Journal of Cellular Plastics

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What is This?

Correlation between injection moulding processing parameters and mechanical properties of microcellular polycarbonate

Andrzej Kornelius Bledzki[1,2], Hendrik Kirschling[1], Martin Rohleder[1] and Andris Chate[3]

Abstract
Since many decades, microcellular foamed materials have been produced basically to reduce the density of the materials in order to get lightweight parts. Meanwhile, it is well known that microcellular foaming by injection moulding offers many more advantages compared to compact injection moulding. Those are, e.g. lower shrinkage and warpage, shorter cycle times, lower clamp forces, reduced viscosity but improved properties of the foamed material in contrast to the compact material. These arguments are all known, but to improve the properties of the material, it is necessary to understand the interrelationship between the morphology and the mechanical properties. Furthermore, it is important to know how the processing parameters influence the morphology and the properties of the produced part. By understanding the relation between processing parameters and the consequential properties, it has become possible to create microcellular foamed parts with exactly defined properties. Through the variation of different processing parameters such as blowing agent concentration, injection velocity, mass temperature, mould temperature, weight reduction and different moulding processes like gas counter pressure injection moulded test, samples were produced to characterise the morphology and the mechanical properties. The experiments were performed with a polycarbonate type from Bayer MaterialScience. The cell size, thickness of the skin layer and distance between the cells were correlated to the processing parameters by means of nonlinear regression equations. Based on these

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equation, 3D graphs were created by variation of two parameters by fixing the remaining parameters to illustrate the relationships. Furthermore, the relation between the morphology and the mechanical properties was correlated, which makes it possible to produce parts through injection moulding with a well-defined Young's modulus or flexural strength.

Keywords

Counter gas pressure, foam density, injection foam moulding, physical foaming/blowing agent, precision mould opening, structural foams, surface quality, thermoplastic foams, unfoams skin layer

Introduction

Foaming of thermoplastic polymers by injection moulding has been performed since many decades. The microcellular foaming is well known since many years and there are many publications in this research area and many patents were applied for products and proceedings. Microcellular foams have advantages such as reduced material consumption, lower processing temperatures, lower viscosity of the polymer melt, avoid shrinkage, reduced density by approximately equal mechanical properties and many more. Especially, the low shrinkage is a very interesting point for industrial manufacturers. However, industrial applications of microcellular foams, which were produced by injection moulding, are very rare. With regard to the well-known advantages of microcellular foamed polymers and the possibility to reduce investments for injection moulding machines,[1,2] it is astonishing that microcellular foam processing has not established in industrial application.

Although positive research results and publications on microcellular foams have been released,[3–5] most of the companies hesitate to apply this technology, because the processing parameters are so extensive and most of the research was not done on industrial scale. Most of the investigations in the past did dealt with industrial processes, but with foam produced with a batch process or other laboratory technologies. On the one hand, microcellular foaming leads to a lower density and to saving material which is a great advantage with regard to the automotive industry trying to reduce the weight of each part in the vehicle. It also allows high technical polymer to compete with mass polymers both in price and density. On the other hand, microcellular processing leads inevitably to a reduction of the mechanical properties. In the first instance, this is not problematic, but at present it is not yet possible to forecast the mechanical properties of an injection moulded foam. The properties of these materials were extensively investigated, but the literature says that the properties of the foamed parts depend on the foaming technology and in particular on the processing parameters during the production.[6,7]

To characterise the properties of microcellular foamed polymers, it is necessary to understand the interrelations between processing parameters, foam morphology and mechanical properties. A correlation of these parameters will allow producing

microcellular foamed materials with exactly defined parameters. This upgrades microcellular foaming and enables the industry to estimate the required processing parameters in order to get optimised foam structures with well-defined mechanical properties.

Mucell[TM] technology

In the early 1980s, the Mucell[TM] principles were developed at the Massachusetts Institute of Technology, USA, to reach higher weight reductions. This technology uses a physical blowing agent to foam the polymer. Usually, blowing agents such as supercritical nitrogen (N_2) and carbon dioxide gases (CO_2) are injected during moulding process by small, precise amounts into the molten polymer. The patents were bought by Trexel Inc., which launched the technology on the market.[8]

Gas counter pressure

Foamed components produced by injection moulding often have a very bad surface quality, which is one of the reasons why industrial application is still rare. The bad surface quality is due to the fact that during the injection into the mould, the blowing agent drifts out of the polymer melt at the glaze front. The polymer bubbles are being destroyed by shearing of the material at the mould surface. This effect can be prevented by the gas counter pressure (GCP) process (Figure 1). For using the GCP technology, an airtight mould and an additional gas injection channel are required. A gas pressure is built up in the empty mould and the melt is injected against this gas pad, which keeps the blowing gas in solution and prevents the creation of surface swirls. Therefore, the GCP has to be higher than the gas solubility pressure of the blowing agent with the specific base polymer. During the melt injection, the counter pressure gas is being exhausted accurately to obtain a constant counter pressure. After the injection process, the gas pad will be exhausted, so that the blowing agent can foam up the polymer melt.[9]
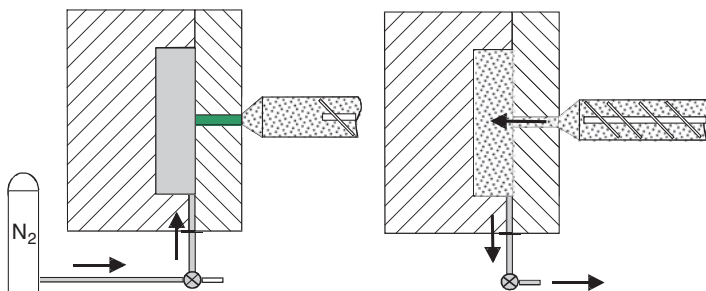

Figure 1. Schematic of the gas counter pressure process.

During this investigation, the GCP technology was not applied to improve the surface quality, but it does influence the morphology of the foamed part. In addition to the other process parameters, such as injection speed, type of supercritical gas and concentration, melt temperature and weight reduction, GCP is another important parameter which affects the properties of the foam (Figure 2). The obvious lower surface roughness also leads to better mechanical properties, because high roughness may act like micro-notches.

While analysing the morphology, it is conspicuous that parts, which were produced with GCP, can be foamed up to the surface. Conventionally produced foams have a clear boundary between the microcellular core and the skin layer.[10] The morphology of the injection moulded parts with GCP usually is quite different from the conventionally injection moulded parts (Figure 3). Contrary to the conventionally foamed material, which has a thick compact skin layer and a clear separation of the skin layer from the foamed core, the parts, which were produced with GCP, show a very thin compact skin layer and do not have this clear separation. Even at the edge of the skin layer, cells can be found, which depends on the counter pressure gas pad in the mould that keeps the blowing agent gas in solution and prevents the escape out of the melt. During the conventional microcellular foaming, the gas in edge areas of the polymer melt escapes, so that the material in the skin layer cannot be blown up.

Experimental details

The analysed material was an unreinforced polycarbonate from Bayer MaterialScience with middle viscosity Makrolon 2805 (density $1.2 \, g/cm^3$). Test samples with the measuring of $160 \times 20 \times 3.2 \, mm^3/4 \, mm$ had been produced according to DIN EN ISO 294 and 10724 with an injection moulding machine (Engel Victory 330H/80V/120 Combi, clamp force 1200 kN) equipped with the MucellTM Technology (Trexel, Inc., Woburn, MA, injection unit with 30 mm MuCell-screw). The mould was also equipped with the GCP technology, which allows improvement of the surface quality and yields another processing parameter that affects the morphology. The used blowing agent was nitrogen.
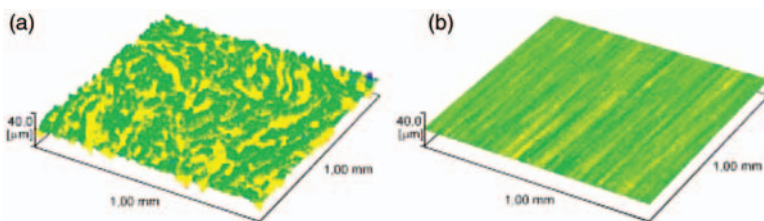

Figure 2. Surface quality: (a) without GCP (RZ = 23.11 μm) and with GCP (RZ = 0.8 μm). GCP: gas counter pressure.

Analysis details

The test bars were concentrically milled out of the produced samples, so that the foamed material could be tested. All test bars were milled out of test samples having the same geometry, so that the influence of the mould geometry on the morphology would be equal for all tests. Equal geometry guarantees reproducible constant testing conditions for all different testing methods (Figure 4).

The following tests were performed.

- Tensile test according to DIN EN ISO 527
- Bending test according to DIN EN ISO 178

The tensile modulus, strength at yield and elongation at yield for the tensile test, and flexural modulus, flexural strength and elongation at flexural strength for the bending test, were analysed to correlate the mechanical properties with the foam morphology.

In order to characterise the morphology of the microcellular foamed materials, they were analysed by microscopy with regard to average cell diameters and distances between the cells in the centre of the foam core, average cell diameters and distances between the cells at the edge of the foam core and thickness of the skin
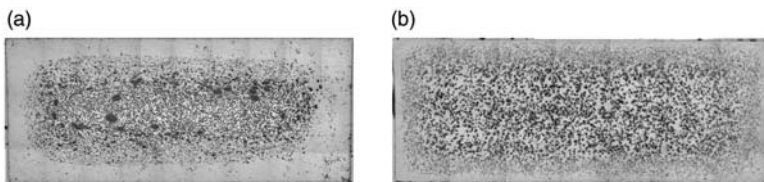

Figure 3. Comparison of (a) conventional foaming and (b) foaming with gas counter pressure.[11]
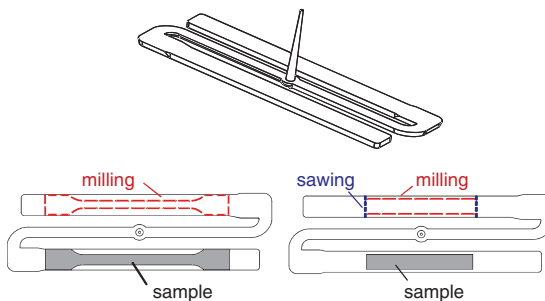

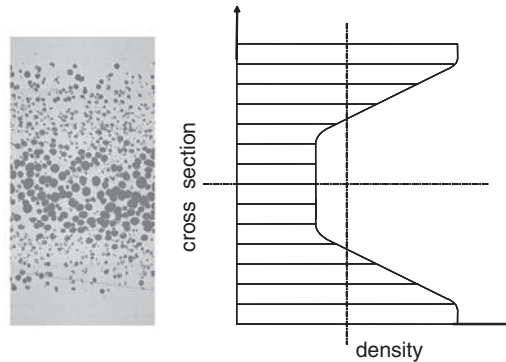**Figure 4.** Sampling method of specimen for tensile and bending tests.

Figure 5. Density change over the cross section of an injection moulded foam.

layer. In addition to the image analysis of the samples, determination of density was accomplished. All produced test samples showed almost spherical cells, so that the analysis of the roundness of the cells was not required.

Microcellular polymers foamed by injection moulding show an integral density course, which means that the density in the middle of the part is lower than the one in the edge (Figure 5).

Preceding analyses showed that it is important to differentiate between cells in the middle of the core and cells at the edge of the core. Because of the integral density over the thickness of the sample, the cell sizes vary, too. Normally, the cell diameter in the middle of the sample is larger than the one in edge areas. It turned out to be useful to divide the sample in three different areas.

The first area is the compact skin layer (area 1). This layer ends at the first cells in the sample. Both at the top and bottom sides, the layer thickness is measured at four points and averaged. The second layer is the cell area at the edge which begins at the end of the skin layer and ends where the cell diameter increases (area 2). The third area lies in the middle of the sample (area 3) (Figure 6).

On the basis of these morphological analyses and the results of the tensile and bending tests, correlations between both were created. Within the scope of this study, a computer program named RESINT was used to create equations by means of linear regression. This program was developed by the TU Riga,[12] elaborated together with the Institut für Werkstofftechnik, Kassel, and adjusted to the problematic nature of polymers.[13,14]

Discussion of the results

In the course of this investigation, all parameters of mechanical properties, morphological analyses and processing parameters were correlated together and the interrelations between them were identified. A complete overview of these results cannot be presented by a few diagrams or sentences. The interaction of the parameters is too large and the influence factors are too many. However, some
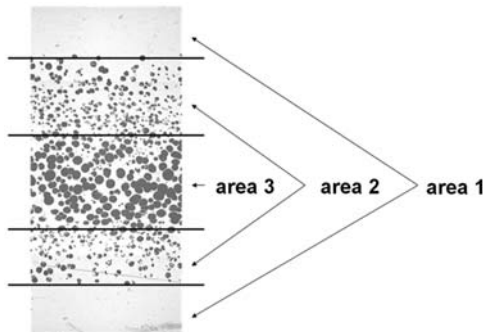
Figure 6. Classification of the three morphology areas.

Table 1. Variation range of the processing parameters

Parameter	Minimum	Maximum
Melt temperature (°C)	272	327
Gas counter pressure (bar)	1	80
Concentration of N_2 (%)	0.13	0.43
Injection velocity (mm/s)	10	80
Density (kg/m^3)	940	1170
Mould temperature (°C)	20	108

parameters are more important than others. The following results should provide a short overview in order to understand the effects of processing parameters on the morphology and the mechanical properties of the test samples (Table 1).

The correlations between the processing parameters, morphology and mechanical properties can be divided in three groups. The first one includes the correlation between the morphology and the mechanical properties of the injections moulded foam samples. Out of this correlation, different models can be defined, which help to understand the interrelationships between cell morphology and mechanical properties of the materials. The second group deals with the correlation between the foam morphology and the main parameters of the injection moulding process. This correlation makes it possible to optimise the cell structure of the material. Both correlations leads direct to a third group, the correlation between the processing parameters and the resulting mechanical properties.

Correlation: Morphology – mechanical properties

The most interesting aspect of the first group is that all mechanical test parameters are influenced by the morphology in the same way. It means that improvement of
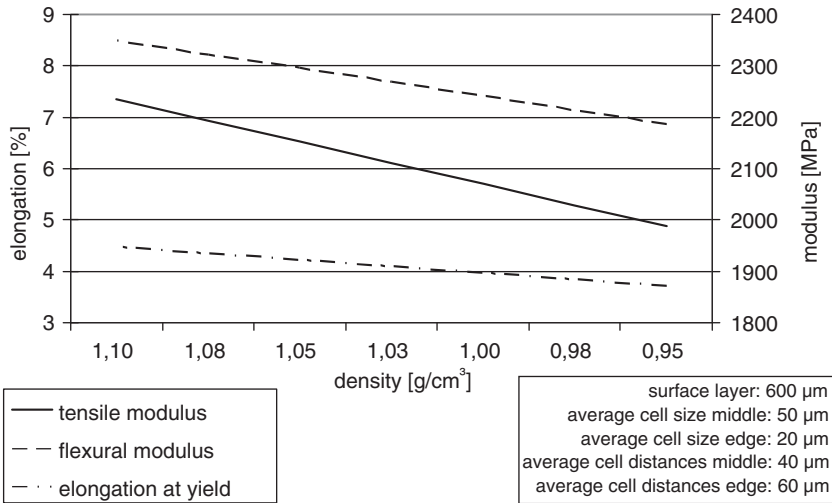
Figure 7. Tensile modulus, flexural modulus and elongation at yield with dependence on the density of foamed polycarbonate.

the tensile modulus leads to improvement of strength at yield and flexural modulus as well. Therefore, manufacturers can improve the one property without worsening the other.

Furthermore, the results showed that there is no ideal morphological model which is best, but there are two models for bending and three models for tensile load, which are equivalent. Thus, the injection moulded microcellular foams show the same structures as sandwich-models, the correlated models also have sandwich structures.

The parameter which influences all analysed mechanical properties most is the density of the produced parts. Figure 7 shows the reduction of the indicated mechanical properties with decrease in density.

Apart from the main influence by density, there are four morphological models which characterise the best morphologies of foamed materials to get best tensile properties. The different models are named after their characteristic density course in U, V_M, V_S and W.

The first model is characterised by a large compact skin layer with clear separation of the foamed core in the middle. In this case, the middle of the core should be composed of cells with large diameters (Figure 8 – model U). At first glance, these results contradict the results of previous studies which indicated that smaller cell sizes lead to an increase in mechanical properties. A smaller average cell size would realise higher mechanical properties in this case, too – which is physically impossible. If the skin layer gets thicker, the density in the core area will decrease by a constant density of the whole part and the only possibility to get lower density in the core material is to get a larger average cell size.
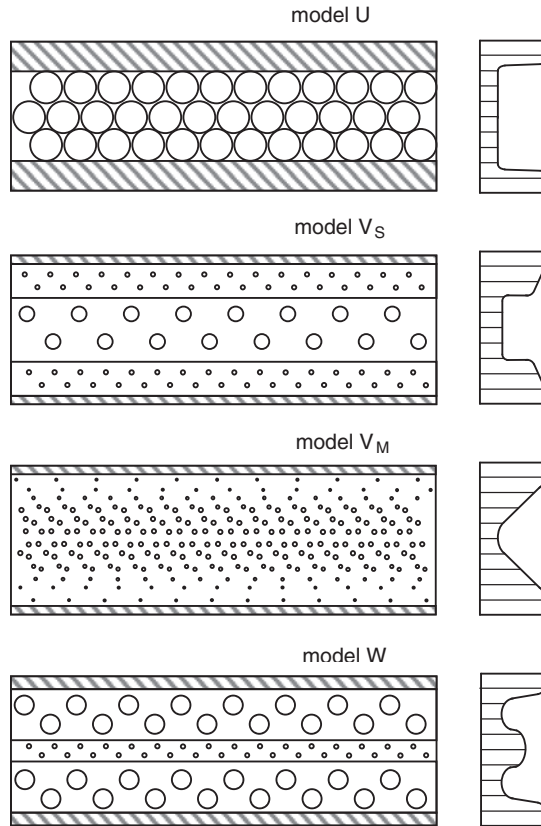
model U

model V$_S$

model V$_M$

model W

Figure 8. Illustration of the ideal morphological models for mechanical tensile and bending load at constant density (cell structure left, density course right).

The first and second models are both on the same level, but the second one has a quite different morphologies. It consists of a thin compact skin layer, but a large microcellular core is adjoining to the skin layer. This area should have smallest possible cell sizes with – that is most important – largest possible distances between the cells. The centre area should also consist of cells with large distances between the cells, but this area did not influence the mechanical properties so much like the cell area did, which adjoins to the compact skin layer (Figure 8 – model V_S). At this model, the thin compact skin layer is compensated through the area adjoining to the compact area, which has few small cells. This area is nearly a compact material and performs like the compact skin layer. A pseudo-thick compact layer was generated, which increases the mechanical properties at constant density. It is an asset if a clear separation exists between the centre cell area and the edge cell area, but in most cases a runny transition can be observed.

The third model is a microcellular foam structure with cell sizes below 10 μm and with a small skin layer (model V_M). This morphological structure is able to improve
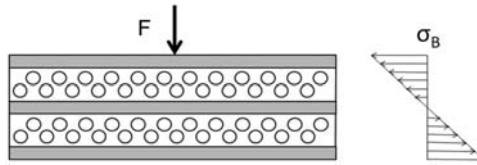
Figure 9. Strain dispersion across the sample thickness at bending load at model W.

the impact strength of polycarbonate if the resin material breaks tough under the same test conditions,[15] but in cases of bending and tensile load, these foam structure are not able to reach excellent stiffness and strength.

The morphology, which is shown in the fourth model (Figure 8 – model W), is very rare, but under special processing parameters, it can be created. The main point of this model is the centre area of the foamed material, which has very small cell sizes with large cell distances between each other. This area acts, analogically to the edge areas in model two, like compact material and it increases the mechanical strength of the moulded part. Together with the compact skin layers, there are three compact areas that have a high strength and between them there is a high blown up foam core. To increase the volume of the three compact areas, it is necessary that the areas between them have a low density in order to keep the density level of the whole part constant. It requires a large average cell size and a short distance between the cells.

The sandwich models U and V_S can be transferred to bending properties as well. With regard to the ideal structure of these models for bending load, those are the best morphological structures. Model W is not suitable for bending load which is shown in Figure 9.

The top skin layer is loaded by compressive stress and the bottom by tensile stress. At the almost compact centre layer of this structure, the stress is very low, as the stress changes from compressive into tensile stress. The centre layer does not reinforce the bending stiffness, which disqualifies model W for bending applications.

Figure 10 exemplarily shows the connection between different parameters. To illustrate the relationships between parameters and the material properties, 3D graphs were created out of the correlation equations by fixing the not figured parameters in the diagram on mean values. If the skin layer is thick, the cell diameter has to be large as well (sandwich model U). If the compact skin layer is small, the adjoining foam area has to be composed of cells with small diameters with large distances between them (sandwich model V).

A good example for the sandwich model U is the examination of the tensile modulus (Figure 11). When the skin layer has a thickness of 800 μm (Figure 11(a)), the Young's modulus decreases when the average distance between the cells increases, too. This can be explained by sandwich model U. Because of the thick skin layer, it is necessary to get a centre area with low density, so that the density of
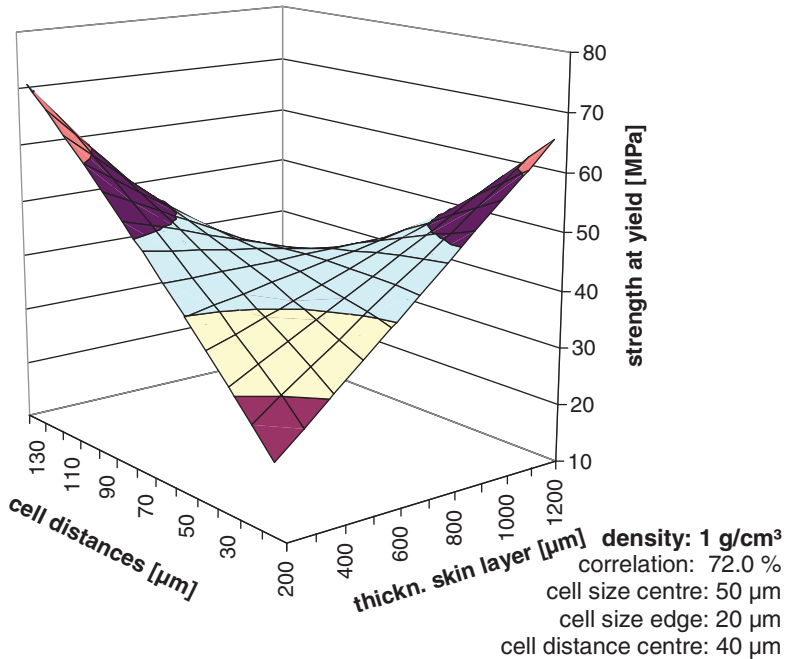
Figure 10. Strength at yield depended on the thickness of the skin layer and the cell distances in the edge area of the foamed core.

the whole part remains constant. This can only be reached by small distances between the cells if the average cell size is constant. If the compact skin layer becomes thinner, it is important to create a pseudocompact area in the foamed material, which is shown in sandwich model V_S and W. With a skin layer thickness of 500 μm, the average cell sizes in the centre area has to get small and above all the distance between them has to get large (Figure 11(b)), shown at sandwich model W. A look at the cell sizes and distances in the edge area (Figure 11) shows that these materials are nearly microcellular.

Correlation: Processing parameter – morphology

In industrial application, it is very important to understand the connections between morphology and mechanical properties, but it is more important to know how to adjust the injection moulding process in order to produce optimised foam structures. For each of the three sandwich models, it is possible to define the most important morphology properties. To transfer these requested properties, five different processing parameters were analysed such as melt temperature, mould temperature, GCP, level of physical blowing agent ($N_2 = $ SCF (supercritical fluid) level) and injection velocity. The density was also analysed as a processing parameter, because it is possible to influence the morphology through the amount of
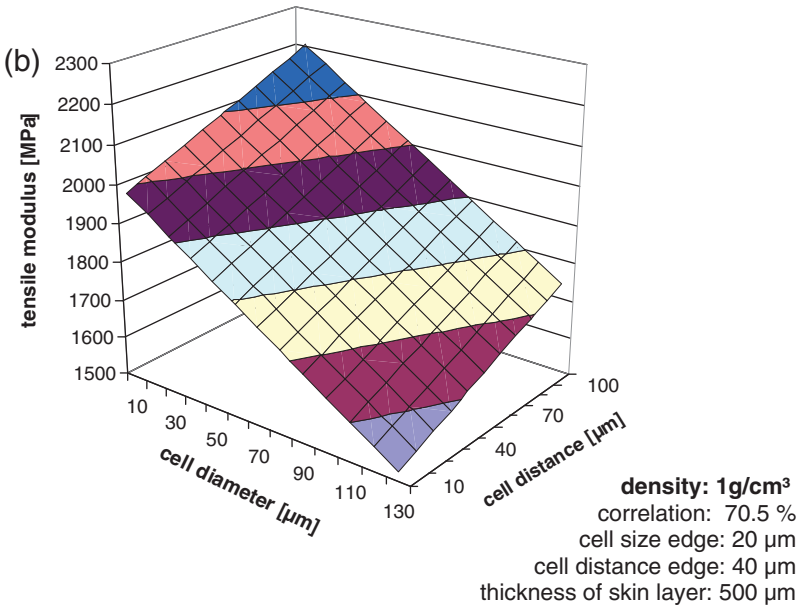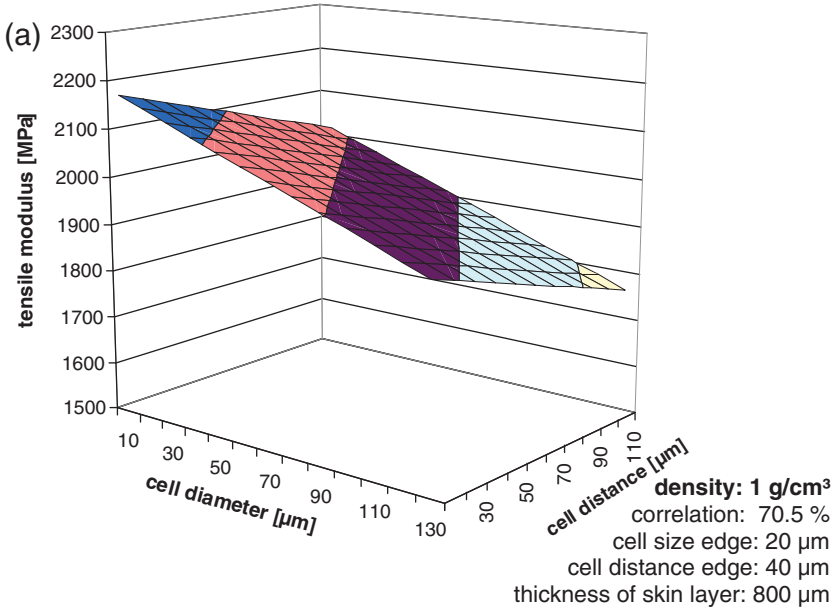
(a)

density: 1 g/cm³
correlation: 70.5 %
cell size edge: 20 μm
cell distance edge: 40 μm
thickness of skin layer: 800 μm

(b)

density: 1g/cm³
correlation: 70.5 %
cell size edge: 20 μm
cell distance edge: 40 μm
thickness of skin layer: 500 μm

Figure 11. Dependency of the tensile modulus on average cell diameter in the centre and average cell distance in the centre at different skin layer thicknesses.

injected polymer mass. On the one hand, the density of the produced part is defined before processing and it is not a process parameter which can be varied; on the other hand, this examination should show how the density influences each morphology parameter. Basically, a higher density leads to better mechanical properties (modulus, strength and maximum elongation). The problem of finding the best processing parameter is that improvement of one morphological parameter often leads to deterioration of another important parameter.

The influence of some processing parameters are showed. It can be seen that there are not one ideal value, but it depends on the other processing parameters, too. These graphs give a short review about the different changes when one parameter is varied. Figure 12 to 17 points out the influence of the density on the morphological parameters. It can be seen that the density is the main influence factor as well on the morphology as also on the mechanical properties.

Figure 12 shows that the influence of the gas concentration and the GCP on the skin layer thickness increases by decreasing density. It is noticeable that the thickness at a low SCF level first decreases, when the density is reduced, but at further reduction of the density, the thickness of the skin layer rises.

The influence of the density on the average cell diameter can be seen in Figures 13 (edge area) and 14 (centre area). Interesting is that the biggest cell sizes in the centre area were reached by a low density reduction and a low concentration of blowing agent. Usually, it is assumed that the biggest cell diameters exist at a high density reduction. This interesting effect can be explained by viewing Figure 15. The average cell diameter in dependence on the density shows a bathtub function (Figure 15), which means that the average cell diameter first becomes smaller by reduction of the density, but at the density of $1.04\,\mathrm{g/cm^3}$, this changes and the cell diameters increase at further density reduction. This can be seen at every GCP and SCF level. Based on the fact that the cell size in the edge area rises but the diameter in the centre is almost constant, this is a possibility to create a model *W* morphology.

The average cell distances in the edge area (Figure 16) and the centre area (Figure 17) show different effects by variation of the density. The average cell distance in the edge area shows a high dependence of the SCF level and the GCP. At low GCPs, a reduction of the density leads to a decreasing of the cell distances, whereas at high GCPs, the cell distances increase by decrease in density. A higher concentration of blowing agent leads in most cases to smaller cell diameters. Only without GCP and at low densities a higher SCF level leads to an increasing of the cell distances in the edge area (Figure 16).

A density reduction leads to smaller cell distances in the centre area such as a lower blowing agent concentration. At a density of $1\,\mathrm{g/cm^3}$, a change takes place. Whereas the cell distances at high SCF levels becomes smaller, the cell distances at low SCF levels raise. However, this is only a small growth and is only theoretical, because it is not possible to reach these high density reduction with such small blowing agent concentrations.
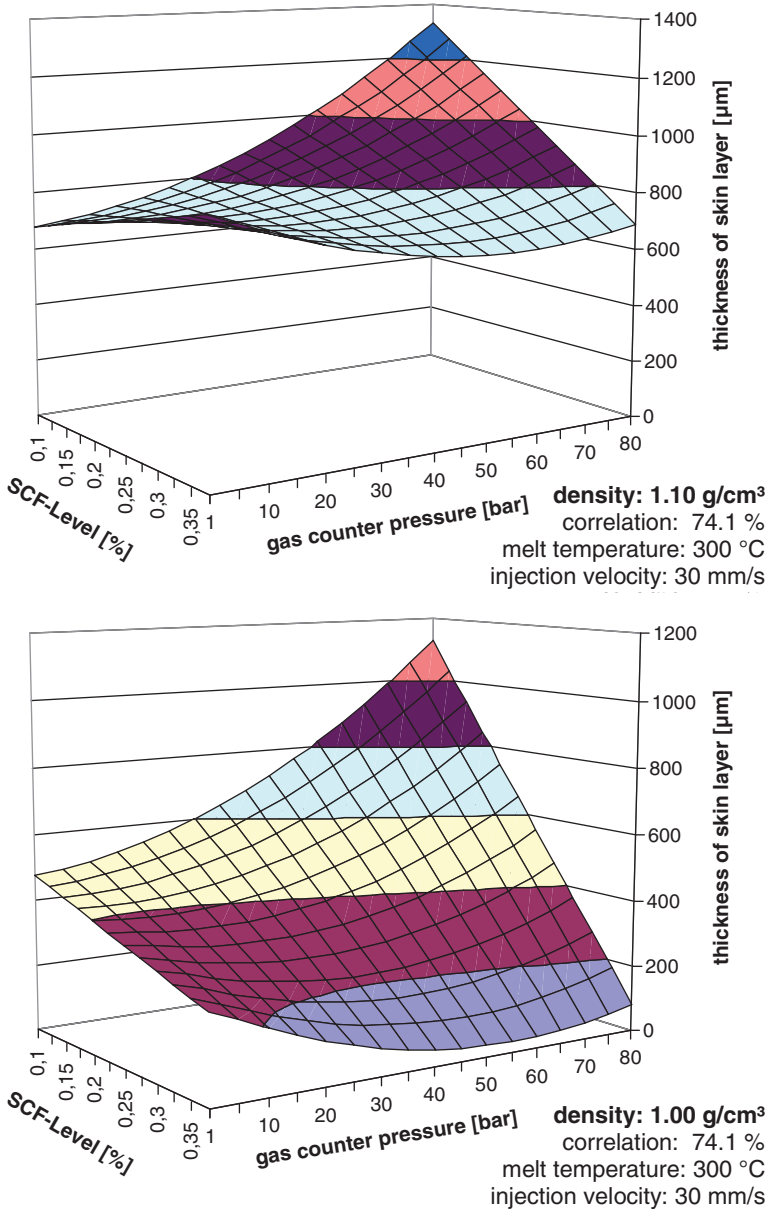
density: 1.10 g/cm³
correlation: 74.1 %
melt temperature: 300 °C
injection velocity: 30 mm/s

density: 1.00 g/cm³
correlation: 74.1 %
melt temperature: 300 °C
injection velocity: 30 mm/s

Figure 12. Influence of the density to the thickness of the skin layer.
SCF: supercritical fluid.

thickness of skin layer [μm]

density: 0.95 g/cm³
correlation: 74.1 %
melt temperature: 300 °C
injection velocity: 30 mm/s
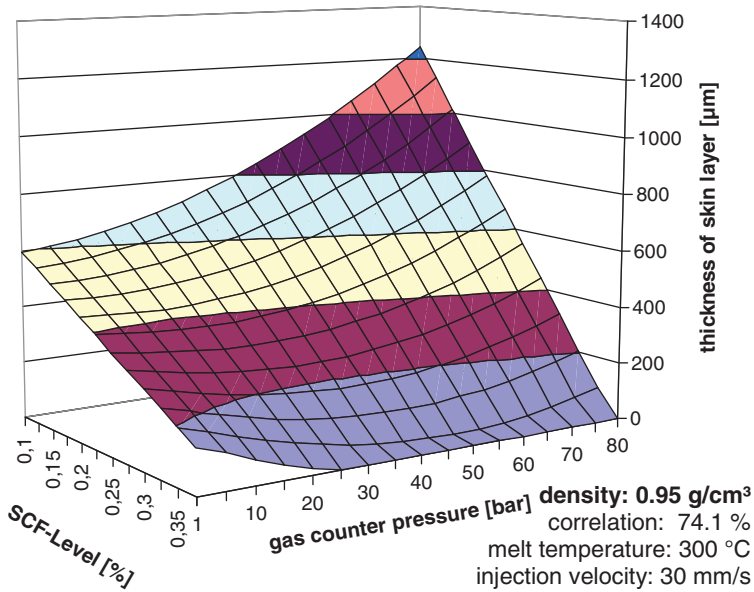
Figure 12. Continued.

Another important processing parameter in addition to density, SCF level and GCP is the melt temperature.

Increase of the melt temperature leads to thinner skin layers at high GCP, whereas without GCP the skin layer becomes thicker by increasing melt temperature (Figure 18). The higher melt temperature leads in combination with GCP to a decrease of the thickness, because the melt cool down slower and so the blowing agent can foam up the material up to the skin. Without GCP, the blowing agent escapes out of the glaze front, and due to the higher melt temperature, the viscosity decreases and so the blowing agent gas can escape better.

By increasing the melt temperature, the average cell diameter in the edge area becomes smaller, because the melt does not cool down quickly and the blowing agent can foam up the polymer closer to the surface (Figure 19). For the average cell diameters in the edge (not figured) and centre areas (Figure 20), the increase of melt temperature has the same effect. The higher polymer chain movability, caused by the higher melt temperature, leads to an increase of the cell size. The effects of the melt temperature on the cell diameter in the centre area are less than the one in the edge area.

The effects of the melt temperature on the average cell distances are very interesting. Figure 21 points out that the largest cell distances in the centre area can be reached by a middle melt temperature (300°C in this case). An increase, but also a decrease leads to smaller cell distances in the centre area.

The influence of the injection velocity is much smaller than the other parameters using GCP (Figure 22). The biggest change can be seen at the skin layer. A higher
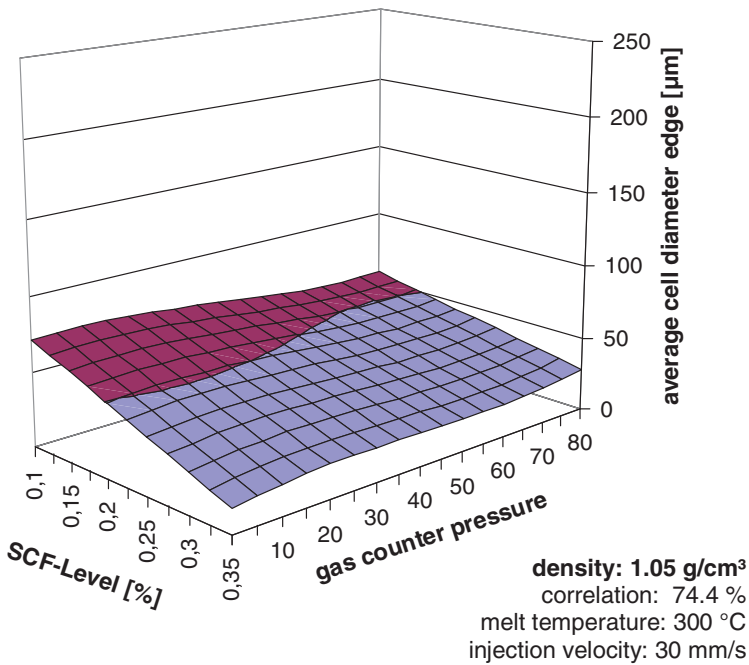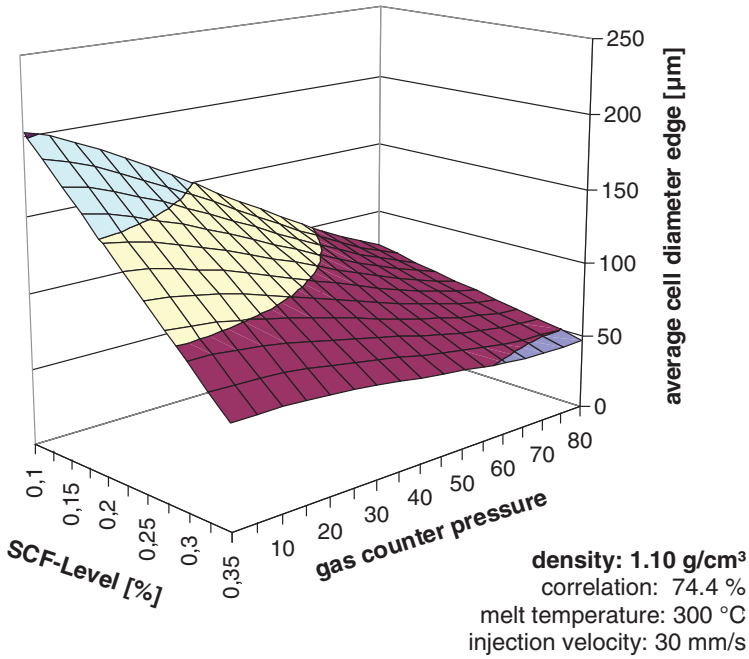
density: 1.10 g/cm³
correlation: 74.4 %
melt temperature: 300 °C
injection velocity: 30 mm/s

density: 1.05 g/cm³
correlation: 74.4 %
melt temperature: 300 °C
injection velocity: 30 mm/s

Figure 13. Influence of the density to the average cell diameter in the edge area.
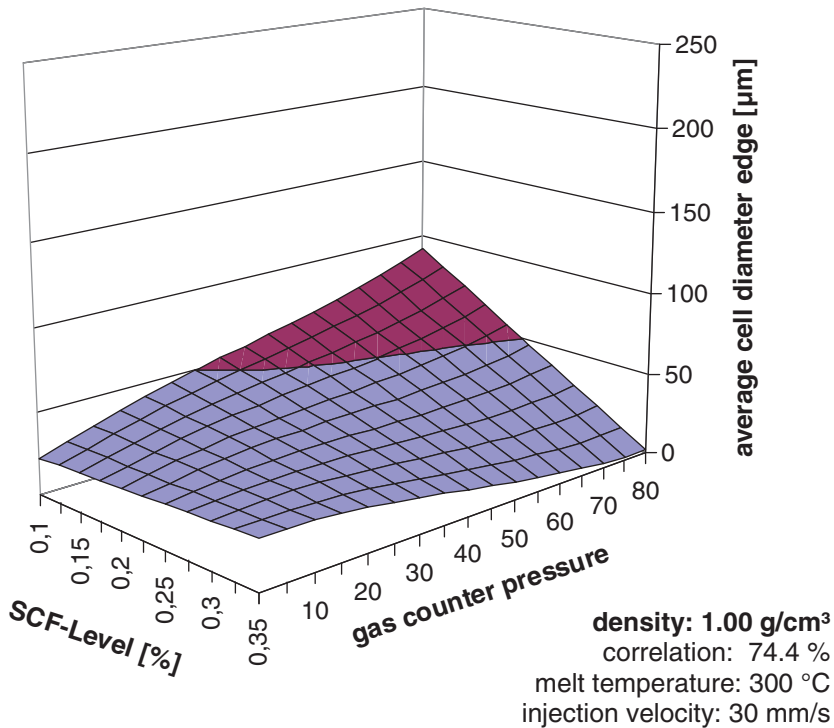SCF: supercritical fluid.

Figure 13. Continued.

injection velocity leads to a thinner skin layer at low blowing agent concentrations and a thicker skin layer at high SCF levels. At a small gas concentration, the higher velocity reduces the time where the gas is able to escape out of the polymer, but a high concentration of the blowing agent in combination with a high injection velocity leads to an oversaturation of gas in the melt and the gas leak from the polymer melt.

The graphs in Figures 23 and 24 are only suitable for the density area from 1.06 to 1.09 g/cm³, because the mould temperature was only varied at this area. During all other experiments, the mould temperature was kept constant at 25°C.

The mould temperature has a great effect on the thickness of the skin layer. At lower mould temperatures, the melt cool down quickly and so the melt in the surface area becomes solid before the blowing agent is able to foam up the material.

Out of these correlations, it is possible to choose the best processing parameters to create as abovementioned morphological structures for improved mechanical properties (Figure 8). The vital parameters for the model *U* are a thick compact skin layer and a large average cell diameter in the centre area. In this area, the parameters GCP as well as the SCF level decisively influence the process. To get a thick compact skin layer, it is advantageous to maintain high GCP, so that the blowing agent cannot escape out of the surface area.[11] It correlates with the average

density: 1.05 g/cm³
correlation: 74.4 %
melt temperature: 300 °C
injection velocity: 30 mm/s

density: 1.00 g/cm³
correlation: 74.4 %
melt temperature: 300 °C
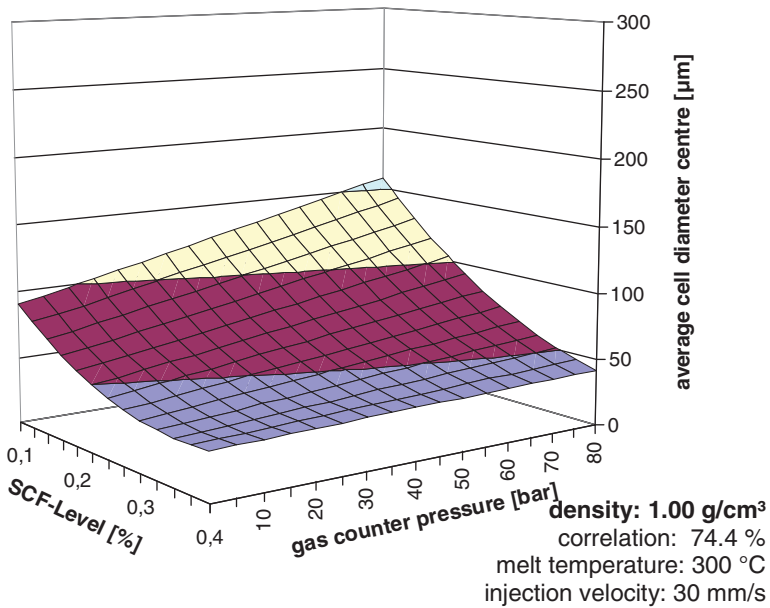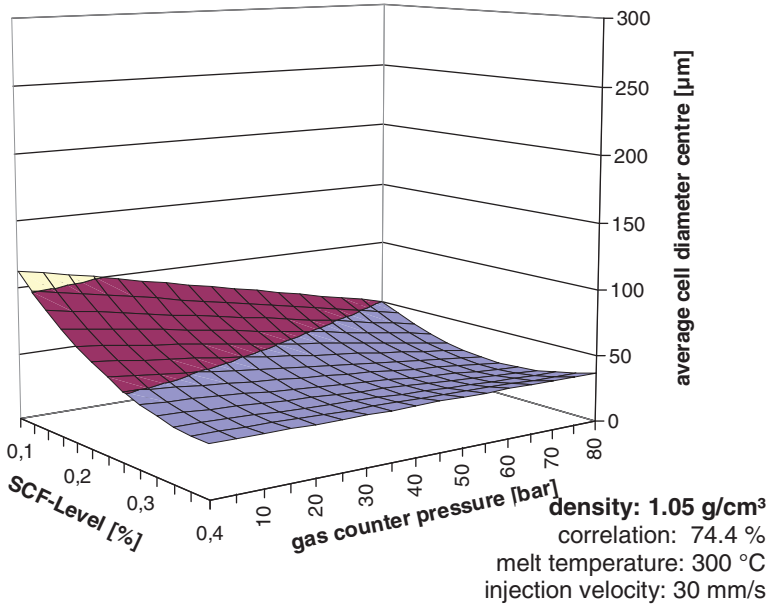injection velocity: 30 mm/s

Figure 14. Influence of the density to the average cell diameter in the centre area in dependence of blowing agent and gas counter pressure concentration.
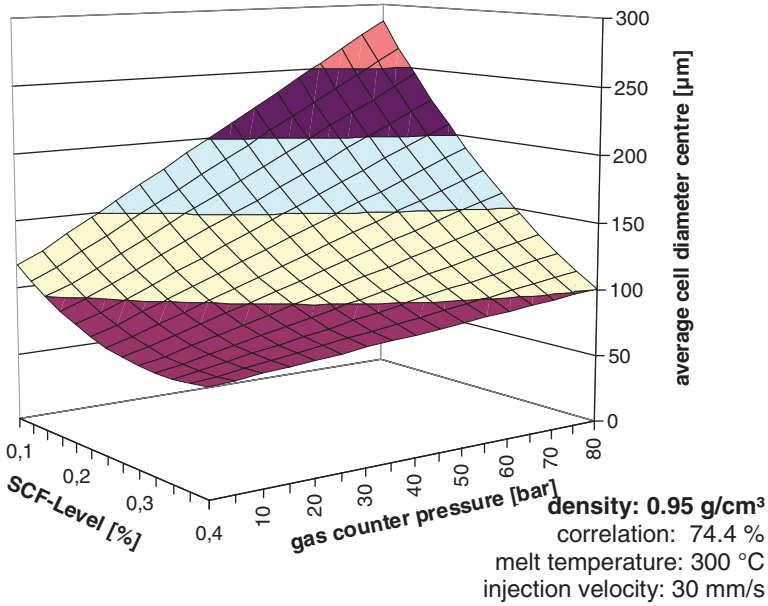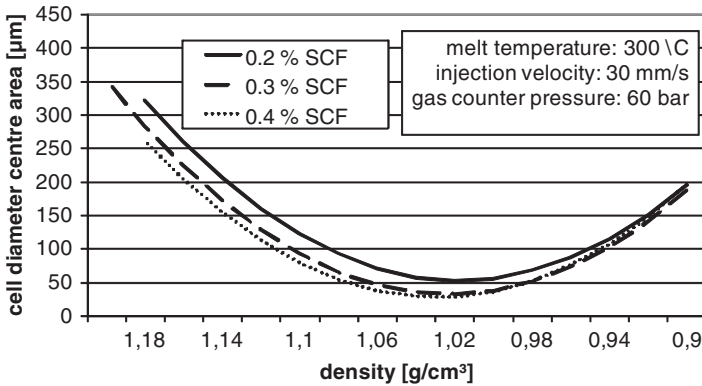SCF: supercritical fluid.

average cell diameter centre [µm]

SCF-Level [%] gas counter pressure [bar]

density: 0.95 g/cm³
correlation: 74.4 %
melt temperature: 300 °C
injection velocity: 30 mm/s

Figure 14. Continued.

cell diameter centre area [µm]

—— 0.2 % SCF
– – – 0.3 % SCF
·········· 0.4 % SCF

melt temperature: 300 \C
injection velocity: 30 mm/s
gas counter pressure: 60 bar

density [g/cm³]

Figure 15. Influence of the density to the average cell diameter in the centre area.
SCF: supercritical fluid.

cell diameter, which increases by higher GCP (Figure 24(b)). Furthermore, the SCF level should be small. The smaller quantity of the blowing agent leads to larger cell diameters and thicker skin layers (Figure 24(a) and (b)).

Model *V* characterises a small average cell size in the edge area with large distances between them. This is problematic, because the main influencing parameters

density: 1.10 g/cm³
correlation: 74.1 %
melt temperature: 320 °C
injection velocity: 30 mm/s

density: 1.00 g/cm³
correlation: 74.1 %
melt temperature: 320 °C
injection velocity: 30 mm/s
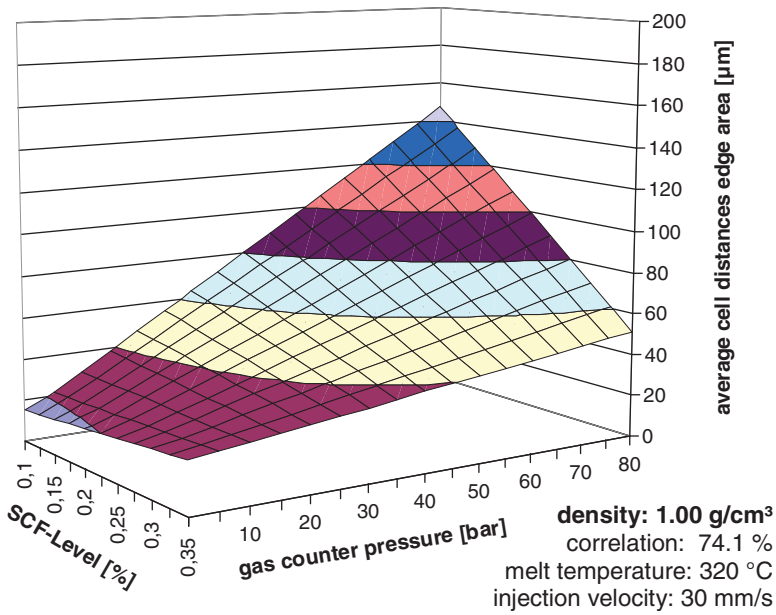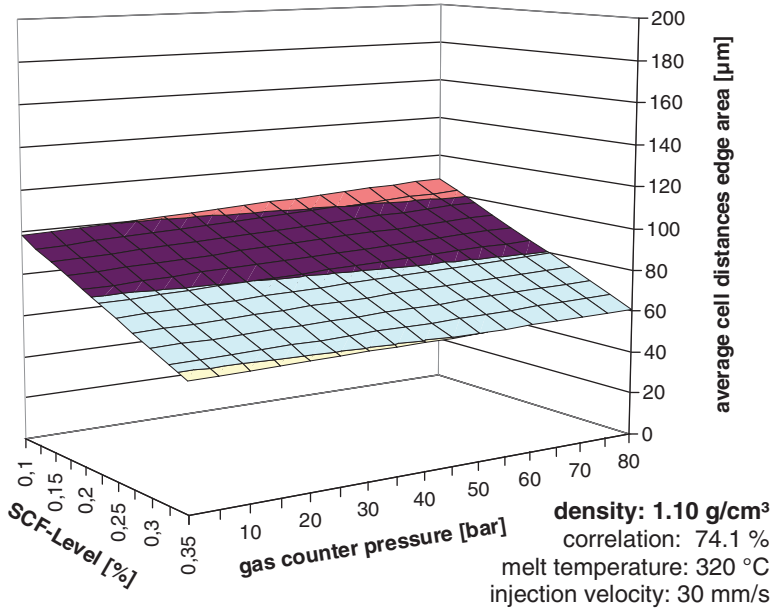
Figure 16. Influence of the density to the average cell distance in the edge area.
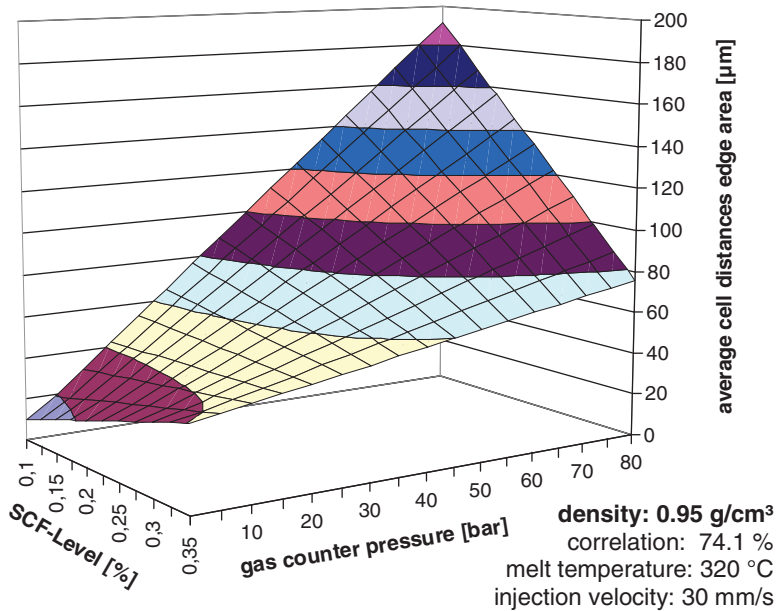SCF: supercritical fluid.

Figure 16. Continued.

are GCP and SCF level as well. To increase the distances between the cells in the edge area, a high GCP is useful and also a low SCF level. A low SCF level, however, leads to an increase in average cell diameter (Figure 25). Therefore, there has to be a balance between minimum cell sizes and maximum cell distances, which can be controlled by the SCF level. A further increase in the average cell distance can be reached by lower melt temperatures. This ensures a fast cool down of the polymer melt in the surface area and prevents foaming up of the blowing agent.

The structure of sandwich model *W* is complicated and very hard to produce. An absolute necessity is the high density of the foamed material. This morphology can only be produced with weight reduction of less than 10%. Figure 26 shows two correlations for the average cell diameter and the distances between the cells in the centre area with weight reduction of $\approx 8.5\%$. Both diagrams show that high SCF level and GCP are necessary for small cell diameters and for large distances between them. The disadvantage of these process parameters is reduction of the compact skin layer (Figure 26).

Correlation: Processing parameter – mechanical properties

Out of the results above, a direct correlation between the processing parameters and the mechanical properties can be done. To understand this relationship, the interaction between morphology and mechanical properties is absolutely necessary.
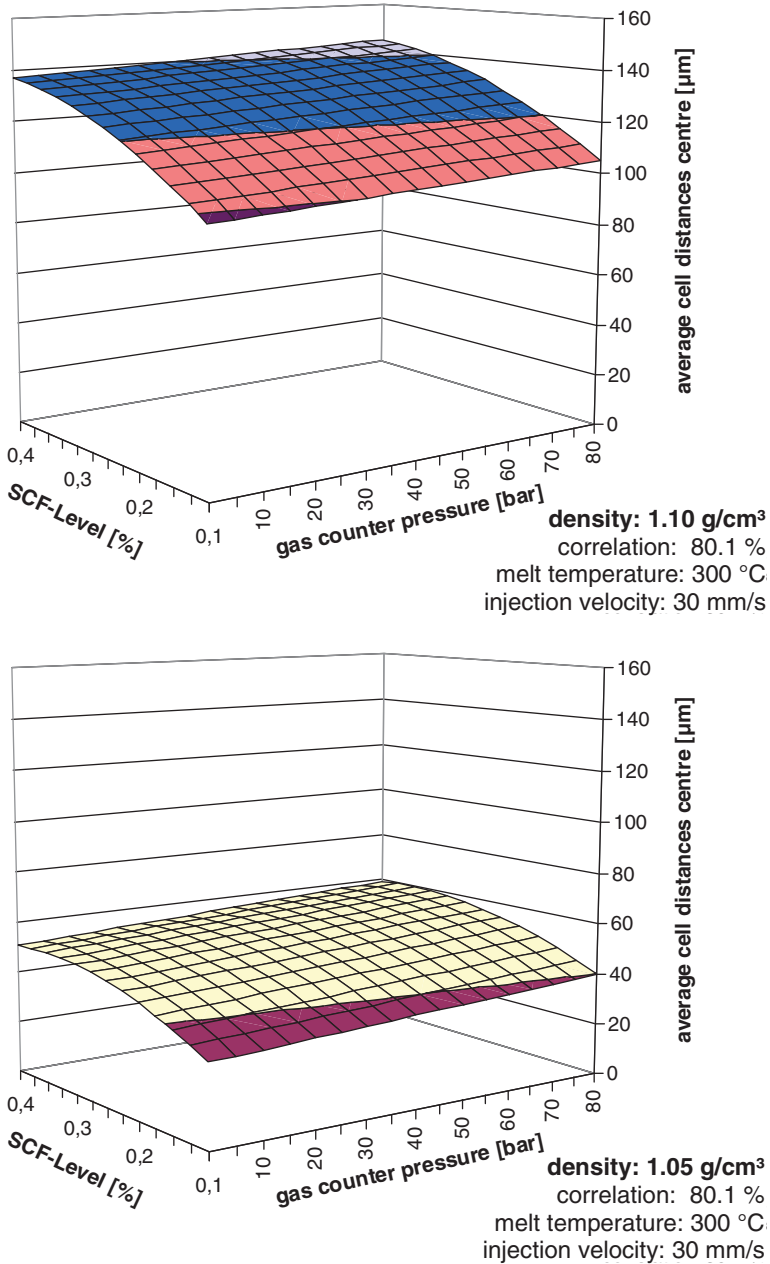
Figure 17. Influence of the density to the average cell distances in the centre area.
SCF: supercritical fluid.

density: 1.00 g/cm³
correlation: 80.1 %
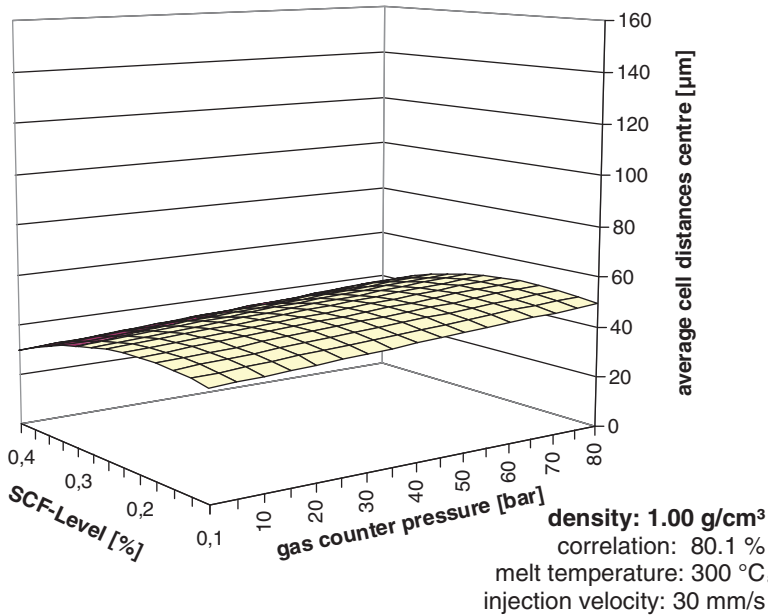melt temperature: 300 °C
injection velocity: 30 mm/s

Figure 17. Continued.

Figure 27 points out the influence of the melt temperature, the SCF level, the GCP and the injection velocity of the injection moulding machine on the tensile modulus in dependence on density of the produced part. Along the whole density range of the test samples, the ideal processing temperature is around 270°C. The higher the melt temperature the lower is the tensile stiffness of the polycarbonate (Figure 27(a)).

The best GCP depends on the density of the produced foam part. For high density foams, a high GCP leads to the highest stiffness, whereas a low GCP shows best the tensile modulus for low density grades (Figure 27(b)). The influence of the blowing agent concentration is similar to the melt temperature. At all analysed densities, low SCF level leads to an increased tensile modulus (Figure 27(c)). The influence of the injection velocity on the stiffness of the foamed material depends on the density. At low densities, a low injection velocity leads to an increase in the tensile modulus. At higher densities, the best results were achieved with high injection velocities (Figure 27(d)). These tendencies could also be noticed for the tensile strength of the analysed materials, but the influence of the processing parameters is smaller than the tensile modulus.
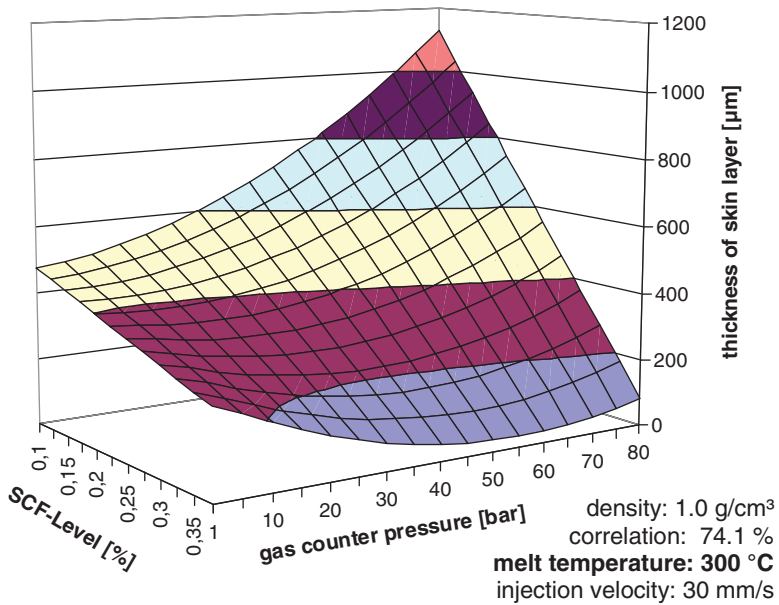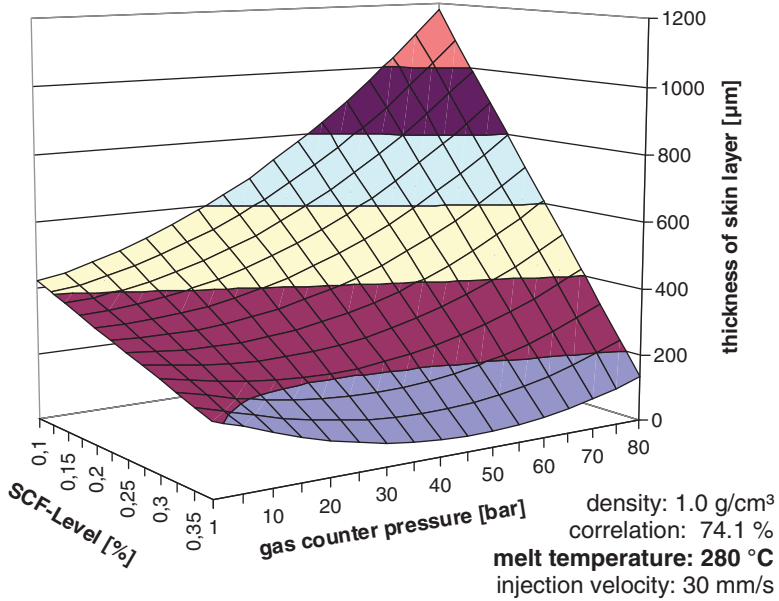
density: 1.0 g/cm³
correlation: 74.1 %
melt temperature: 280 °C
injection velocity: 30 mm/s

density: 1.0 g/cm³
correlation: 74.1 %
melt temperature: 300 °C
injection velocity: 30 mm/s

Figure 18. Influence of the melt temperature to the thickness of the skin layer.
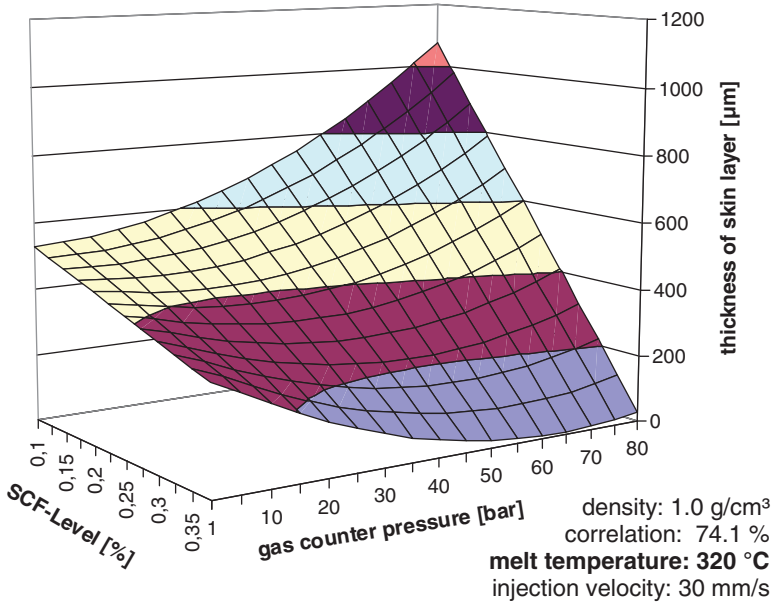SCF: supercritical fluid.

Figure 18. Continued.

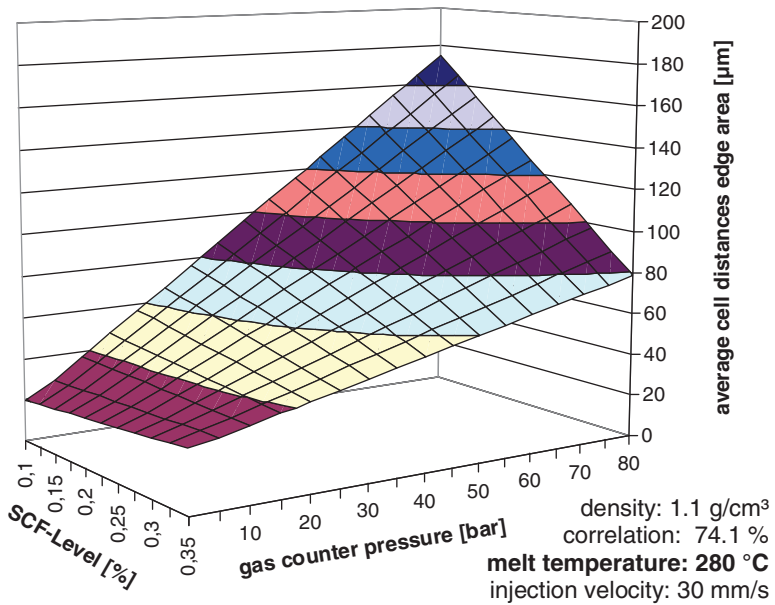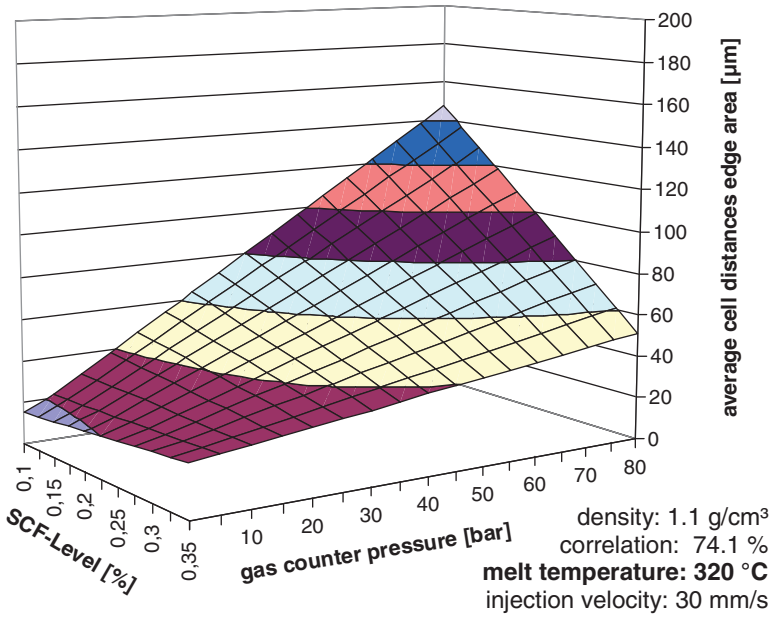**Figure 19.** Influence of the melt temperature to the average cell distance in the edge area. SCF: supercritical fluid.
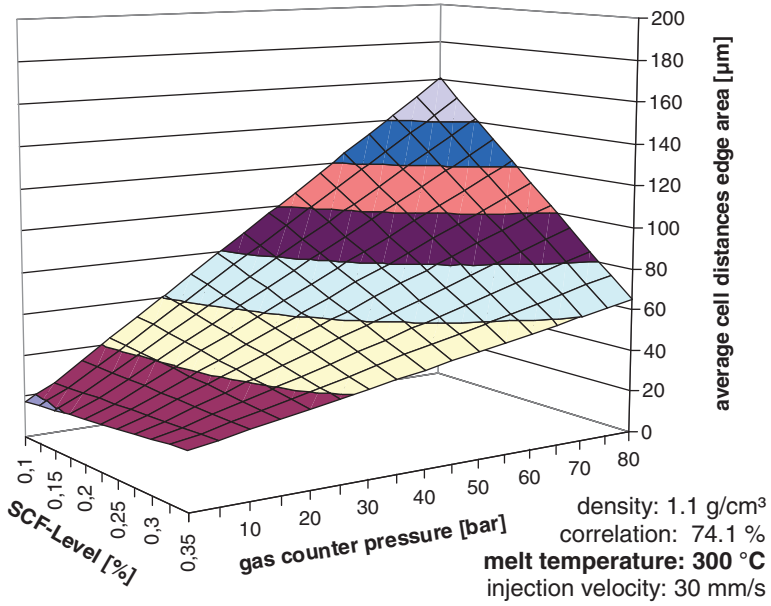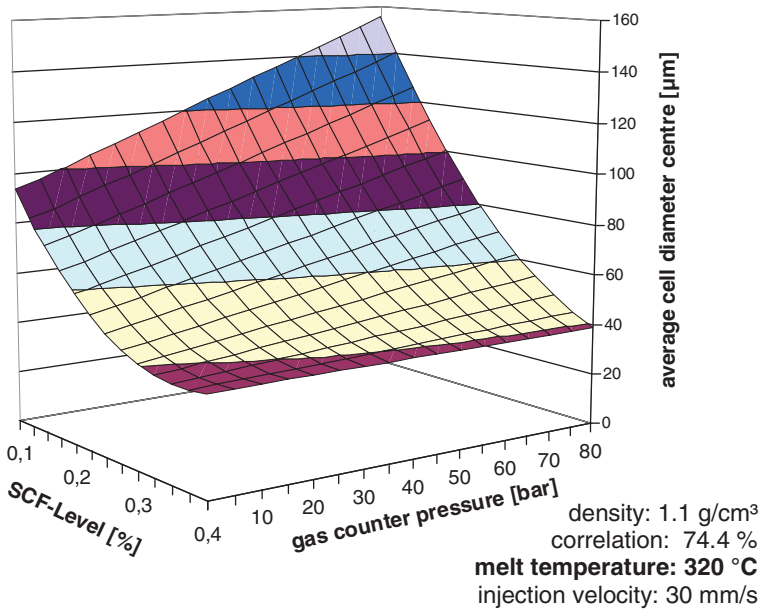
density: 1.1 g/cm³
correlation: 74.1 %
melt temperature: 300 °C
injection velocity: 30 mm/s

density: 1.1 g/cm³
correlation: 74.1 %
melt temperature: 320 °C
injection velocity: 30 mm/s

Figure 19. Continued.

density: 1.1 g/cm³
correlation: 74.4 %
melt temperature: 300 °C
injection velocity: 30 mm/s

density: 1.1 g/cm³
correlation: 74.4 %
melt temperature: 320 °C
injection velocity: 30 mm/s
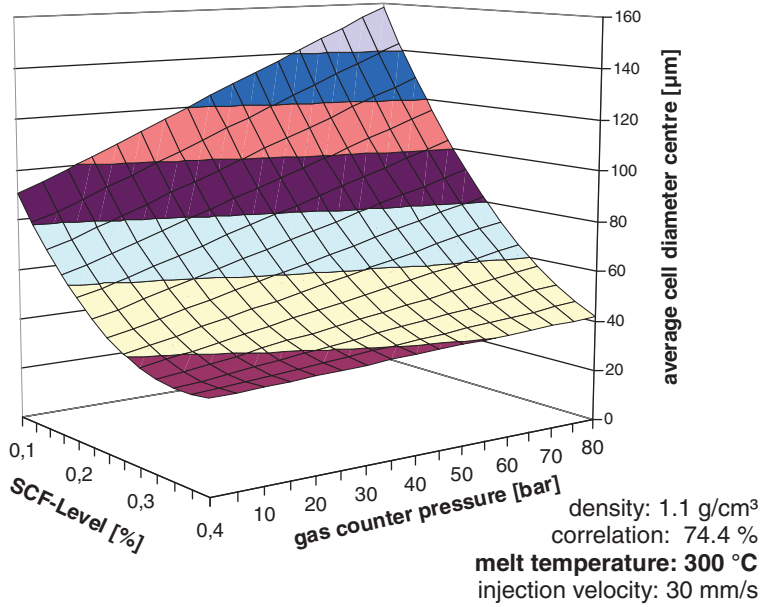
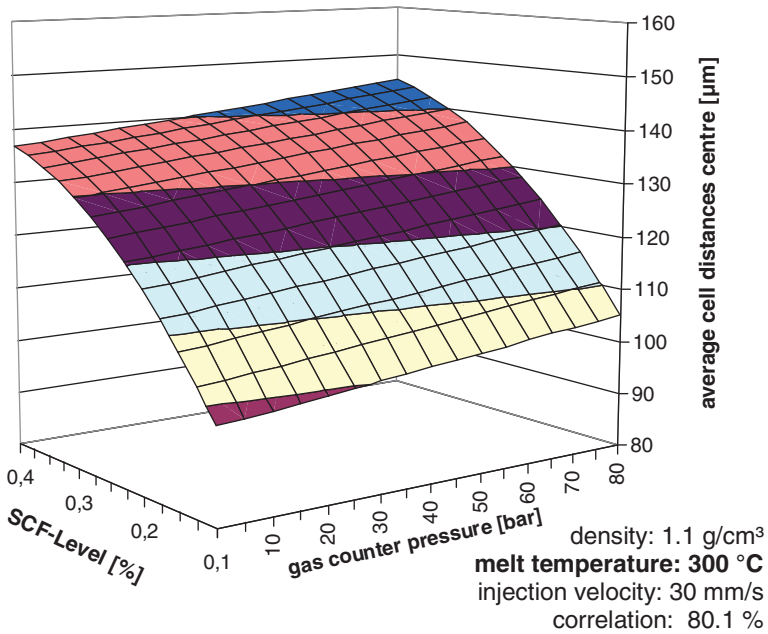**Figure 20.** Influence of the melt temperature to the average cell diameter in the centre area. SCF: supercritical fluid.

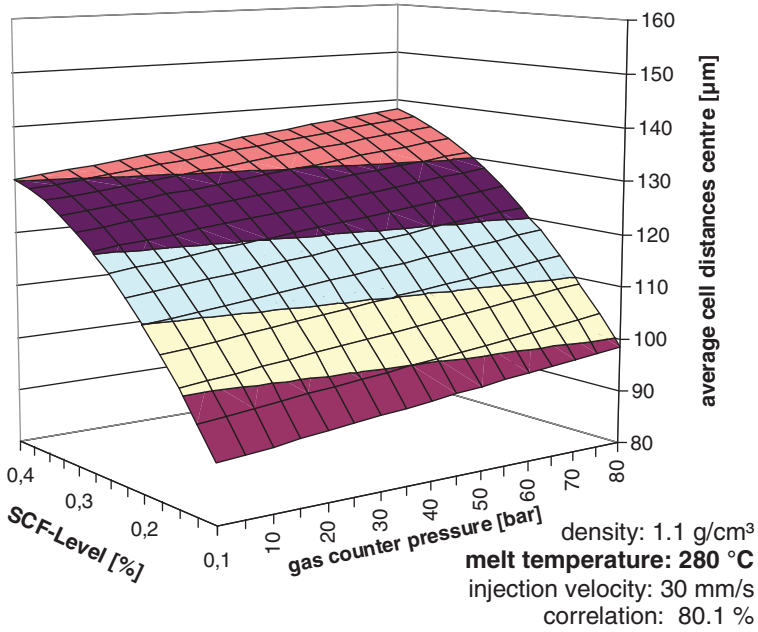**Figure 21.** Influence of the melt temperature to the average cell distances in the centre area.
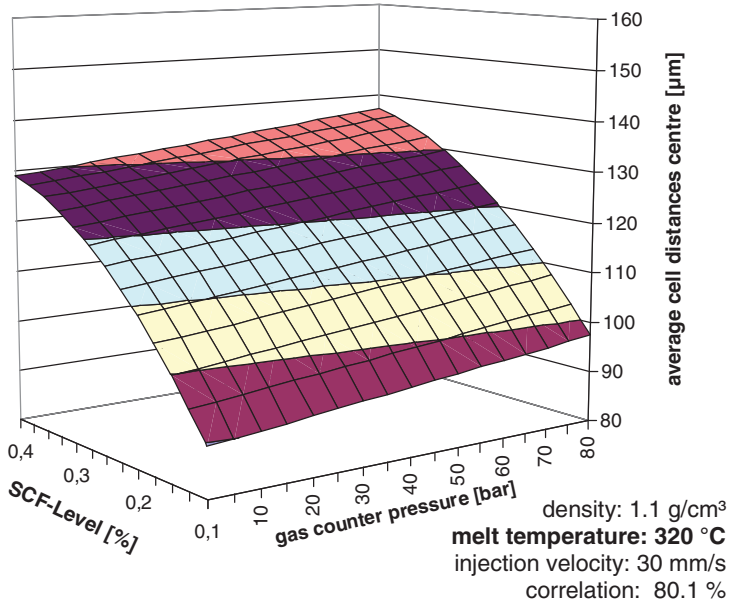SCF: supercritical fluid.

density: 1.1 g/cm³
melt temperature: 320 °C
injection velocity: 30 mm/s
correlation: 80.1 %

Figure 21. Continued.

density: 1.0 g/cm³
melt temperature: 300 °C
injection velocity: 30 mm/s
correlation: 74.1 %

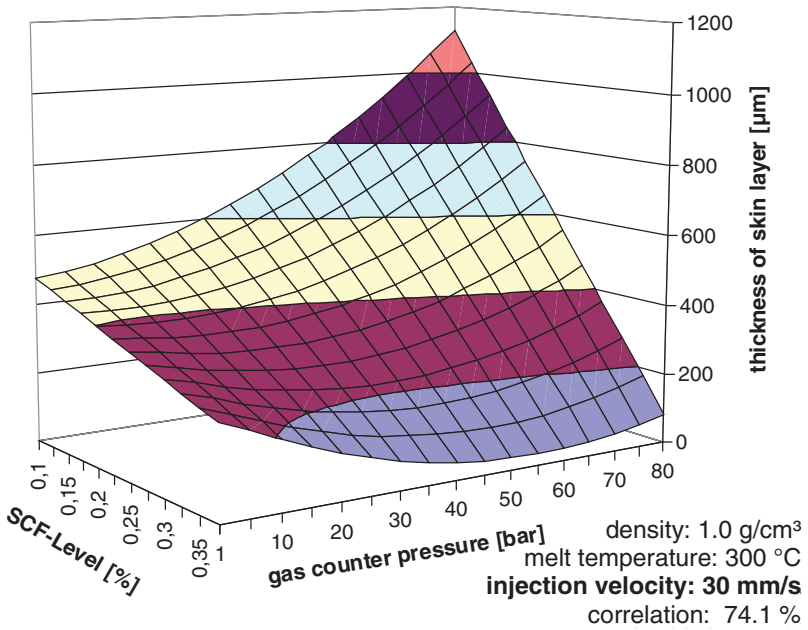**Figure 22.** Influence of the injection velocity to the thickness of the skin layer.
SCF: supercritical fluid.

density: 1.0 g/cm³
melt temperature: 300 °C
injection velocity: 50 mm/s
correlation: 74.1 %

density: 1.0 g/cm³
melt temperature: 300 °C
injection velocity: 80 mm/s
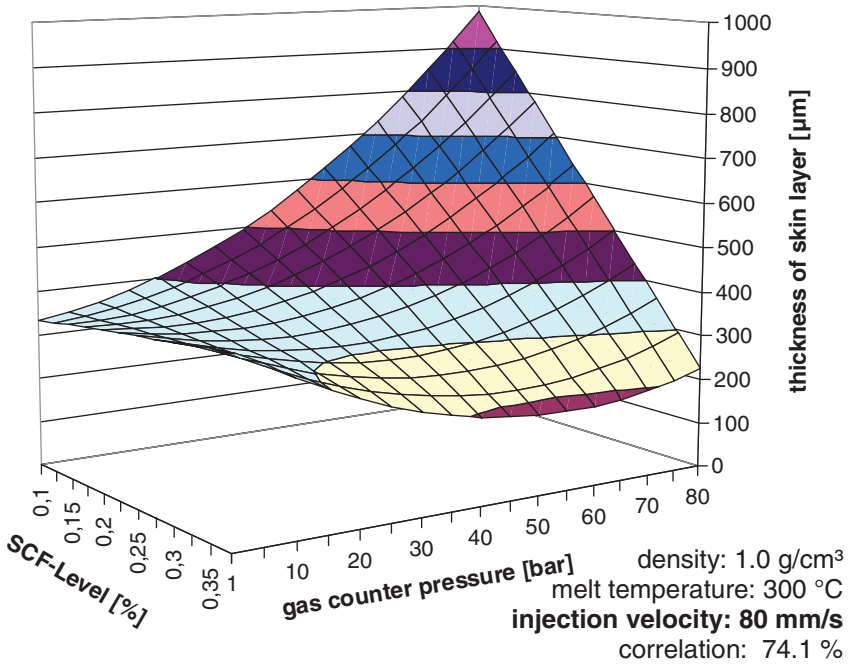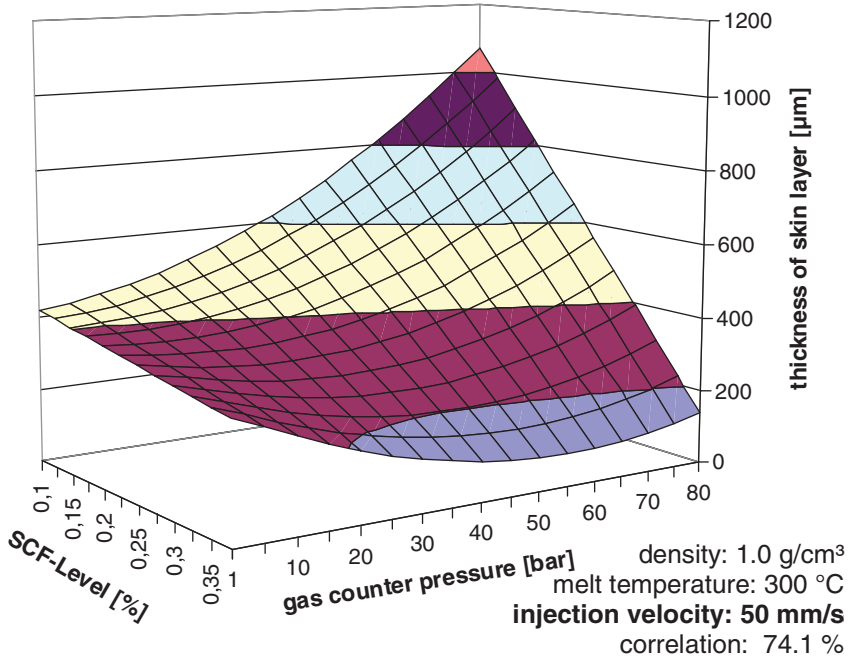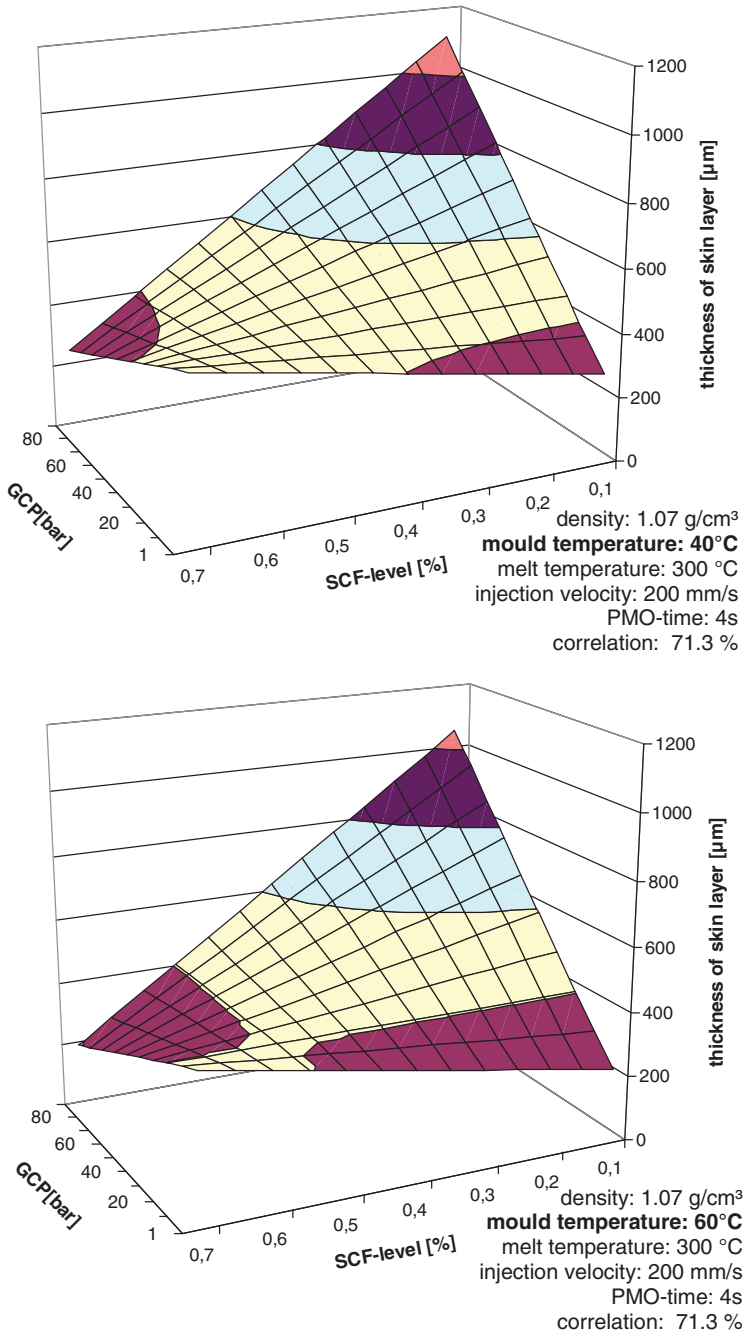correlation: 74.1 %

Figure 22. Continued.

Figure 23. Influence of the mould temperature on the thickness of the skin layer. GCP: gas counter pressure and SCF: supercritical fluid.
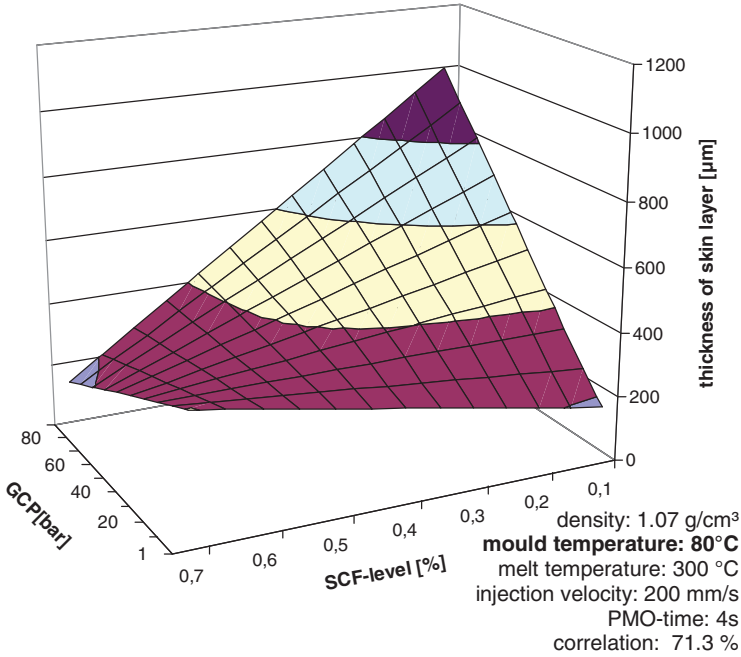
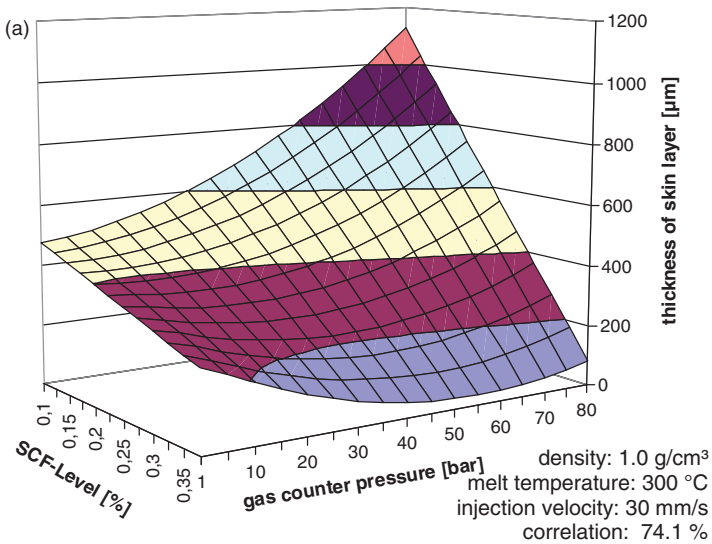**Figure 23.** Continued.

Figure 24. The influence of GCP and SCF level on the thickness of the skin layer (a) and the average cell size in the centre (b).
GCP: gas counter pressure and SCF: supercritical fluid.
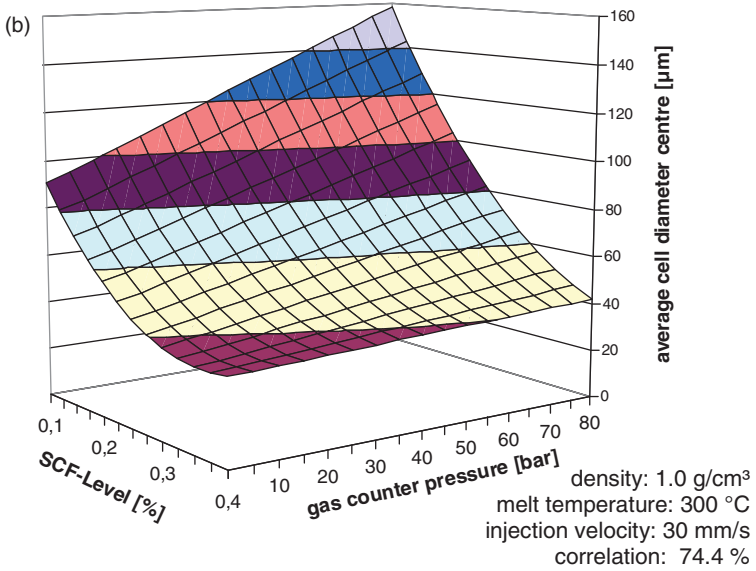
Figure 24. Continued.
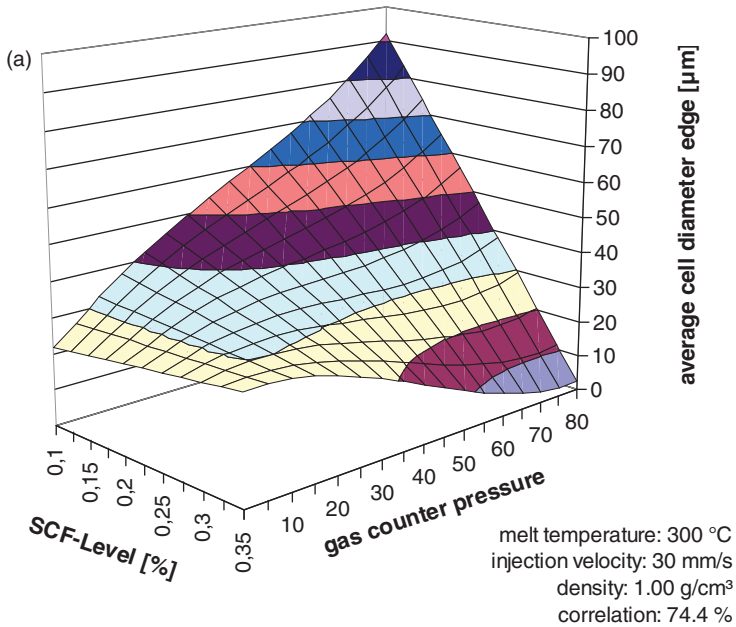
Figure 25. The influence of GCP and SCF level on the average cell size (a) and distances between the cells (b) in the edge area.
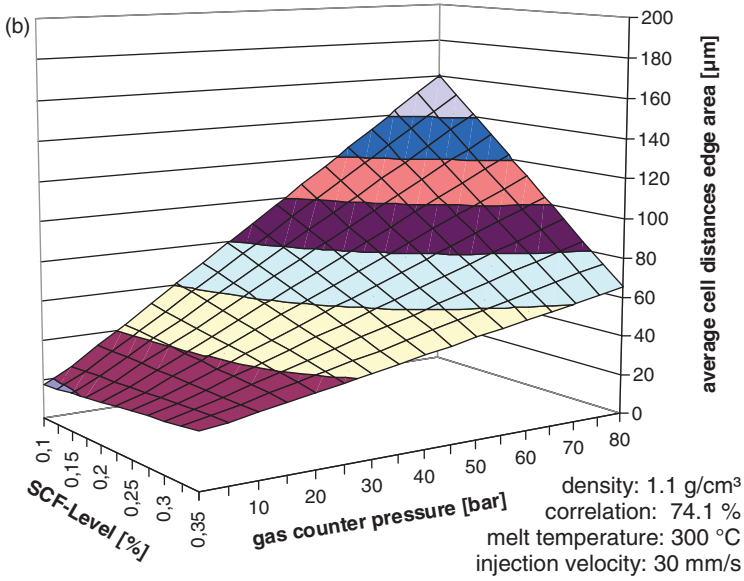
Figure 25. Continued.
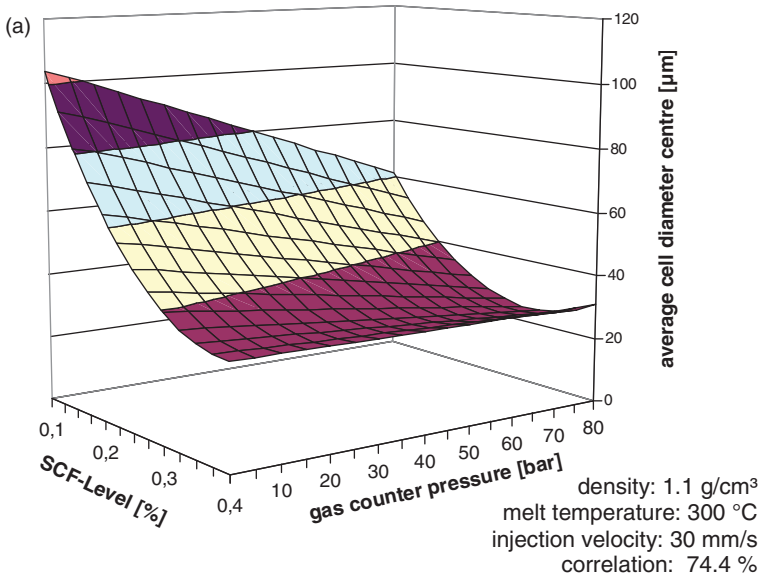
Figure 26. The influence of the GCP and the SCF level on the average cell size (a) and distances between the cells (b) in the centre area.
GCP: gas counter pressure and SCF: supercritical fluid.
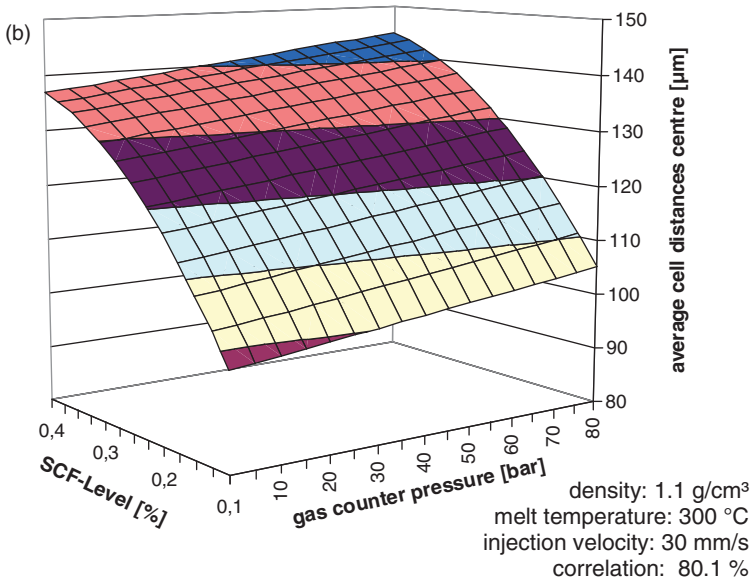
Figure 26. Continued.
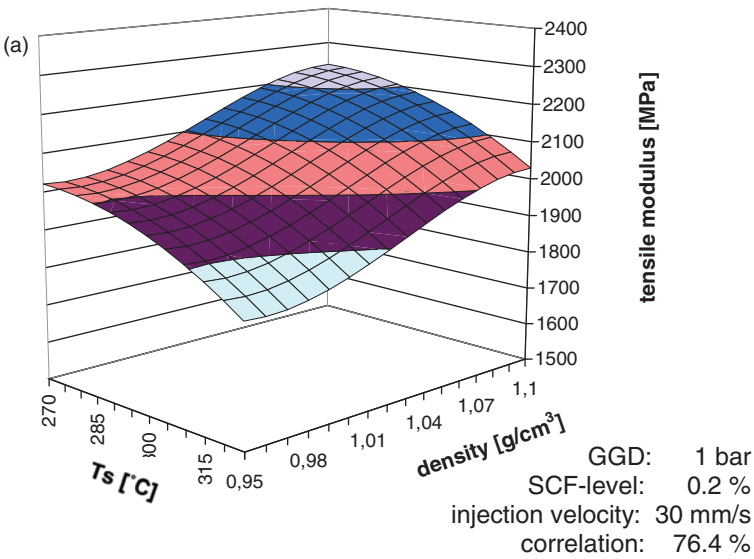
Figure 27. The influence of melt temperature (a), SCF level (b), GCP (c) and injection velocity (d) on the tensile modulus in dependence on the density.
GCP: gas counter pressure and SCF: supercritical fluid.

(b)

tensile modulus [MPa]

GCP [bar]

density [g/cm³]

SCF-level: 0.2 %
melt temperature: 300 °C
injection velocity: 30 mm/s
correlation: 76.4 %

(c)

tensile modulus [MPa]

SCF [%]

density [g/cm³]

GCP: 1 bar
melt temperature: 300 °C
injection velocity: 30 mm/s
correlation: 76.4 %

Figure 27. Continued.

(d)

2500
2400
2300
2200
2100
2000
1900
1800
1700

tensile modulus [MPa]

0,95
0,98
1,01
1,04
1,07
1,1

65

30

v_E **[mm/s]**

density [g/cm³]

GCD:	1 bar
melt temperature:	300 °C
SCF-level:	0.2 %
correlation:	76.4 %

Figure 27. Continued.

Table 2. The influence of the processing parameters on the morphology of foamed polycarbonate

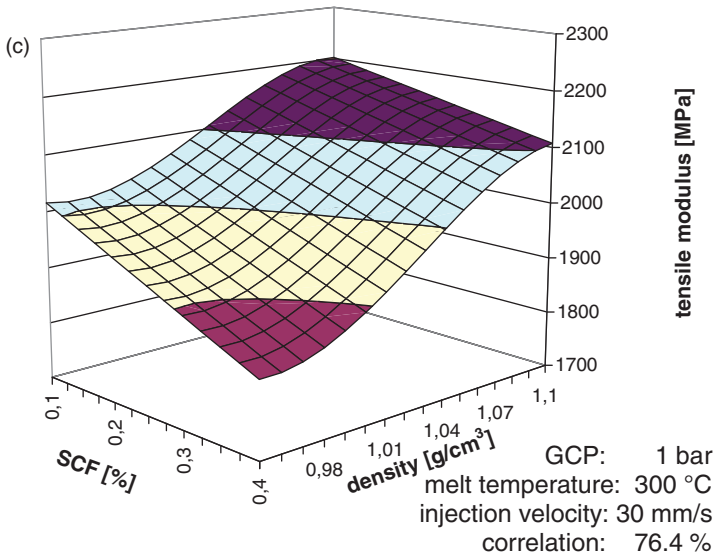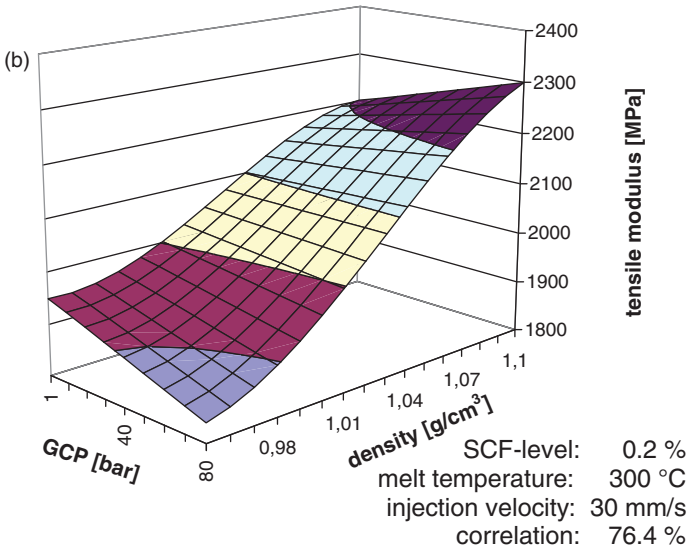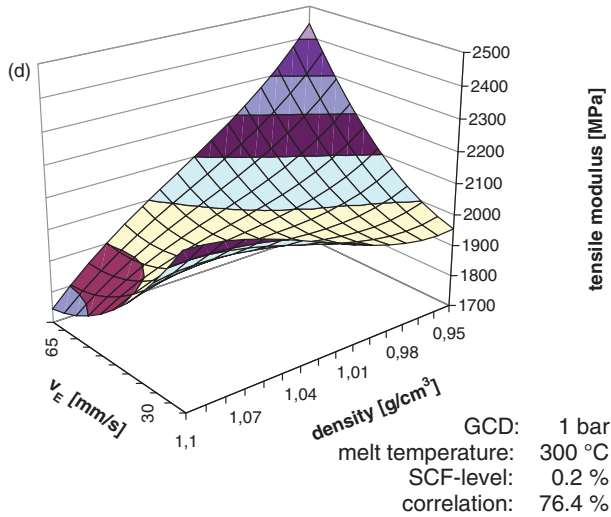| Higher melt temperature, T_{ME}	Mucell		Mucell + GCP	
	low SCF	high SCF	low SCF	high SCF
skin layer	↑	↑	↓	↓
cell distance edge	↓ ▲	↓ ▲	↓ ▲	↓ ▲
cell diameter edge	↑	↓	↑	↓
cell distance centre	⌣⌣	⌣⌣	⌣⌣	⌣⌣
cell diameter centre	↑	↑	↓	↓
Higher injection velocity, v_I	Mucell		Mucell + GCP	
	low SCF	high SCF	low SCF	high SCF
skin layer	↓	↑ ▼	↓	↑ ▼
cell distance edge	↓	↓	↓	↓
cell diameter edge	↑	↓	↓	↑
cell distance centre	↑	↑	↑	↑
cell diameter centre	↓ ▲	↓ ▲	↓ ▲	↓ ▲
Higher SCF-concentration	Mucell		Mucell + GCP	
skin layer	↓ ▲		↓	
cell distance edge	↑ ▼		↓	
cell diameter edge	↑ ▼		↓	
cell distance centre	⌣ ▼		⌣ ▼	
cell diameter centre	↓		↓ ▲	
higher mould temperature, T_{MO}	Mucell		Mucell + GCP	
	low SCF	high SCF	low SCF	high SCF
skin layer	↓	↓	↓	↓
cell distance edge	↑	↑	↓	↓
cell diameter edge	↓	↓	↑	↓
cell distance centre	↑	↓	↑	↓
cell diameter centre	↑	↑	↓	↑
Deviation by high density foams: ▼ ▲				
Deviation by high blowing agent concentration: ⌣ ⌢				

GCP: gas counter pressure and SCF: supercritical fluid.

Table 3. The influence of the processing parameters on the bending and tensile properties of foamed polycarbonate

	Higher injection velocity		Higher SCF-level	
	Mucell	Mucell + GCP	Mucell	Mucell + GCP
Tensile modulus	↑ ▼	↑ ▼	↓	↓
Tensile strength	↑ ▼	↑ ▼	↓	↓
Flexural modulus	↑ ⇧	↑ ⇧	↷	↷
Flexural strength	↑ ⇧	↑ ⇧	↑ ⬆	↑ ⬆
	Higher melt temperature		**Higher mold temperature**	
	Mucell	Mucell + GCP	Mucell	Mucell + GCP
Tensile modulus	↓	↓	↓	↓
Tensile strength	↓	↓	↓	↓
Flexural modulus	↓ ⬆	↓ ⬆	↓	↓
Flexural strength	↓ ⬆	↓ ⬆	↓	↓
Deviation by:	High density foams: ▼ ▲ high blowing agent concentration: ⇓ ⇧ High injection velocity: ⬆			

GCP: gas counter pressure and SCF: supercritical fluid.

Conclusions

It was pointed out that correlation between morphological structure and mechanical properties as well as correlation between processing parameters and foam morphology was observed and could be specified. The experiments and subsequent analysis show that it is possible to produce foamed materials with a well-defined morphology structure and therefore, specifically optimised mechanical properties. By evaluating the results of correlation, the authors of this article come to the conclusion that all bending and tensile properties were influenced by the morphological structure in the same way. While improving one tensile property by the injection moulding process, all other tensile properties as well as bending properties are being improved at the same time. Furthermore, as a result, it is clearly obvious that three different sandwich models, which are optimal for tensile and bending (not model *W*) load, can be created. These three models are equated and each of them leads to good mechanical properties. The **GCP** technology does not only lead to massively better surface qualities, but also a suitable procedure for influencing the foaming process.

Table 2 points out an overview of the relation between processing parameters and morphology. The arrows show in which direction each morphological parameter is influenced by the processing. The curved arrows point out that these values have a non-linear behaviour and show a maximal or minimal turning point. Under special circumstance, the influence changes. In this case, the deviation by changing other parameters are marked with triangles (high density), thick arrows (high injection velocity) or thick open arrows (high SCF level). Some changes depend on the

density of the foamed material. A higher injection velocity leads at lower densities to thicker skin layers, whereas it leads at higher densities to a reduction of the skin layer thickness for example. This knowledge enables custom-made polymer foams with optimised properties for each application.

In addition to the connection between morphology and processing parameters, Table 3 points out the influence of the processing parameters to the bending and tensile properties of the microcellular polycarbonate foams. In case of different tendencies for different densities, the tendency for higher density foams is labelled by a triangle.

Funding

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