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# Study of the foaming mechanisms associated with gas counter pressure and mold opening using the pressure profiles

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## HIGHLIGHTS

- Structural foam with high quality surface is made on foam injection molding process.
- Monitoring pressure profiles at different cavity locations in foam injection molding.
- Clarification on foaming mechanism of foam injection molding with GCP and MO process.

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## ABSTRACT

We investigated the foaming mechanisms associated with the gas counter pressure (GCP) and mold-opening processes during foam injection molding for products with high quality surface. The molding process involved injecting a polymer/nitrogen solution into a nitrogen-pressurized mold cavity. The pre-loaded cavity pressure (that is, the GCP) prevented cell nucleation and growth within the polymer melt. This was the case until the GCP was released (without opening the mold) or until the melt filled the mold cavity completely. Then the cavity thickness was suddenly increased by opening the mold. In an attempt to understand the mechanism of cell nucleation and growth, we monitored the pressure profile at several locations in the mold cavity during the molding process. We found that the pressure history in the mold cavity, both as a function of space and time, was the dominant factor that determined cell morphology. By applying the GCP and the mold-opening process, the cell size uniformity was improved when compared with conventional foam injection molding. These methods did not compromise the achievable void fraction. Using GCP and the mold-opening process also significantly improved the surface qualities of the foamed parts. This was because the premature cell growth at the flow front during the mold filling stage had been eliminated.



## 1. Introduction

Foam injection molding usually involves injecting a polymer/blowing agent solution into a mold cavity, and letting the gas bubbles nucleate and grow as the solution pressure is lowered (Hornsby, 1982). The cell structure is stabilized when the polymer melt is cooled to below its transition temperature, which is usually the glass transition temperature. Foamed parts produced in this way have many advantages over their solid counterparts. These include the following: The absence of sink marks on the part's surface; a weight reduction that does not significantly compromise the mechanical properties; a lower injection pressure (that is, a lower clamping force) due to the plasticizing effect of the gaseous blowing agent; better weld line quality due to a shorter injection time and, therefore, less melt cooling, a shorter time cycle because of the enhanced cooling caused by both the cell growth and the good contact with the cold mold's surface during cooling; and a higher stiffness-to-weight ratio in the foamed parts (Hornsby, 1982; Ahmadi and Hornsby, 1985a; Hikita, 2002; Chen et al., 2008).

During the past decades, injection-molded foam products with microcellular (that is, with a cell density above $10^7$ cells/cm$^3$) or fine-celled (that is, with a cell density of between $10^4$ and $10^7$ cells/cm$^3$) structures have been produced using various foam molding technologies (Bledzki et al., 2007; Xu and Pierick, 2001; Michaeli and Habibi-Naini, 2004; Lee et al., 2009; Park and Xu, 2007; Yoon et al., 2009; Ameli et al., 2014; Chu et al., 2015;

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Shaayegan et al., 2016a). These have been widely applied in the insulation, automotive, and construction industries. However, these products have two major limitations. First, the cell sizes vary over the part area. This is mainly caused by the variable pressure and thermal history during the molding process, but it may also result from undissolved and large gas pockets in the polymer melt, which occur due to poor mixing in the plasticating unit. Second, they have a rough surface, or "swirl pattern", finish. This is because the gas bubbles, which appear at the flow front during the mold filling, are brought to the mold's surface by the well-known fountain flow effect, and they are ruptured there by shear force (Lee et al., 2009).

In 2008, in our foam injection molding study (Lee et al., 2009) we used an advanced structural foam molding system (Park and Xu, 2007; Xu et al., 2008; Bledzki et al., 2012), which involved a molding process similar to the one described above. However, the injection unit guaranteed the dissolution of the environmentally-friendly blowing agents, $CO_2$ and/or $N_2$, because it enhanced the unit's mixing and pressure controls. That study showed how cell morphology (that is, cell size and cell density) is heavily influenced by the mold cavity's pressure history. Specifically, when the cavity pressure was lower than the solubility pressure (that is, the minimum pressure needed to prevent phase separation) and the pressure before the gate was higher than that, cell nucleation occurred at the gate under a high rate of pressure drop. Thus, a high cell density resulted (Lee et al., 2009; Lee and Park, 2006). On the other hand, when the cavity pressure was higher than the solubility pressure, cell nucleation occurred inside the cavity (after the gate), under a low rate of pressure drop, which produced a lower cell density (Lee et al., 2009). It was, therefore, thought that promoting a high pressure before the gate and a low pressure inside the cavity would be the best way to generate uniform fine-celled structures. Such a pressure profile was achieved by using a mold design, a high injection speed, and proper blowing agent contents (Lee et al., 2009; Lee and Park, 2006). Thus, foams with up to a 40% void fraction and a cell density of up to $10^8$ cells/cm$^3$ were manufactured. Although this strategy still produced variable cell sizes in the melt flow direction, it did not improve the part's surface quality at all.

The surface quality of structural foams influences not only their aesthetics, but also the molded parts' mechanical and optical properties (Ahmadi and Hornsby, 1985a; Pantani et al., 2005). To see how blowing agents affected the surface qualities of injection-molded foams, Turng et al. compared the surfaces of foams produced with supercritical nitrogen and thermoplastic microsphere (Peng et al., 2012). They found that with the correct amount of thermoplastic microsphere, the part's surface quality was improved when compared with parts produced using supercritical nitrogen. However, it was still not possible to produce parts with a class-A (that is, a visually defect-free) surface quality. To obtain a class-A surface quality with foamed parts, Chien et al. (2004) and Turng and Kharbas (2004) used a co-injection molding process to cover the foamed part with a solid layer, and they were able to successfully produce foams with a solid-like surface. Another popularly investigated way to achieve a class-A surface quality is to integrate special mold operations, such as gas counter pressure (GCP) (Chen et al., 2011, 2012, 2013; Bledzki et al., 2004; Shaayegan et al., 2016b; Olabisi, 1981; Shibuya et al., 1990), into the structural foam molding process. This is done to prevent cell nucleation and growth at the flow front during the filling stage. Li et al. analyzed the influence of the GCP process on the foaming behavior during filling. They suggested that controlling the critical melt flow front pressure could effectively eliminate the surface swirls on microcellular injection-molded parts (Li et al., 2014).

On the other hand, it has been suggested in several literatures (Shaayegan et al., 2016b; Holdredge, 1985; Kyritsis and Simmonds, 1974; Ameli et al., 2015) that GCP works better in conjunction with the mold-opening process. This causes an increase in the mold cavity thickness after the mold is filled, and thus it increases the pressure drop rate (Chen et al., 2011). Otherwise, the high mold cavity pressure induced by the GCP, which is higher than the solubility pressure, will inhibit cell nucleation and growth during the filling stage. Wu and Lee (1994a, 1994b, 1994c) systematically investigated the influence of GCP and the processing conditions on the structural foam molding of high-impact polystyrene (HIPS). When GCP was applied, they found that the surface roughness was significantly reduced. Sporrer et al. (2006) reported that a class-A surface and a high void fraction could be achieved in foaming by using a breathing mold (that is, a mold with an opening). In addition, Ishikawa and Ohshima (2011) investigated the foaming behavior in a mold that had an expandable mold cavity (that is, a so-called core-back mold) by placing a visualization system and a pressure transducer in one position in the mold cavity. They varied the gas concentration and the speed of the core-back process. Then, they compared their experimental results with the cell nucleation and growth models that had been derived from batch foaming. However, none of these studies attempted to measure the real-time pressure history at various locations in the mold cavity, and to relate this to the molded parts' cell morphology. Little attempts had been made to elucidate the fundamental foaming mechanism by monitoring the right pressure profile for a fine-cell formation from GCP and the mold-opening process, although Shaayegan et al. and Ahmadzai et al. used a visualization system to investigate foaming phenomena in the thermoplastic injection-molding process (Shaayegan et al., 2016a, 2016b, 2016c, 2016d, 2016e; Ahmadzai et al., 2014).

In our study, we have tried to clarify the foaming mechanism related to the structural foam molding process incorporating GCP combined with the mold-opening step by measuring the real-time pressures at different points in a melt-flowing channel. We have used the advanced structural foam molding system from our previous study (Lee et al., 2009). The polymer materials and the blowing agent were high-density polyethylene (HDPE) and $N_2$, respectively. We recorded the pressure profiles inside the mold cavity under various processing conditions in order to elucidate the relevant foaming mechanisms while we obtained the structural foams with class A surface. We have presented the results for GCP processing without mold opening first. Then, for comparison, we have shown the results for GCP processing with mold opening.

## 2. Gas counter pressure (GCP) processing background

GCP foam molding is meant to supplement the single-nozzle structural foam molding process to enhance the surface finish of parts. It requires that the mold be charged under pressure. The counter pressure in the mold cavity suppresses any premature bubble expansion at the leading edge of the flow front, thereby preventing any surface swirls that would result from the fountain effect (Ahmadi and Hornsby, 1985a; Sporrer et al., 2006).

GCP foam molding was developed by a team of researchers at the Institute for Metal Science and Technology in Bulgaria (Ahmadi and Hornsby, 1985b). In this process, a pressure-tight mold is charged with GCP prior to the injection of plastics. After proper in-mold counter-pressure is applied, a predetermined shot containing a dispersed and compressed blowing agent is injected into the mold. During the mold filling, the venting should be controlled so that the counter-pressure remains consistent while the unfilled mold volume is reduced. Immediately following the mold filling, the GCP is released so that the expanding foam can fill the cavity's remaining volume, thereby generating a foamed part with a solid, smooth skin (Ameli et al., 2015).