Advanced Structural Foam Molding Using a Continuous Polymer/Gas Melt Flow Stream

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ABSTRACT: This article introduces a patented advanced structural foam molding technology. By the implementation of a means of continuing the polymer matrix melt flow stream, the processing conditions are made consistent, and the injected gas is thus uniformly dispersed throughout the polymer matrix. Compared with its predecessors targeted at similar applications, this new technology generates single-phase polymer/blowing agent solutions and is therefore capable of producing parts with smaller cell sizes, more uniform cell size distributions, higher void fractions, and similar geometric accuracy. Fine-celled parts ($>10^6$ cells/cm^3) with high void fractions ($>30\%$) were successfully produced in this research with an advanced structural foam molding machine that was built in house. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 109: 2855–2861, 2008

Key words: blowing agents; foams; injection molding; voids

INTRODUCTION

Structural foams are plastic foams manufactured with conventional preplasticating-type injection-molding machines; a physical blowing agent, a chemical blowing agent, or both are employed in the process to produce a cellular (foam) structure. The structural foam molding technology was invented and improved by Angell and coworkers.[1–3]

Low-pressure, preplasticating-type structural foam molding machines are most commonly used to create structural foams because the required size of the molding system for producing large products is smaller than that of conventional injection molding on account of the lower cavity pressure.[4] Because the generated cells compensate for the shrinkage of injection-molded parts during cooling, structural foams typically have outstanding geometric accuracy. The advantages of foam injection molding include the absence of sink marks on the part surface, reduced weight, low back pressure, a faster production cycle time, and a high stiffness-to-weight ratio.[5–7] Because of this unique set of advantages, low-pressure, preplasticating-type structural foam molding technology has been widely used for manufacturing large products requiring geometric accuracy.

There are, however, a number of drawbacks to this technology. First, the cell number density (or cell density) of structural foams is typically very low (i.e., $<10^3$ cells/cm^3), the cell size is very large (i.e., >1 mm), and the cell size distribution is very non-uniform. Structural foams also have a low-quality surface, a very low void fraction, and poor mechanical properties (due to the large gas pockets). The processing conditions and the product quality are inconsistent as well.

This article introduces an advanced structural foam molding technology, based on a preplasticating-type system, that eliminates these drawbacks. This technology facilitates the uniform dispersion/dissolution of gas in the polymer melt during the structural foam molding process, thereby minimizing the creation of large undissolved gas pockets.

PROBLEM STATEMENT

In today's commonly used low-pressure structural foam molding technology using a low-pressure, preplasticating-type system (a so-called piggyback system), the amount of injected gas (typically N$_2$) is normally beyond the local or global solubility limit. Because of the overdosed gas content and the pressure fluctuations during each cycle, the injected gas cannot completely dissolve into the polymer.

Furthermore, an inconsistent amount of gas is injected into the polymer melt because of the non-steady nature of the existing molding process. A shutoff valve is typically used between the plasticating extrusion barrel and the plunger to prevent the reverse flow from the plunger to the extrusion barrel. However, this shutoff valve cannot completely decouple the functions of the extrusion barrel and the plunger. Because the valve needs to be shut off

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during the injection period, the plasticating screw must stop rotating; otherwise, the material exiting the extrusion barrel can go nowhere, and the system pressure may exceed the safe limit. Once the injection and molding operations have been completed, the valve opens, polymer accumulates in the plunger, and the screw again begins to rotate. This stop-and-flow process causes significant pressure fluctuations in the extrusion barrel. Because the amount of injected gas is greatly affected by the barrel pressure, the fluctuations in the barrel pressure lead to inconsistent gas dosing in the polymer melt stream. A nonuniform polymer/gas mixture is attained as a result, which is detrimental to the achievement of a uniform, fine-celled foam structure.

The aforementioned limitations of most structural foam molding machines result in foam products with undesirable properties. First, these structural foams typically have numerous large and uncontrollably formed gas pockets, especially along the weld lines, governing the maximum achievable void fraction for the final foam products. The void fraction determines how much material is saved in comparison with its solid counterpart, and it is therefore desirable to maximize the achievable void fraction. In current structural foaming technology in a low-pressure, preplasticating-type system, the achievable void fraction is typically determined by the shot size and the geometry of the product. Products with a complicated geometry have a low void fraction because it is difficult to fill the mold completely with foamed material on account of the mold's high flow resistance. In other words, when such a product is being manufactured, more material needs to be injected for the mold to be entirely filled; a product with a low void fraction is thus yielded. In contrast, products with a simple geometry have a high void fraction because it is easier to fill a mold with a straightforward shape that poses low flow resistance. If decreasing the shot size results in a higher void fraction for a given geometry, the rate of scrapping and recycling the defective products is increased because of the large and uncontrollably formed gas pockets in the final products. Second, the inconsistent and excessive gas dosing ultimately leads to the deterioration of the mechanical properties of the foam through the formation of large gas pockets. Third, the nonuniform and excessive addition of gas causes serious surface defects, such as nonuniform surface swirling, color contrast across the weld lines, and weld line traces on the part's surface.

BACKGROUND

Because of the significant advantages offered by structural foams, efforts have been made to overcome the shortcomings of structural foam molding

technology. Trexel, Inc., developed a microcellular injection-molding technology (MuCell technology) based on a reciprocating-type injection-molding machine.[8,9] A great deal of work has been done to further improve the quality of the foams created with the MuCell process. Turng and coworkers[10,11] investigated the effects of changing the process conditions on the microcellular foams. Kanai et al.[12] reported microcellular foams with a good cell structure and surface quality created by optimization of the type of material. Sporrer et al.[13] reported that a class A surface could be achieved with a breathing mold.

In 2000, Shimbo et al.[14] reported an alternative microcellular foam process using a preplasticating-type injection-molding machine. The screw plasticated the polymer while the plunger injected the polymer into the mold cavity. This method of microcellular foam molding is very similar to structural foam molding.

Another alternative foam injection-molding process was developed at IKV (Germany).[15] In this system, the gas was injected with a specially designed injection nozzle mounted between the plasticizing unit and the shutoff nozzle of a conventional injection-molding machine. To achieve a quick, homogeneous distribution of gas, the surface-to-volume ratio was maximized with a ring-shaped die that contained a torpedo. Gas was injected through both the surface of the torpedo and the inner surface of the ring-shaped die, both of which were made from porous, sintered metal. To achieve a more homogeneous polymer/gas solution, additional static mixing elements were mounted between the gas injection nozzle and the shutoff nozzle. This technology was later commercialized by Sulzer Chemtech.[16]

FUNDAMENTALS OF ADVANCED STRUCTURAL FOAM MOLDING

Structure of the advanced structural foam molding machine

This new technology[17] enables uniform gas dispersion and complete (or substantial) gas dissolution in the polymer melt, despite the nonsteady molding process. Recognizing that the stop-and-flow molding behavior inevitably causes inconsistent gas dosing, our design allows the flow of the polymer melt to continue (i.e., not to stop during the injection period). Figure 1 shows a schematic of the advanced structural foam molding machine developed at the University of Toronto.[17] This machine comprises a positive displacement pump, such as a gear pump, and an additional accumulator attached between the extrusion barrel and the shutoff valves (one shutoff valve is located before the plunger and the other is
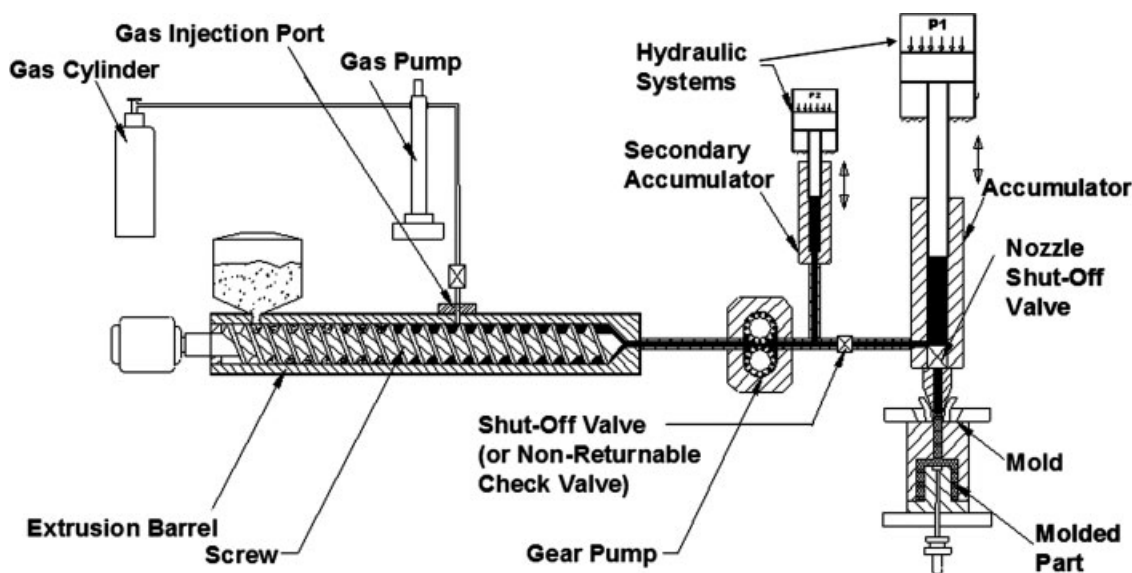
Figure 1 Schematic of the advanced structural foam molding machine (taken from ref. 17).

located at the nozzle). The approach is to completely decouple the gas dissolution step from the injection and molding operations with the positive-displacement gear pump and to maintain steady-state gas dissolution. During the injection and molding operations, the plasticating screw rotates, and the generated polymer/gas mixture accumulates in the added accumulator. After the injection and molding operations, the accumulated polymer/gas mixture moves to the plunger to be injected in the next cycle. This technology ensures that the pressure in the extrusion barrel is relatively constant and that consistent gas dosing is attained, so a uniform polymer/gas mixture is achieved regardless of the pressure fluctuations in the plunger. This technology is patented.[17]

Homogeneous distribution and complete dissolution of the blowing agent

To maintain consistent gas dosing of the polymer and to completely (or substantially) dissolve all the gas in the polymer melt, the screw must rotate at a relatively constant speed.[17] The advantages of having a constant rotational speed of the screw are two-fold. First, consistent gas dosing is easily realized because the pressure fluctuations inside the extrusion barrel are minimized. Second, maintaining a high pressure guarantees the dissolution of the injected gas into the polymer melt. A uniform polymer/gas mixture, in which the gas has been completely (or substantially) dissolved and there is a constant gas-to-polymer weight ratio, provides the basis for improved uniform, fine-celled foam structures. Figure 2 compares the foaming processes of conventional and advanced structural foam molding.

The gear pump is an essential part of the improved process because it controls the pressure in the extrusion barrel, thereby maintaining a consistent polymer-to-gas weight ratio.[17] This can be understood as follows. The pressure in the extrusion barrel will be relatively constant because of the positive displacement of the gear pump for the viscous polymer melts. Because the gas flow rate depends strongly on the barrel pressure, a constant gas flow rate can be obtained by the maintenance of a constant pressure in the extrusion barrel, as mentioned previously. The flow rate of the polymer/gas mixture can be controlled by the variation of the rotational speed of the gear pump. By the independent control of the flow rates of both the gas and the polymer/gas mixture, the polymer flow rate can also be controlled; thus, both a consistent polymer-to-gas weight ratio and a uniform polymer/gas mixture can easily be achieved by the use of the gear pump. These advantages cannot be achieved with a shutoff or nonreturnable check valve.

An additional accumulator is required to accommodate the material during each cycle's injection period so that the screw can continuously rotate and gas can be continuously injected into the melt.[17] The constantly rotating screw represents a significant difference from all previous structural foam molding technologies based on a low-pressure, preplasticating-type system. Once the pressure in the extrusion barrel is relatively stable, it becomes easier to control the flow rate of the injected gas into the polymer, and the gas can be more uniformly dispersed into the melt.

When a consistent gas-to-polymer weight ratio is achieved, the injected gas will dissolve completely if a sufficiently high pressure is maintained in both the
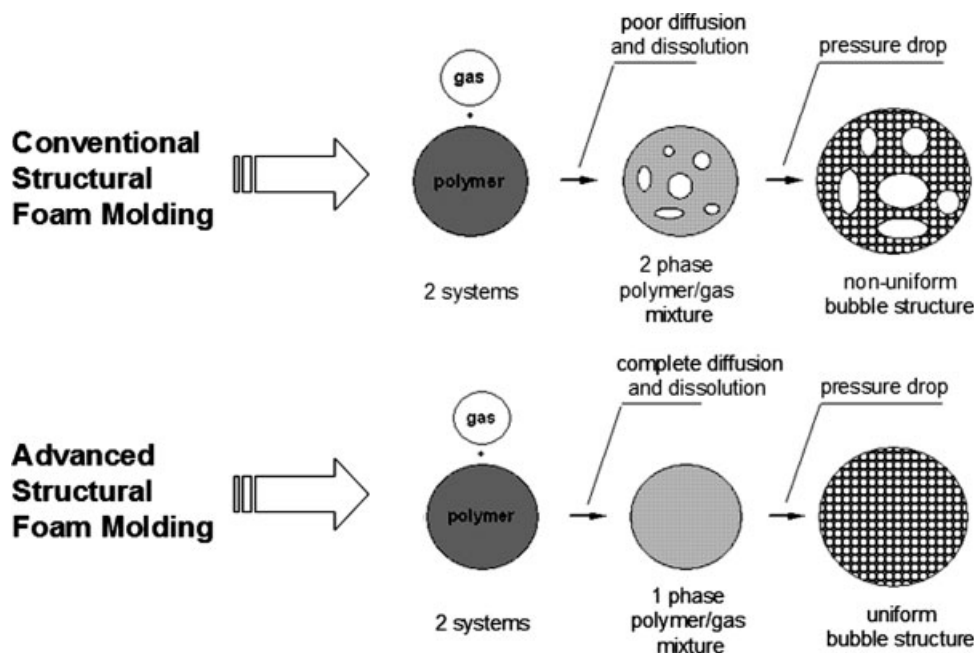
Figure 2 Foaming processes of conventional and advanced structural foam molding.

extrusion barrel and the accumulators. A sufficiently high pressure means that the melt pressure is much higher than the solubility pressure for the given amount of gas injected into the polymer melt. In addition, maintaining a sufficiently high pressure after complete dissolution of gas prevents the formation of a second phase in the polymer melt during the accumulation stage. Because the solubility pressure for the gas content necessary to produce a fine-celled structure [e.g., 1–10 MPa for 0.1–1.0 wt % N_2 in high-density polyethylene (HDPE)][18] is low compared to the pressure limit of existing low-pressure, preplasticating-type structural foam molding machines (maximum allowable pressure $\sim$ 3000 psi), a sufficiently high pressure can easily be maintained in the advanced structural foam molding machines.

EXPERIMENTAL

Materials

An HDPE resin (H5534) manufactured by Equistar Chemical (Houston, TX) was used in this study. Its density is 0.947 g/cm^3, its melting temperature is 123°C, its crystalline ratio is 66%, and its melt flow index is 34 g/10 min. Two kinds of talc were used as nucleating agents: Ultratalc 609 and Polybloc from Specialty Mineral (Bethlehem, PA). The average particle sizes of Ultratalc 609 and Polybloc were 0.8 and 2.5 μm, respectively. N_2 was used as a blowing agent.

Preparation of the HDPE/talc compounds

A 1 wt % talc master batch was prepared with an intermeshing and corotating twin-screw extruder with a screw diameter of 30 mm (ZSK-30, Werner & Pfleiderer, Ramsey, NJ; length/diameter ratio = 38 : 1). The HDPE was then dry-blended with the talc master batch in a 1 : 1 ratio to produce three variations of HDPE/talc compounds with active talc contents of 0.1, 0.5, and 1.0 wt %, respectively.

Experimental setup

The advanced structural foam molding machine consists of three subsystems: the extrusion subsystem, the injection subsystem, and the control system. The extrusion subsystem consists of a 5-hp motor (Allen–Bradley 1329R, Rockwell Automation, Cambridge, ON, Canada), a speed controller (Allen–Bradley 1336 Impact, Rockwell Automation), a 3/4″ extruder (05-25-000, Brabender, Hackensack, NJ) with a mixing screw with a 30 : 1 length/diameter ratio (05-00-144, Brabander, Hackensack, NJ) for plasticating the polymer pellets and for dispersing the injected blowing gas throughout the melt, a positive-displacement syringe pump (manufactured by ISCO, Inc., Lincoln, NE) for injecting the blowing gas, a gear pump (PEP-11, Zenith (Monroe, NC); 1.2 cc/rev) for controlling the melt flow rate, and a gas injection port for injecting the blowing gas. The injection subsystem consists of a plunger-type injection-molding machine (Mini-Jector 50, Mini-Jector Corp., Newbury, OH) for completing the injection process. The control system includes four pressure transducers

TABLE I
Summary of the Experiments

| Set | Nucleating agent | | | Blowing agent (N_2) content (wt %) |
	Type	Size (µm)	Content (wt %)	
1	No talc			0.1
2	No talc			0.2
3	No talc			0.5
4	Talc	0.8	0.1	0.1
5	Talc	0.8	0.1	0.2
6	Talc	0.8	0.1	0.5
7	Talc	0.8	0.5	0.1
8	Talc	0.8	0.5	0.2
9	Talc	0.8	0.5	0.5
10	Talc	0.8	1.0	0.1
11	Talc	0.8	1.0	0.2
12	Talc	0.8	1.0	0.5
13	Talc	2.5	0.1	0.1
14	Talc	2.5	0.1	0.2
15	Talc	2.5	0.1	0.5
16	Talc	2.5	0.5	0.1
17	Talc	2.5	0.5	0.2
18	Talc	2.5	0.5	0.5
19	Talc	2.5	1.0	0.1
20	Talc	2.5	1.0	0.2
21	Talc	2.5	1.0	0.5

(PT462B-10M-6/18, Dynisco, Franklin, MA) for detecting the pressures at different locations, 12 temperature controllers and 12 thermocouples for maintaining a consistent processing temperature in the system, a screw-speed computer control system for maintaining a consistent barrel pressure, and a timer for controlling the shot size. A cylindrical mold cavity, 0.5 in. in diameter and 1 in. long, was used in this study.

Experimental procedures

Twenty-one sets of experiments were conducted with different talc sizes, talc contents, and N_2 contents, as shown in Table I.[19] Two sizes of talc (0.8

and 2.5 µm) were used. The talc content was varied from 0.1 to 1.0 wt %, and the N_2 content was varied from 0.1 to 0.5 wt % (these relatively low levels were due to the low solubility of N_2). The processing temperature was set to 160°C along the extruder, and the temperature for the bypass nozzle and injection nozzle was set to 135°C. The mold temperature for the cylinder-shape mold was set to the room temperature. The sampling quantity for each set of experiments was 10 shots.

Foam characterization

The void fraction and the cell density were used to characterize the foam samples. The foam density was determined by the water displacement method (ASTM D 792-00). The relative density (Φ) is the ratio of the bulk density of HDPE and HDPE/talc compounds to the measured density of the foam sample. The void fraction is

$$\text{Void fraction} = \left(1 - \frac{1}{\Phi}\right) \times 100\% \qquad (1)$$

The cell density was calculated from a scanning electron micrograph. The samples were first dipped in liquid nitrogen and then fractured to expose their cellular morphology. The fracture surfaces were then gold-coated with a sputter coater to enhance their conductivity, and the microstructures were examined with a JEOL (Peabody, MA) JSM-6060. The cell density, which is defined as the number of cells per unit of volume of unfoamed material, was then determined as follows:

$$\text{Cell density} = \left(\frac{nM^2}{A}\right)^{3/2} \times \Phi \qquad (2)$$

where n is the number of bubbles in the micrograph, A is the area of the micrograph, and M is the magnification factor of the micrograph.
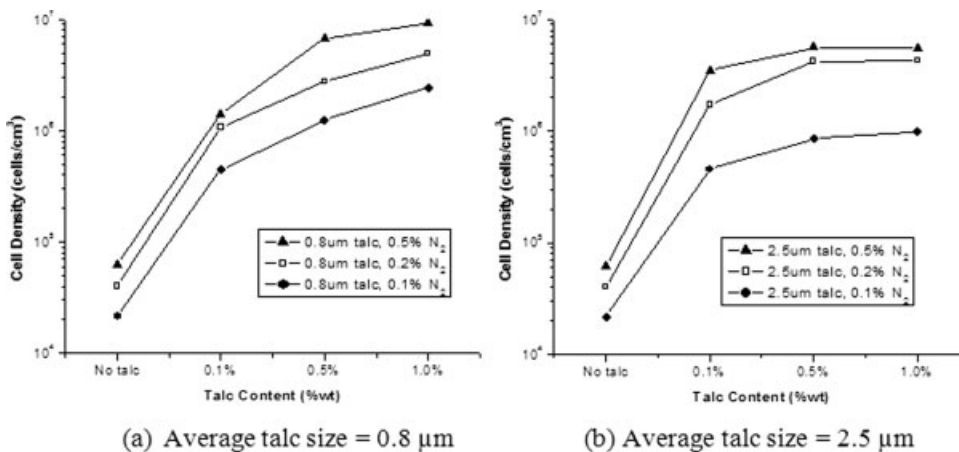

(a) Average talc size = 0.8 µm   (b) Average talc size = 2.5 µm

Figure 3 Cell density with respect to the talc content: (a) average talc size of 0.8 µm and (b) average talc size of 2.5 µm.
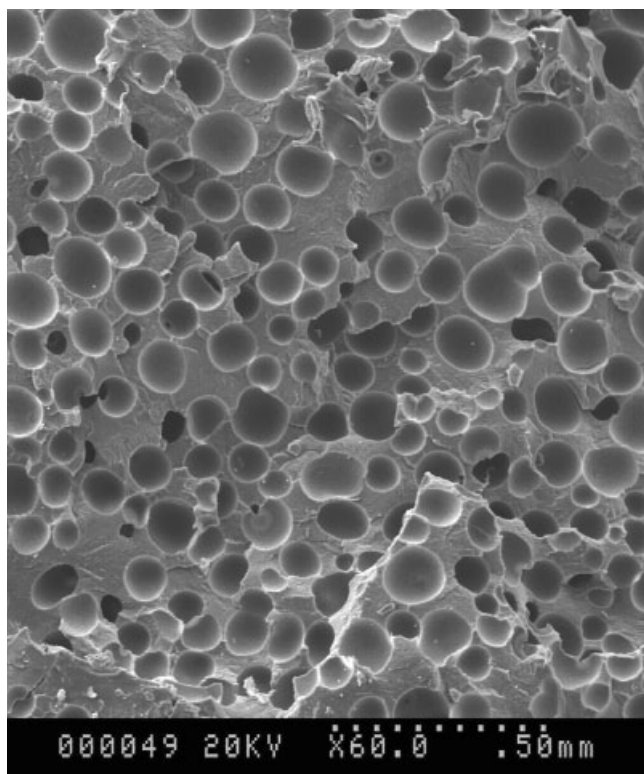
Figure 4 Typical cell morphology of the foams obtained by advanced structural foam molding [set 9: 0.5 wt % talc (0.8 μm), 0.5 wt % N_2].

RESULTS AND DISCUSSION

Cell density and cell size

The cell density results achieved with this technology (see Fig. 3) proved to be more favorable than those obtained with conventional structural foam molding techniques. For all combinations of the talc size, talc content, and N_2 content, very uniformly distributed fine-celled structures were obtained throughout the volume of the structural foams. Fig-

ure 4 shows the typical cell morphology obtained from the advanced structural foam molding. The cellular structures were very uniform even for the cases in which no talc was used, although the cell densities were relatively low, around 10^4–10^5 cells/cm^3 (i.e., cell sizes between 0.5 and 1 mm). When talc was added, the cell density increased dramatically to 10^5–10^7 cells/cm^3 (i.e., cell sizes between 0.05 and 0.5 mm), and the cell structure was more uniform. Remarkably, when the N_2 content was higher than 0.2 wt %, the cell density became greater than 10^6 cells/cm^3, even with as little as 0.1 wt % talc. These results demonstrate that the cell morphology of structural foams is improved significantly when the heterogeneous cell nucleation mechanism is used appropriately by the proper distribution of the talc particles and uniform dissolution of the gas in the melt. It is obvious that the heterogeneous nucleation mechanism is not used appropriately in existing structural foam molding systems, even with the added talc particles, because the injected N_2 gas did not dissolve uniformly in the polymer melt.

The cell density increased with increasing talc content, reaching a saturation point at 10^6 cells/cm^3. The cell nucleation behavior as a function of the blowing agent content was very different for each of the two talc particle sizes because of a larger surface/volume ratio and greater tendency of segregation for the smaller particles. Although the total number of talc particles increased by an order of magnitude as the talc particle size decreased from 2.5 to 0.8 μm, the cell density did not increase in proportion to the number of talc particles. Overall, however, as the talc content increased, the cell density increased for both talc particle sizes. Similarly, it was observed that as the blowing agent content increased, the cell density increased for both talc particle sizes. These results demonstrate that the talc particle size, talc content, and blowing agent content
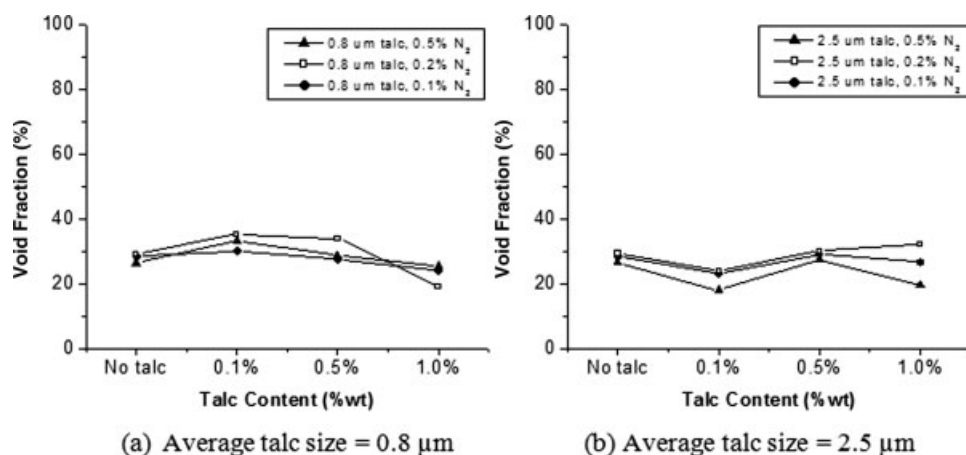

(a) Average talc size = 0.8 μm

(b) Average talc size = 2.5 μm

Figure 5 Void fraction with respect to the talc content: (a) average talc size of 0.8 μm and (b) average talc size of 2.5 μm.

significantly affect the cell density of the structural HDPE foams produced with the advanced structural foaming technology.

All cell-nucleation results for the injection-molded structural foams were comparable to results obtained in our laboratory for extrusion foams[20] made with the same plastic, the same nucleating agent, and the same blowing agent with low-pressure-drop-rate dies. This is a strong indication that the cell nucleation mechanisms of the advanced structural foam molding are exactly the same as those of conventional extrusion foaming.

Void fraction

For each set of experiments, void fractions up to 35% were successfully achieved without the formation of any large gas pockets (Fig. 5) and without the nonuniform cell structure commonly seen in conventional structural foams. Although a reduced shot size enabled an increase in the void fraction at the cost of a greater cell size, a very uniform cellular structure was achieved. This indicates that high-quality foam with a very high void fraction can be obtained from this technology. Therefore, the improved technology eliminates the scrapping or recycling of defective structural-foam products due to the formation of large gas pockets, even for foams with a very high void fraction.

The cellular morphologies were observed to be constant over a period of several hours, indicating that the injected N_2 was dispersed throughout the polymer (HDPE) melt. Therefore, this new technology eliminates the time variation in product quality due to undissolved N_2 that is commonly observed in conventional structural foams.

CONCLUSIONS

This article introduces an advanced structural foam molding technology that improves the dispersion of the blowing agent throughout the polymer matrix, thereby eliminating the drawbacks of structural foams created with the conventional process. This new technology uses a modified preplasticating-type (or piggyback) injection-molding machine. By the introduction of a way to continue the polymer matrix melt flow stream by the use of an additional accumulator and a gear pump, the processing conditions are made more consistent, and the injected gas is distributed more uniformly throughout the polymer matrix. Structural foams produced with this technology have smaller cells, a more uniform cell structure, and a larger void fraction, thus saving more material.

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