SIMULATION OF THE RESIN TRANSFER MOLDING PROCESS (RTM) BY ANALYSIS OF THE PROCESS FUNDAMENTALS

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ABSTRACT

Lightweight design is a major sphere of activity in the automotive industry. The application of endless fiber reinforced thermosetting plastics is one of the most powerful techniques for the reduction of weight while keeping high mechanical properties. The resin transfer molding process is predestined for this because it can be highly automated and it creates parts for direct painting. The cycle times longer than 20 minutes need to be shortened in order to implement those parts in large scale production. Especially the injection of the resin needs to be accelerated. However, a higher flow front velocity may induce void formation. The modified capillary number has turned out to be a good measure of the volumetric void content. Closer examinations using a DoE method were conducted, showing that the void formation is influenced by a larger amount of factors. The results of these examinations are discussed in this paper.

1. INTRODUCTION

The automotive industry is forced to reduce carbon dioxide emissions. An aim of 95 g/km of fleet emissions in 2020 has been defined [1]. In combination with the exhaust gas limits, which require weight increasing after-treatments, the car manufacturers face a major obstacle. Electric drives require large-scale batteries also leading to massive weight increase and a lower range. In both cases lightweight design with fiber reinforced plastics (FRP) gives a contribution to a solution of the problem.

The resin transfer molding process (RTM) has been identified as a value creating production method for FRP [2]. The possibility of a high automation and the low effort in post processing yield a high potential for the integration into automotive production processes [3]. A fiber preform is inserted into the mold. The resin wetting the fibers is injected and cures at a raised temperature. Acceleration can be achieved by higher injection pressures. However, higher resin velocity may lead to inconsistencies in the flow front pattern [4]. These inconsistencies are the main reason for micro scale air entrapments resulting in a higher void content. A closer look on the factors influencing the void formation could enable a more precise model of the wetting. This knowledge can be used to implement a fast zero-fault production.

2. VOID FORMATION

The quality of the RTM process can be defined by different factors. The cycle time and the void content are the most important measures for output and part quality. However, both aims are the result of several of factors, partially with converse effects. Firstly, the most important factors need to be identified.

Voids in composites are basically air entrapments. They can be created by different formation mechanisms. These can be divided into chemical, physical and flow induced mechanisms. The void shapes can also be divided into two major types. The voids can be spherical air bubbles that can mainly be observed in the flow channels between the fibers. In the other case they are located in the fiber bundles and show a cylindrical shape. In figure 1 the formation mechanisms and the main shapes are presented.

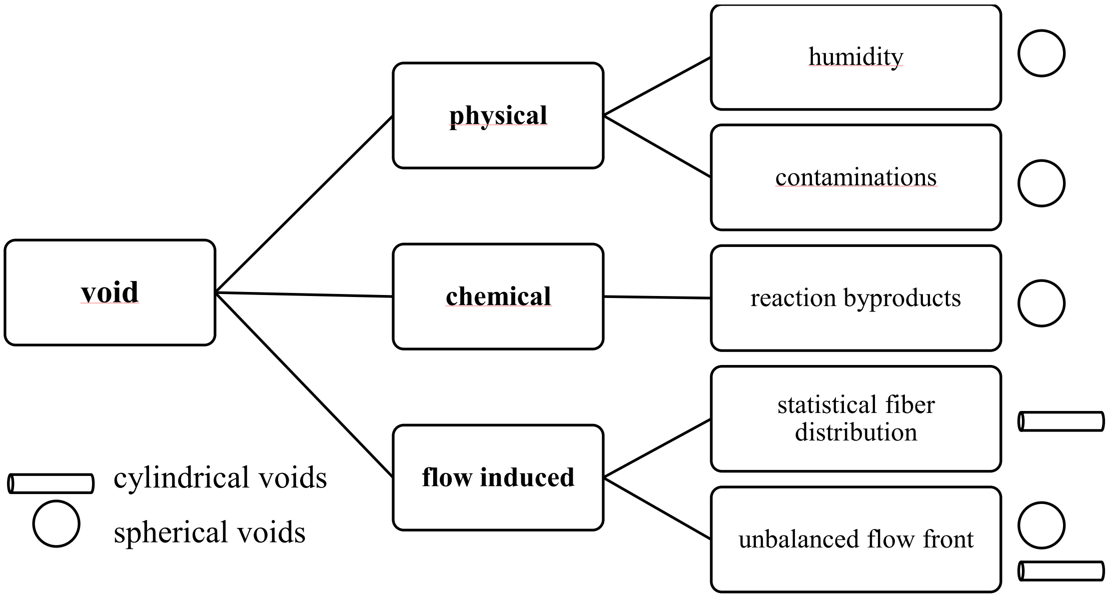

Figure 1 Void formation mechanisms and shapes

The mechanism for spherical void formation is mainly outgassing of any substance contained in the resin. These substances may be humidity, other evaporating fluids, gases or byproducts of the reaction between resin and hardener. These mechanisms can mainly be detected in the flow channels since the rate of formation is higher in areas of high resin volume ratios. Those are mainly the flow channels.

The spherical void formation can also be flow induced. If the resin flow in the bundles has a higher velocity than in the flow channels, the resin will flow around the air in the flow channels and enclose it [5]. This especially occurs at fiber crossing points. If the resin flow in the flow channels is higher, cylindrical voids can be detected in the bundle because the air in the volume between the single filaments is entrapped. In this way the cylindrical shape is formed. A similar mechanism is the air entrapment due to the statistical fiber distribution. If the local fiber volume content in the bundle and, in correlation to that, the permeability differs, the overflow can also be detected. Figure 2 shows the flow induced void formation mechanisms. Here the flow front velocity in the flow channels is faster and the flow front in the bundle is uneven. As a result, both mechanisms are visible and cylindrical voids occur.

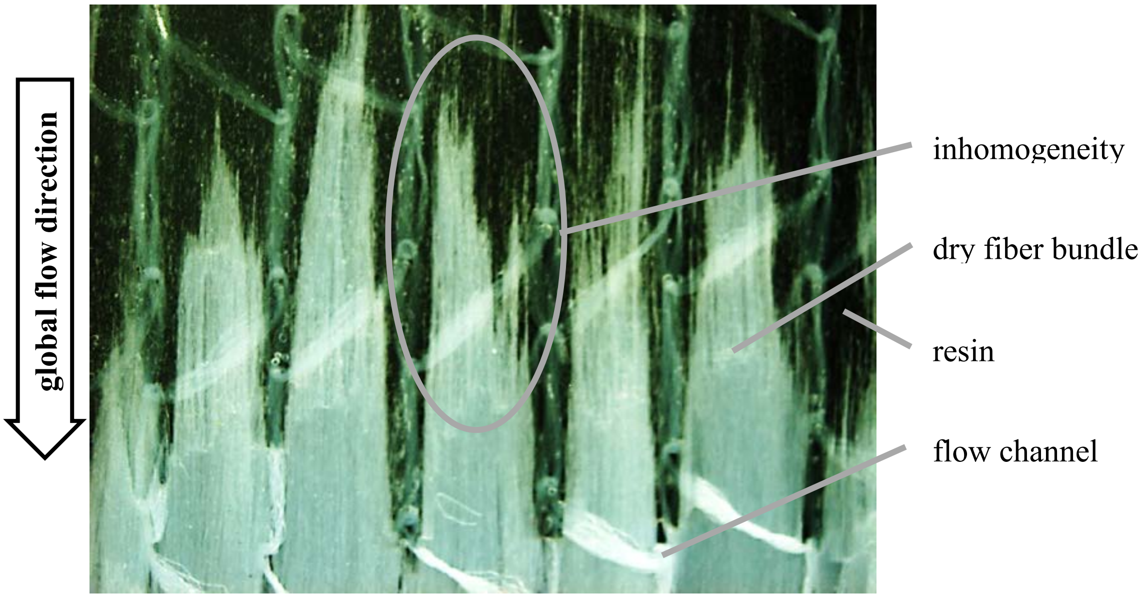

Figure 2 Mechanisms for flow induced void formation in a unidirectional fiber mat

The flow induced void formation mechanisms are the main reason for void creation because they cannot be avoided by the right choice of the materials and the material handling. Knowledge of the process and its parameters is required for that reason. Thus the flow behavior in the microscopic scale needs to be examined more precisely.
In general, the resin flow in composites can be described by Darcy's law as shown in formula (1). It has been developed for the description of fluids in porous media. Here, the permeability is an important factor. It describes the flow resistance in the fiber bed which is influenced by the fiber volume content, the fiber diameter, the fiber alignment and the fiber distribution [6]. This globally determined factor changes in a microscopic consideration for every extracted area.

$$Q = \frac{KA}{\mu}\frac{\Delta p}{L} \qquad (1)$$

with:

K	permeability
A	cross section area
μ	resin viscosity
Δp	pressure drop
L	flow distance

The difference in permeability can especially be found between the fiber bundles and the flow channels. The distances between the fibers are within a range of few micrometers and less. The flow channels excel this by a rate of 10 to 100. Hence the large difference in permeability becomes clear.
The driving force of the resin flow is the pressure difference. Generally, this difference results from the applied injection pressure and the optionally applied vacuum pressure. However, the presence of fibers in the mold generates an additional capillary pressure. It is effective in small diameters. As shown in formula (2) the capillary pressure for the fiber direction mainly depends from the flow diameter [7]. Therefore the capillary pressure is comparatively high in the fiber bundles. It can exceed 37 kPa [7].

$$P_c = \frac{4\,\sigma\,\cos\theta}{D_e} \qquad (2)$$

with: P_c capillary pressure in fiber direction
σ surface tension of the resin
θ contact angle between fiber and resin
D_e equivalent diameter of the pores in a fibrous form

The resin flow in the two areas of the fiber preform depends on several factors. This results in a difference between the bundles and the flow channels in the flow front velocity. The flow front is uneven and the overflow creates spherical or cylindrical voids.

The modified capillary number has proven to be a good tool to gain information about void formation [8]. The measurements were performed by Patel and Lee. Here, the most important driving forces of the resin flow in both, flow channels and fiber bundles, are included to create a value showing the proportion of the flow front velocities.

$$Ca^* = \frac{\bar{v}\,\mu}{\sigma\,\cos\theta} \qquad (3)$$

with: $\bar{v}$ global flow front velocity
μ resin viscosity

The volumetric void content in the composite depends on the capillary number. As figure 3 shows, a range with a high void content of spherical voids at low capillary numbers is recognizable. This range is connected to a low flow front velocity. The capillary effect soaks the resin through the bundles and entraps air in the flow channels. At higher flow front velocities the volumetric void content reaches a minimum. Here, an equal flow front can be observed. A further increase of the flow front velocity shows the permeability difference between both areas. The capillary effect can no longer balance the lower permeability. The resin flow in the flow channel exceeds the flow in the bundles. In consequence, air in the bundles is entrapped and cylindrical voids occur. The volumetric void content as a function of the modified capillary number is shown in figure 3. The measurements were conducted using different oils and unidirectional glass fiber mats. A production of parts with a poor void content is only possible in a process with a capillary number in the suggested range between 0.003 and 0.03 [8].

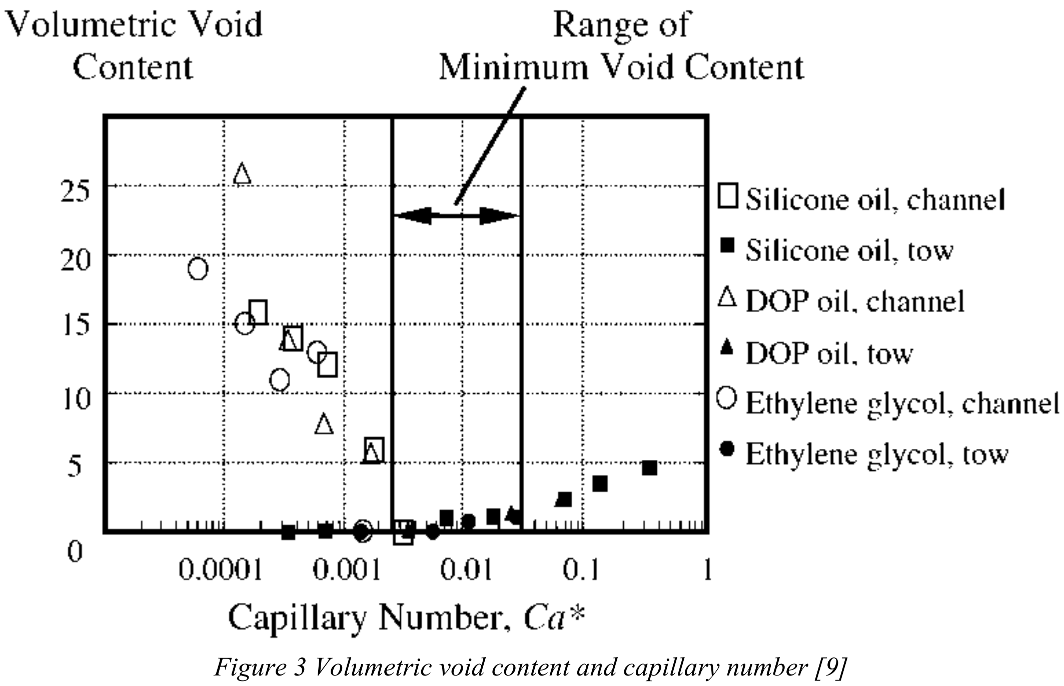

Figure 3 Volumetric void content and capillary number [9]

3. MEASUREMENTS

The void content as shown by Patel and Lee depends on only a few factors but the examinations were conducted only with unidirectional fibers and non-reactive fluids. Many composites are manufactured using woven fabrics. These are more advantageous for the assembly of the preform because the draping of fabrics, especially twill weave or satin weave, causes less wrinkling. However, there are other possible influences on the void creation by an uneven flow front. The thickness of the fiber bundles, for instance, affects the developing of voids. If the voids occur because the flow front velocity in the flow channels differs too much from the velocity in the bundles, bundles with a greater thickness might show greater differences. Thus the bundle thickness is one important factor to focus on. Another factor is the finish that coats the fibers to generate a more intense bonding to the resin. It also influences the contact angle which is included in the capillary number. The formulation of the finish is not published by the producers. Thus an analysis on the effects on the part quality is constructive.

The influences of these three factors on the void formation need to be determined by reliable measurement. The experiments were performed using a glass mold. This mold allows the examination of the global flow front development in the mold during the injection of the resin. The injection point is placed in the center of the mold, while the vents with an applied vacuum pressure are set at the corners of the mold. The flow front velocity is measured using a HD camera. A scale printed on the glass enables the calculation of the velocity by recording the injection time.

The experiment was conducted using the design of experiments method (DoE). This allows determining the effects of each factor. The factors and the chosen degrees are summarized in figure 4.

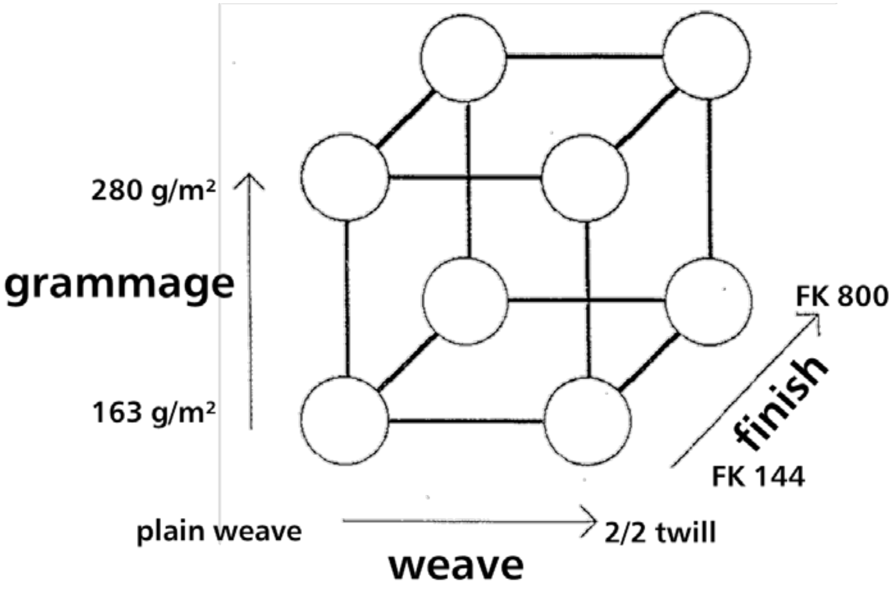

Figure 4 design of experiments for the measurement of influencing factors on the volumetric void content

The other process parameters must be determined in preliminary tests. The mold temperature was set to 40°C. The most important factor for the flow front velocity is the injection pressure. The aim is a process that crosses the suggested range of the capillary number to see the differences in the void content. In figure 5 the capillary numbers of experiments with different injection pressures are shown. The experiments were conducted using 280 g/m² FK800 twill weave fibers. A vacuum pressure of 80 kPa was applied additionally. It can be seen that the process crosses the suggested range at a summarized injection pressure of 180 kPa. All examinations were conducted using this injection pressure in order to enable a comparison of the chosen factors.

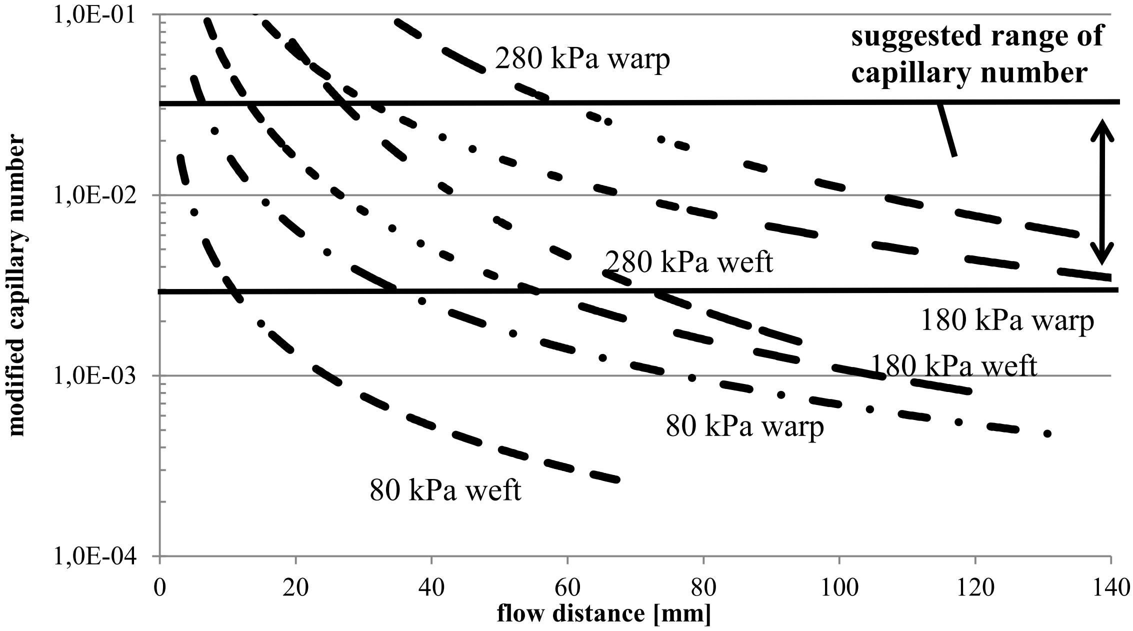

Figure 5 measured modified capillary number at different injection pressures

The capillary number was calculated at different points and samples were selected to determine the volumetric void content. The points were chosen in both weft and warp direction in distances of 20, 70 or 120 mm. All samples show low void contents under 2 % at capillary numbers in the suggested range. In figure 6 the FK144 twill weave samples are shown as an example. However, the examinations indicate that the samples with different weight per unit area show different void formation rates at the same capillary number.

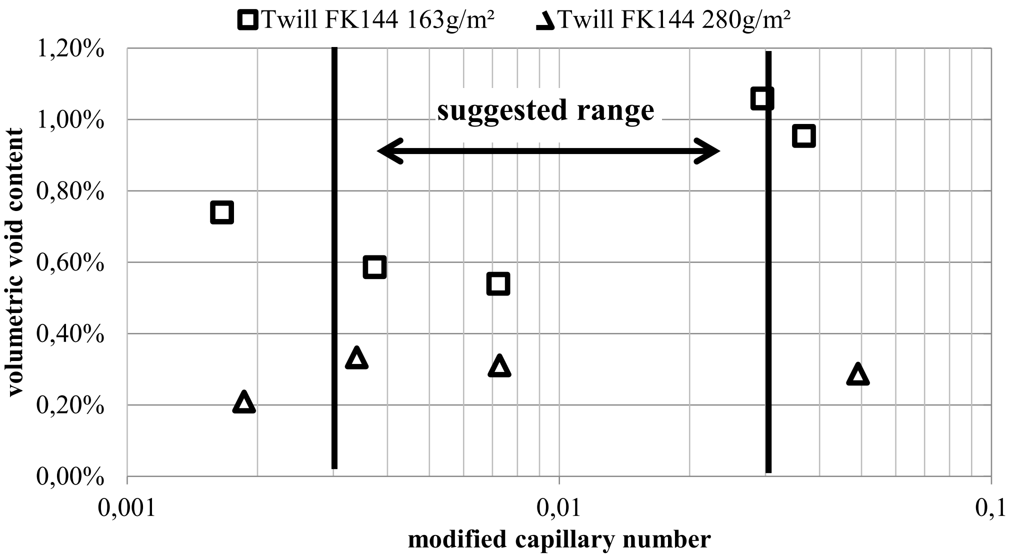

Figure 6 Dependence of the volumetric void content from the capillary number at measured samples

The DoE permits a detailed analysis of the effects of the examined factors. A comparison of the volumetric void content of all samples demonstrates a strong interdependency of the grammage and the weave. As a basis for the comparison the average of all samples in a produced part was calculated. The results are illustrated in figure 7.

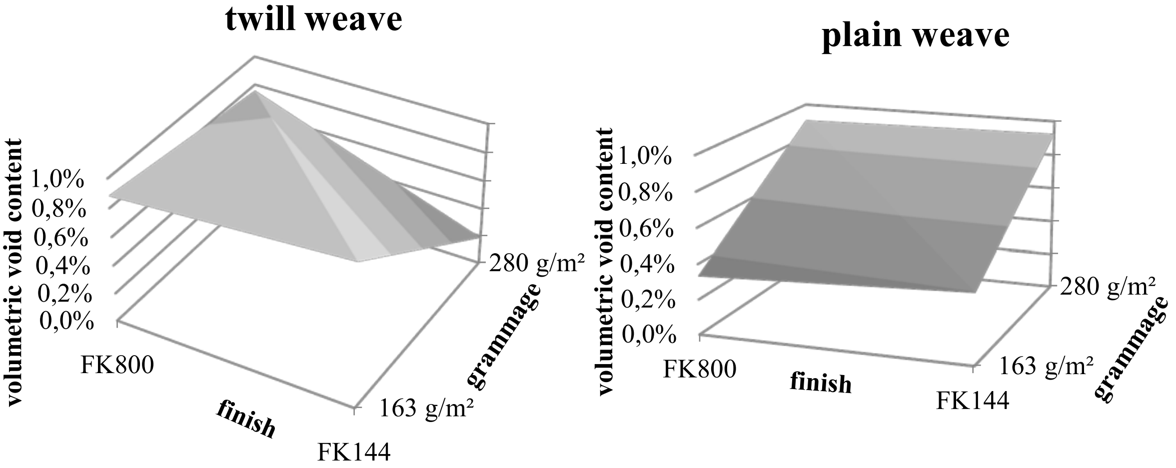

Figure 7 volumetric void content as a function of finish and grammage for twill and plain weave

The effect of the grammage on the volumetric void content turns from inversely proportional at the twill weave to proportional at the plain weave. While the lowest void content was measured at the higher grammage of the twill weave, the lower grammage of the plain weave with 163 g/m² shows better results. A possible reason for the interdependency is the undulation of the fiber bundles. This factor distinguishes between the two weave types. In theory a higher grammage increases the distance between the flow fronts in the bundles and the flow channels – regardless of where the voids are created. In contrast, the results of the examinations differ from this.

The finish has a low influence on the void content, especially at the plain weave. This indicates that the capillary number already considers all effects of the finish. Only the twill weave with a grammage of 280 g/m² shows a comparatively low void. Taken as a whole, the void content of all measured points is still in an acceptable range [10].

4. CONCLUSIONS

For an implementation of the RTM process into automobile serial production the cycle time must be decreased significantly. Keeping high quality, process acceleration can only be achieved by an accurate knowledge of the process fundamentals. Here, a closer look on the void formation mechanism shows that most voids that occur are flow induced. The key to a high quality part is the development of a uniformly flow front. It can be described by the modified capillary number for unidirectional fibers. Process examinations were conducted to screen the flow behavior in woven fabrics.

The modified capillary number has turned out also to be a good measure for the volumetric void content at those fiber reinforcements. The composites show low void contents that are acceptable for mass production. But on closer examination more influences on the volumetric void content are detectable. The effects of the grammage of the fabrics, the finish and the weave were examined. An influence of the grammage on the void content became visible as well as a strong interdependency on the weave.

A closer examination of those two factors should be conducted to give a clear picture of the flow behavior in woven composites. Marcel and thickness of the fiber bundles apparently play an important role to be examined more in detail.

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