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Study of the bubble nucleation and growth mechanisms in high-pressure foam injection molding through *in-situ* visualization

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ABSTRACT

Although major efforts have been made to uncover the complex mechanisms of bubble nucleation and dynamics in foam injection molding, most theories and interpretations still require additional experimental verification. An innovative visualization mold was employed with which the mechanisms of bubble nucleation and growth in high-pressure foam injection molding were investigated. For the first time, the development of the cell structure in high-pressure foam injection molding was comprehensively explored and experimentally verified via *in-situ* visualization using polystyrene and supercritical carbon dioxide system. Two bubble-nucleation mechanisms were observed, namely, the nucleation due to a pressure drop at the gate during filling, and the nucleation due to melt shrinkage in the cavity after filling. It was the cavity pressure that determined which bubble-nucleation mechanism was dominated between these two in high-pressure foam injection molding. The final cellular structure and morphology of the foamed parts were, in turn, determined by the governing bubble-nucleation mechanism. It was concluded that a melt packing pressure is required to re-dissolve the bubbles nucleated at the gate back into the melt, and that a larger packing pressure was needed with a higher cell density by increasing the injection speed, the gate resistance, or the blowing-agent content. Because of the high resistance in the narrow cavity, the bubbles within the cavity were not pressurized uniformly, when the packing pressure was applied. A higher cell density increased the compressibility of the two-phase gas–melt mixture, aggravating the non-uniformity of the pressure in the cavity. Consequently, the bubbles far from the gate could not be pressurized immediately, and thereby could not dissolve into the polymer melt quickly. Additionally, the lower temperature of the melt far from the gate further delayed the permeation of gas into the polymer.

1. Introduction

The global energy crisis and environmental pollution concerns are forcing industries to find ways to manufacture lightweight products by using less materials and consuming less energy while obtaining comparable and/or superior properties to their conventional solid counterparts. In this context, the foam injection molding (FIM) technology is one of the most promising available technologies. This is because of its capability to produce low-density parts with high geometrical accuracy and a high stiffness-to-weight ratio in rapid production cycles [1]. However, achieving a uniform and high-cell-density

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microstructure, which is critical for obtaining superior mechanical properties in foamed plastics [2], is challenging in FIM. The difficulty arises from the absence of a clear and comprehensive understanding of cell nucleation mechanism(s) and the complexities of bubble dynamics in FIM. In this regard, extensive research has been carried out devoted to investigating: (i) the effect of processing parameters on the microstructure and morphology development [3–6], (ii) the effect of micro- or nano-sized particles on cell nucleation [7–10], and (iii) the mechanical properties of foamed parts in low-pressure FIM [11–14]. In addition to the experimental works, numerous theoretical and numerical studies have been done to model and predict the development of bubbles considering different processing parameters [15–21].

While a great deal of research has been conducted to improve the cellular structure [1,5,7], the surface quality [22–24], and the physical and mechanical properties of FIM parts [25–29], a few studies were dedicated to the investigation of governing mechanisms of bubble nucleation and growth *per se*, especially in high-pressure FIM experiments. Lee et al. proposed strategies to obtain structural foams with a high void fraction and improved structure uniformity in low-pressure FIM based on the mold cavity pressure profile, by inducing proper gate-nucleated cells [1]. Wang et al. observed that the shape of the formed bubbles in FIM experiments shifted from elongated to circular bubbles, parallel to the flow direction, by increasing the shot size [30]. They argued that while elongated bubbles were formed during filling, the circular bubbles were formed during the cooling stage [30].

Although significant contributions have been made for a better understanding of complicated FIM phenomena, structure characterizations were performed mainly on the final cell morphology using empirical approaches. Thus, the details of the governing mechanism(s) remain unclear and not fully understood. Additionally, most of the theoretical simulations were not experimentally verified. Therefore, *in-situ* observation of foaming phenomena drew significant attention from researchers, which was a method utilized earlier to study various aspects of injection molding [31–35], or to uncover the underlying mechanisms in simpler foaming processes such as static foaming [36,37], foaming under an extensional stress [38,39], and foaming under a shear stress [40]. Online monitoring of the FIM phenomena would provide far greater insights into the governing mechanisms of each stage of the foaming process under different conditions.

A few attempts have been made to study the bubble nucleation and growth behaviors in FIM using direct visualization techniques. Villamizar and Han investigated the bubble dynamics under various processing parameters in low-pressure conventional FIM, and bubble collapse using melt packing pressure [41]. Mahmoodi et al. visualized and modeled the non-isothermal growth and collapse of carbon dioxide (CO_2) bubbles in polystyrene (PS) [42,43]. Ishikawa and coworkers visualized the formation of CO_2 and nitrogen (N_2) bubbles in polypropylene in high-pressure FIM followed by mold opening. They observed that the number density and the rate of formed bubbles were increased by the core-back rate and by the percentage of the dissolved gas in the melt. In addition, the number density of nucleated bubbles was much higher using N_2 compared to CO_2 in their experiments [44,45]. Based upon the melt pressure inside the mold cavity in FIM, Yamada et al. observed that the bubbles formed during filling sustained in the melt at regions with lower cavity pressures, while bubbles at high pressure and elevated temperature regions of the central core shrank completely and new bubbles were reformed during cooling. This resulted in a multilayer cellular structure in the core region of the foam injected parts [46].

Despite numerous efforts to study the cellular structure and morphological development in FIM, there are still ambiguities about the structural development in the high-pressure FIM. In the current research, a unique *in-situ* visualization mold, equipped with 4 pressure sensors, was employed to investigate the mechanisms of bubble nucleation and growth in the high-pressure FIM process in full detail. A series of critical experiments were carried out using PS and CO_2 as a case example. The cell nucleation mechanisms identified from this study provide essential guidelines to optimize the processing conditions for obtaining more uniform and predictable cellular structures in high-pressure FIM.

2. Theoretical description of low- and high-pressure foam injection molding

In FIM process, a homogeneous melt/gas mixture is injected into a closed mold cavity and the expandable melt/gas mixture generates a foam structure. The bubble-nucleation mechanism strongly depends upon the type of FIM process, the type and amount of the blowing agent, the type and amount of the nucleating agent, and the resistance of the gate.

In low-pressure FIM such as the conventional structural foam molding technology [1,15, 41], a short-shot is typically used to partially fill the mold cavity, and bubble nucleation generally occurs due to the pressure drop obtained across the gate. When the melt/gas mixture, under a pressure higher than the gas solubility pressure before the gate, enters the mold cavity and experiences a pressure lower than the gas solubility pressure, cell nucleation occurs. In this case, the relative pressure level before and after the gate is a key parameter in controlling the bubble nucleation rate.

While a high void fraction, up to 35%, can be easily achieved in low-pressure FIM, the structure suffers from a considerable non-uniformity at different locations of the foamed part. This is attributed to the varying cell-nucleation rates from the changing pressure after the gate during mold filling, to the pressure gradient, to the temperature gradient, and to the coalescence of the growing cells [1]. The pressure after the gate (defined as the "after-gate" pressure in this paper) changes as a function of the (mold filling) time. In the beginning, the mold cavity is empty; hence the after-gate pressure is equal to the ambient pressure (unless gas counter pressurized). As the melt/gas mixture enters the mold cavity, its temperature decreases (due to the contact with the cold cavity surface) and its viscosity increases, which creates more resistance and thereby increases the after-gate pressure. While the after-gate pressure is lower than the solubility pressure, cell nucleation will still occur at the gate, where the pressure goes below the solubility pressure at the gate. But since the pressure difference between the solubility pressure and the after-gate pressure (i.e., the driving force for cell nucleation) decreases, the cell