AUDI ULTRA-RTM: A TECHNOLOGY FOR HIGH PERFORMANCE AND COST EFFECTIVE CFRP PARTS FOR HIGH VOLUME PRODUCTION

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Keywords: ultra-RTM, sandwich technology, process control, sandwich, integral construction

Abstract

The present study deals with the further development of the resin transfer molding (RTM) process to reduce process time and costs. This new technology - internally known as ultra-RTM – allows it the first time to produce large, integral and high performance carbon fiber reinforced (CFRP) sandwich structures with very short cycle times. Key for realization is a technology to reduce the in-mold pressure during the process as much as possible. This target could be achieved with an innovative process control using the in-mold sensors to adjust the pressure.
In the first step the influence of several small gaps on the in-mold pressure was investigated. The theoretical approaches of the correlations between fiber volume content, mold gap, resin front velocity and in-mold pressure could be proven. As a result the maximum in-mold pressure could be reduced by up to 90 % in comparison to a high pressure (HP) RTM process. Furthermore it was possible to successfully use integrated position sensors to adjust and control the in-mold pressure during the compression phase. With those described possibilities to adjust and reduce the in-mold pressure it is now possible to produce large CFRP-Sandwich structures with an integrated design, fiber volume content > 50 % and lightweight foam cores with very short cycle times.

1. Introduction

Within the last few years the Audi AG researched and developed the ultra-RTM technology which allows a cost-effective manufacturing for high-performing CFRP structures. The aim was the combination of a high volume production process with the lightweight and performance potential of an integral sandwich design for large and complex CFRP structural components. This innovative ultra-RTM technology enables the sophisticated combination of fast-curing resins (cure-time 60-120s), sandwich technology with low density foam cores (<150 kg/m³) and functional integration for large structural CFRP components (~10 kg weight).
In order to achieve those targets, the entire mold filling has to be realized in a very short period of time while the in-mold pressure needs to be reduced to avoid any possible damage of the foam core.
Key to success is the ability to limit and reduce the in-mold pressure with an innovative process control. For this purpose the tool must be equipped with intensive sensor technology to influence the process parameters online. Beside the key benefits, the ultra-RTM process allows to use smaller molds, lower pressing forces and results also in a very robust process with a minimum of scrap parts. For the first time, this technology could be implemented in the new Audi chassis platform Modular Sports-Car System (MSS).

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2. State of the Art and Fundamentals

In the automotive industry, the HP-RTM process has shown great success in the high volume production of CFRP for structural components during the last few years [1]. During this process, resin, hardener and an internal release agent are mixed under high pressure and are injected into a closed mold. The curing of the resin happens within a few minutes at temperatures around 110-140 °C. The in-mold pressure during the injection can reach values of 100-200 bar depending on the size of the component and the processing time. This requires large pressing forces of around 10.000-20.000 KN per m² excluding the necessary force for fiber clamping and mold sealing. Consequently, presses with up to 36.000 KN pressing force and RTM molds of 85 tons are used as an example for serial production [2]. The high in mold pressure with RTM is very challenging for the injection system, the mold and the press itself and furthermore has a large influence on the lifetime of seals, ejectors and other components. Finally the machine hourly rate and therefore the component pricing results directly from machine and tool pricing.
Further development of the HP-RTM is using a small gap during injection with a following compression phase. This process is known as Compression-RTM (C-RTM) or Advanced-RTM (A-RTM) [3] [4].
Mainly two different options for the closing of the mold after the injection are to be described. First the compression can be achieved by a linear or a step by step increase of the pressing force. This is called force controlled compression. Secondly the mold can be closed gap controlled where the gap in the mold is closed via a linear ramp. Close to the end of the closing operation, the pressing force increases in a none-linear function until the mold is completely closed or the maximum pressing force is reached (Figure 1).

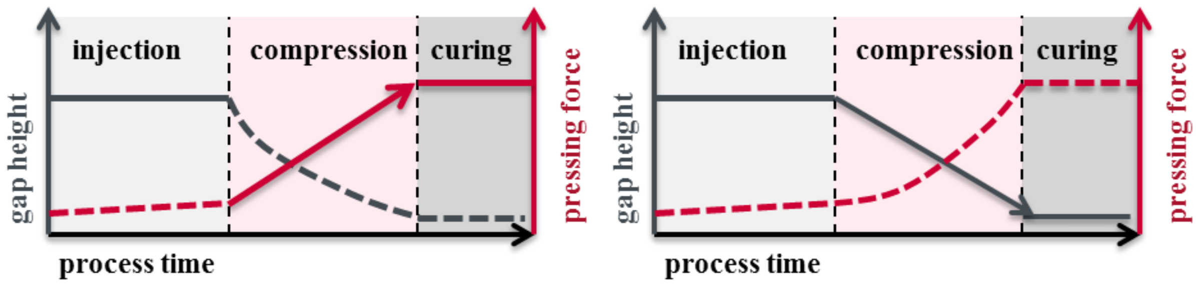

Figure 1: force controlled (left), gap controlled (right) C-RTM process

The injection and compression theory are also used in the ultra-RTM process and are explained in the following.

2.1 Theory – Darcy’s law

Darcy’s law describes the steady flow of an incompressible fluid through a porous medium [5] [6].

$$v = \frac{\dot{V}}{A} = -\frac{K}{\eta} * \nabla p \tag{1}$$

The flow velocity of the resin is described by *v* in [m/s], the direction dependent permeability *K* in [m²] and η in [Pas] represents the dynamic viscosity of the matrix. The pressure gradient ∇p shows the pressure increase per millimeter [N/mm³] which is proportional to the in-mold pressure. This shows that a lower pressure during the injection can be obtained by a change in dynamic viscosity, flow velocity or permeability.

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The viscosity of the epoxy resin used is assumed as constant due to its nearly consistent and sufficiently low viscosity during the processing period. A different method is to influence the permeability of the non-crimped fabric (NCF), which was not further investigated in this work. Instead, the permeability can be influenced by the fiber volume content [7]. This can be achieved by a small gap injection which also leads to a decrease in velocity of the flow front. This shows that two different parameters can be influenced at once by a simple gap in the mold. This relationship is discussed further on.

2.1.1 Increase in Cross Section Reduces the Flow Velocity

In the following consideration, the resin flow front is assumed to proceed linear. Finally, the size of the gap *s* [mm] is defined as an additional mold opening considered from the thickness of the component *d*. With a constant volume flow $\dot{V}$ [g/s] and a constant amount of fiber in the mold, the flow front velocity *v** is only dependent on the cross sectional area *A** [mm²] and therefore on the size of the gap and the resulting fiber volume content φ^*.

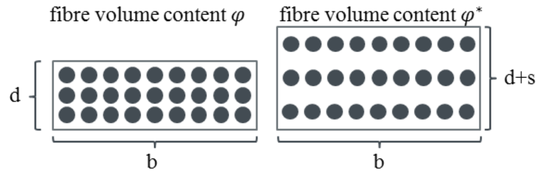

Figure 2: cross-sectional area *A* without gap (left), *A** with gap (right)

Up to an investigated gap of 1 mm, it is assumed that the NCF used in the preforms is not overflown by the resin. Instead it is considered that the resin flows through the textile homogeneously. This contradicts the hypothesis that the textile is first overflown due to the gap and later is infiltrated in the direction of thickness by closing the mold [3] [8] [9] [10].
The reduction in flow front velocity through a gap during the injection phase is described by putting the flow front velocity with gap *v** in relation to *v* without gap (Figure 3).

2.1.2 Permeability of the NCF is Increased Through a Reduction in Fiber Volume content

The fiber volume content and the flow front velocity are reduced by the gap during the injection. As described earlier, the permeability of the textile is dependent on the fiber volume content. The permeability at a reduced fiber volume fraction *K** can be estimated with the given permeability *K* of the given NCF with the law by Konzeny and Carman [11][12].

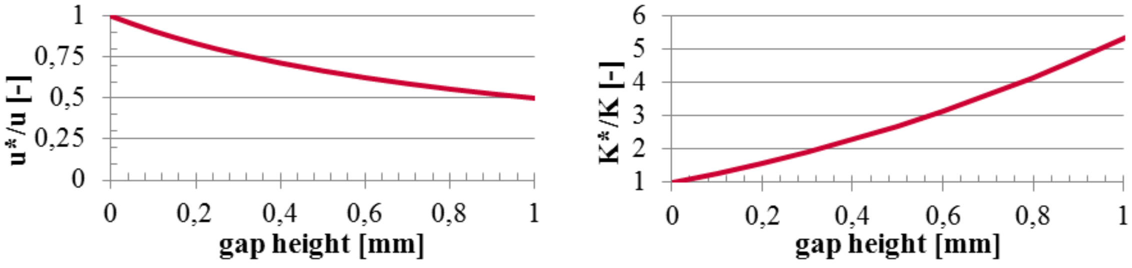

Figure 3: influence of gap size on the flow front velocity (left) and permeability (right)

A comparison of the flow front velocity and permeability (Figure 3) shows, that the influence of the increased permeability outweighs the reduced flow front velocity.

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2.1.3 Resulting In-mold Pressure by the Influence of the Gap

If the two effects are superimposed, the change of the pressure gradient in dependence of the component thickness and the gap height can be represented (Figure 4).

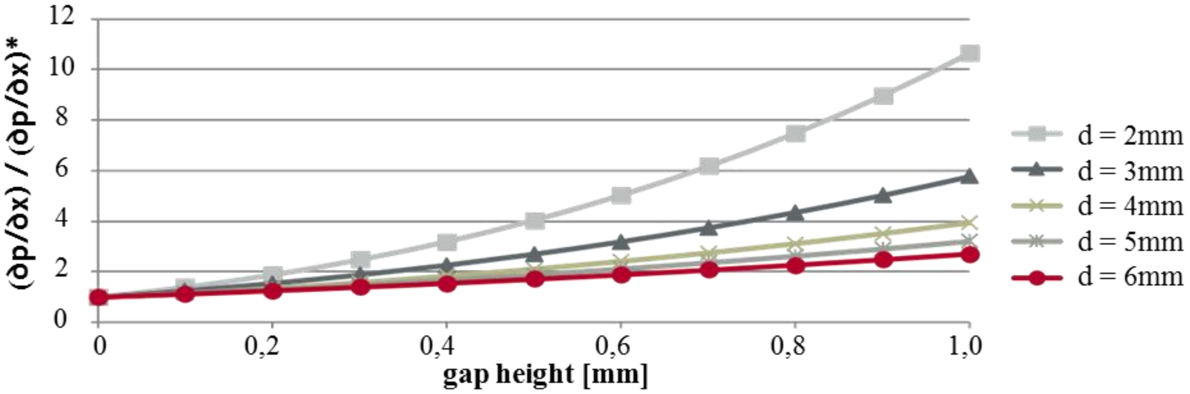

Figure 4: decrease of the pressure gradient in relation to the component thickness *d* and gap height *s*

The gap injection has a big influence on the pressure gradient, especially with thin parts at a small gap. A typical CFRP structural component has areas of different thickness. Usually between 1 – 6 mm depending on the required strength and stiffness. It is for this reason that the resin front usually will also flow through very thin areas while the injection phase. Those very thin areas have the biggest impact to the in-mold pressure beside the resin flow length. This is the reason why the gap injection has such a high influence on the in-mold pressure even with complex parts with thicker an thinner areas.

2.2 Used Materials and Mold Setup

For the manufacturing of these components, a rapid curing 2k-epoxy resin with a curing time of 60-120 seconds at a mold temperature of T = 120 °C was used. The mixing ratio of resin : hardener : release agent is 100:16:2.2. The NCF with 300 gsm was manufactured with a 50K carbon fiber in 0/90° and +/-45° orientation. The tests were carried out with a 10.000 KN RTM press and a three component HP dosing machine at a mixing pressure of 120 bar. The tool for the flat specimens has the possibility to user either a sprue in the middle or on the side. It also has choice of point or line runner in the middle or on the side and is equipped with a vacuum seal and a fiber clamping along the edges of the preform. Specimens can be produced with a thickness between 1 – 25 mm and a fiber volume content of up to 60 %. The flat dimensions are 1100 x 550 mm. The mold has included twelve digital pressure sensors in the upper and lower half and in the transverse and longitudinal axis. It also has four digital displacement sensors and PT100 temperature sensors at each corner. All plates were produced with a fiber volume content of 50±2 % at a thickness of 2±0.05 mm and were injected at a constant volume flow between 20-100 g/s.

3. Results

Figure 5 shows the average pressure distribution of an injection with 90% resin of the necessary amount for a fully filled plate using the classic RTM-process with no gap. L1 – L4 are different positions for the pressure sensores wich are on a straight line behind the injection gate. Each pressure sensor in the upper mold face (O) has an opposite sensor on the bottom mold face (U).

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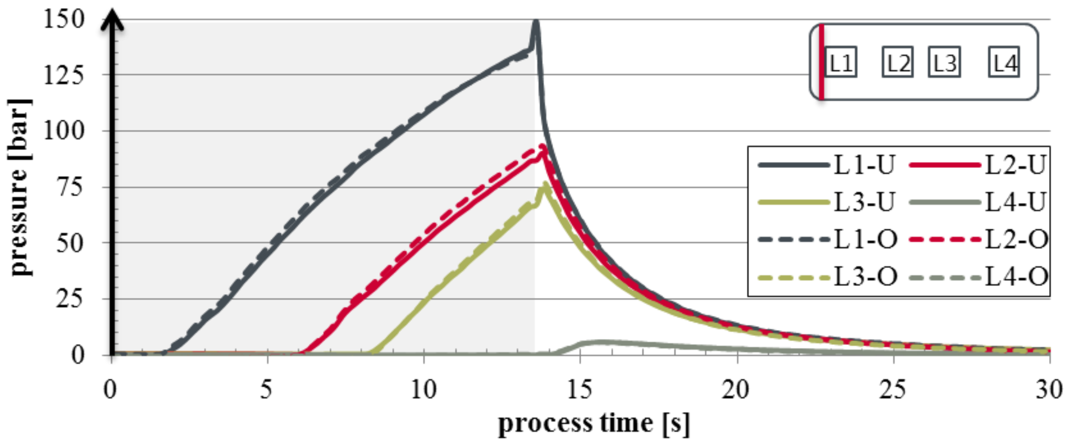

Figure 5: HP-RTM - averaged process data of pressure sensors

The injection into the evacuated mold starts at t = 0 s and stops at t = ~13,5 s. With a constant resin output rate the pressure at each pressure sensor raises almost linear. The behavior until the end of the injection phase is described be Darcy's law. The small deviation from the initial gradient is explained due to insufficient closing force and therefore a small opening of the tool with progressing injection time. The exact position of the flow front can be seen by the sudden increase in pressure by the different position of individual pressure sensors. The pressure peaks at the end of the injection occur due to excess resin in the mixing chamber which is rapidly shot into the mold at the closing of the mixing head. The pressure drop after the injection phase and the late deflection by sensor L4 can be described by the part injection of 90% of the test plate. This is because after the injection phase, the material slightly continues to flow due to capillary forces and pressure compensation. If the pressure curve at the top and bottom half of the mold are identical, the overflow or uneven injection between upper and bottom mold face can't be observed.

3.1 Permeability of a Textile

The permeability of the textile used was determined by using a one-dimensional in-plane permeability test facility with four parallel cavities in saturated and unsaturated condition. The average of a biaxial NCF 0/90° at 300 gsm in dependence of the testing direction and fiber volume content is shown in Figure 6. This shows that the permeability of a given NCF significantly increases as the fiber volume content decreases.

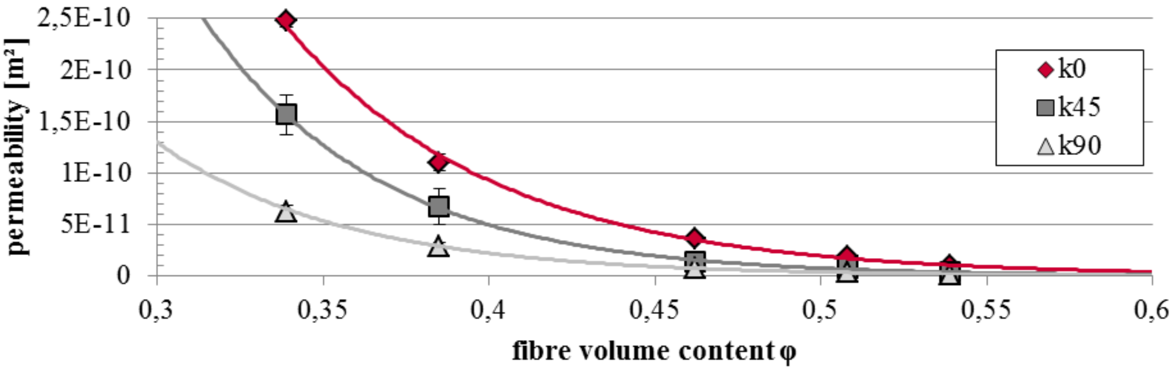

Figure 6: Permability of a 300 gsm 0/90° biaxial NCF

3.2 Influence of Gap on Pressure Inside the Mold

The influence of the gap injection on the flow front velocity and the injection behavior can be illustrated using a filling study. For this study, panels with a lineal sprue near the side and a constant resin flow at different gap heights were used. It was proven that the assumptions made (linear flow front, no overflowing of the preform, the infiltration in z axis and the reduction in flow velocity v) were accurate. It can be observed that the flow front starts to become more undefined above mold gabs above 1 mm. The figure 7 shows the mold pressure sensor nearest to the sprue in relation to the height of the gap. This shows that through this simple measure the maximum pressure during the injection time can be reduced by up to 90%.

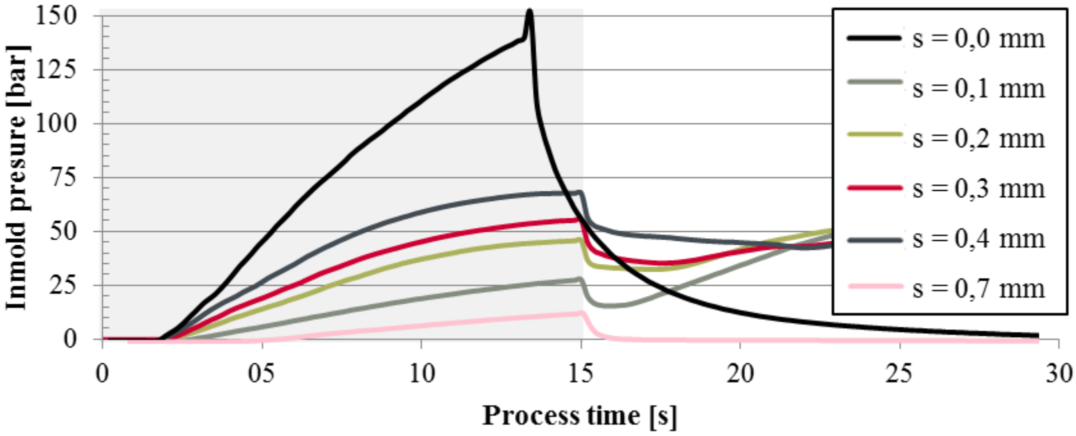

Figure 7: influence of the gap to the in-mold pressure

The resin flow front velocity *v* can be determined using the sensor position and the process time. Fugure 8 shows the comparison of the test results with the analytic approach done in (2.1.3). It shows a good correlation of the analytic approach with the experimental results for two different resin flow rates.

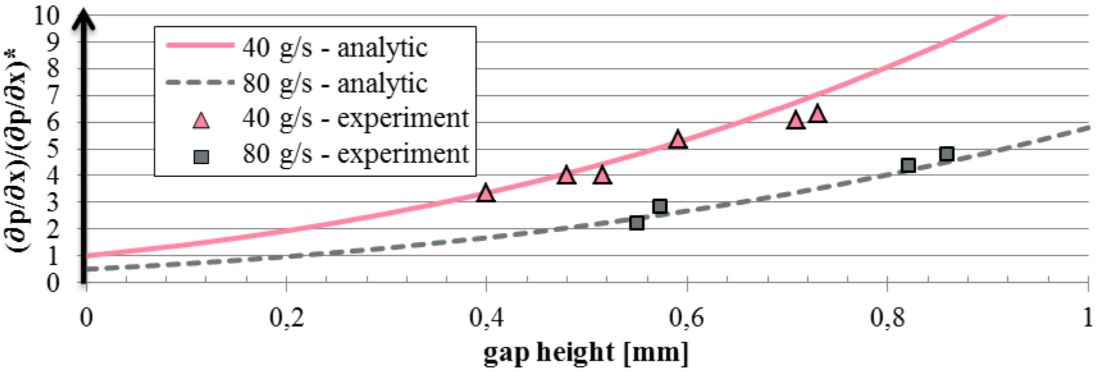

Figure 8: decrease of the pressure gradient in relation to the gap height

With the presented approach it is now possible to reduce the maximum in-mold pressure while the injection phase. But as described earlier on the gap also has to be closed once the injection is completed. The time it takes for the injection and the compression must not exceed the processing time of the resin. Therefore usually the gab has to be closed very fast which results in a quick increase of the in-mould pressure.

A smaller gap during the injection phase usually causes a larger pressure at the end of the injection but results in a lower pressing force due to the compression phase. This is because of the resin has to flow much less distance to the infiltrate the rest of the dry fibers. In the case of a lager gap, this occurrence is inversed and the flow distance that is still to be covered during the compression phase increases. The final pressure at the end of the compression phase is defined by closing speed, the total amount of resin respectively the clamping force and therefore can not be directly controlled or restricted.

3.3 Ultra-RTM for Pressure Controlling during Compression Phase

Due to the described problems above a new software was devoloped and integrated into the press control system. With this software the in-mold pressure and the distance sensores of the tool can be used as controlling parameters the closing speed of the mold. Those integrated distance sensors are used to control the gap of the mould. The controlling method using the position of the press is not precise enough. This is due to the tool being compressed by the press and the inner pressure not giving precise information about the real position.With this operating mode, the mold can be closed after the injection using a given maximum pressure, a maximum compression force and a control time. The press then regulates the force build up using different pressure sensors automatically. This allows the pressure inside the mold to be controlled and limited (Figure 9 and Figure 10). Hereby, specific foam materials can be used effectively.

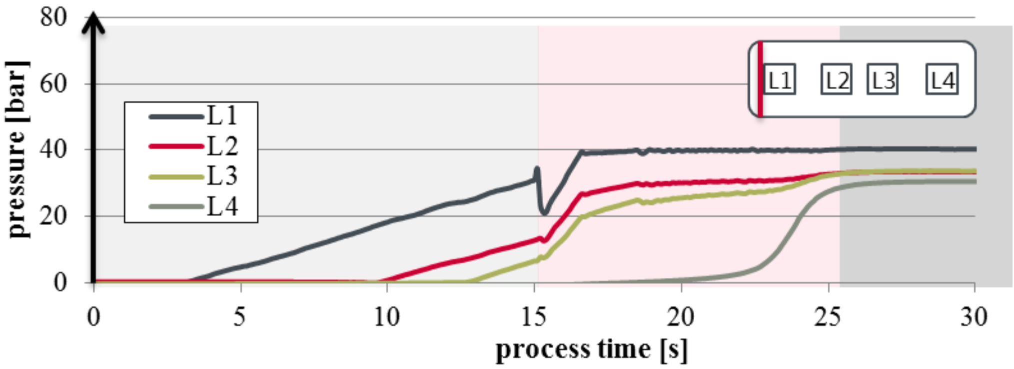

Figure 9: ultra-RTM – in mold pressure with pressure controlled compression

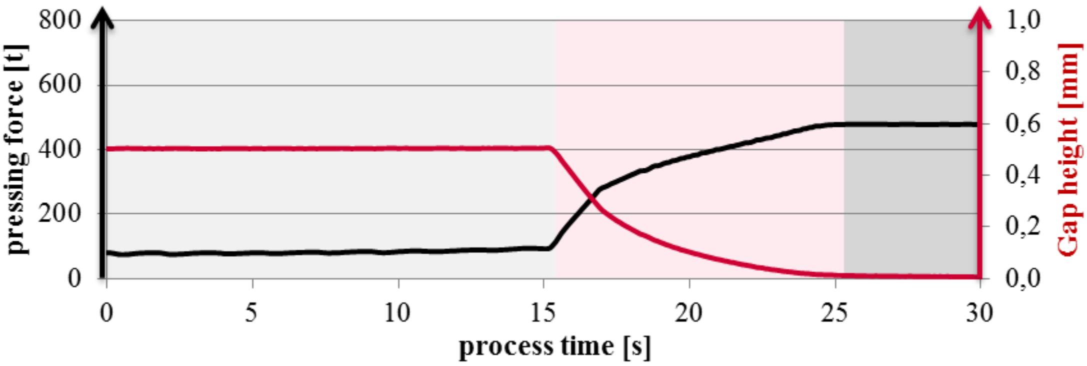

Figure 10: ultra-RTM - pressing force and gap height with pressure controlled compression

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4. Conclusion

The test results show that the reduction of the fiber volume content can significantly reduce the permeability of the textiles by up to 90%. This leads to a drop of the in-mold pressure of equally up to 90% by simply allowing a gap between upper and lower mold of maximum 1mm.
The overflowing of the NCF due to faster resin flow could not be seen using the given gap size and parameters. This shows that the assumed model to describe the in-mold pressure using the mentioned influencing factors is adequately exact.
In order to reduce the high in-mold pressure during compression and to control it effectively, a new press control was developed. Using the integrated position sensors, the pressure inside the mold can now be regulated for the first time. This new operating method now enables the manufacturing of large integral structures with high fibre volume content, integrated foam cores and short cycle times necessary for high volume production. Additional positive effects of the reduced pressures are shown in the required machinery costs.

5. Acknowledgement

This research was supported by Dipl.-Ing. Sebastian Fröhlich (University of Stuttgart). We gratefully acknowledge the support of the involved partners and persons.

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