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THE EFFECT OF INJECTION MOLDING PARAMETERS ON MICROCELLULAR FOAM MORPHOLOGY

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Abstract

Microcellular foam injection molding with physical blowing agent (MuCell®) delivers monetary benefits, processing advantages and freedom of product design by reducing shrinkage. In conjunction with an advanced mold technology, so-called Pull and Foam method, there is great potential in controlling the foam structure of the component locally. In this study, Polycarbonate (PC) components were produced with nearly compact outer skin and a closed cellular core. To understand the relation between processing parameters and the consequential properties, blowing agent concentration, injection velocity, and mold temperature were varied. Cell size, thickness of the skin layer, distance between cells and the density of the component were correlated to the processing parameters. Reflected light-microscopy (RLM) was used for 2D structure characterization. X-ray micro-computer tomography (µCT) was utilized to gain an insight on the sphericity of cells. Therefore, merged and elongated cells were also taken into account to create microcellular foamed parts with exactly defined properties.

Introduction

Compared to compact injection molding, the microcellular foam injection molding accompanies not only material and weight saving, but also promises numerous processing advantages gained from reduced viscosity, due to dissolved gas, such as shorter cycle time and reduced clamping force [1, 2]. The use of physical blowing agents (nitrogen (N_2), carbon dioxide (CO_2)) equipped with special mold technology, the so-called *pull and foam method*, generates a density reduction up to 50 % [3]. By using the *pull and foam method*, the cavity volume can be locally extended by moving a core inside the closed mold. In this way, injection molded foams with nearly compact outer skin and a closed cellular core are achieved. The size, shape and quantity of cells vary considerably from the center of the component towards the compact skin [4].

To understand the relationships between the morphological and mechanical properties, it is necessary to understand how the process parameters affect these properties. For example, a change in the morphological properties can be obtained by varying the injection speed, melt temperature, mold temperature, amount of weight reduction and different molding processes (e.g. core back system, gas counter pressure system)[5-7]. Tromm et al. created partially foamed PC specimens along with thin-walled areas by using the pull and foam method. For the maximum foaming ratio [-] (final position/ basic position) of 2.7, a density reduction of approximately 55% was achieved. It was observed that the pore diameter was increased in correlation with the enhancement of foaming ratio [7].

Since the mechanical properties are usually reduced by foaming, the design of the molded part should be adjusted to avoid premature failure [8-10]. Several studies have attempted to understand the influence of process conditions on the resulting mechanical properties of foamed parts [11- 17]. Bledzki et al. presented the correlation between processing parameters and the structural foam morphology as well as the correlation between morphological structure and mechanical properties in FIM (foam injection molding) by using gas counter technology. They reached the conclusion that, the deviation in the part's morphology and mechanical properties depend on the density [5]. Cramer noted that mechanical properties of test specimen with almost identical densities vary by up to 40 %. This illustrates the enormous optimization potential that a specifically adjusted morphology has on the mechanical properties of foamed components [6].

The aim of this paper is to provide a better understanding for the interaction between processing parameters and the consequential morphological properties. To obtain divergent foam morphologies blowing agent concentration, injection velocity and mold temperature were varied during FIM by using a physical blowing agent in combination with the pull and foam mold technology. Finally, the differentiation of the cell size, thickness of the skin layer, distance between cells and the density of the component subjected to processing parameters are correlated to mechanical properties.

Experimental

Materials and Experimental Details

The analyzed material was unreinforced polycarbonate (Makrolon® 2405) from Covestro AG (Leverkusen, Germany) with 19 cm^3/10 min MVR (300 °C/ 1,2 kg) and a density (ρ) of 1.20 g/cm^3.

Precise amounts of supercritical N_2 were introduced as a physical blowing agent into the molten polymer by using MuCell® technology (Trexel, Inc., Woburn, Massachusetts). Test samples with dimensions of 120 mm x 80 mm and a thickness of 3 mm had been produced by using an all-hydraulic single component injection molding machine (Arburg Allrounder 470S, Arburg GmbH + Co KG, Loßburg, Germany, injection unit with 25 mm MuCell-screw). The mold was also equipped with a core-back insert to mold four rectangular ribs of different widths (4/ 6/ 8/ 10 mm). The height of the ribs was adjusted to 7.5 mm additional to the 3 mm thickness of the plate. The melting temperature was of 290 °C. Mold temperature, injection velocity and blowing agent content (SCF-level, supercritical fluid level) varied according to full factorial design of experiments (DoE) with 3 factors at 2 levels (Table 1).

Table 1. The variation of the processing parameters

Parameters	**Abbr.**	**Min.**	**Max.**
Mold Temperature [°C]	T_{mold}	30	80
Injection Velocity [cm^3/s]	V_{inj}	50	150
Blowing Agent Content [%]	SCF-Level	0.4	0.8

Tensile Testing

The extended rib with the width of 10 mm was tested on a universal testing machine (Z010, Zwick Roell, Ulm, Germany) according to ISO 527-1 [18].

In order to only test the foamed material, the compact part (Figure 1 (a)) was removed. Subsequently, the foamed rib was milled out concentrically, as it is shown in Figure 1 (c). The testing speed was set to 2 mm/min for each material. Prior to the tensile tests, the specimens were kept at standard conditions (23 °C/ 50 % relative humidity) for at least 16 hours. 5 samples were tested for each test run.

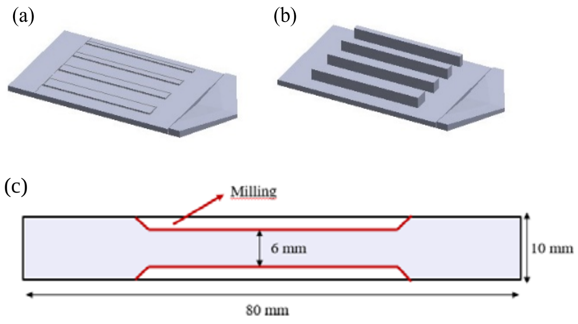

Figure 1. Preparation of the specimen for tensile test (a) before cavity expansion, (b) after cavity expansion, (c) dimension of the foamed rib after milling

Morphology

Once the compact part (Figure 1 (a)) was removed, the extended rib with the width of 10 mm was cut in the middle with the length of 30 mm (shown in Fig. 2), to investigate the foam structure. These cuts with skin layers were embedded in resin, grinded, polished and examined using a digital light microscope (Keyence VHX series, Keyence, Ōsaka, Japan) with the dark field method (dark cells and bright matrix, 50X magnification). 3 samples were examined for each test run.

The X-ray micro tomography (µCT) was done using a Zeiss XRadia 520 Versa microscope (Zeiss, Oberkochen, Germany). The re-constructed data was evaluated using the AVIZO (FEI) software. Rectangular samples ~2.78 mm in length, ~2.78 mm in width and ~3.85 mm in height were scanned to gain an insight on the sphericity of the cells and the cell volume throughout a cross section of the specimens. For each sample, images were taken with a resolution of 1.99 µm/pixel and an exposure time of 4.5 s with a standard voltage setting of 80 kV and 7 W.

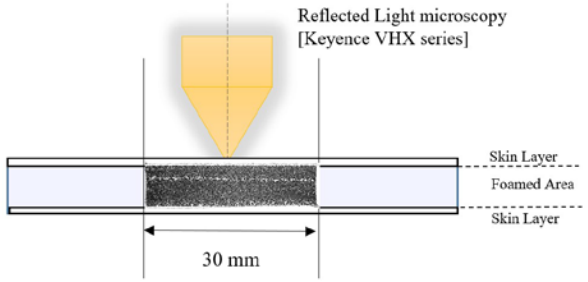

Figure 2. Investigation area of digital light microscopy

Density

The measurement was carried out with a density measuring system of the type 6060/60801 from Sartorius AG (Göttingen, Germany). This system consists of a precision measuring scale and a fixture for determining the sample weight in a reference liquid based on the buoyancy method. All measurements were carried out with water (density ~1 g/cm^3). A piece of 30 mm length, 10 mm width and 7.5 mm height cut from the middle of the rib was used (Figure 2). 3 samples were measured for each test run.

Results and Discussion

Mechanical properties

Figure 3 shows the amount of strain depending upon cell diameter. With the increase in cell diameter, the elongation at break and yield increases steadily. According to the results, a finer cell structure conducts a higher amount of plastic deformation in comparison to smaller cell structures. It can be related to a better molecular orientation in the material and therefore an increase in the energy dissipated during crack growth [4].

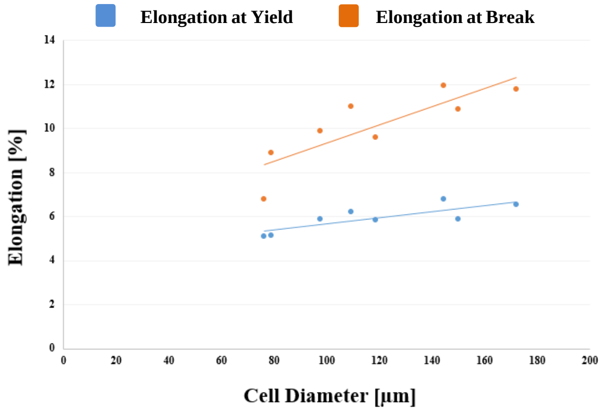

Figure 3. Elongation at break and yield of different diameter of polycarbonate foam samples

In accordance with Figure 4, a higher SCF level leads to an increase of the Elastic modulus. On the other hand, higher injection velocities cause an attenuation in the Elastic modulus. It is also visible, that the standard deviation decreases with a lower mold temperature.

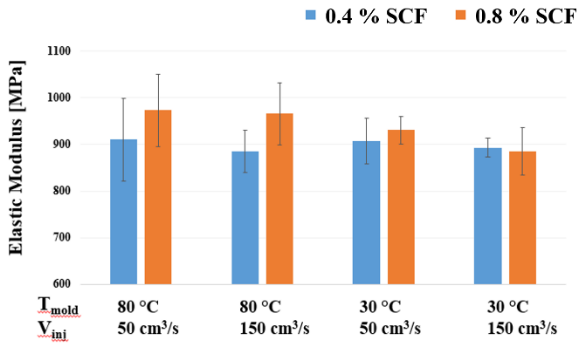

Figure 4. Elastic Modulus of samples with different mold Temperature (T_{mold}) and injection velocity (V_{inj}) subject to amount of blowing agent content (SCF)

Morphology

Figure 5 illustrates the density profile of 3 different specimens in the direction of cross section area with microscopic photos. The variance in density is obtained via processing parameters (subsequently SCF-level/T_{mold}/v_{inj}). As it is shown in Figure 5, foamed structures of microcellular polymers introduce an integral density, therefore the density in the middle of the part is lower compared to the edge. The size, shape and amount of cells can be varied from the centre of the specimen towards the skin layer [5].

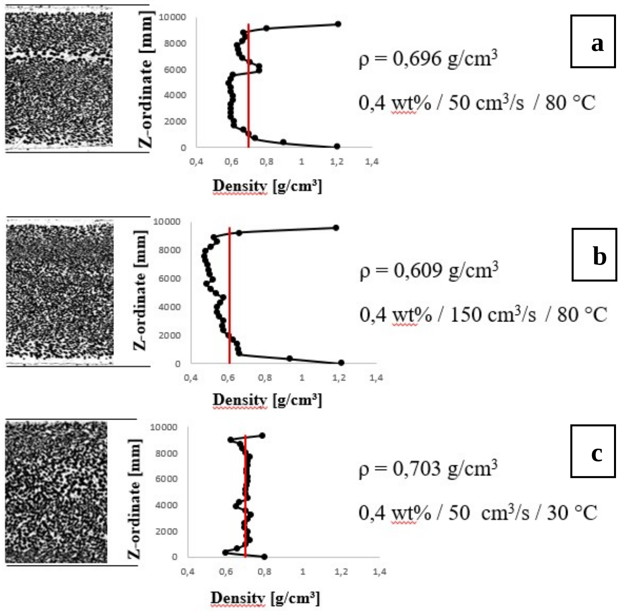

Figure 5. Density profile towards cross section of the specimen related to injection molding processing parameters.

It is also noticeable that, the density distribution was found to be more homogeneous at lower mold temperature. The larger void fraction in the density profile is linked with a lower density. The reduction of injection velocity also shows an influence on void fraction, by increasing cell size. The smaller quantity of the blowing agent leads to larger cell diameters and thicker skin layers. A further increase in the average cell distance can be reached by lowering mold temperatures. The elongation of the foamed structure shows an increase with further homogeneity of the cell structure. In Figure 5 elongation at break (a) is 9.58 %, while (c) shows 11.88 %.

Figure 6 gives information related to cell volume over cross section. It can be seen that, the cell volume distribution varied with the change of processing parameters. The size of cells was increased by decreasing mold temperature. The homogeneity of the cell structure can be obtained by increasing the mold temperature as well as the injection velocity. Higher injection velocities result in less time for diffusion of gas into early foamed cells, which favors the nucleation, correspondingly the homogeneity of the part is increased [4].

It was found that abrupt transition of the cell size, induces a higher Elastic modulus. Fig. 6 (a) shows uniform and smaller cell size distribution and an Elastic modulus of 884.50 MPa. However, Figure 6 (d) involves a wide range of cell size and more abrupt dispersion, therefore, causing

Elastic modulus to increase to 910.16 MPa. This variation of cell size distribution was created by reducing injection velocity from 150 cm^3/s to 50 cm^3/s. On the other hand, it was also deduced that the reduction of the cell size leads to an increment in tensile strength. The tensile strength results of Figure 6 (a) and (b) are, subsequently, 21.69 MPa and 19.99 MPa.

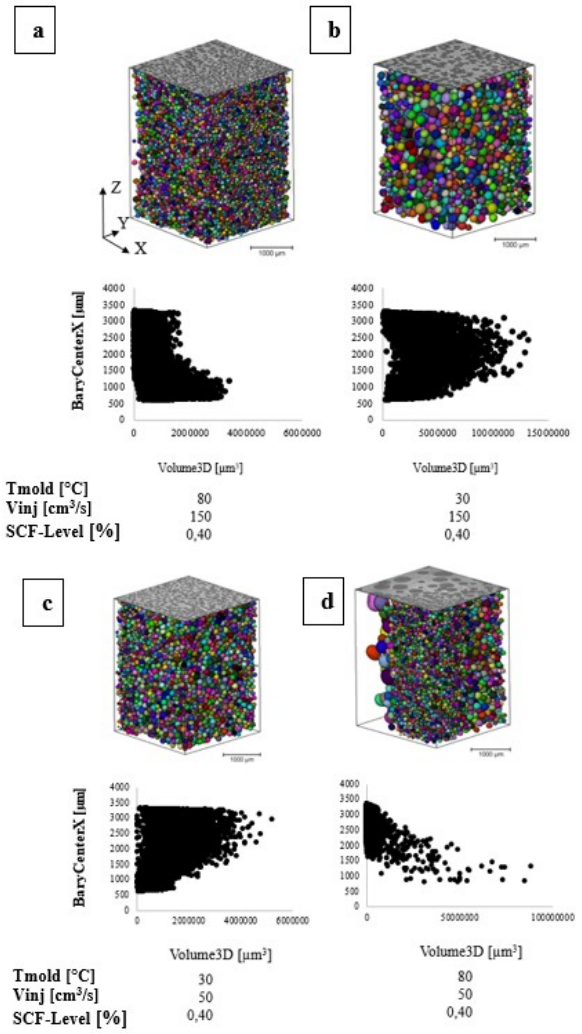

Figure 6. The X-ray micro tomography (µCT) and cell volume 3D profile towards cross section of the sample with different processing parameters (BaryCenterX indicates position of cells´ barycenter in the direction of “x”)

Sphericity

To determine the shape of the cells, the Aspect Ratio 3D was used as an indicative. A low aspect ratio is a sign to elongated cells. An aspect ratio closer to 1 indicates higher cell roundness. Figure 7 shows the Aspect Ratio 3D values in dependency of the sample cross section and Table 2 gives information regarding the processing parameters of the displayed samples.

According to the results, utilization of a higher amount of blowing agent inclines the elongation of cells towards the edge layer. It is also noticeable that a lower blowing agent content in conjunction with a lower mold temperature increases the roundness of cells.

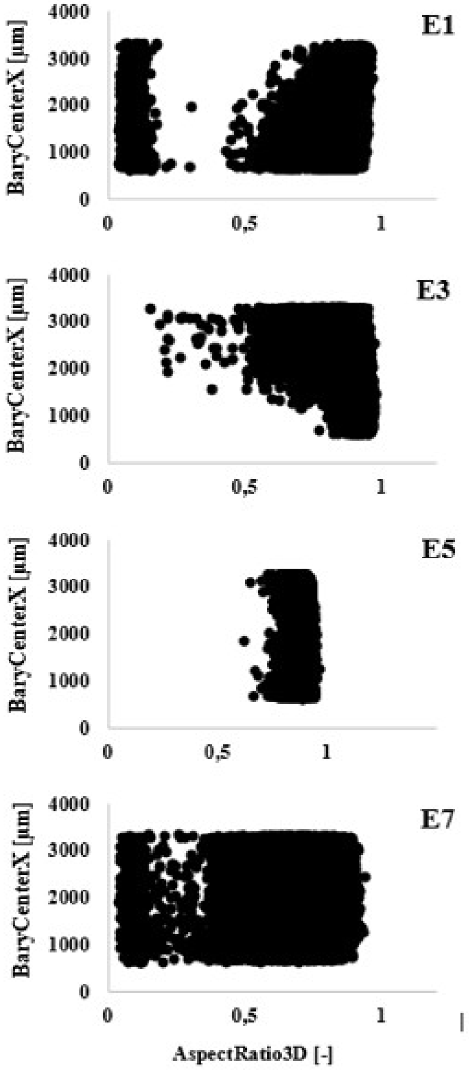

Figure 7. The Aspect Ratio 3D in dependency of sample cross section (BaryCenterX indicates position of cells´ barycenter in the direction of “x” shown in Fig. 6 (a))

Table 2. Processing parameters of the samples displayed in Figure 6

Sample	SCF-Level	Mold Temperature [°C]	Injection Velocity [cm^3/s]
E1	0.8	80	150
E3	0.4	80	150
E5	0.4	30	150
E7	0.8	30	150

Tensile test results, as presented, show that, a finer cell structure produces higher amount of plastic deformation in comparison to a smaller cell structure. While higher SCF level leads to an increase in Elastic modulus, higher injection velocity causes a reduction. It was also deduced that the reduction of cell size leads to an increment in tensile strength. When it comes to morphological characterization of foamed structure, an integral density course is observed, therefore the density in the middle of the part is lower than at the edge. The size, shape and amount of cells can be varied from the centre of the specimen towards the integral skin [5]. The homogeneity of the density profile was enhanced at lower values of SCF-level. The larger void fraction in the density profile is interrelated to the lower density. Usage of higher amount of blowing agent inclines elongation of cells towards the edge layer. It is also observed that lower blowing agent content in conjunction with lower mold temperature increases the roundness of cells.

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