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FORMATION OF MORPHOLOGY AS A FUNCTION OF PROCESS CONTROL BY FOAM INJECTION MOLDING OF A FUNCTIONALLY GRADED COMPONENT

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Abstract

A special mold technology enables the production of foam injection molded components with locally differing foaming ratios. Thus, components with functionally graded foam structures can be produced in one processing step. The method (*pull and foam* method) is based on the idea of creating components with thin-walled areas with a high surface quality and partially foamed, thick-walled areas (e.g. with the function of integrated structural elements) in a controlled foaming process. This paper describes the characteristics of the structure and density in the differentially foamed areas in correlation with the essential processing parameters.

Introduction

The special molding technology is a variation or advancement of the precision mold opening (PMO) method, which is also referred to as the breathing mold and negative compression process. In a standard PMO process, a melt containing blowing agent is injected into the cavity at a high speed and under high pressure. In doing so, the cavity is filled volumetrically, and a most compact filling of the form without foaming is aimed for. After an optional delay time, the entire cavity is opened to a predefined extent to induce the expansion of the blowing agent by means of the pressure drop. Opening is realized by the movement of the clamping unit. The result is a component with a compact skin layer and a closed-cell, foamed core area.

During foam injection molding using the special mold technology, the so-called *pull and foam* method, the cavity volume is only locally expanded by moving cores inside the closed mold. Thus, the foaming is restricted to the areas unblocked by the moved cores. In contrast, adjacent areas remain nearly compact. This gradation possibility of this process enables the production of thin-walled, flat components with locally foamed areas of a large volume with a stiffening function.

Owing to the various arrangements and directions of movement of the cores, as well as due to the option to create locally foamed structures while adjacent areas remain nearly compact, the *pull and foam* method is much more flexible in comparison to the standard PMO method. Unlike in the PMO method, the foaming is not restricted to the mold parting line. Like the PMO method, *pull and foam* also offers the advantages of an improved surface quality, a homogeneous distribution of the density along the flow path, and a high reduction of the density. Moreover, it also provides the option to extend the limitations and design guidelines of ribbed components. A detailed description of the process and first results by using different materials and blowing agents are shown in [1-3].

The PMO method has already been extensively researched at numerous national and international institutes and research centers. The influence of process control on the resulting morphology, the corresponding mechanical properties and the improvement of the surface quality were examined using diverse materials. Intensive investigations in this regard were done i.a. at the Department of Polymer Materials at the University of Bayreuth [4-6], the IKV at the University of Aachen [7-9], the LKT at the University of Erlangen-Nuremberg [10, 11], the IfW at the University of Kassel [12-14], the Department of chemical engineering at the University Laval, Quebec (Canada)/ Department of chemical engineering, Universidad de Guadalajara (Mexico) [15] and the MPML at the University of Toronto [16].

Using the *pull and foam* method further influencing factors or conditions must be taken into account. Effects occur due to the simultaneous development of the thin-walled (nearly compact) and the thick-walled, highly foamed areas with partially extreme wall thickness differences. This is also the case for the essentially differing ratios between the compact skin layer and the foamed core. Regarding these effects, a general transferability of the already acquired results is only conditionally possible. The ratio of the surrounding skin layer, which constantly is in contact the cooled mold wall, to the volume of the foam core strongly differs in the demonstration component on hand when compared to conventional components manufactured using the PMO method. The corresponding conditions strongly influence the structure formation.

Experimental Details

The basic process control and the general influence of the processing parameters on various material systems with chemical and physical blowing agents were determined in pre-tests. Besides the essential processing parameters, i.e., injection speed, material and mold

temperature, the process-specific processing parameters blowing agent content, foaming ratio (adjustable via a variable core pulling position) and delay time (time between injection and pulling of the core) are of great significance [1-3].

On the basis of the fundamental processing parameters, a robust process setting was selected, and the process-specific parameters were varied, in order to be able to assess their influence on the developing structure. Owing to the fact that physically foamed components generally have a more homogeneous pore structure with a lower density gradient in the component cross section than chemically foamed ones, the results of physically foamed materials are described in this paper. Essentially, the focus is limited to the PC/ABS blend, which shows a comparably homogeneous pore structure and a clearly defined skin layer. This makes it possible to assess the influence of process control more easily. In order to be able to evaluate the influence of the delay time better, the results of physically foamed polycarbonate will also be shown.

Using a demonstrator mold, the components were manufactured with variations in the processing parameter settings. The demonstrator part is a thin-walled plate with the dimension of 120 mm x 80 mm and a wall-thickness of 1.5 mm. Via a movable core in shape of a crossed rib or bar construction the volume of the mold can be changed by creating bars with a width of 8 mm and a continuously adjustable height from 0 mm up to 9 mm, see Figure 1. For the investigations melt containing blowing agent was volumetrically injected at basic position with a bar height of 2 mm (additional 1.5 mm basic wall thickness = total thickness of 3.5 mm). Starting from this basic position the bar construction was pulled up to a height of 8 mm (9 mm for PC) and the foam expanded in the extended volume. In doing so the volume in these areas was expanded up to a ratio of 2.71 (3 for PC). In the following this expansion ratio, defined as volume after pulling the core in relation to the basic volume (each is bar height and basic wall-thickness) is called foaming ratio (FR). The parts were cut for examinations as can be seen in Figure 2.

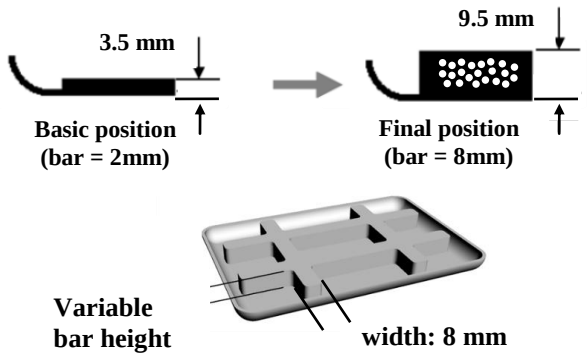

Figure 1: Demonstration component with variable bar height

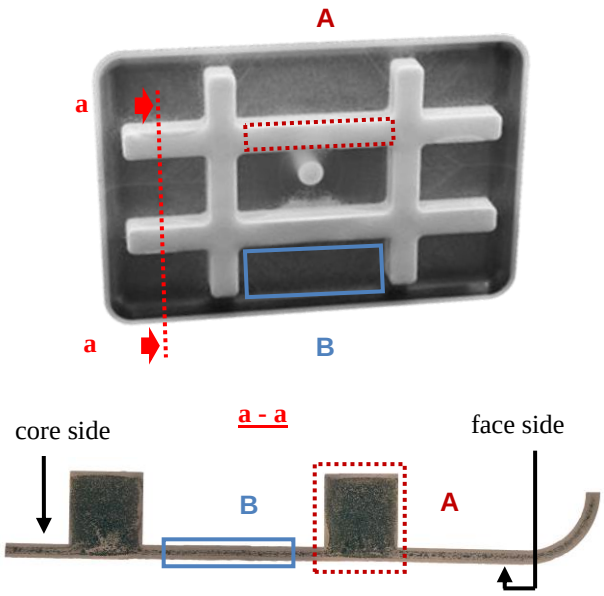

Figure 2: Guided cutting and description of examined areas of the demonstration component

Material and Processing Parameter

In the following section, the results of a polycarbonate / acrylonitrile-butadiene-styrene polymer blend (PC/ABS) and supplementary excerpts of the results of the polycarbonate (PC) are shown.

- PC/ABS (Schulablend®, Schulmann):
  ρ = 1,13 g/cm³, MVR = 14 cm³ / 10 min
- PC (Makrolon® 2805, Bayer):
  ρ = 1,20 g/cm³, MVR = 9 cm³ / 10 min

N2 was used as a physical blowing agent. The blowing agent content that means the level of supercritical fluid (SCF) was varied within the processing window recommended for the materials. The foaming ratio (FR) was set by means of the variably adjustable core of the demonstration component for defined bar heights. The third parameter of influence that was varied was the delay time (t_D), meaning the time between the volumetric filling of the mold and pulling of the core.

- Blowing agent content (SCF): 0,4 wt% / 0,8 wt%
- Foaming ratio (FR): 1,29/ 1,57/ 2,14/ 2,71/ (3)
- Delay time (t_D): PC/ABS: 0s/ 1s;
  PC: 0s/ 3s/ 5s

Results – Density

By using the buoyancy method, density measurements were carried out for the foamed bar areas with varying foaming ratios (Figure 2, area A) and for the thin-walled areas without a later cavity enlargement (Figure 2, area B).

Figure 3 shows a scatterplot with connection lines of means of the relative density values at different foaming ratios. It illustrates the density of the foamed PC/ABS in regards of the density of the unfoamed compact material as a dimensionless ratio $\pi\rho$ [-] (density foam/ density compact material) in dependency of the foaming ratio FR [-] (final position/ basic position). The figure shows 2 groups of values – the values for area A and area B at different process settings.

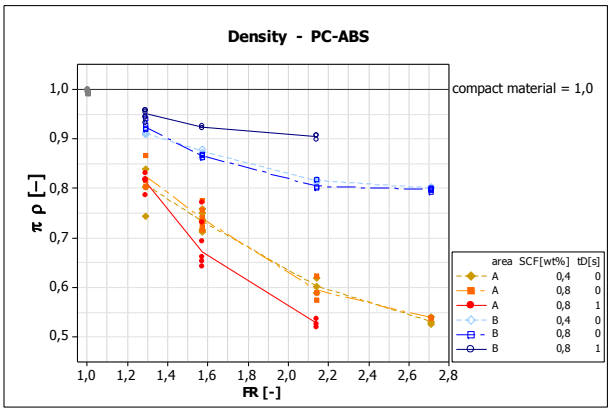

Figure 3: Density of PC/ABS related to the density of unfoamed compact material plotted over foaming ratio

As was to be expected, the density in the foamed bars (A) strongly decreases with the increasing foaming ratio. For the maximum foaming ratio of 2.71 (bar height 8 mm), a density reduction of approximately 55% was measured. However, the density of the thin-walled areas is also affected by the foaming ratio of the bar area. The higher the volume of the foamed bar (A), the larger the foaming in the adjacent, thin-walled area (B). The drop in pressure induced by the local enlargement of the cavity has an effect on the plastic core of the thin-walled area (B). The density reduction at the maximum foaming ratio of 2.7l in this area is approximately 20%. A clear influence of the delay time can be determined. In the thin-walled area (B) a high delay time leads to a smaller amount of foaming, that means a higher density. A longer cooling time, which corresponds with the increasing delay time, leads to a lower content of plastic core. In the highly foamed area (A) a contrary effect can be established. A high delay time leads to a lower density. This effect increases with a higher foaming ratio. The blowing agent content had no significant influence in the varied processing window. The mean values are nearly identical.

Results – Skin Layer Thickness

Longitudinal and transverse cuts were made in the component for the assessment of the structure (skin layer thickness and pore structure), see Figure 2. These cutouts were embedded in resin, grinded, polished and examined using a light microscope. The thicknesses of the skin layers were measured for a distance of approximately 40 mm (calculation of the average layer thickness via polygonal areas). The core, which shapes the foamed bars, is not thermically separated from the mold. Both cavity halves (face side and core side) were set to the same temperature (θ_W = 75°C).

The cross section of the component is examined in form of a simplified, three-piece structure: the skin layer on the face side, the foamed core area, and the skin layer on the side of the core. In Figure 4, the ratio of each layer thickness in correspondence to the total thickness of the component is depicted as a dimensionless ratio π_D [-] (layer thickness/ total thickness) for PC/ABS. A ratio of π_D = 1 corresponds with 100%. The figure shows a stacked bar chart where the share of each layer of the total thickness can be seen. The bars are grouped by equal process settings.

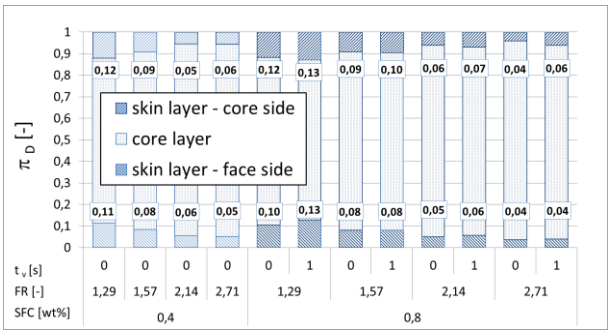

Figure 4: Ratio of layer thickness in correlation with the total thickness of the component

As expected, the ratio of the skin layers in regards of the total thickness reduces as the foaming ratio increases [see 11]. The absolute skin layer thicknesses (in mm) remain nearly constant independent of the foaming ratio. At the same foaming ratio and a constant delay time, a slightly lower skin layer thickness correlates with higher blowing agent content [see 12, 14]. Generally a longer delay time leads to slowed cell growth and a thicker skin layer on both sides owing to a larger amount of heat conduction to the mold wall independent of the foaming ratio and blowing agent content, as well as an increase of the viscosity also occurs close to the skin layer [see 5, 11]. Only observing the skin layer thicknesses at low blowing agent content, it becomes evident that the values are nearly equal on both sides of the component. If the

blowing agent content is higher, the amount of the skin layer on the side of the core is slightly higher.

Results – Morphology

In order to be able to quantify the pore structure, the pore diameter was selected as an indicator. For this purpose, a homogeneous section was selected in the center of the foamed structure and the pore areas were measured using two-dimensional cross sections (Figure 5). The measurements were carried out at a magnification of 200x – 500x by the help of photo-editing software. The average pore diameter or pore median was calculated by measurements of the single pore areas.

Figure 5: Measurement of the pore areas in a homogeneous, uninterrupted area

Exact absolute values cannot be determined using this method. On the one hand, the idealization is achieved, meaning the pores have the ideal, round shape. One the other hand, a measurement error occurs which is described as the tomato slice effect in literature. This error results from the fact that the pores are only dissected in their center in the rarest cases. By center the area with the largest diameter is meant. Thus, owing to the mostly off-center area measurement, one obtains a slightly lower pore diameter than in reality. The measurement error is of a systematic nature and does not affect the qualitative influence assessment. In order to obtain statistical security, three components of each test setting are measured. Therefore, there are up to 1000 measurement values per test setting. Moreover, the single batches were examined in regards of their homogeneity and normal distribution.

The measurement results are displayed in Boxpolts. In this way distribution and scattering of large measurement series can be evaluated in a good way. One box represents 50% of the measurement values, the vertical lines represent the deviation and the stars indicate outliers. The horizontal line within each box is the median value which is less sensitive against outliers than the arithmetic average. Figure 6 and figure 8 depict the idealized pore diameter as a function of the process settings. It´s called idealized because the diameter is calculated by the measurement of the pore areas assuming that the pores are ideal round shaped. One box represents the measurement values of three components from one test setting. For the assessment of the effects the median and the scattering of the different process settings were compared.

Figure 6 depicts the idealized pore diameter for PC/ABS in dependency of foaming ratio, blowing agent content and delay time.

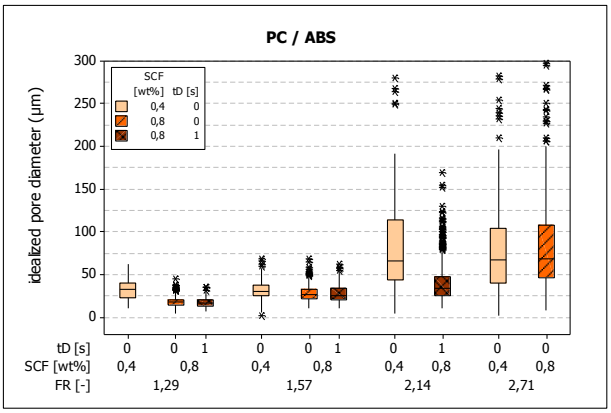

Figure 6: Idealized pore diameter of PC/ABS in correlation with the processing parameters

The observed tendency of the pore diameter to increase in correlation with the rising foaming ratio can be confirmed. Moreover, an increasing scatter of measurement values can be observed in correlation with an increasing foaming ratio, meaning the structure is increasingly inhomogeneous. The blowing agent content affects the pore diameter and data distribution. A high blowing agent content leads to smaller pore diameters [see 12, 13] and to a smaller scattering. In regards of the delay time, only conditional statements can be made. For a delay time of 1s and a foaming ratio of 2.14 (6mm bar height) the structure of PC/ABS is very inhomogeneous. No representative area for measuring the pores can be selected (Figure 7). In the context of the delay time varied here, no effect of the delay time can be determined up to a foaming ratio of 1.57.

In order to still be able to assess the influence of the delay time on the structure development, an excerpt of the results of a PC will be shown in the following section. Even after longer delay times of up to 5 s, homogeneous pore structures were identified and measured for this material at a medium foaming ratio.

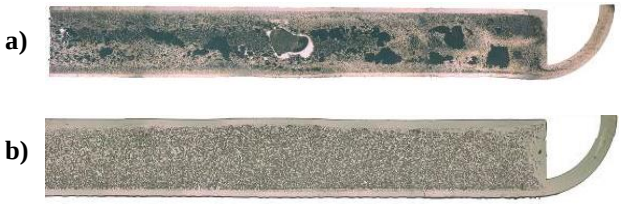

Figure 7: Morphology at FR = 2.17 (a: PC/ABS, t_D = 1s; b: PC, t_D = 5s)

The idealized pore diameters of the PC in correlation with the foaming ratio and delay time are illustrated in Figure 8.

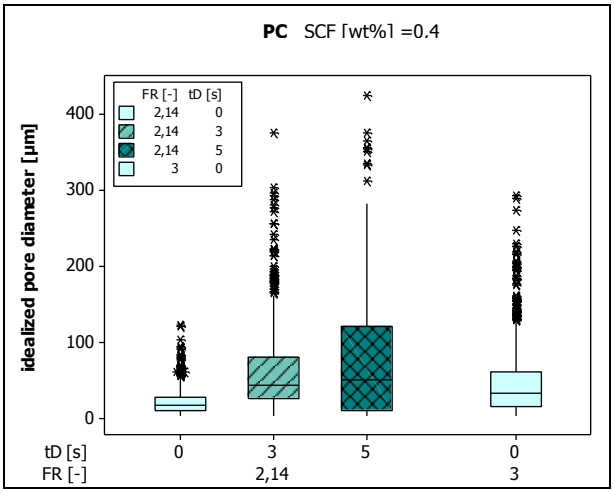

Figure 8: Idealized pore diameter in correlation with the processing parameters - PC

An increasing pore diameter and increasing scattering can be evaluated for PC with a higher foaming ratio. But the variation of the delay time from 0s to 3s and 5s proves to have a larger influence on the pore diameter than the variation of the foaming ratio at a constant delay time. The longer the delay time, the larger the pore diameter and the scattering of data (meaning the pore structure is more inhomogeneous) [12].

A partial diverging influence of the delay time on the pore size is dealt with in the extensive examinations with PMO and physical blowing agents with PC/ABS in [13] and PC in [12]. As the delay time increases, a clear reduction of the pore diameter can be seen. However, if delay times are extended, the diameter increases again (the diameter passes through a minimum). This effect is described as a function of SCF, and is much more pronounced when the SCF is lower [12, 13]. However, these results refer to lower density reductions.

Conclusions

In conclusion, the influences of the processing parameter on the structure of PC/ABS will be described in area charts. In doing so, the influences of the parameter settings can be qualitatively and clearly illustrated.

Figure 9 illustrates the density (area A) in relation to the compact material, figure 10 the skin layer thickness (exemplarily the face side) and figure 11 the median of the idealized pore diameter (median is more nonsensitive in face of outliers than the average). The results are represented as a function of foaming ratio and blowing agent content. Due to the incomplete data basis in regards of the delay time for PC/ABS, the results listed refer to a constant delay time of 0s.

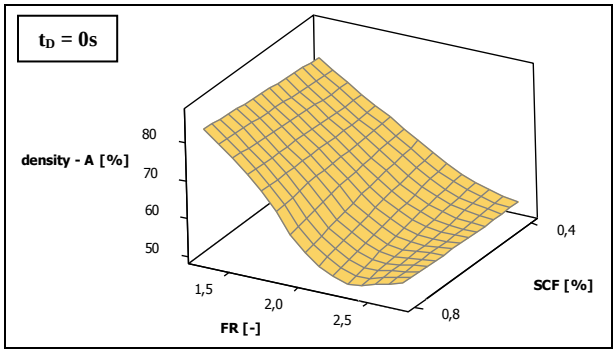

Figure 9: Density in correlation with the blowing agent content and foaming ratio; t_D = const. = 0s

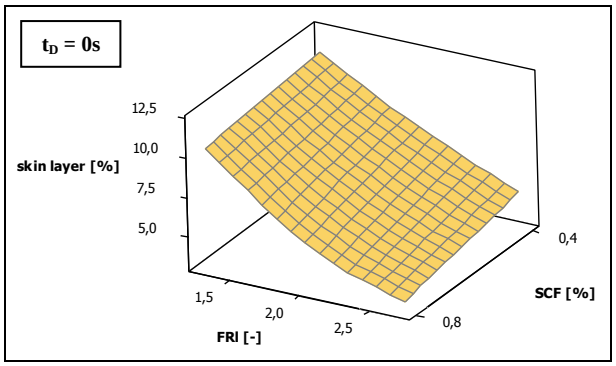

Figure 10: The skin layer thickness (face side) in correlation with the blowing agent content and foaming ratio; t_D = const. = 0s

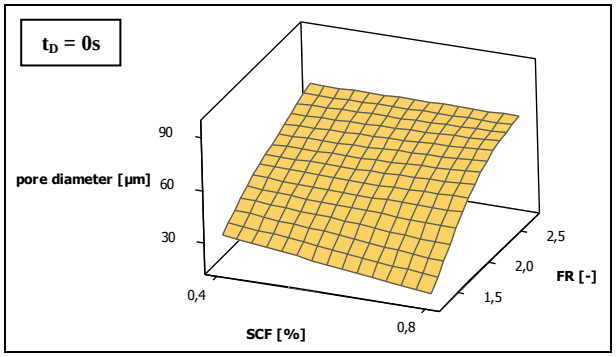

Figure 11: Theoretical median of the pore diameter in correlation with the blowing agent content and foaming ratio; t_D = const. = 0s

Essentially, the results of the investigations can be compared with the PMO method. However, all effects do not display the same characteristics and effective directions. Here, the component geometry (local pressure, temperature and flow conditions), the special material type and the specific processing window plays an essential role.

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