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Journal of Cellular Plastics 2010 46: 415 originally published online 2 July 2010
DOI: 10.1177/0021955X10368332

Correlation Between Morphology and Notched Impact Strength of Microcellular Foamed Polycarbonate

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ABSTRACT: Polycarbonate has the reputation of having a tough breaking behavior, but it is widely unknown that this applies only to special conditions. The impact strength of polycarbonate depends on the temperature, thickness (with a tough brittle transition as thickness increases), contribution of notch tip radius, impact speed, physical blowing agent, molecular weight of the polymer, and processing parameters. Research results indicate that microcellular foams produced by injection molding with physical blowing agent (MuCell^{TM} Technology by Trexel) show a significantly higher notched impact strength than compact polycarbonate if the compact material is brittle under the same testing parameters. However, if the compact polycarbonate breaks toughly, the notched impact strength of the foamed material is always lower. Therefore, it is highly important to pay attention to the testing parameters and conditions when comparing the toughness of the foam with that of the compact material. The toughness of microcellular foams has similar properties like PC/ABS and PC/PP blend systems, which provides the possibility to combine the higher impact strength with the advantages of microcellular foaming such as weight reduction, lower shrinkage, shorter cycle times, lower clamp forces, and reduced melt viscosity. In order to use technologies and conditions, which are applied in the polymer industry as well, all materials were produced by an injection

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Figures 1, 3, 4, 8–11, 13–18, 20 and 22 appear in color online: http://cel.sagepub.com

0021-955X/10/05 0415–26 $10.00/0 DOI: 10.1177/0021955X10368332

molding process. Special processing technologies such as gas counter pressure and precision mold opening were used in order to reach microcellular foam structures with cell diameters around 10 μm. These technologies yield exactly adjustable foam morphologies. Special morphologies are required to improve the notched impact strength of the foamed material. Two different equivalent models were extracted from the analyses, which indicate a significantly higher notched impact strength than the compact material under the same testing conditions. The knowledge of the ideal foam morphologies enables the industry to produce foamed materials with improved mechanical properties.

KEY WORDS: microcellular foam, injection moulding, polycarbonate, notched impact strength.

INTRODUCTION

The thermoplastic foam industry is a long established branch of the polymer industry. Foaming of thermoplastic polymers by injection molding has been performed since many decades. Microcellular foaming has also been well known for many years. Many publications deal with this research area, and many products and proceedings were patented. Microcellular foams provide benefits such as reduced material consumption, lower processing temperatures, lower viscosity of the polymer melt, avoided shrinkage, reduced density while having approximately equal mechanical properties compared to the compact material, and much more. Especially the low shrinkage is a very interesting point to industrial manufacturers. However, industrial applications of microcellular foams produced by injection molding are very rare. With regard to the well-known advantages of microcellular foamed polymers and the possibility to reduce investments for injection molding machines [1,2], it is astonishing that microcellular foam processing has not been established in industrial application yet. Especially the notched impact strength is a highly complicated property, as it depends on many influencing factors. Results of the interrelation between morphology, processing parameters as well as bending and tensile properties emerged in one of our former investigations [3,4]. In this research project, the influence of the morphology on the toughness of polycarbonate is going to be investigated in order to strengthen the position of the foam technology on the market.

The notched impact strength of microcellular polycarbonate foams was examined in many investigations all of which dealt with phase separation, gas super saturation, precipitation with a compressed fluid anti solvent or polymerisation of monomers, but not with injection molding. All these foaming processes are only relevant during laboratory investigations and have no prospects for industrial applications.

Furthermore, these studies do not pay attention to the thickness of the skin layer; as it was too thin, it was removed or ignored [5–8]. All samples, which were created during this study, more or less showed a thick compact skin layer, which has a significant influence on the mechanical properties of polycarbonate foams.

Microcellular foam injection molding is rarely applied despite the fact that microcellular foaming provides lower density and material saving benefit, which is a great advantage for the automotive industry attempting to reduce the weight of each vehicle part. However, microcellular processing inevitably leads to a reduction in mechanical properties. It is not yet possible at present to forecast the mechanical properties of an injection molded foam.

In the case of polycarbonate, a microcellular structure does not automatically lead to a reduction in mechanical properties. Regarding the notch impact strength, it is well known that a microcellular phase separation improves the notch impact strength of brittle breaking polycarbonate. Brittle polycarbonate breaks by crazing and not by shear yielding. Nevertheless, the microcellular phase-separated morphology can induce shear yielding. Therefore, polycarbonate is a (pseudo-) ductile polymer [9]. The deformation type depends on the entanglement density (or entanglement molecular weight). Polymers with a small entanglement density tend to become brittle by crazing. In materials with a greater entanglement density, shear deformation dominates.

The notched impact strength of a brittle matrix, which breaks by crazing can be achieved by filling it with another phase, for example, of rubber particles, which enable local uncritical multiple crazing in larger polymer volumes. The crazing is influenced only by the diameters of the filler. The filler diameter must be below a specific maximum, which decreases with increasing matrix ductility.

The morphological factor in dealing with a (pseudo-)ductile (e.g., polycarbonate) matrix is the distance between the fillers, for example, rubber particles, and the second phase, which is called inter-particle surface-to-surface distance or ligament thickness. The critical ligament thickness increases for 'tough-brittle-transition' with increasing ductility of the polymer matrix [9].

In the case of a PC/PP blend [10], it was shown that the distance between the voids is responsible for the change in breaking behavior. There is a critical ligament thickness area which depends on the respective matrix polymer and can be considered as a material constant [9,11].

If the distances are too small, there will not be a rise in tension between the micro voids or particles and no shear deformation can be initiated. However, the distances should not be too large either, otherwise the capability of shear deformation decreases. Only ligament thicknesses smaller than the maximum are adequate to make a transfer of the triaxial stress state between the micro voids into an uniaxial stress state possible, which causes shear deformations of the matrix distances between the micro voids.

The maximum of ligament thickness depends on the load speed, temperature and, slightly, on the void diameters. The minimum correlates with double of the critical minimal limit of the plastic zone [12].

A correlation of the morphology and toughness of polycarbonate and between the morphology and processing parameters will allow the production of microcellular foamed materials with exactly defined properties. Consequently, the microcellular foaming technology will be upgraded and allow 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 eighties, 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 like supercritical nitrogen (N_2) and carbon dioxide gases (CO_2) are injected into the molten polymer during the molding process in small, precise amounts. The patents were bought by Trexel Inc., which launched the technology in the market [13].

PRECISION MOLD OPENING

For technical parts, the MuCell process can achieve a weight reduction in the range of 5–15%, depending on the flow path and part thickness. Significantly higher weight reductions can be achieved then combining the MuCell process with the so-called ‘precision mold opening’ (PMO) (also known as ‘venting’, ‘negative compression,’ or ‘breathing mold’). The volumetrically filled mold cavity can deliberately be enlarged to the desired part thickness (Figure 1).

Even large area foam parts produced by this process have very high flexural strength and a comparatively good surface (however, high surface qualities cannot be achieved).

Precision mold opening is particularly suitable for producing packaging parts, in particular for insulation packaging. Potential applications also include door modules or dashboard supports for automotive engineering where both dimensional stability and flexural strength are required. The wall thicknesses that can be obtained by precision opening are three to four times higher than the initial wall thickness in the individual case. Foam parts of PE-HD and PP with ultimate wall thicknesses up to 10–12 mm have already been produced [14].

Furthermore, the PMO technology (in combination with the Gas Counter Pressure technology – GCP) enables the creation of microcellular foam structures with cell diameters of less then 10 μm without any nucleation agents or other additives. Figure 2 shows different

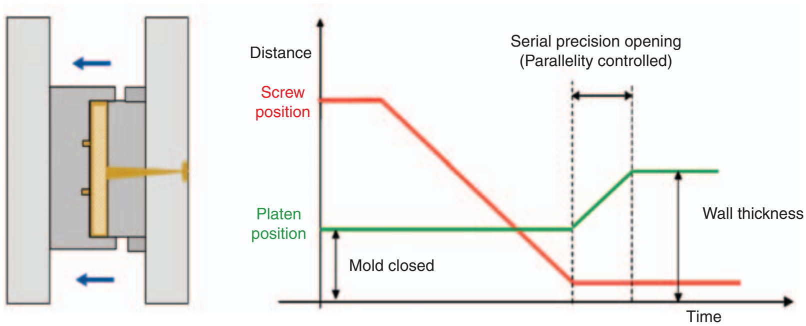

Figure 1. Frame molds and molds with vertical flash face (left) are both suitable for use in precision opening. After volumetric filling of the cavity, the enlargement of the mold cavity should, if possible, be carried out with parallelism control (right) [1].

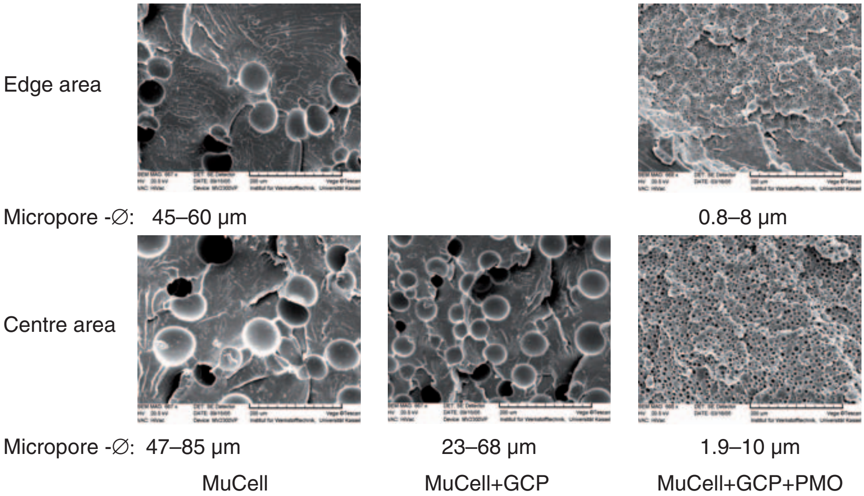

Figure 2. Scanning electron micrographs of the skin and core foam structure of test bars of 4.24 mm in thickness (length 185 mm, width 20 mm), produced from polycarbonate with MuCell, MuCell + gas counter pressure, and MuCell + gas counter pressure + precision mold opening with a density reduction of 10%.

morphologies, captured with a scanning electron microscope, which were created with the standard MuCell technology, MuCell + GCP and MuCell + GCP + PMO.

GAS COUNTER PRESSURE

Foamed components produced by injection molding often have very bad surface qualities, which is one of the reasons why industrial application is still rare. The bad surface quality is due to the fact that the blowing agent drifts out of the polymer melt at the glaze front during the injection into the mold. The polymer bubbles are destroyed by shearing of the material at the mold surface. This effect can be prevented by the gas counter pressure process. For using the gas counter pressure (GCP)-technology, an airtight mold and an additional gas injection channel are required. Gas pressure is built up in the empty mold 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 gas counter pressure has to be higher than the gas pressure of the blowing agent. During melt injection, the counter pressure gas needs to be accurately defined exhausted to obtain a constant counter pressure (Figure 3). After the injection process, the gas pad will be exhausted, so that the blowing agent can foam up the polymer melt [6].

In combination with the PMO technology, GCP leads to another processing parameter additionally to injection speed, the type of supercritical gas and concentration, melt temperature, mold temperature, and weight reduction, which influence the morphology of the foam structure. The obvious lower surface roughness also leads to better

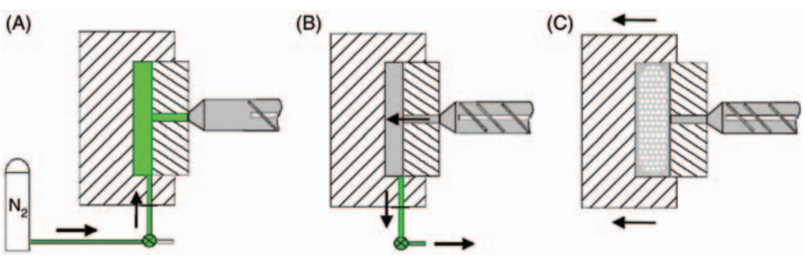

Figure 3. Schematic picture of the gas counter pressure process in combination with precision mold opening [14].

mechanical properties, because high roughness may have the same effects like micro notches, which reduces the toughness as well as the bending and tensile strength.

While analyzing the morphology, it is conspicuous that parts produced with gas counter pressure can be foamed up to the surface. Conventionally produced foams have a clear boundary between the microcellular core and the surface layer [15]. The morphology of the injection molded parts with GCP usually is quite different from the conventional injection molded parts. Contrary to the conventionally foamed material, which has a thick compact surface layer and a clear separation of the surface layer from the foamed core, the parts that were produced with GCP have a very thin compact surface layer and do not have this clear separation. Even at the edge of the surface layer, cells can be found, a fact that is due to the counter pressure gas pad in the mold that keeps the blowing agent gas in solution and prevents its escape from the melt. During conventional microcellular foaming, the gas in the edge areas of the polymer melt escapes so that the material in the surface layer cannot be blown up.

EXPERIMENTAL DETAILS

The analyzed materials were unreinforced polycarbonates from Bayer Material Science with three different melt viscosities, Makrolon 2205 (low viscosity, MVR: 36 cm^3/10 min), Makrolon 2805 (middle viscosity, MVR: 9.5 cm^3/10 min), and Makrolon 1239 (high viscosity, MVR: 3 cm^3/10 min). Nitrogen (N2) was used as the blowing agent.

Test samples with measurement of 160 mm $\times$ 20 mm and a thickness of 3.2 or 4 mm had been produced according to DIN EN ISO 294 and 10724 with an injection molding machine (Engel Victory 330H/80V/120 Combi, clamp force 1200 kN) equipped with the MuCell™ Technology (Trexel, Inc., Woburn, MA, injection unit with 30 mm MuCell-screw). The mold was also equipped with the precision mold opening and the gas counter pressure technology. The Charpy notched impact test was carried out edgewise according to DIN EN ISO 179. The depth of the polycarbonate remaining in the bar under the notch was approximately 8 mm. The notch angle was constantly positioned at $45^\circ \pm 1^\circ$ and the radius of curvature was of Type A (0.25 mm $\pm$ 0.05 mm). The notches were produced with a notching machine (NOTCHVIS from CEAST). The annealing time for testing at room temperature (23°C) was 12 h in standard atmosphere and 2 h at a temperature of -30°C.

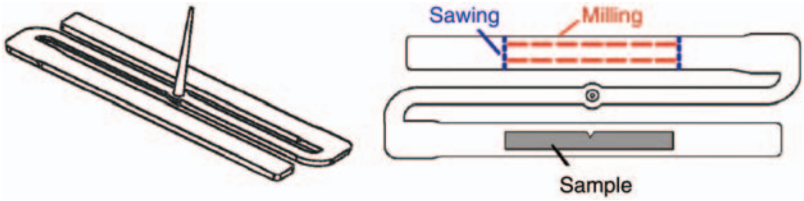

Figure 4. Sampling method of specimen for the Charpy notched impact test.

ANALYSIS DETAILS

The test bars were milled concentrically out of the produced samples so that the foamed material could be tested. By the preparation of the samples the compact skin layer on the sides where the samples had been notched. This guarantees that the notch depth is larger than the skin layer and a homogenous foam morphology across the sample (Figure 4).

INVESTIGATION OF THE MORPHOLOGY

Fracture surfaces were created by cryogenic crushing and observed by microscopy. Images of the morphology were characterized by a computer controlled image analysis system.

The program scanned the void structures and determined the following measuring data:

- Void diameters,
- Void distances,
- Thickness of the skin layer.

These measured values were the basics for the numeric calculation. In addition to the image analysis of the samples, the density was determined. All produced test samples showed almost spherical cells so that an analysis of the roundness of the cells was not required.

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

Preceding analyses showed that it is important to differentiate between cells in the middle of the center 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

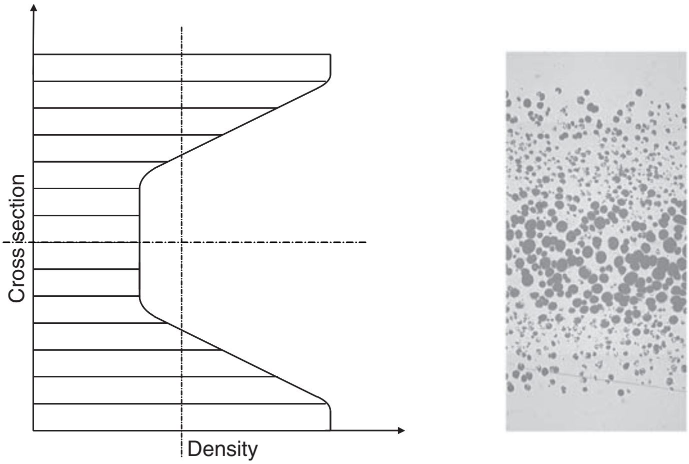

Figure 5. Density change over the cross-section of an injection molded foam.

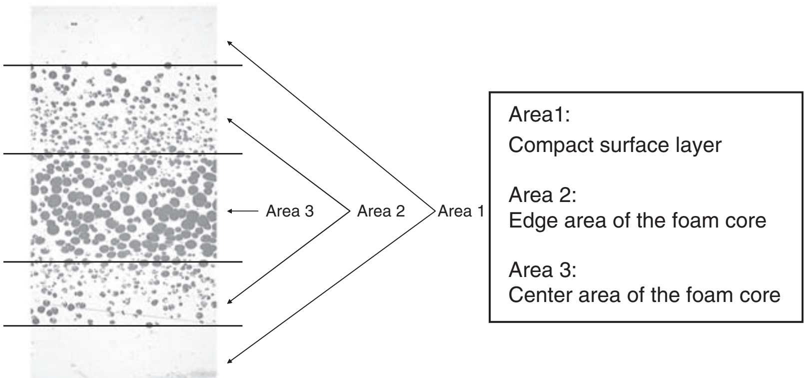

Figure 6. Classification of the three morphology areas.

the middle of the sample is larger than the one in the edge areas. It has turned out to be useful to divide the sample into three different areas [3,16,17].

The first area is the compact surface layer. This layer ends at the first cells in the sample. Both at the upper side and at the bottom, 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 surface layer and ends where the cell diameter increases. The third area lies in the middle of the sample (Figure 6).

On the basis of these morphological analyses and the results of the Charpy notched impact tests (according to DIN EN ISO 179/1eA), correlations between the morphology and the toughness were created. Throughout this study a computer program named RESINT, which creates equations by means of linear regression, was used.

This program was developed by the TU Riga [18], elaborated together with the Institute of Materials Engineering in Kassel and adjusted to the problematic nature of polymers [19,20].

BREAKING BEHAVIOR OF POLYCARBONATE RESINS

The knowledge about the breaking behavior of polycarbonate resins is absolutely necessary for the evaluation of the breaking behavior of polycarbonate microfoams.

The breaking behavior of compact polycarbonate is dominated by crazing and therefore by elastic material behavior at −30°C. The shear yielding behavior increases below approx. −25°C. Thus, the crazing and shear yielding as well as the elastic plastic material behavior characterizes the breaking behavior at room temperature [21,22]. The notched impact behavior of polycarbonate depends on the molecular weight, thickness, temperature, radius of notch curvature, impact speed, concentration of physical blowing agent, and processing parameters.

Figure 7 shows the Charpy notched impact strength of Makrolon 2805 with variations of thickness and temperature.

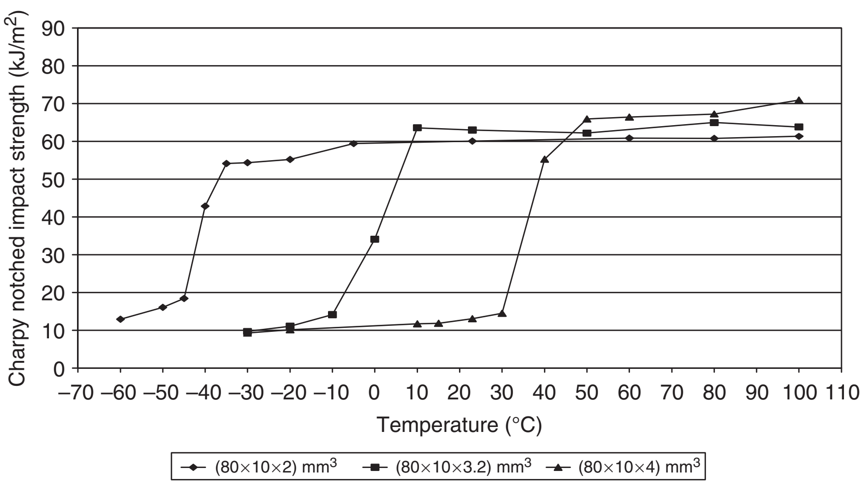

Figure 7. The influence of temperature on Charpy notched impact strength with test bars of 2, 3.2, and 4 mm in thickness (Makrolon 2805, DIN EN ISO 179, notch geometry A) [7].

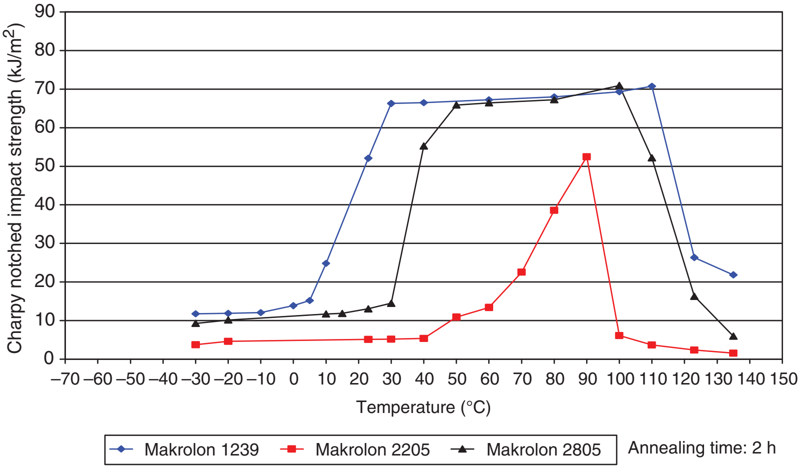

Figure 8. Notched impact strength of the different polycarbonate types (DIN EN ISO 179, notch geometry A, thickness 4 mm).

Furthermore, it is very important which type of polycarbonate is used. The higher the molecular weight, the stronger will be the toughness of the polymer. Figure 8 points out that Makrolon 2805 with a thickness of 4 mm shows a brittle breaking behavior at 23°C whereas Makrolon 1239 breaks tough. Makrolon 2205 is very brittle due to its low molecular weight and does not show a tough breaking behavior until the temperature rises up to 80°C. This makes it very hard to get a tough breaking behavior by foaming up the material because the conditions are far from ideal. Furthermore, polycarbonate falls into brittle at temperatures higher than 90°C, depending on the thickness, molecular weight, and annealing time [23,24].

DISCUSSION OF RESULTS

The results of the notched impact strength analysis can be divided into two groups. If the polycarbonate resin breaks tough under the same test conditions, the foams belong to group one. In this case, a compact structure without cells is the optimum. The notched impact strength of the resin material cannot increase and foaming up the polymer leads to a decrease in toughness. In order to sustain high impact strength by foaming these materials, the morphology has to be oriented towards the compact resin structure. This implies a low density reduction, a large compact surface layer, and few cells with large cell distances between them. The higher the density, the better will be the toughness of the material (Figure 9).

An exception is Makrolon 2805 with a thickness of 3.2 mm at 23°C, which shows a 'bath tub'-function (Figure 12). The resin polycarbonate exerts a tough breaking behavior. A low density reduction leads to a decrease in impact strength, whereas a higher weight reduction makes the toughness increase until the density is less than 1.04 g/cm^3 (Figure 10). However, the foamed material never reaches the notched impact strength of the resin material under these testing conditions (Figure 9). This 'bath-tub'-function depends on the high embrittlement of Makrolon 2805 when being foamed up, which leads to explicitly lower notched impact strength. This embrittlement can be balanced by a higher density reduction like in the case of the materials of group 2, which can be seen subsequent to this passage.

The cell sizes and distances in the edge area are less important than in the center area. The average cell size in the center should be as small as possible and the cell distances as large as possible in order to reach the best impact strength. This morphology can only be achieved with a high density, and it is very similar to the compact material.

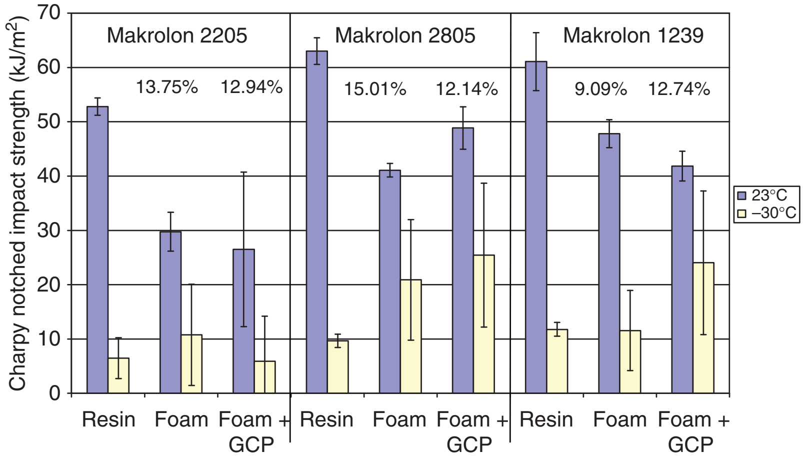

Figure 9. Notched impact strength (DIN EN ISO 179, notch geometry A) of resin and foamed polycarbonate with a thickness of 3.2 mm (density reduction in percent).

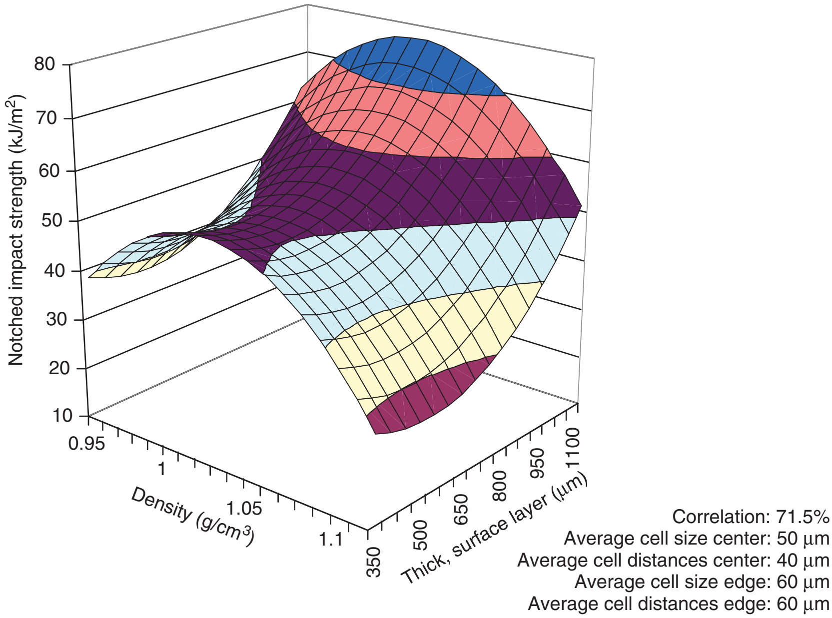

Figure 10. Correlation of notched impact strength (DIN EN ISO 179, notch geometry A) in dependence on density and thickness of the compact surface layer (Makrolon 2805 – 3.2 mm – 23°C).

Group 1 includes Makrolon Type 1239 at 23°C both in form of samples with a thickness of 4 mm and such with a thickness of 3.2 mm. The two polycarbonate types with lower viscosity only show a tough breaking behavior when the samples have a thickness of 3.2 mm or less. The samples with a thickness of 4 mm always show a brittle breaking behavior and belong to group 2 (Figure 11). All samples of polycarbonate resin broke brittly at −30°C and belong to group 2.

The more interesting foams are materials whose resin polycarbonate shows a brittle breaking behavior under equal test conditions. They all belong to group 2 and it is possible to improve their notched impact strength by microcellular foaming. The results of this investigation show that there are two different solutions, which increase the notched impact strength of polycarbonate.

The first possibility to increase impact strength is to create a microcellular structure (Figure 12 – model V_M; the density course looks like a V) with small cell sizes and a thin compact surface layer. Furthermore, the relation between cell diameter and cell distance is significant, to get a tough breaking behavior, it depends on the

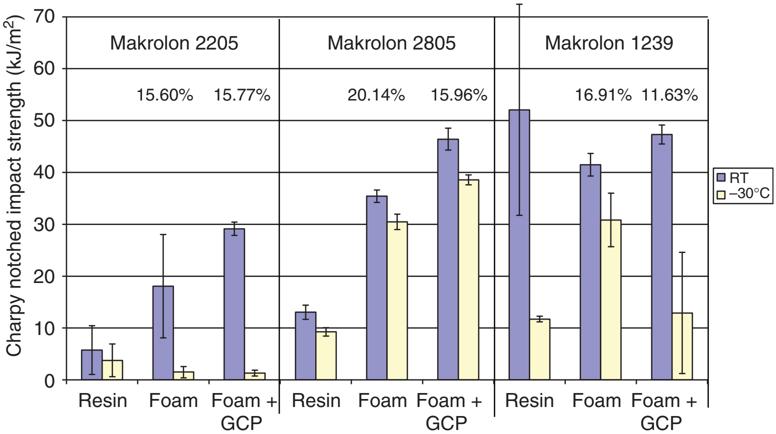

Figure 11. Notched impact strength (DIN EN ISO 179, notch geometry A) of resin and foamed polycarbonate with a thickness of 4 mm (density reduction in percent).

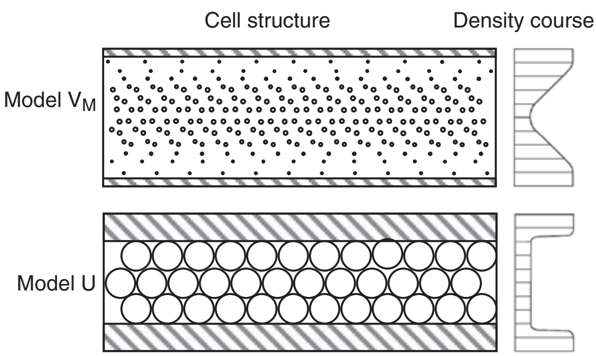

Figure 12. Ideal morphology structures to improve notched impact strength.

thickness, the testing temperature and the molecular weight. The average cell size has to be less than 10 μm if an enhanced toughness is to be achieved by a microcellular structure [25,26]. In this study, it only worked for Makrolon 1239 with a thickness of 4 mm when the impact test was performed at −30°C. Theoretically, it is possible to increase the notched impact strength of all polycarbonate foams in comparison to the resin polycarbonate if it breaks brittly. In this case, the average cell size has to be around 1 μm or less [21]. Figures 13 and 14 show the impact strength in dependence on the cell diameters and distances for microcellular polycarbonate foams.

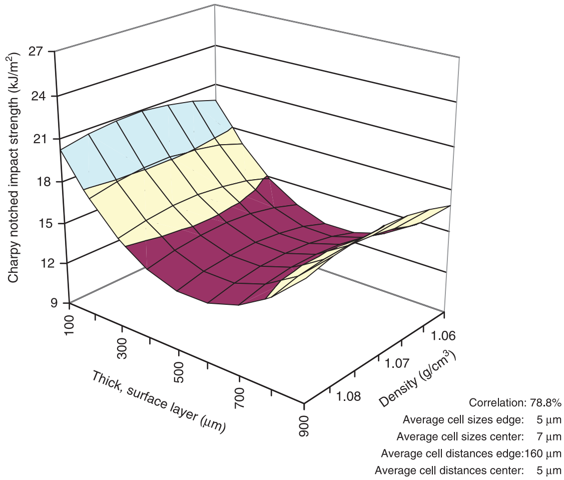

Figure 13. Correlation of the Charpy notched impact strength in dependence on the thickness of the surface layer and the density (DIN EN ISO 179, notch geometry A, Makrolon 2805, 4 mm, -30°C).

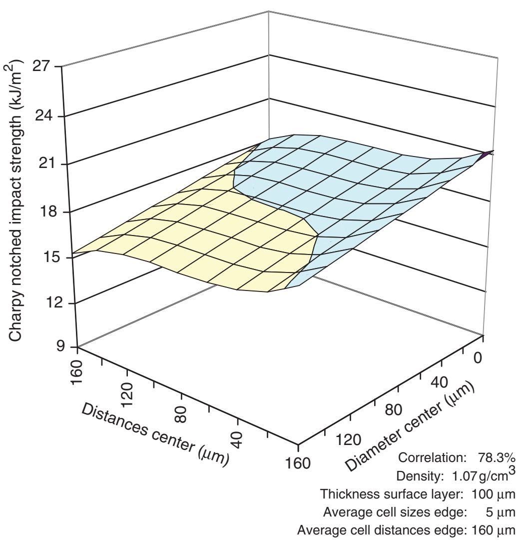

Figure 14. Correlation of the Charpy notched impact strength in dependence on the cell diameters and distances in the center area (DIN EN ISO 179, notch geometry A, Makrolon 2805, 4 mm, -30°C).

Another solution to increase the toughness of polycarbonate by foaming is to create a sandwich structure (Figure 12 – model U; the density course looks like a U). The most important morphological parameter is the thickness of the surface layer. The bigger the surface layer, the higher the notched impact strength. The cause of the increase in toughness with regard to this morphology is shown a diagram in Figure 7. While the 4 mm sample shows a brittle breaking behavior at −30°C, the sample with a thickness of 2 mm shows a tough breaking behavior at the same temperature.

The compact surface layers of these sandwich structures act like compact resin polycarbonate. The thickness of these surface layers is always less than 2 mm and they are tough until −40°C (Figure 15). It is absolutely necessary to use this pseudo-sandwich structure so that the compact surface layer has a sharp boundary with the foamed core. Therefore, the cell sizes in the core area have to be large (Figure 16); the cell distances between them have to be small.

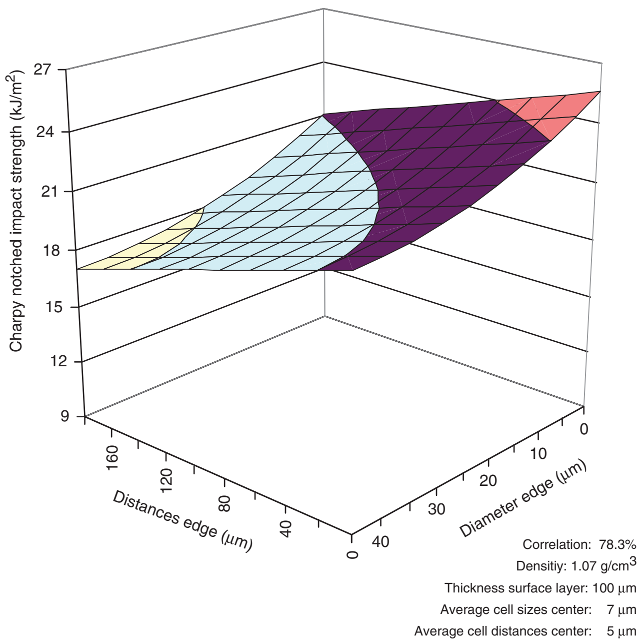

Figure 15. Correlation of the Charpy notched impact strength in dependence on the cell diameters and distances in the edge area (DIN EN ISO 179, notch geometry A, Makrolon 2805, 4 mm, −30°C).

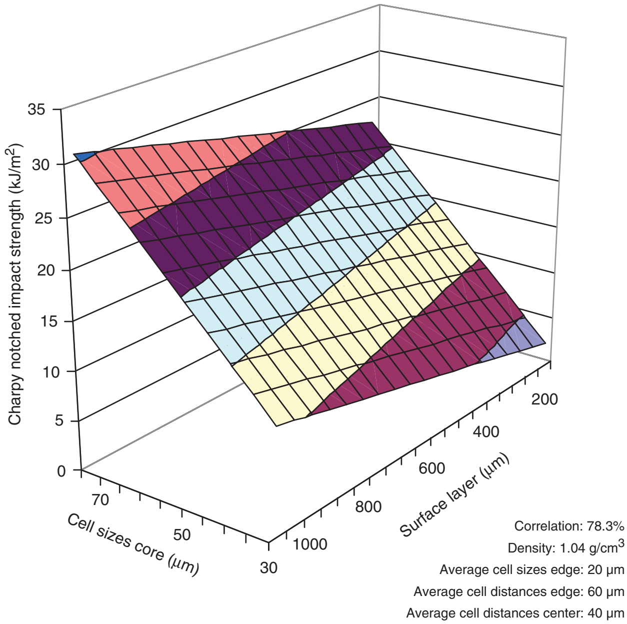

Figure 16. Correlation of the Charpy notched impact strength in dependence on the cell sizes in the center area and the thickness of the compact surface layer (DIN EN ISO 179, notch geometry A, Makrolon 2805, 4 mm, -30°C).

Figure 17 points out the relation between the thickness of the surface layer and the impact strength. It shows that it is also important to reduce the density to achieve a sharp boundary between the surface layer and the foam core; otherwise the structure cannot act like a sandwich model.

As shown above in Figure 18, there are two opposing ways to reach tough breaking behavior of the materials in group 2. Both methods are equally suitable; until now, only the microcellular model for Makrolon 1239 (4 mm, -30°C) has been verified. Furthermore, Figure 17 points out that not only the cell sizes in the edge area, but also the cell sizes in the center area should be as large as possible when a suitable sandwich structure is meant to be created. This is due to the fact that, at constant density, the thickness of the surface layer can only increase if the density in the foam core decreases. Therefore, the cell size in the whole foam has to be large and the distances between the cells (not shown in this figure) have to be small.

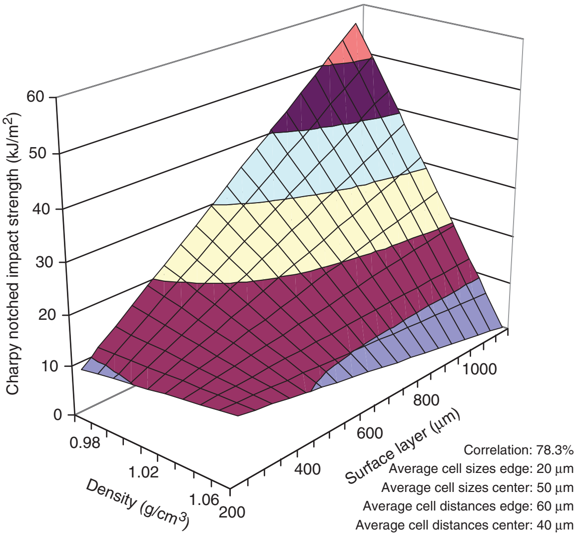

Figure 17. Correlation of the Charpy notched impact strength in dependence on the density and the thickness of the compact surface layer (DIN EN ISO 179, notch geometry A, Makrolon 2805, 4 mm, −30°C).

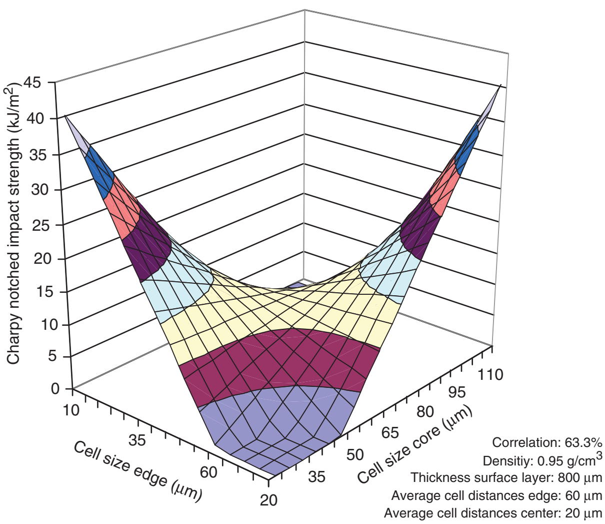

Figure 18. Influence of the cell size on the Charpy notched impact strength of Makrolon 1239 (DIN EN ISO 179, notch geometry A, 4 mm, −30°C).

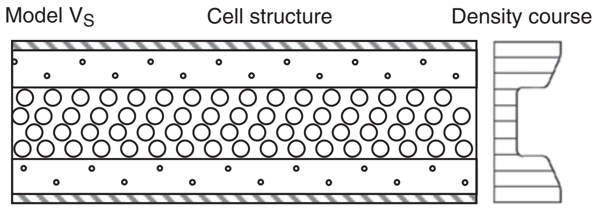

Figure 19. Sandwich model with a pseudo-thick compact surface layer.

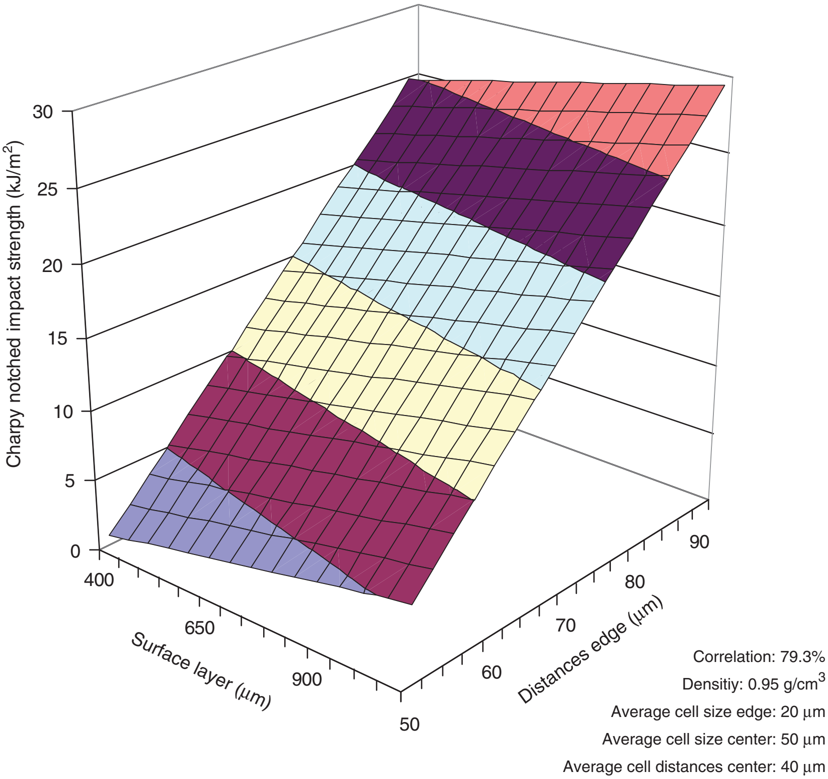

Figure 20. Correlation of the Charpy notched impact strength (DIN EN ISO 179, notch geometry A, Makrolon 2205, 4 mm) at 23°C in dependence on the thickness of the compact surface layer and the average cell distances in the edge area.

If the compact surface layer is small, it can even reach such high notched impact strength when the cell sizes in the edge area are small and the distances between the cells are large. In this case, the edge area of the foam core acts like a compact surface layer, too, and consequently, a thicker pseudo-compact surface layer exists. In this case, a sharp boundary between the center area of the foam core and the compact surface layer is required to use the sandwich structure model. In Figure 19, such a structure can be seen.

Figure 20 exemplary shows that a small compact surface layer can be compensated by small cell sizes (20 μm) and large cell distances in the edge area of the foam core. This correlation can be assigned to all other materials of group 2. This model is called V_S model, because it is a sandwich model and the density course looks like a V.

CONCLUSION

The notched impact strength of polycarbonate can be increased by microcellular foaming if the resin polymer shows brittle breaking behavior under the same testing conditions. There are two equal models that have shown to be able to produce an increase in the toughness of polycarbonate.

The first model uses a microcellular structure with an average cell size of 10 μm or less. However, it is very hard to create these structures by injection molding and they require special processing technologies like PMO and GCP, which were applied in this investigation. Therefore, not only do the cell sizes have to be small also, the relation between average cell size and average cell distance has to be adequate (Figure 21). The voids of microcellular foamed polycarbonate act in the same way like ABS, PP, or other incompatible blend polymers and are able to increase the notched impact strength [25,26].

To reach a higher toughness of PC, it is necessary that the voids in the polymer matrix have a small ligament thickness between the cells so that an uniaxial stress state prevails. This affords plastic flow and leads to a tough breaking behavior. If the distances between the cells are too large, the uniaxial stress state changes into a triaxial stress state, which inhibits plastic flow, and the matrix breaks brittle.

The second model aims at creating a sandwich structure with a thick compact surface layer and a sharp boundary between surface layer and foam core. Due to the high dependence of the impact strength on the thickness of the material, the compact surface layers break tough, whereas a sample of resin polycarbonate material breaks brittle under the same conditions.

The differences between a brittle breaking resin material and microcellular foamed material can be seen in Figure 22. The graph shown is equal for foamed PC with a higher impact strength which was reached by a sandwich model and the microcellular foamed PC where the higher impact strength results from the microcellular structures.

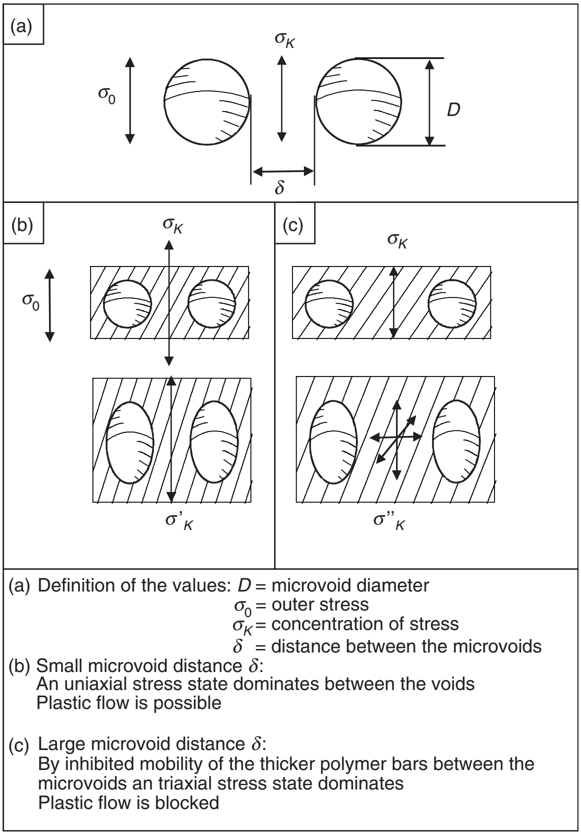

Figure 21. Stress and deformation behavior of polycarbonate.

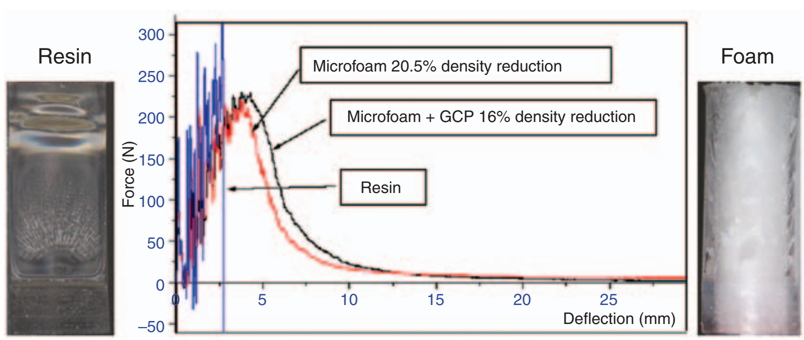

Figure 22. Force–deflection graph and fracture images of resin and microcellular foamed material during the Charpy notched impact strength test (Makrolon 2805, 4 mm, 23°C, DIN EN ISO 179, notch geometry A).

The foamed polycarbonate breaks tough with shear lips and long fringe deformation (right fracture image – Figure 22). The crack starts in the curvature where a stable crack growth and a plane stress condition exist. The resin material breaks brittly with a stretch zone and short fringe development, and the crack starts at the crack initiation area (left fracture image – Figure 22). The surface of the break is smooth and glossy. An instable crack growth and a plane strain condition exist.

If the resin material shows tough breaking behavior, it is not possible to increase the notched impact strength by microcellular foaming. In this case, the ideal foam structure is close to the one of resin material, which leads to high density, a thick compact surface layer, and small cell sizes.

Figure 23 points out the dependency of the toughness on the different morphological parameters. In case of a tough breaking

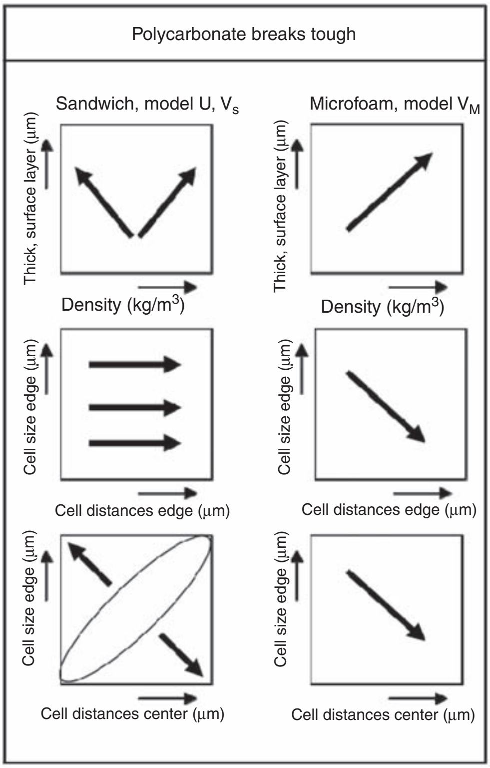

Figure 23. Overview of the breaking behavior of foamed polycarbonate (higher notched impact strength in the direction of the arrow).

behavior of the resin material, a high density and a thick compact surface layer leads to the highest notched impact strength of foamed PC. Large cell distances in the edge and the center area in combination with small cell sizes also have a positive effect on the notched impact strength. If the foamed polymer has a high density reduction, then the best toughness can be reached by a thick compact surface layer combined with large cell sizes and small distances between the cells in the center area.

In case of a brittle breaking behavior of the resin polycarbonate, it is possible to reach high notched impact strength by a thick compact surface layer at a low density in combination with large cell sizes and small cell distances in the center area (sandwich model). The cell sizes have to be small and the cell distances large if the compact surface layer is thinner to create a pseudo compact layer. If the compact surface layer is thick, then the cell sizes should be large and the distances between them small. The other possibility to improve the notched impact strength is to create a microcellular structure (model V_M), which has very small cell sizes (10 μm and less) and small distances between the cells. Table 1 points out the cell diameter – cell distance ratio for different material types, sample thicknesses, and testing temperatures.

The compact surface layer can be both thin – then the microcellular structure is dominant – and thick – then the compact surface layer is dominant (Figure 24).

As seen above, there are different ways to improve the notched impact strength of polycarbonate, but only if the resin polymer breaks brittle, the toughness of the foamed material can be greater than the resin material. So for each application, the breaking behavior of the resin polycarbonate has been proved to know, which is the best morphology for foamed parts in this application. By optimized morphological design,

Table 1. Cell diameter–cell distance ratio for different polycarbonate types, testing temperatures and thicknesses.

Cell diameter / Cell distance	3.2 mm thickness		4 mm thickness	
	23°C	−30°C	23°C	−30°C
Makrolon 2205	–	>1.8	>1.4	>2.0
Makrolon 2805	–	>1.5	>0.9	>1.7
Makrolon 1239	–	>1.3	–	>1.5

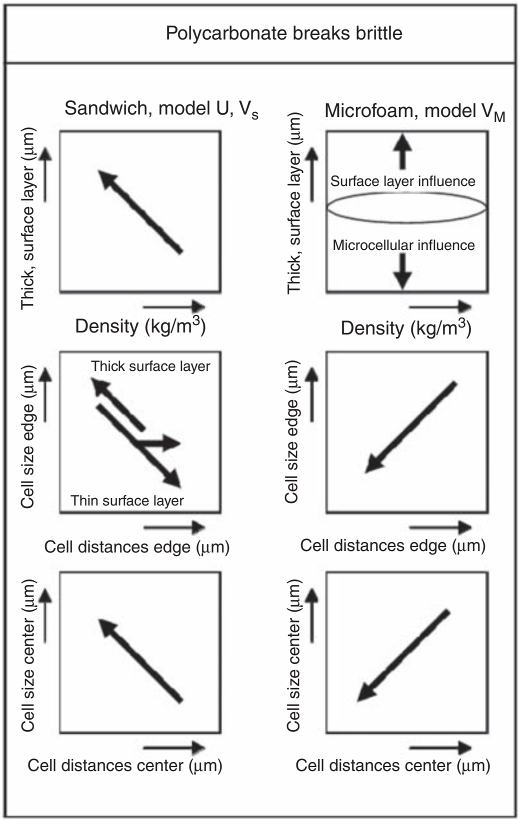

Figure 24. Overview of the breaking behavior of foamed polycarbonate (higher notched impact strength in the direction of the arrow).

it is possible to improve the notched impact strength by around 400% compared to the resin material.

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