Effect of gas pressure on the microstructure of parts foamed with the novel microcellular injection molding technology Ku-Fizz™

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Abstract
The increasing demand for lightweight and economical automotive components boosts investigation of advanced materials and new lightweighting technologies. This work employs the novel microcellular injection molding technology Ku-Fizz™. The process introduces gas with granulates at moderate low pressures into the feed zone of the injection molding machine. Ku-Fizz is controlled by gas pressure; thus, a simple plate geometry was molded and the effect of various gas contents on the microstructure was analyzed. The material used was a chemically coupled glass fiber-reinforced polypropylene compound. Optical microscopy was employed to measure the foam microstructure. Micro-computed tomography was used to quantify the fiber volume fraction and the orientation tensors. Results of the fully characterized microstructure showed cell density increasing and cell size decreasing with gas pressure and melt flow direction. Fiber length increased with gas content. Cell growth displaced fibers from the center of the part towards the mold surface, changing the fiber concentration and global fiber orientation.

KEYWORDS
fibers, foams, injection molding, microstructure

1 | INTRODUCTION

Strict emission and fuel economy regulations are driving the automotive industry into the lightweight material market. While there are many technologies to improve fuel efficiency, lightweighting car components is the most significant one. A 10% reduction in vehicle weight can result in a 6–8% fuel economy improvement as less energy is required to accelerate a lighter object. Vehicular equipment manufacturers are compelled to develop new lightweighting technologies and investigate advanced materials to meet the stringent governmental regulations. One option is to retrofit existing structures made out of steel with materials such as high-strength steel, aluminum, magnesium, composites and plastics due to their lightweighting potential. Long fiber-reinforced thermoplastics (LFTs) have gained wide acceptance in the automotive industry due to their high performance in terms of mechanical properties, resistance to numerous corrosive media, low density, and ability to be shaped and tailored to satisfy performance requirements. In addition of using advanced materials, car manufacturers also investigate new technologies to reduce the vehicle weight even further. Introducing gas
into the polymer, commonly known as microcellular injection molding (MIM), can cut back the weight by an additional 15%.\textsuperscript{[9,10]}

Physical foam molding has already demonstrated its potential in the automotive industry.\textsuperscript{[11-15]} Specifically, the MIM technology MuCell\textsuperscript{®} has gained popularity and acceptance among car manufacturers. MuCell is licensed by Trexel Inc., Wilmington, MA, and is backed by a master part patent on injection molding (IM) of microcellular material published in Europe\textsuperscript{[16]} and the US.\textsuperscript{[17,18]} The technology employs a physical blowing agent (PBA) which is introduced at a supercritical state into the polymer melt during plasticization. Injection of the gas laden melt into the mold cavity induces cell nucleation due to the thermodynamic instability generated by a rapid change in pressure. Cells grow until the melt freezes.\textsuperscript{[9]} A cellular structure within the plastic part is created with cell densities (CD) as high as $10^9$ cells/cm$^3$ and pore sizes on the order of 10 $\mu$m\textsuperscript{[19-21]} in the vehicle sector MuCell has been utilized for visible and non-visible parts. The center console of the Mercedes-Benz C-Class (W 205) was produced with MuCell technology and a weight reduction of 20% was reported.\textsuperscript{[12]} Ford foamed instrument panels displaying a 1 lb weight reduction, compared to their solid counterparts for Ford Escape and Kuga cross/utility vehicles. Volkswagen developed a foamed instrument panel for the VW Golf 7, which also exhibited a 1 lb weight reduction versus the prior model.\textsuperscript{[13]}

Upgrading traditional IM machines to offer MIM capabilities requires a high upfront capital investment. As an example, for a Krauss Maffei KM 650–4300 CX IM machine the additional investment to implement MuCell is 35% of the IM machine costs.\textsuperscript{[22]} Required modifications include a plasticizing unit with a specially designed screw to generate a single-phase solution and a super critical fluid (SCF) metering, delivery and dosing system. These modifications lead to additional complexity in controlling the process.\textsuperscript{[10,23,24]} To overcome these drawbacks, other MIM technologies have emerged (Table 1). Optifoam and Ergocell did not finish commercialization or were driven out of market due to MuCell’s patents.\textsuperscript{[9]} ProFoam and Ku-Fizz use an alternative approach, where gas at moderate low pressure is directly added to the polymer pellets by employing a special hopper unit. Gas and granulate enter the barrel together and the PBA diffuses into the polymer during plasticization. With ProFoam manufacturing of parts cannot occur continuously. This drawback is solved by Ku-Fizz (previously named IQ Foam). The main difference between the technologies are interior design variations in the hopper unit that allow for a continuous, steady process.

As shown in Table 1, both, the technology and the pressure operating window for MuCell and Ku-Fizz are notably different. Thus, Ku-Fizz needs to be studied to evaluate if an acceptable foam microstructure can be achieved with such low gas pressures. In this work, fiber-reinforced polypropylene (PP) plates were foamed under various nitrogen gas pressures and the effect on the microstructure was analyzed. Detailed information of the cellular structure is crucial, as it affects the mechanical performance of molded parts. The presence of fibers adds complexity because the foamed composite’s performance will additionally depend on fiber orientation (FO), fiber length (FL), and fiber concentration (FC).\textsuperscript{[33]} Information obtained on global and thickness-wise cell and fiber microstructure will aid in the evaluation of future simulation efforts and improve the accuracy of mechanical design software predictions. Thus, guaranteeing that Ku-Fizz foamed parts can be safely introduced into vehicles. This work should offer a guideline for preliminary process settings and will act as a starting point for further research and simulation.

### TABLE 1  Overview of microcellular injection molding technologies

| Trademark | Technology | Pressure range [bar] | Reference |
|-----------|------------|----------------------|-----------|
| MuCell    | SCF injection into melt | 80–200               | [16,17]   |
| Optifoam  | Special mandrel SCF injection nozzle plus static mixer | 400               | [25–28]   |
| Ergocell  | Dynamic mixer for SCF dosing plus plunger for injection | -                 | [9,10,28] |
| ProFoam   | Gas fed to pellets in special hopper unit | 5–50               | [29–31]   |
| Ku-Fizz   | Gas fed to pellets in special hopper unit | 5–30               | [23,24,32]|

Ku-Fizz was developed at Volkswagen AG. The technology employs a two-chambered hopper unit which introduces pellets and PBA under moderate low pressures into the feed zone of an IM machine (Figure 1). The system is designed for PBA pressures up to 30 bar, to which the gas can be directly supplied from the cylinder. Due to the prolonged exposure time between gas and polymer along the plasticizing unit, sufficient gas diffuses into the polymer and eliminates the need of additional mixing elements. It also eliminates the need to rise the gas to a SCF state. Gas diffusion occurring in the two-chambered hopper unit is negligible.
The hopper unit contains two gas injectors, which introduce the PBA, valves, to regulate the gas flow and two actuators, to allow the material to pass through the unit and to lock each chamber. Initially, both actuators are closed, and the chamber is free from material and PBA. When actuator 1 opens, material from the hopper drops into the upper chamber. The chamber is locked and the PBA is injected until reaching the desired pressure. Actuator 2 opens the airlock between both chambers and pellets fall into the lower chamber, which is connected to the injection unit. PBA fills the available space. Actuator 2 closes and the remaining gas from the upper chamber is re-routed to the lower one. A second gas injector adds PBA to the lower chamber to ensure the gas pressure remains constant. Pellets are transported away by a standard reciprocating screw and gas diffuses into pellets and melt. Actuator 1 opens, refills the upper chamber and the cycle is repeated. Ku-Fizz is solely controlled by gas pressure, thus can be automated and driven by an electronic system managing actuators and gas injectors, regardless the original software control of the IM machine.[24]

3 | EXPERIMENTAL

3.1 | Materials and processing conditions

The material used in this work was a 30 wt% glass fiber in a PP matrix (STAMAX PPGF30 YM 243) commercially available from SABIC™. The material was supplied in the form of coated pellets with a nominal length of 15 mm, which also represents the initial and uniform length of glass fibers. The used E-glass fibers (ρ = 2.55 g/cm³) are chemically coupled to the PP matrix (ρ = 0.91 g/cm³). The fiber diameter was measured to be 19 ± 1 μm using an optical microscope.

To remove any moisture in the material, it was dried at 80°C for at least 2 h before processing. Parts were molded on a Krauss Maffei 200–1000/390/CZ Multinject IM machine (KraussMaffei Group GmbH, Germany) equipped with a Ku-Fizz unit. The IM machine had a clamping force of 2000 kN and a screw diameter of 55 mm. A simple plate geometry was chosen in this work to allow for a direct correlation between processing conditions and microstructure. The rectangular plates had dimensions of 400 x 100 mm and a thickness of 3.5 mm, as shown in Figure 2. Plates were foamed at various gas pressures while the other processing conditions were kept constant (Table 2). Nitrogen was used as the PBA for all trials. A PSA MIDIGAS nitrogen generator (Parker-Hannifin Corporation) was employed to recover high-purity nitrogen from air. The gas had a purity of 99.9% with an oxygen amount of <500 ppm in continuous operation.

3.2 | Measurement of foam microstructure

The microcellular structure was studied transversal to the melt flow direction at three locations along the center
line of the part: close to the gate (R1), in the center of the plate (R2), and at the end of the flow path (R3) (Figure 2). Samples were extracted, cold mounted in acrylic resin, and their cross-sections were grinded and polished with a Metprep 3™ Grinder/Polisher system (Allied High Tech Products Inc). Multiple overlapping micrographs were taken (Motic BA310Met microscope equipped with a digital AmScope MA1000 camera) and stitched together to cover the entire cross-sectional area of each specimen. A magnification factor of 5 ensured that bubbles as small as 3 μm could be captured. Monterde, did preliminary work on Ku-Fizz foamed plates, and by using SEM analysis, it was shown that only 1.5% of all cells are smaller than 5 μm.\textsuperscript{[23]} Thus, the employed analysis method was found as sufficiently precise. Micrographs were adjusted for an appropriate level of contrast (thresholded) and the foam microstructure was analyzed with the 2D Image Pro analysis software (Media Cybernetics Inc., Rockville, MD). Thickness-wise cell size (CS), CD and aspect ratio data were obtained by assigning 15 regions of interests (ROIs) across the plate’s thickness and conducting an analysis in each ROI. CD was estimated by\textsuperscript{[34]}:\n
\[
\text{Cell density} = \left( \frac{n}{A} \right)^{\frac{1}{2}} \tag{1}
\]

where \(n\) is the number of cells in the micrograph or in the respective ROI for thickness-wise data, and \(A\) the area of the micrograph or the ROI in cm\(^2\), respectively.

The mean CS was calculated from the optical micrograph using the following equation\textsuperscript{[35]}:

\[
\text{Cell size} = \frac{\sum_{i=1}^{n} d_i}{n}, \quad \tag{2}
\]

where \(d_i\) is the average diameter of the cell, \(n\) the number of cells in the micrograph or in the respective ROI. For thickness-wise information, large cells protruding multiple ROIs were attributed to the corresponding ROI where the cell’s majority was located. Interconnected or clustered cells were counted individually, if a boundary was evident. If no boundary could be detected and it was not possible to identify single cells constituting to a larger, deformed cell, the cluster was counted as one bubble. Due to the high occurrence of irregularly shaped cells, the aspect ratio was determined as the ratio between major axis and minor axis of an ellipse equivalent to the region of the cell. At least five plates per testing condition were analyzed to ensure accuracy and repeatability of results.
3.3 Measurement of fiber microstructure

FO and FC were determined by using the X-ray microcomputed tomography (μCT) approach. Discs of dimensions 21 mm² x 3.5 mm were scanned with an industrial μCT system (Metrotom 800, Carl Zeiss AG, Oberkochen, Germany). Previous studies with the same material have shown that a voxel size of 5 μm adequately captures the fiber geometry. Table 3 summarizes the acquisition parameters for the μCT scans in this work.

The μCT data set was processed with VG StudioMAX (Version 2.2, Volume Graphics GmbH, Heidelberg, Germany) to obtain the through thickness values of fiber volume fraction and second-order orientation tensor components. The FL measurement technique presented in was employed in this work. This technique consists of fiber dispersion and a fully automated image processing algorithm to quantify the fiber length distribution (FLD). The Kunc-correction was applied to all results, as down-sampling methods preferentially capture longer fibers and thus skew the real FLD.

4 RESULTS AND DISCUSSION

4.1 Effect on foam microstructure

The molded plate weight as a function of gas pressure is shown in Figure 3. A 16% plate weight reduction is seen with an applied maximum gas pressure of 25 bar. The plate weight decreased almost linearly with increasing gas pressure starting at 10 bar. For 7.5 bar and 10 bar, a similar weight reduction of 5% was noticed. Obeloer who worked with ProFoam, recorded a maximum weight reduction of 12.4% and 13.9% for plates foamed at 5 bar and 10 bar, respectively. A weight reduction of 1% was observed when the gas pressure was increased from 7.5 bar to 10 bar, while with Ku-Fizz only a 0.1% weight reduction was noted. Obeloer noticed the linear increase in weight reduction stopping at 35 bar as the curve started to level off. This behavior could not be seen in Figure 3. Starting at 30 bar the ball sector valves employed in the Ku-Fizz hopper unit reach their working limit and cannot close properly. Gas escapes through the hopper, leading to a weight reduction and foam microstructure resembling the one seen at 25 bar. While custom-made ball sector valves are available up to 50 bar gas pressure, they are expensive and defeat the cost-effectiveness of Ku-Fizz, thus will not be used in production.

The cell morphology under different gas pressures is shown in Figure 4. Dark areas indicate cells, gray areas represent the polymer, and fibers are shown in white. As the gas amount increases, CD increases and thus CS decreases. An increased gas pressure leads to a higher gas concentration in the melt and causes a higher cell nucleation rate. At low gas pressures (7.5 bar and 10 bar), the nucleation rate is low. Due to the small number of formed cells, the diffusion paths of PBA are considerably longer. Thus, only a small available percentage of PBA can contribute to cell growth. Cells that have nucleated however, have a high growth rate leading to large bubbles which can have a maximum diameter of up to one fifth of the plate thickness. Such large coalesced cells can cause the mechanical properties of a part to deteriorate rapidly. Figure 4 further illustrates, that a well-defined cell structure was achieved for the 25 bar setting. Consequently, indicating that the PBA content employed in Ku-Fizz is sufficient to manufacture a microcellular composite.

While at low gas pressures (7.5 bar and 10 bar) the cell structure is mostly uniform across the sample thickness, a pronounced core-shell structure develops with increasing gas pressure, which is inherent to the IM process and thick MIM parts. This structure shows a solid

| Parameter          | Value   |
|--------------------|---------|
| Voltage [V]        | 80      |
| Current [A]        | 110     |
| Integration time [ms] | 1000    |
| Gain [-]           | 8       |
| Number of projections [-] | 2200    |
| Voxel size [μm]    | 4.5     |

FIGURE 3 Plate weight as a function of gas pressure
skin layer, a center core layer and a transition layer (shell) between skin and core. During processing the temperature distribution along the thickness direction of the plate has a bell-shape, in which the temperature in the core layer is higher than at the shells. The cells, therefore, grow more in the core due to the low matrix viscosity. Near the mold surface, cells are smaller due to the faster matrix solidification.\cite{9,42,44,45} Zhang et al. indicated that an increasing stress in the polymer melt promotes bubble nucleation.\cite{44} Since the shear stress is higher in the shell layers, an increased CD can be found in those regions. All samples showed a distinct skin layer which reduces in thickness with increasing gas pressure and with flow path. Compact skin layers are a result of the following: rapid solidification of the melt after coming in contact with the mold surface, redissolution of PBA within cells into the polymer melt and a restraint of foaming by high cavity pressure.\cite{46,47}

Global CD and CS data as a function of gas pressure are shown in Figure 5. As visible in Figure 4, CD increases while the mean CS decreases with increasing gas pressure. This trend corresponds with work published by\cite{9,29,42,48–52} investigating the effect of gas pressure on foamed parts. At higher gas pressures the nucleation energy barrier is lower and the nucleation supersaturation degree can be achieved faster. Therefore, cells nucleate earlier and more often, leading to a higher nucleation rate and CD. As cell nucleation and growth are two competitive factors, a fast nucleation rate equals a low cell growth rate. Thus, smaller cells are formed.\cite{52} Cells have an average size of 170 μm and a CD of 6*10^3 cells/cm^3 at low gas pressures. At 25 bar, a minimum average CS of 55 μm and a CD of up to 5*10^6 cells/cm^3 were recorded. A maximum CD of 5.1*10^5 cells/cm^3 was reported at the end of flow path for the 20 bar setting. Typical MuCell foamed parts have a CS of 100 μm or less and a CD of around 10^6 cells/cm^3.\cite{48,52} Thus, a comparable microcellular structure was achieved when the Ku-Fizz process was operated at 20 bar and 25 bar.

Zhang et al. showed that temperature decreases slightly along the part’s flow path.\cite{44} First simulation work with Ku-Fizz also showed a lower temperature and increased viscosity at the end of the cavity. A larger viscosity means a higher growth resistance. Thus, cells in R3 are generally smaller than in R2 and R1. Close to the gate (R1), the material cools down slower, causing cell growth.\cite{42} CD generally increases along the flow path with R3, showing the highest CD (R1 < R2 < R3). Our results do not align with the data published by Zhang et al. and Lee et al., as an increasing CS and a decreasing CD from the center of the plate towards the end of flow path were observed in these studies.\cite{44,50} Both found the pressure state decreasing along the part and showed a bigger pressure drop closer to the gate, which promotes cell nucleation. On the contrary, Ahmadzai et al. foamed a simple plate geometry with a general purpose polystyrene and found that CD increased towards the end of the cavity.\cite{53} As by\cite{44,50} the seen trend was explained with the dropping system pressure towards the end of the cavity. However, Ahmadzai et al. argued that a high system pressure tends to suppress cell growth and may even cause cells to collapse. Hence, the number of nucleated cells is smaller near to the gate and larger towards the end of the cavity.\cite{53,54} Other researchers also recorded the average cell diameter decreasing with distance from the gate and thus an increasing CD.\cite{9,47,51,55} Monterde, performed preliminary work with Ku-Fizz by comparing its foam microstructure to parts manufactured with MuCell. The results from Ku-Fizz evidenced CD was the highest in R1, followed by R3 and R2. The largest cells were located at the end of the cavity.\cite{23} Pressure state, diffusivity and concentration of the gas, temperature and shear stress distribution are all interdependent factors that affect the final foam microstructure.
Through-thickness CD and CS data as a function of gas pressure and location are shown in Figure 6. The boundary between different regions becomes more defined with increasing gas pressure, as CD and CS transition from a mostly uniform distribution across the sample thickness to a pronounced core-shell structure. An increased standard deviation can be noticed for plates foamed at low gas pressures, since cell shape and size were very large and irregular. In some cases, individual cells covered 20% of the plate’s thickness. Close to the gate (R1), flow entry effects are present, creating a more homogenous core-shell structure, compared to R2 and R3 where the structure is more pronounced.

Global and thickness wise aspect ratio are shown in Figure 7 and Figure 8. It can be seen that with increasing gas pressure cells transform from highly irregular shapes to more spherical ones. To keep cells uniform, spherical and small is desired to truly take advantage of the MIM technology. However, non-uniform CS distributions are common for MIM PP parts.[9] Generally, cells become more spherical along the flow path, as they reduce in size. This trend does not align with data published by Wang et al., as for regions far away from the gate cells became severely deformed (47). In this work, the foam microstructure was only analyzed transversal to the melt flow direction as cells are preferentially aligned in melt flow direction. Consequently, possible deformations visible in parallel to the melt flow could not be captured.

During the mold filling stage, the melt flow is a laminar shear flow that exhibits the fountain flow effect at the flow front.[47,56] This effect forces the melt at the flow front towards the cavity surface. Since bubbles do not have inertia they follow the streamlines of the polymer. The melt flow velocity is smaller at the cavity wall than in the center layer of the mold cavity. This results in a large shear rate gradient. In such flow field, cells will be deformed by the shear stress. Close to the cavity wall, the shear stress is high and cells will be deformed to an ellipsoidal shape with a large axis ratio.[47] This explains the observed increased aspect ratio close the mold walls, as shown in Figure 8. Deformation increases as the melt moves forward, additionally stretching the bubbles. For parts with a large flow length to wall thickness ratio, cells can transform to long and thin strips which eventually break up into a series of smaller bubbles or cause the evolved gas in bubbles to redissolve into the polymer melt.[47] Wang et al. reported that in the center layer, cells have a nearly ideal spherical shape due to a zero shear rate.[47] In this study, cells had the highest aspect ratio in the center layer, which can be attributed to the temperature gradient that is at a maximum in the center region. Increased temperature allows prolonged cell growth. Some cells are so close and big, that they can overlap and then either experience wall rupture, merge into larger even more deformed bubbles, or they stay clustered together.[9,42] Deformed cells tend to orientate slightly along the melt flow direction. The degree of orientation of the bubbles depends upon shear rate, melt viscosity, surface tension and bubble size.[47,56]

4.2 Effect on fiber microstructure

The presence of glass fibers promotes nucleation and refines the cell structure. Fibers act as heterogeneous nucleation sites during foaming. They provide crevices to trap gas and form nuclei.[51,57] As shown in Figure 9, FL significantly increases with gas pressure. Shear viscosity and pseudoplasticity of the matrix play a dominant role in fiber attrition. Dissolved gas acts as a plasticizer and reduces the melt viscosity and thus the occurrence of fiber breakage during processing.[8,58] In the center of the
plate, $L_W$ for compact samples is 1.23 mm and was increased to 1.64 mm at 25 bar gas pressure. Thompson et al also reported less fiber breakage with increasing PBA. The authors found that the introduction of PBA increased the non-Newtonian behavior and blunted the shape of the velocity profile. This reduced the quantity of fibers experiencing shear flow and lowered fiber rotation and thus the occurrence of fiber breakage.\cite{8} It can be further seen in Figure 9 that FL increases with melt flow direction. This trend was also observed by Goris and Phelps et al., where IM LFT samples showed an increased FL at the end of flow path.\cite{37,58} Goris explained this phenomenon with a higher nominal FC present in the region, suggesting that the last filled portion of the part carries longer fibers.\cite{37} Phelps et al. attributed it to the fountain flow effect.\cite{58}

FO is a crucial microstructural parameter that affects the mechanical properties, shrinkage and the dimensional stability of molded parts.\cite{59} As seen in compact IM, fibers arranged in a multi-layer orientation pattern, commonly referred to as core-shell structure (Figure 10). The core layer consists of fibers predominantly aligned in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Cell density and cell size through sample thickness at varying gas pressures and plate locations, close to gate (R1), center of the part (R2), and end of flow path (R3). Solid line represents cell density and dotted line indicates cell size.}
\end{figure}
cross-flow direction \((a_{22})\), while fibers in the shell are oriented along the flow direction \((a_{11})\) due to the fountain flow effect and the no-slip condition on the mold walls.\(^{[37,60]}\) The orientation in thickness direction \((a_{33})\) is mostly uniform with average values of 0.06.

The global diagonal components of the orientation tensor are shown in Figure 11. It can be observed that with increasing gas pressure, fibers become oriented in flow direction. This trend is explained by analyzing Figure 12. As the PBA content rises, the core region becomes thinner, and thus the shell region becomes thicker. In the shell, fibers are predominantly oriented in flow direction, therefore attributing to an increased global value of \(a_{11}\). As the core becomes thinner, less fibers are oriented in cross-flow direction, causing \(a_{22}\) to decrease.

\(\mu\)CT data (Figure 13) also showed core thinning and underlined the trend seen in Figure 11 and Figure 12. Green/blue regions demonstrate fibers that are

**FIGURE 7**  Global cell aspect ratio as a function of gas pressure and plate location. Close to gate (R1), center of the part (R2), and end of flow path (R3)

**FIGURE 8**  Bubble aspect ratio through sample thickness at varying gas pressures. Close to gate (R1), center of the part (R2), and end of flow path (R3). Data shows the aspect ratio trend and does not include error bars to ease in trend visualization. Standard deviation is on average 0.2 [-]

**FIGURE 9**  Fiber length as a function of gas pressure and sample location, close to gate (R1), center of the part (R2), and end of flow path (R3). Initial fiber length before processing is 15 mm
aligned in flow direction \((a_{11})\), whereas red/orange regions represent a crossflow orientation state \((a_{22})\). It can be seen that the green/blue shell layers become wider with PBA content. Along the melt flow direction, samples close to the gate showed a wider core layer than those at R2 and R3 (Figure 12). A broader core layer gives rise to an increased \(a_{22}\). This is caused by the radial flow near the gate. In R2 and R3, the flow is fully developed, and its flow characteristics do not change anymore. Therefore, a constant FO was reached and a defined core-shell structure is visible.

While FO is mainly dependent on processing conditions for compact IM, Figure 11 and Figure 12 clearly showed that PBA content has an impact on the final FO in MIM parts. Gas acts as a plasticizer and changes the rheology of the matrix material, hence giving fibers the ability to rotate easier.\(^{[8,61]}\) However, the high FC present in this work increases melt viscosity and favors fiber-fiber interaction.

**FIGURE 10** Typical core-shell microstructure of MIM molded parts. One represents the melt flow direction and 2 the cross-flow direction, respectively. Fibers are shown in white, cells in black and matrix in gray. (A) Skin layer with no cells and fibers mostly oriented in flow direction, (B) shell layer with small cells and the majority of fibers still being oriented in flow direction, (C) shell layer closer to center region with increased cell size, and (D) core layer with large cells and fibers oriented in cross-flow direction.

**FIGURE 11** Global fiber orientation as a function of gas pressure and location. Close to gate (R1), center of the part (R2), and end of flow path (R3).
interactions. Both, can act as obstacles that hinder fiber rotation. Additionally, it has been reported that the presence of gas causes fiber disorientation due to cell growth around fibers. Shaayegan et al. experimentally studied carbon fiber rotation during bubble growth in polystyrene melt. They reported that fibers in close proximity to a growing cell experience rotational and translational displacements or a combined motion of

**FIGURE 12** Fiber orientation as a function of gas pressure and location. Close to gate (R1), center of the part (R2), and end of flow path (R3)
both due to the melt's biaxial stretching. Shaayegan et al. also showed that a growing bubble continuously increases the fiber's angle and its distance from the cell center. Additionally, multiple fibers move closer to each other in the radial direction as the cell grows. Fibers with a closer initial location to a bubble exhibited a greater magnitude and rate of rotation. It was also found that fibers with a smaller initial angle resulted in a greater degree of FO. It can be clearly seen that the presence of gas results in a more complex FO distribution analysis, as growing cells push fibers out-of-plane. A displacement of glass fibers due to bubble growth can be seen in Figure 14. Measurements indicated a maximum fiber volume fraction in the core layer for compact samples. Shell layers and surface regions showed fewer fibers. At 7.5 bar and 10 bar, the FC dropped by 27% and 22% in the core when compared to compact IM samples as fiber volume becomes occupied by growing cells. At low gas pressures, cells have a high growth rate, resulting in large bubbles (Figure 4). As those cells keep growing in size, fibers are significantly displaced towards the shells, visible in a FC increase of 16% and 14%, respectively. This results in FC distributions which have their maximum in the shell layers rather than the core. At high gas pressure (25 bar), cell growth rates slow down and cells are smaller. Fibers are only slightly displaced from the core, resulting in a FC peak that resembles the compact one. Only a 5% FC reduction was recorded in the core. FC dropped in the shells compared to lower pressure settings, however, the FC was still elevated when compared to the compact IM samples.
to compact plates. It was further noticed that FC reduced in the transition layer between core and shells with increasing gas pressure. Figure 12 shows that fibers in that transition layer are predominantly oriented in flow direction. Thus, growing cells not only displace fibers from the core, but also induce a fiber re-orientation along the flow direction (Figure 15). This factor contributes to the increase in global $a_{11}$ observed in Figure 11.

5 | CONCLUSIONS AND OUTLOOK

In this work, the novel MIM technology Ku-Fizz was employed. Ku-Fizz is controlled by gas pressure, thus, the effect of gas pressure on foam and fiber microstructure was investigated. Experimental results showed foamed plates exhibiting a core-shell microstructure for cells and fibers due to the fountain flow effect. CD predominantly increased and CS decreased with gas pressure and with melt flow direction. As CD increased, the bubble aspect ratio decreased. At high gas pressure settings, Ku-Fizz was able to achieve CDs as high as $5.1 \times 10^5$ cells/cm$^3$ and C5s as low as 55 μm, creating a microcellular structure which is comparable to MuCell. FL increased with gas pressure due to the reduced melt viscosity. A distinct narrowing of the core and a marked change in global FO were recorded with increasing gas pressure. It appears that growing cells induce a fiber re-orientation along the flow direction. FC distribution graphs showed fibers moving towards the mold surface due to cell growth. This phenomenon was more notable for low gas pressures because of the increased growth rate.

Introducing gas causes a complex foam and fiber microstructure that affects the mechanical and physical properties of the final part. Being able to accurately predict the microstructural variations across the part thickness is a key factor in the automotive industry. Moldex3D developed a tool to simulate the microstructure of MuCell foamed components. There is insufficient research on how to model other MIM processes besides MuCell. Investigations on Optifoam, Ergocell, ProFoam and Ku-Fizz have been solely experimental nature until this point. Future work will involve validating the models implemented in Moldex3D to evaluate their ability to predict the microstructure present in Ku-Fizz foamed parts. Results will show if those models can be used after fitting parameter determination, need to be adapted or if a new model needs to be proposed to accurately capture the foaming behavior seen in Ku-Fizz. The performance of the multiphase foamed composite will also be analyzed by using Digimat-MF and COMSOL Multiphysics.

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AUTHOR CONTRIBUTIONS

Jörg Hain developed the Ku-Fizz technology. Sara Andrea Simon and Jörg Hain conceived and designed the experiments. Sara Andrea Simon and Jörg Hain performed the experimental study. Sara Andrea Simon conducted the microstructure analysis and analyzed the data. The manuscript was written by Sara Andrea Simon Tim Osswald supervised the project and was involved in all stages of the research. All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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