order to reduce the geometrical complexity of the part. Figure 3 shows the components of the tool. Just one of four edges of the plate is sealed with the heating element and the reduced cavity height, on the other three edges a conventional silicone cord with rectangular cross section is used. A local higher temperature is achieved by a steel strip which is tempered by electric heating cartridges. This steel strip is mounted to the upper mould and allows the adjustment of its height respective the distance between heating element and lower tool/metal sheet (gap height). Multilayer thermal insulation panels with gas filled space in between were used as thermal insulation. The temperatures of the upper and lower mould can be measured with thermocouples at four different positions. Three electric heating cartridges each are used for thermal supply. The injection strategy can be adapted with different positions for sprue and riser.

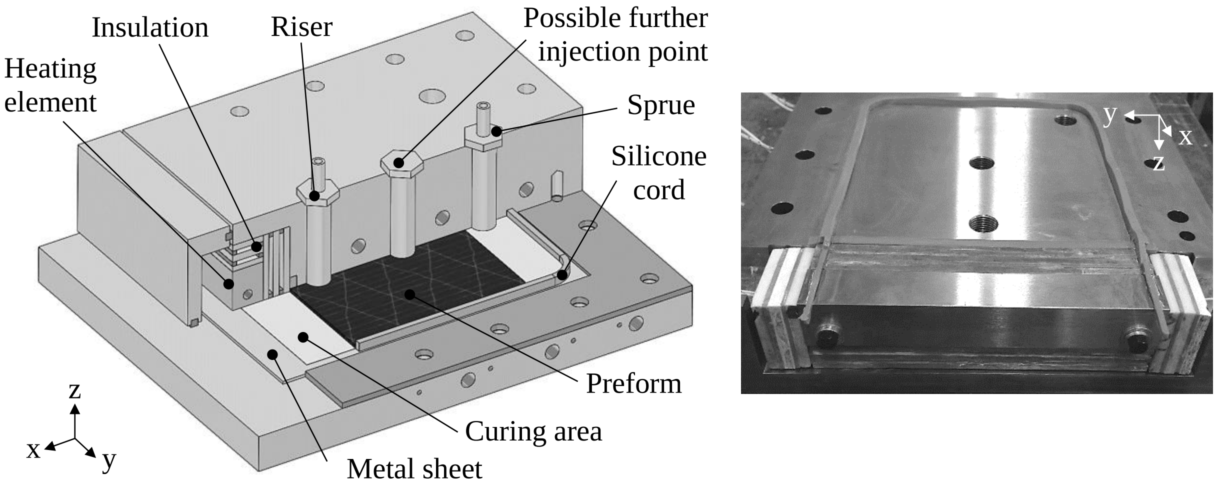

Figure 3: Sectional view (left) and upper mould with sealing components (right) of the RTM-tool for flat plates

First tests showed that the injection in the middle of the mould causes a circular resin propagation. While the resin reaches the middle of the seal at first and then cures accordingly, the effective cross-section of the flow channel decreases and the flow velocity increases. This led to uneven results over the length of the heating area and leakage at the sides of the innovative sealing. The remedy was to inject into an area of the cavity far away from the heating element without preform. In this way the area without preform is filled up with resin first, whereupon an even resin front distribution is achieved. The size of the cavity and the preform as well as the dimensions of the heating and insulation area are documented in table 1.

	Length, dimension x [mm]	Width, dimension y [mm]
Cavity	150	150
Preform	125	
Insulation area	19	
Heating area	22	

Table 1: Dimensions of the tool

First the cavity is evacuated with a vacuum pump. Preheating, mixing and injection into the mould are carried out with a RTM machine. The mixed matrix (resin and curing agent) is injected under an initial temperature of 80 °C. The infiltration is performed with a constant pressure of 5 bar. The cavity is tempered up to 120 °C while the temperature of the heating element was changed between different experiments.

2.3 Methods

Experiments with different parameters of the sealing (e.g. gap height, temperature) are carried out on the prescribed RTM tool in order to achieve a complete sealing and good laminate quality. In the present research, the parameters of the RTM process (e.g. injection pressure) remain unchanged.

The objectives of the investigation are functionality of the sealing and laminate quality. The quality of the sealing is optically determined by the required curing distance and the uniformity of the curing result. With the help of digital image evaluation, the result can be quantified in relation to the area wetted by the resin in the sealing zone. The laminate quality is determined mechanically by interlaminar shear (ILS) tests and optically by microscope images. The ILS tests are carried out in accordance with DIN EN 14130. Specimens with a length of 20 mm and a width of 10 mm are placed in a three-point loading fixture, with the CFRP facing the two bearing points and the indenter hitting the steel side with a constant test speed of 1 mm/min. For microscope images, samples are taken from the plate, embedded, grinded and polished. Microscope images are made parallel and rectangular to the fibre direction in order to see potentially irregularities like voids.

2.4 Results

The technological feasibility of the concept could be proven on a two-dimensional level. The result of a preliminary test as well as the sampling positions from the manufactured hybrid plate are shown in figure 4. In this case, the steel strip was heated to 250 °C and the upper and lower mould to 120 °C. The gap between the heating element and the metal surface was adjusted to 0.1 mm. In fact, it was possible to stop the flow front within the gap. In addition, it was found that the cavity had a very homogeneous temperature distribution at all measuring points thanks to the thermal insulation, which leads to good laminate quality.

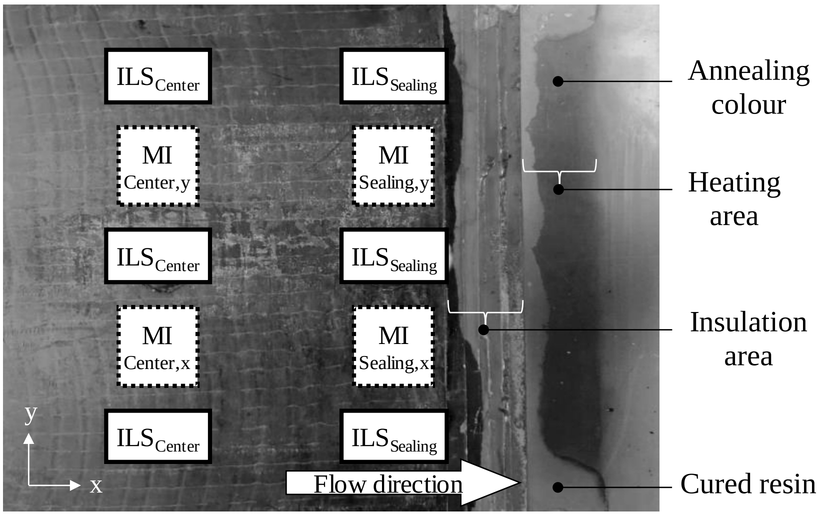

Figure 4: Result of a test with new sealing technology (gap height 0.1 mm, heating element temperature 250 °C)

The effect of the heating element, which delivers a locally higher temperature can be seen on the right side of manufactured plate (figure 4). The surface of the metal sheet shows annealing colour on the area where the metal is not exposed to the resin. This effect enables a precise definition of the resin propagation due to the colour difference. In the middle of the sealing area the resin cures after less than 10 mm. Furthermore, the distance covered by the resin until curing is constant except the areas at the side, as the resin streamed as far as the end of heating element. This is an indication for the channelling effect, which can occur at the edge of the cavity due to an insufficient filling of the cavity with the preform.

The results of the ILS tests show the failure of the CFRP, which occurs in stages. Therefore, the failure force is evaluated at the first local force maximum in order to characterise the strength of the laminate before any damage appears. Figure 5 shows the results of the ILS tests with respect to the sampling positions and temperature of the heating element. Test results are compared in which complete sealing was achieved with the same gap height (0.1 mm) but at different temperatures of the heating element (250 °C; 300 °C).

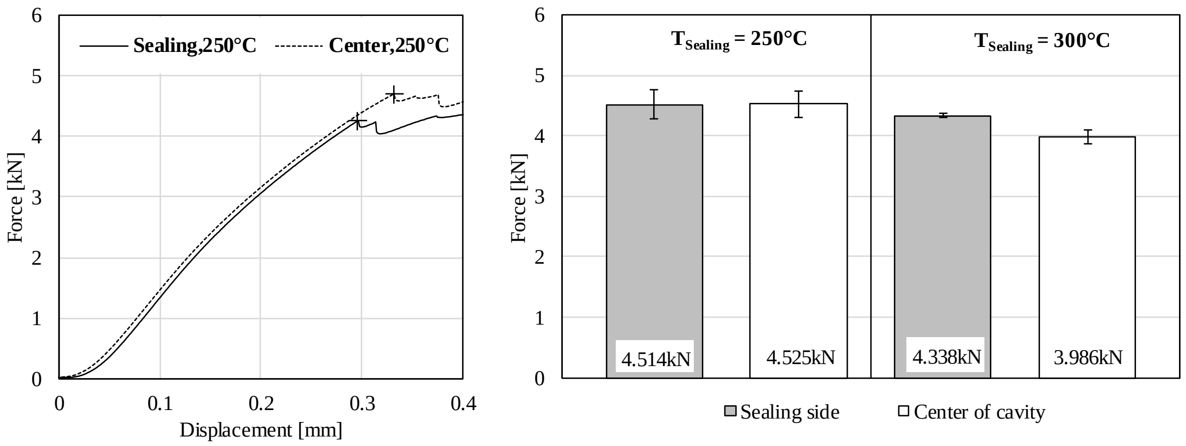

Figure 5: Results of Interlaminar Shear tests, (left) two representative force-displacement-curves, (right) average of maximum forces with respect to sampling positions and temperature of heating element

The left diagram of figure 5 shows the stage wise failure of samples next to the sealing and out of the center of the cavity. Neglecting the different maximum forces, the force-displacement curves are similar after the first partial failure occurs. Successively, the force increases by a small amount until renewed partial failure occurs. This behaviour continues until the load capacity of the CFRP is reached and only the steel is bent. All samples show adhesive failure in the boundary layer between metal and FRP. Just in small areas, the CFRP adheres to the metal and interlaminar failure between the fibre layers appears (figure 6).

The bar chart in figure 5 summarises the strength of specimens adjacent to the heating element and those from the center of the cavity with respect to two different temperatures of heating element. Within the setting of 250 °C for heating element temperature, the position of the sampling does not affect the measured strength. At a heating element temperature of 300 °C, the samples show a lower average strength. Surprisingly, samples from the center of the cavity exhibit slightly reduced strength compared to those from the sealing area. This allows the interpretation that the heating element temperature should be low to achieve uniform and good results. At 250 °C a constant laminate quality can be achieved. Further decrease in temperature results in incomplete sealing, but this may be prevented by an optimised heating element shape or other measures.

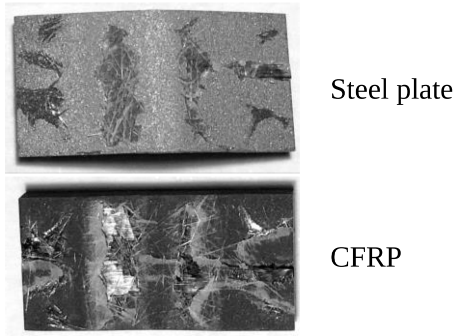

Figure 6: Representative image with high percentage of adhesion failure

From microscopic investigations it was observed that the sealing element has no negative effect on laminate quality. Figure 7 shows the alignment of the fibres as they are taken from the x-z-plane. Resin rich areas are noticeable due to the warp thread that connects the tows of the fibre mats. Furthermore, some polishing defects could not be avoided. Otherwise there are no imperfections that derive from the RTM process or the higher temperature at the sealing area.

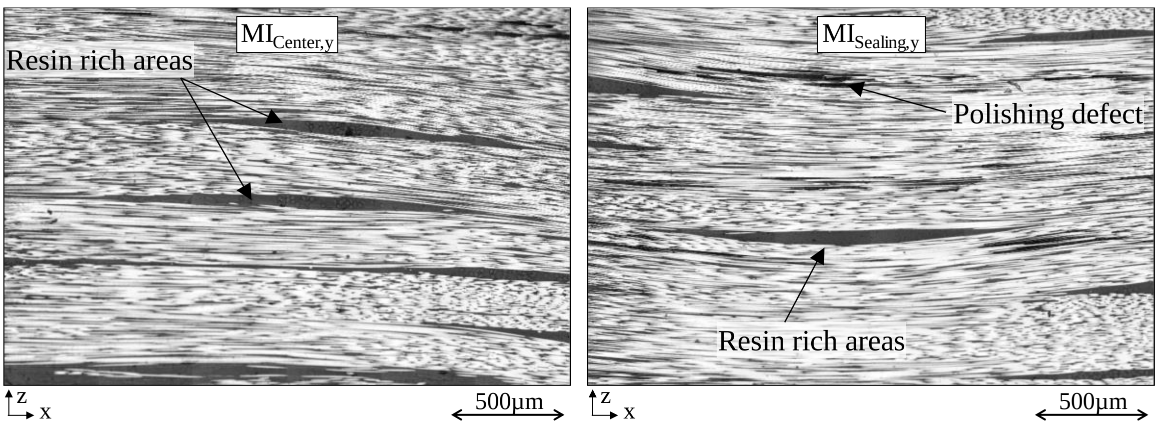

Figure 7: Microscope images parallel to the fibres at different positions of sampling (gap height 0.1 mm, heating element temperature 250 °C)

The same good result is obtained by the micrographs from the y-z-plane, i.e. perpendicular to the fibres (figure 8). These images show only a very small part of the sample (scale 20 µm) to be able to detect the single fibres. However, the image is representative for the whole sample, since images were taken at different points of the samples.

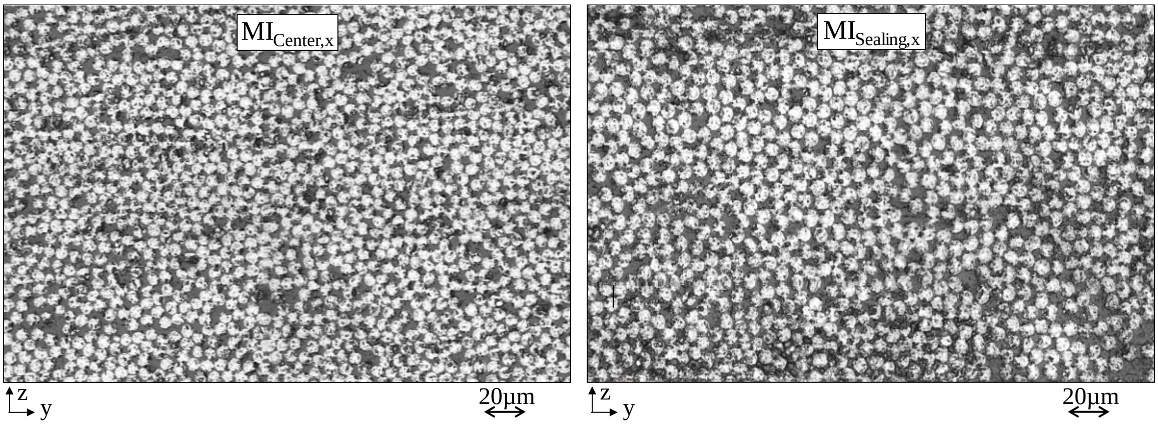

Figure 8: Microscope images perpendicular to the fibres at different positions of sampling (gap height 0.1 mm, heating element temperature 250 °C)

3 CONCLUSION AND OUTLOOK

The feasibility of the innovative sealing concept could be proven. The temperature of the heating element as well as the gap height have been evaluated in order to analyse the functionality of the innovative sealing concept. Results from ILS tests and microscope images showed that the locally higher temperature (250 °C) of the heating element does not negatively influence the laminate quality. With a gap height of 0.1 mm, a complete sealing could be achieved.

Thus, the use of locally accelerated resin curing for tool sealing represents an enormous technological advantage. The elimination of conventional sealing materials results in significant process advantages compared to conventional methods. The downtimes for maintenance and for changing the sealing materials can be minimised, whereby complex lightweight structures can be manufactured in large series with significantly shortened process times.

In the future other parameters like surface roughness and contour of the sealing area have to be investigated in order to optimise the sealing and exploit the development potential that is still open. For this purpose, design of experiment (DOE) methods and multi-variable tests help to figure out the main effects and interferences between process parameters. Furthermore, interactions between parameters of the sealing and the RTM process have to be analysed. Limits of use as well as robust sealing parameters that are applicable to many tool structures should be defined.

For this, the sealing technology needs to be transferred to three-dimensional tools in order to investigate the geometrical effect of production parts. In order to show the applicability for serial production, researches will focus on complex parts like a hybrid drive shaft. The reinforcement of an automotive drive shaft not only offers many property improvements and thus high economic potential, but is also particularly suitable for testing the new sealing technology due to the high production requirements. Beyond that the aim is to improve the scalability of the sealing concept for three-dimensional complex structures by reducing the thickness of insulation and heating elements. Different materials with low thermal conductivity for insulation and heating elements with high power and good formability will be investigated.

ACKNOWLEDGEMENTS

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