Materials Research Express

PAPER

The effect of injection process for microcellular foaming on the cell morphology and surface quality of Polyamide 6

Tuanhui Jiang, Heng Zhang, Xiangbu Zeng, Chun Zhang, Wei Gong and Li He

Abstract

Microcellular foamed polymers have been widely used in the traffic field. However, it is difficult to successfully manufacture microcellular foamed products that simultaneously possess good cell morphology, small size, high cell density, and great surface quality. In this paper, polyamide 6 (PA6) injection microcellular foams were manufactured via short-shot and core-back foaming process to investigate the effect of the foaming process on cell quality and surface quality. Results showed that the core-back injection PA6 foams possessed a smaller cell size, higher cell density, lower cell deformation, and greater surface glossiness than short-shot foams. The cell density of core-back PA6 microcellular foams reached to 12.5 × 10⁵ cell/cm³, which is almost 3.5 times greater than that of the short-shot foams when the weight reduction was 10%. The PA6 microcellular foams manufactured via the core-back foaming process had higher surface glossiness with different weight reduction, whereas the surface glossiness of short-shot microcellular foams dramatically declined with an increase in weight reduction. Hence, the core-back foaming process can be used to fabricate microcellular foamed polymers with good cell morphology, small size, high cell density, and fine surface quality under high weight reduction; this was beneficial for producing products that have good surface quality and high weight reduction and are used in automobiles, high-speed trains, and airplanes to reduce energy consumption.

1. Introduction

Microcellular foamed polymer materials are foamed materials that have uniform cells and a cell diameter of less than 100 μm; microcellular foamed polymer materials have been widely used in automobiles, aerospace applications, and household appliances because they have the advantages such as being light weight, consuming less energy, being lower cost, and having sound insulation characteristics. Microcellular foaming molding technology mainly includes batch processing [1–3], solid-state molding [4–6], extrusion [7–11], and injection molding [12–15]. Because of its high production efficiency and the ability to form complex and precise products with one-time, Microcellular injection molding has many industrial applications because it has high production efficiency and products that are both complex and precise can be formed. Thus, microcellular injection molding has attracted the attention of many companies, scientific research institutions, and universities for in-depth research [16–18]. Microcellular foam injection molding technology is mainly divided into two processes: core-back foaming [19–21] and short-shot foaming [22–24].

Polyamide (PA) possesses good mechanical properties, low-temperature resistance, wear-resistance, and self-lubricating characteristics; it has been widely used in automobile parts, such as chassis protection shells, front-end frames, engine covers, and intake manifolds [25, 26]. With the development of lightweight automobiles, the lightweight of PA components has become an important research field. Yuan et al. used SCF N₂
as a blowing agent to study the effects that short-shot injection molding has on the PA6/nanocomposite; the results showed that the PA6/nanocomposite had a smaller cell size, better uniformly distributed cells, and higher tensile strength than neat PA6 [27]. Hwang et al. used CO$_2$ as a foaming agent to study the short-shot injection molding process of PA6/montmorillonite (MMT) composites; the results showed that adding MMT to PA6 decreased the mean cell size and improved the mechanical strength and thermal stability [28]. Wang et al. prepared glass fiber-reinforced polyamide foams using the short-shot foaming process, and the results showed that a slow injection speed, increased injection temperature, and increased injection volume were beneficial for increasing the tensile strength; meanwhile, the dielectric constant decreased when a microcellular foam structure was created [15]. Ruiz et al. investigated the cell morphology of microcellular foamed polypropylene that was prepared using the core-back foaming process and gas counter pressure technology with chemical foaming agents. It was found that injection time affected the cell structure, and the material formulation (especially the type of foaming agent used) controlled the average cell size; also, good surface quality can be obtained through the combination of core-back foaming and gas counter pressure [29]. Lee et al. researched the foaming mechanism of high-density polyethylene via the combination of core-back foaming and gas counter pressure; it was found that the key parameter was the pressure in the mold cavity as a function of position and time, which determined the morphology of the cells. Compared with the ordinary short-shot foaming process, the combination of core-back foaming and gas counter pressure improves the uniformity of the cell size [30].

To date, as far as we know, a large number of studies have almost all focused on the study of cell size, morphology, and distribution, and there has been little research reported regarding the effect that foaming has on the surface quality of microcellular foamed parts. In this paper, chemical foaming masterbatch was used as a gas source, PA6 microcellular foamed materials with different weight reductions were prepared via short-shot foaming and core-back foaming, and the influences of these two processes on the cell morphology and surface quality of the parts were investigated. This study provides theoretical guidance and experimental support for improving the surface quality of injection molding microcellular foamed parts and provides technical guidance for developing new spray-free processes for lightweight automotive parts.

### 2. Experiment

#### 2.1. Experimental materials

Polyamide 6 (PA6: M2500i, melt index of 26.4 g/10 min (235 °C, 2.16 kg), density of 1.13 g/cm$^3$) was obtained from Guangdong Xinhui Meida Co., Ltd. Chemical foaming masterbatch (F-70, gas production volume of 35 ml g$^{-1}$) was obtained from Eiwa Fine Chemical Industry (Changshu) Co., Ltd.

#### 2.2. Sample preparation

PA6 pellets were placed in a dryer (SHD-12, SHINI PLASTICS TECHNOLOGIES, INC.) for 4 h at 105 °C, mixed with foaming masterbatch in a mass ratio of 98:2, and then added to the injection hopper of an injection molding machine (TTI-205Ge-420, Donghua Machinery Co., Ltd.). The temperature gradient of the barrel from the hopper to the nozzle was 200-220-230-240-250-250-250 °C. The injection speed was 30%, and the injection pressure was 40 bar. The mold temperature was 80 °C, and cooling time was 25 s. Foaming samples with different weight reductions (0%, 5%, 10%, 15%, 20%, and 25%) were prepared via short-shot foaming and core-back foaming, and the mold cavity pressure was recorded using a pressure sensor (6190CAG, KISTLER Corporation). The mold cavity was a rectangular box with a length, width, and thickness of 270 mm, 175 mm, and 4 mm, respectively. The selective processing parameters were listed in table 1.

### Table 1. Microcellular foam injection molding process parameters.

| Parameters          | Value (short-shot) | Value (core-back) |
|---------------------|--------------------|-------------------|
| Injection temperature (°C) | 250                | 250               |
| Injection pressure  (bar)    | 40                 | 40                |
| Injection rate (%)         | 30                 | 30                |
| Shot size (cm$^3$)         | 180.5, 171, 161.5, 152, 142.5 | 180.5, 171, 161.5, 152, 142.5 |
| Core-back distance (mm)    | /                  | 0.2, 0.4, 0.6, 0.8, 1.0 |
| Core-back speed (mm s$^{-1}$) | /                  | 20                |
| Weight reduction (%)       | 5, 10, 15, 20, 25  | 5, 10, 15, 20, 25 |
| Cooling time (s)           | 25                 | 25                |
2.3. Testing and characterization

Characterization of cell morphology. The foaming sample was cut into a spline with a length of 80 mm and a width of 10 mm, as shown in figure 1. A 2 mm deep notch was made using a notch sample maker; the sample was then soaked in liquid nitrogen for 3 h and then taken out to break. Then, the cell morphology was observed on a scanning electron microscope (KEKY-EM6200, KYKY Technology Co., Ltd.) after spraying gold.

Apparent density measurement. According to the ISO 1183 standard. The density at least 5 samples was tested on an electronic analytical balance (XS205, Mettler-Toledo), and the average value was calculated.

Cell size characterization. Image-Pro Plus software was used to calculate the average cell diameter, cell density, and the long and short axes of the cells in the brittle section SEM image, according to formulas (1), (2) and (3), respectively.

\[
D = \frac{1}{n} \sum_{i} D_i \quad (1)
\]

\[
V_f = 1 - \frac{\rho_f}{\rho_0} \quad (2)
\]

\[
N_0 = \left[ \frac{n}{A} \right]^{\frac{1}{2}} \left[ \frac{1}{1 - V_f} \right] \quad (3)
\]

In the above formula, \(D\) is the average cell diameter (μm), \(n\) is the number of cells in the SEM image, \(V_f\) is the porosity, \(\rho_f\) is the foamed sample apparent density (g/cm\(^3\)), \(\rho_0\) is the unfoamed sample apparent density (g/cm\(^3\)), \(N_0\) is the cell density (cell/cm\(^3\)), and \(A\) is the electron microscope photo area (cm\(^2\)).

Characterization of cell deformation. The long-axis (L) and short-axis (B) of the deformed cell were statistically averaged, and the deformation \(F\) was calculated according to formula (4).

\[
F = \frac{L - B}{L + B} \quad (4)
\]

Surface gloss measurement. The surface gloss measurement follows ASTM D523 standard, using a surface gloss meter (JFL-BZ60, Tianjin Jinfulun Technology Co., Ltd.). The measurement position is shown in figure 1(c). The value appearing on the surface gloss meter is recorded as the surface gloss (GU) and 5 samples were tested to calculate the average surface gloss value.

2.4. Core-back and short-shot

Core-back Microcellular injection molding process is a novel technology to further increase the polymer foam’s weight reduction. In the core-back foaming process (1a), a full-shot is normally used to fill out the mold cavity.
with a gas-charged melt. Once the filling stage is complete, the mold cavity expands in the thickness direction for a certain distance at a set opening speed, which creates a pressure drop. Therefore, a large number of bubbles are formed. The core-back speed and the core-back distance are two major set parameters for core-back foaming process that directly affect the cell density and the weight reduction of the final foam, respectively. In the short-shot foaming process (1b), the gas-charged melt partially fills the mold cavity and then fills up the mold cavity via the formation and growth of cells.

3. Results and discussion

3.1. Effect of foaming process on the cell morphology

Figure 2 shows the cell morphology of the microcellular foamed PA6 material with different foaming processes. From comparing a low-magnification SEM image of microcellular foamed PA6 prepared via short-shot foaming and core-back foaming, it can be seen that only the short-shot foamed material with a weight reduction of 25% had large droplet-like cells at the interface between the foam and the skin layer (figure 2(e)). When the weight reduction reached 25%, the volume of gas-charged PA6 melt injected into the mold cavity was minimized, and so, the mold reserve space was maximized in the short-shot foaming process. The cell formed rapidly in the front of the melt, and then in the core layer cells rapidly grew because the melt flow filled the mold; at the same time, the fast cooling rate in the skin layer froze the elongated cells and to a certain extent limited the rebound of the elongated cells. Therefore, larger droplet-shaped cells formed at the interface between the foam and the skin layer [31].

When the weight reduction was 5%, the foaming area and the cell density were small for samples that were formed via both the short-shot and core-back foaming processes. In short-shot foaming, the average cell size gradually increased, and the distance between cells decreased with increasing weight reduction; however, the cell distribution was uneven. In the short-shot foaming process, the cells ruptured and merged as the weight reduction increased to 15% (figures 2(c1)–(e1)). In the core-back foaming process, the average cell size gradually increased, and the distance between cells decreased when the weight reduction exceeded 5%. The cell shape was relatively regular and tended to be round, and only a few cells merged when the weight reduction was 20% (figure 2(i1)). From comparing figures 2 (a2)–(j2), it is seen that the cell size distribution gradually broadened when the weight reduction was more than 5% in samples that were formed both via short-shot and core-back foaming. However, the cell size and cell size distribution of PA6 microcellular foams that were manufactured via core-back foaming were smaller and narrower than that samples that were prepared via short-shot foaming at
the same weight reduction, indicating that injection microcellular PA6 foams that were fabricated via core-back foaming had more uniform and small cells. Figure 3 shows statistical data for the cell parameters and skin thickness of PA6 microcellular foamed materials with different values of weight reduction under the conditions of short-shot foaming and core-back foaming. According to the analysis shown in figure 3(a), it is seen that the cell size of the PA6 microcellular foams that were prepared via short-shot foaming increased linearly with an increase in weight reduction. However, the cell size of PA6 microcellular foams that were manufactured via core-back foaming first decreased and then increased with an increase in weight reduction, and a minimum cell size of 50.51 μm was obtained when the weight reduction was 10%. The cell size of microcellular foams that were fabricated via core-back foaming was smaller than that of samples fabricated via short-shot foaming when the weight reduction exceeded 5%.

The cell density first increased and then decreased with an increase in the weight reduction, as seen in figure 3(b). The cell density of PA6 microcellular foams that were prepared via core-back foaming reached $12.5 \times 10^5$ cell cm$^{-3}$, which was almost 3.5 times greater than that of the samples that were prepared via short-shot foaming when the weight reduction was 10%. The cell density of the PA6 microcellular foams that were fabricated via core-back foaming was almost unchanged when the weight reduction was increased from 10% to 20%, but the cell size gradually increased slightly. It was suggested that almost none of the cells ruptured and merged when the weight reduction was 10%–20%. When the weight reduction reached 25%, the cell density suddenly dropped to $7.22 \times 10^5$ cell cm$^{-3}$, which indicated that cells ruptured and merged during the rapid cell growth when the weight reduction exceeded 20% [32]. However, the cell density of PA6 microcellular foams that were manufactured via short-shot foaming only reached a maximum of $9.91 \times 10^5$ cell cm$^{-3}$, when the weight reduction was 20%. Furthermore, the cell density of PA6 microcellular foams fabricated via core-back foaming was significantly higher than that of samples fabricated via short-shot foaming after the weight reduction exceeded 5%. The classical nucleation theory predicts that the cell nucleation rate $N$ is given by:

$$N = C_0 f_0 \exp \left( - \frac{\Delta G}{KT} \right)$$

where $C_0$ is the concentration of gas molecules, $f_0$ is the frequency factor for gas molecules joining the nucleus, $K$ is the Boltzmann’s Constant, $T$ is the temperature in K, and $\Delta G$ is the activation energy. The activation energy for nucleation is given by:

$$\Delta G = D G$$

Figure 3. Cell parameters of PA6 microcellular foams that were manufactured via short-shot and core-back foaming with different reduction: (a) cell size, (b) cell density, (c) cell deformation, and (d) skin thickness.
\( \Delta G = \frac{16 \pi \gamma^3}{3 \Delta P^2} \)  

\( \gamma \) is the surface energy of the polymer and, \( \Delta P \) is the pressure drop of the gas/polymer solution. The effect of the pressure drop on the cell nucleation density can be qualitatively assessed from equations (5) and (6).

Equation (6) shows that a higher drop in pressure leads to a lower activation energy barrier, which leads to a higher nucleation rate, as indicated by equation (5). In microcellular injection molding, the drop in pressure is approximately the pressure of the mold cavity. Also, the pressure established in the mold cavity via core-back foaming is much higher than the pressure established via short-shot foaming (as seen in figure 7), and thus, PA6 microcellular foams that were fabricated via core-back foaming had higher cell density [7].

The cell deformation of PA6 microcellular foams that were prepared via the two foaming processes shows two different trends with an increase in weight reduction, as seen in figure 3(c). Cell deformation increased linearly with an increase in weight reduction in samples prepared via short-shot foaming, whereas the cell deformation in the samples prepared via core-back foaming gradually decreased. The cell deformation of PA6 microcellular foams that were fabricated via short-shot foaming was 3.85 times greater than that of the samples that were fabricated via core-back foaming when the weight reduction reached 25%; this indicates that the cells were more regular and had a smaller degree of deformation under the core-back foaming process. The thickness of the skin layer in the PA6 foams that were prepared via short-shot and core-back foaming was not much different when the weight reduction was less than 15%. When the weight reduction was continually increased to 20% and 25%, the skin layer of the samples that were prepared via core-back foaming was thinner; specifically, the core layer had a larger foaming range. From the analyses discussed above, the PA6 microcellular foams that were prepared via core-back foaming had a more uniform cell distribution, smaller size, higher cell density, and a smaller degree of cell deformation under the same weight reduction conditions; this indicates that the core-back foaming process was better than the short-shot foaming process.

### 3.2. Influences of different foaming processes on the surface quality of PA6 microcellular foams

Results of surface light microscopy of PA6 microcellular foams are presented in figure 4. As the weight reduction increased in the short-shot foaming process, the gas mark and silver streaks on the surface of the foams gradually increased (figures 4(a)–(e)). When the weight reduction was 5%, there was still a small amount of gas marks although the surface was flat, as seen in figure 5(b). The gas marks on the sample surface increased significantly when the weight reduction reached 15%, and the gas marks on the surface were more serious when the weight reduction was further increased to 25%. However, the surface of the microcellular foams that were fabricated via core-back foaming was still flat without obvious gas marks, silver streaks, and pits when the weight reduction was increased; this was close to the surface quality of the unfoamed PA6 material.

To more clearly characterize the effects that different foaming process conditions have on the surface of PA6 foaming material, SEM was used to characterize the surface of samples that were prepared via short-shot and core-back foaming, and the results are shown in figure 5. Figure 5(a) is a surface SEM image of the unfoamed PA6 as a control group. Because the processing accuracy of the mold is \( \pm 5 \, \mu m \), vertical stripes of tool cutting marks are seen on the surface of the unfoamed PA6 sample. Figures 5(b)–(f) shows SEM images of the surface of short-shot foaming PA6 materials with different weight reduction. It is seen that vertical and disordered stripes appeared on the surface of short-shot foaming microcellular foams, and these stripes became denser and more turbulent with an increase in weight reduction. When the weight reduction reached 25%, an abundance of deeper grooves and holes appeared on the surface. Microcellular foamed materials that were prepared via core-back foaming had no vertical and disordered stripes on the surface; only the cutting marks formed during the mold processing were visible, and there were the same as for the unfoamed PA6 surface. The surface morphology
hardly changed with an increase in the weight reduction, and this indicates that the surface of the PA6 microcellular foamed material that was prepared via core-back foaming was remarkably better than that of the material that was prepared via short-shot foaming.

To quantitatively characterize the surface quality of PA6 microcellular foams that were manufactured via core-back foaming and short-shot foaming with different reductions, the surface glossiness of microcellular foams was tested, as seen in Figure 6. The surface glossiness of the short-shot foamed sample decreased rapidly at first, and it slowly decreased after the weight reduction exceeded 15%, as seen in Figure 6(a). Therefore, the surface quality of PA6 microcellular foams became worse as the weight reduction increased during short-shot foaming. The surface glossiness dropped to 20.8 when the weight reduction increased to 20%; this was a reduction of 38.8% compared to unfoamed PA6. Moreover, the weight reduction further increased to 25%, the surface glossiness decreased to 19.1, which was a reduction of 43.8% compared to unfoamed PA6. This seriously deteriorated the surface quality of microcellular foamed PA6 materials that were prepared via short-shot foaming. However, with an increase in the weight reduction of the foamed sample, astonishingly, the surface glossiness of microcellular foamed samples that were manufactured via core-back foaming was stable with values between 31 and 32. This is only a reduction of about 6% compared with the surface glossiness of unfoamed PA6, indicating that the PA6 microcellular foams that were fabricated via core-back foaming had a relatively stable surface quality and almost no gas marks on the surface. Interestingly, the surface glossiness of the microcellular foams that were prepared via core-back foaming does not deteriorate with a thinning of the skin layer thickness, as seen in Figure 6(b). Also, the surface glossiness of PA6 microcellular foams that were prepared

Figure 5. SEM images of surface of PA6 samples prepared via different foaming process and with different reduction weights: (a) neat PA6 without foaming, (b)–(f) short-shot foaming, and (g)–(l) core-back foaming. The number in the lower-left corner represents the weight reduction.
via short-shot foaming decreased linearly with a thinning of the skin layer. Furthermore, the surface glossiness deteriorated sharply as the thickness of the skin layer decreased when the thickness of the skin layer was less than 1.44 mm.

From the above analysis, it can be seen that the surface quality of PA6 microcellular foams that were prepared via short-shot foaming deteriorated sharply with an increase in the weight reduction. The surface of PA6 microcellular foams that were manufactured via core-back foaming have good surface glossiness, and the surface glossiness does not deteriorate with an increase in the weight reduction; specifically, the surface quality of the PA6 microcellular foams that were prepared via core-back foaming was much better than that of the samples that were prepared via short-shot foaming.

3.3. Mechanism analysis of the foam quality and surface quality of PA6 microcellular foams

The pressure curves and pressure peak of the PA6 melt in the mold cavity with short-shot and core-back foaming are shown in figure 7. The pressure of the mold cavity reached more than 20 MPa in the core-back process, demonstrating that a high-pressure field was established. Because higher mold cavity pressure increases the solubility of a gas, even a small amount of gas escapes into the mold during the PA6 melt filling process, and this is also redissolved into the PA6 melt under higher pressure [30, 33–35].
Different from the core-back foaming process, the PA6 melt did not completely fill the entire mold cavity in the short-shot foaming process. Also, a part of the cavity space is left for the PA6 melt to foam. The pressure established in the mold cavity after short-shot foaming injection is very small, and the melt pressure in the mold cavity decreased rapidly with an increase in weight reduction. When the weight reduction was 5%, the cavity pressure peak was 7.2 MPa; when the weight reduction was increased to 10%, the cavity pressure peak was only 1.6 MPa. When the weight reduction was increased to 25%, the cavity pressure peak was only 1.2 MPa, and the cavity pressure was reduced by 83% compared to the sample with a 5% weight reduction. Because the pressure established in the mold cavity is extremely small (Figure 7), the gas-charged PA6 melt immediately nucleated and grew when PA6 melt was injected into the mold cavity under the short-shot foaming process. The front PA6 melt was first foamed, and it quickly ruptured because of the smallest pressure in the mold cavity and low PA6 melt strength. Meanwhile, the inertia flow that was generated via the injection and impetus produced by cell rapid growth moved the broken cells at the front of the PA6 melt forward. Because of the low mold temperature and the laminar flow phenomenon of the PA6 melt, the core layer has the largest flow velocity and the skin layer has the smallest flow velocity. Therefore, the ruptured cell at the front is continuously moved to the skin layer. The difference in the speed of the melts in different layers caused the ruptured bubble to elongate and freeze in the skin layer, as shown by a schematic diagram in Figure 8(b). When the weight reduction is greater, less PA6 melt filled the mold and more space in the mold was reserved. The longer melt flow and migration distance during the foaming process resulted in a more obvious fountain effect, and consequently, the cell rupture at the front of the melt was more serious. The densification of vertical stripes and the aggravation of disorder intensified the formation of gas marks on the surface of the microcellular foams that were manufactured via short-shot foaming. Hence, the surface quality of short-shot foaming PA6 material deteriorated with an increase in weight reduction.

4. Conclusions

PA6 microcellular foams with different weight reductions were prepared using short-shot foaming and core-back foaming. The core-back foaming microcellular foams possess lower deformation of cells, smaller cell size, and narrower cell size distributions with the same weight reduction, compared to the samples prepared using the short-shot foaming process. PA6 microcellular foams that were manufactured via core-back foaming had higher surface glossiness with different weight reduction, whereas the surface glossiness of short-shot microcellular foams dramatically declined with an increase in weight reduction; in particular, the skin thickness was thinner than 1.4 mm. The reason for the poor cell morphology and surface quality of materials that were prepared via short-shot foaming is the low melt pressure in the mold cavity. The core-back foaming process enables the fabrication of microcellular polymers that have good cell morphology, small size, high cell density, and fine surface quality under high weight reduction; this is beneficial for producing products that have good surface
quality and high weight reduction and can be used in automobiles, high-speed trains, and airplanes, etc to reduce energy consumption.

**Data availability statement**

All data that support the findings of this study are included within the article (and any supplementary files).

**Funding**

This research was funded by The Science and Technology Foundation of Guizhou Province (No. [2019]1176), Research Institute Service Enterprise Action Plan Project of Guizhou Province (No. [2018]4010), The Science and Technology Program of Guizhou Province (No. [2019]5634), and National Natural Science Foundation of China (No. 51863003).

**Conflicts of Interest**

The authors declare no conflict of interest.

**ORCID iDs**

Tuanhui Jiang  [https://orcid.org/0000-0002-2639-455X](https://orcid.org/0000-0002-2639-455X)

Li He  [https://orcid.org/0000-0003-1736-8058](https://orcid.org/0000-0003-1736-8058)

**References**

[1] Guo Qingting, Wang Jin and Park C B 2006 A microcellular foaming simulation system with a high pressure-drop rate. *Ind. Eng. Chem. Res.* 45 6153–6161

[2] Mehdi M 2007 The effect of pressure drop rate on the microstructures of unfilled and glass-filled abs microcellular foams *Iran. Polym. J.* 16 839–849

[3] Antunes M, Realinho V and Velasco J I 2010 Study of the influence of the pressure drop rate on the foaming behavior and dynamic-mechanical properties of CO2 dissolution microcellular polypropylene foams *J. Cell. Plast.* 46 551–571

[4] Wang L, Zhang J, Yang X, Zhang C, Gong W and Yu J 2014 Flexural properties of epoxy syntactic foams reinforced by fiberglass mesh and/or short glass fiber *Mater. Design.* 55 929–936

[5] Wang L, Yang X, Zhang J, Zhang C and He L 2014 The compressive properties of expandable microspheres/epoxy foams *Compos. Part B-Eng.* 56 724–732

[6] Wang L, Zhang C, Gong W, Ji Y, Qin S and He L 2017 Preparation of microcellular epoxy foams through a limited-foaming process: a contradiction with the time-temperature-transformation cure diagram *Adv. Mater.* 30 1–6

[7] PARK C B 1995 Effect of the pressure drop rate on cell nucleation in continuous processing of microcellular polymers *Polym. Eng. Sci.* 35 432–440

[8] Laguna-Gutierrez E, Van Hooghten R, Moldenaers P and Angel Rodriguez-Perez M 2015 Effects of extrusion process, type and content of clays, and foaming process on the clay exfoliation in HMS PP composites *J. Appl. Polym. Sci.* 132 1–12

[9] Tabatabaei A and Park C B 2017 *In-situ* visualization of PLA crystallization and crystal effects on foaming in extrusion. *European Polym. J.* 96 505–519

[10] Jiang R, Liu T, Xu Z, Park C B and Zhao L 2019 Improving the continuous microcellular extrusion foaming ability with supercritical CO2 of thermoplastic polyester ester elastomer through *in-situ* fibrillation of polytetrafluoroethylene *Polymers-Based*. 11 1–16

[11] Rion M, Aussia G, Grohens Y, Gaudry T, Veille J M and Férec J 2020 Thermoplastic foaming with thermo-expandable microcapsules: mathematical modeling and numerical simulation for extrusion process *Chem. Eng. Sci.* 227 1–14

[12] Yilmaz G, Ellingham T and Turmg L S 2018 Improved processability and the processing-structure-properties relationship of ultra-high molecular weight polyethylene via supercritical nitrogen and carbon dioxide in injection molding *Polymers-Based*. 10 1–15

[13] Jewelyn G, Rees A, Griffiths C A, Jacobi M and Novel A 2019 A novel hybrid foaming method for low-pressure microcellular foam production of unfilled and talc-filled copolymer polypropylenes *Polymers-Based*. 11 1–15

[14] Kim H K, Sohn J S, Ryu Y, Kim S W and Cha S W 2019 Warpage reduction of glass fiber reinforced plastic using microcellular foaming process applied injection molding *Polymers-Based*. 11 1–12

[15] Wang X, Wu G, Xie P, Gao X and Yang W 2020 Microstructure and properties of Glass Fiber-Reinforced Polyamide/Nylon Microcellular Foamed composites. *Polymers-Based*. 12 1–11

[16] Ishikawa T and Ohshima M 2011 Visual observation and numerical studies of polymer foaming behavior of polypropylene/carbon dioxide system in a core-back injection molding process *Polym. Eng. Sci.* 51 1617–1623

[17] Shaheen Y, Mark I H, Tabatabaei A and Park C B 2016 A new insight into foaming mechanisms in injection molding via a novel visualization mold *Express. Polym. Lett.* 10 462–469

[18] Dugad R, Radhakrishna G and Gandhi A 2020 Recent advancements in manufacturing technologies of microcellular polymers: a review *J. Polym. Res.* 27 1–23

[19] Roch A, Kehret L, Huber T, Henning F and Elsner P 2015 Investigations on injection molded, glass-fiber reinforced polyamide 6 integral foams using breathing mold technology *AIP Conf. Proc.* 1664 1–5

[20] Ishihara S, Hijima Y and Ohshima M 2018 Preparation of open microcellular polyactic acid foams with a microfibrillar additive using coreback foam injection molding processes *J. Cell. Plast.* 54 765–784
Wang L, Wakatsuki Y, Hikima Y, Ohshima M, Yusa A, Uezono H and Naitou A 2019 Preparation of microcellular injection-molded foams using different types of low-pressure gases via a new foam injection molding technology Ind. Eng. Chem. Res. 58 17824–17832

Chen S-C, Liao W-H and Chien R-D 2012 Structure and mechanical properties of polystyrene foams made through microcellular injection molding via control mechanisms of gas counter pressure and mold temperature Int. Commun. Heat. Mass. 39 1125–1131

Wang G, Zhao G, Dong G, Mu Y and Park C B 2018 Lightweight and strong microcellular injection molded PP/talc nanocomposite Compos. Sci. Technol. 168 38–46

Zhou Y G, Cao G H and Cheng Y F 2020 Effect of cellular uniformity on the necking propagation of foam injection molded PP/HDPE blend parts I. Appl. Polym. Sci. 137 1–12

Volpe V, Lanzillo S, Affinita G, Villacci B, Macchiarelo I and Pantani R 2019 Lightweight high-performance polymer composite for automotive applications Polymers. 11 1–16

Ryu Y, Sohn J S, Yun C S and Cha S W 2020 Shrinkage and warpage minimization of glass-fiber-reinforced polyamide 6 parts by microcellular foam injection molding Polymers. 12 1–17

Yuan M, Turng L S, Gong S, Caulfield D, Hunt C and Spindler R 2004 Study of injection molded microcellular polyamide-6 nanocomposites Polym. Eng. Sci. 44 673–686

Hwang S-S, Liu S-P, Hsu P P, Yeh J-M, Yang J-P, Chang K-C and Chu S-N 2011 Effect of organoclay and preparation methods on the mechanical/thermal properties of microcellular injection molded polyamide-6-clay nanocomposites Int. Commun. Heat. Mass. 38 1219–1225

Reglero Ruiz J A, Vincent M, Agassant J-F, Claverie A and Hack S 2015 Morphological analysis of microcellular PP produced in a core-back injection process using chemical blowing agents and gas counter pressure Polym. Eng. Sci. 55 2465–2473

Lee J W S, Lee R E, Wang J, Jung P U and Park C B 2017 Study of the foaming mechanisms associated with gas counter pressure and mold opening using the pressure profiles Chem. Eng. Sci. 167 105–119

Chen S C, Hsu P S and Lin Y W 2011 Establishment of gas counter pressure technology and its application to improve the surface quality of microcellular injection molded parts Int. Polym. Proc. XXVI 275–282

Wu S, He L, Zhang C, Gong W, He Y and Luo Y 2017 Visualization observation of cells growth in low-density polyethylene foaming processes Polym. Test. 63 367–374

Shaayegan V, Wang G and Park C B 2016 Study of the bubble nucleation and growth mechanisms in high-pressure foam injection molding through in-situ visualization Eur. Polym. J. 76 2–13

Shaayegan V, Wang C, Costa F, Han S and Park C B 2017 Effect of the melt compressibility and the pressure drop rate on the cell-nucleation behavior in foam injection molding with mold opening Eur. Polym. J. 92 314–325

Bai Y et al 2018 Polystyrene foam with high cell density and small cell size by compression-injection molding and core back foaming technique: evolution of cells in cavity Macromol. Mater. Eng. 303 1–11