APPENDIX

JOURNAL PUBLICATION

W. Kaewmesri, P.C. Lee, C.B. Park, and J. Pumchusak, *Effects of* CO_2 *and Talc Contents on Foaming Behavior of Recyclable High-Melt-Strength PP*, Journal of Cellular Plastics, 42(5), 405-428, 2006.

Effects of CO_2 and Talc Contents on Foaming Behavior of Recyclable High-melt-strength PP

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ABSTRACT: This article presents an experimental study on the foaming behavior of recyclable high-melt-strength (HMS) branched polypropylene (PP) with CO_2 as a blowing agent. The foamability of branched HMS PP has been evaluated using a tandem foaming extruder system. The effects of CO_2 and nucleating agent contents on the final foam characteristics have been thoroughly investigated. Low density (i.e., 12–14-fold), fine-celled (i.e., 10^7–10^9 cells/cm^3) PP foams were successfully produced using a small amount of talc (i.e., 0.8 wt%) and 5 wt% CO_2.

KEY WORDS: recyclable HMS PP, low density, fine-celled PP foams, CO_2 content, talc content.

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0021-955X/06/05 0405–24 $10.00/0 DOI: 10.1177/0021955X06066995

INTRODUCTION

Recently, consumption of raw plastic materials has significantly increased worldwide, and automotive manufacturing industries are attempting to reduce the quantity of non-recyclable plastic scraps which must be disposed of in landfills [1]. Therefore, the action of the plastic manufacturers has shifted to potentially recyclable materials such as non-crosslinked polypropylene (PP): the potential polymer for the bumper system, instrument panel, seat, and other interior trim components. Therefore, it is worthwhile to study the processability of recyclable polypropylene for foaming applications.

Foamed polymers possess a cellular structure that is created by the expansion of a blowing agent. This internal structure provides unique properties that enable foamed plastics to be effectively used for various industrial applications such as automotive and packaging [2–4]. Foamed plastics have been provided in a wide range of bulk densities (i.e., 24–40 $\mathrm{kg/m^3}$) [2] which mainly determine their mechanical properties. Low density foams (i.e., $<64\,\mathrm{kg/m^3}$) [2] are primarily used for insulation and packaging applications, and high density foams are primarily used for load bearing applications such as structural parts [4].

In addition to foam density, size and distribution of cells also influence the final properties of the foam. Conventional plastic foams have relatively poor mechanical properties because the cell size is typically larger than 100 μm, and the cell size distribution is very non-uniform. On the other hand, foams with very fine cells and uniform cell distribution exhibit better mechanical properties such as toughness [5], impact strength [6–9], and tensile strength [10] according to previous researches. Fine-celled foams are characterized by a cell size smaller than 100 μm and a cell-population density larger than $10^6\,\mathrm{cells/cm^3}$. These foamed materials can reduce the weight significantly and thereby lower the material cost [3,11,12].

The process of making fine-celled polymers has been developed based on a thermodynamic instability which is induced by rapidly dropping the solubility of gas in the polymer melt to drive cell nucleation and cell growth to produce foam expansion. This technology was first produced in a batch process, but the diffusion rate was very low, and it required a long time for gas saturation. In order to overcome this limitation, polymer was foamed in an extrusion process. In this continuous foaming method, a much shorter time was needed to saturate the polymer with gas. When polymer was melted in the extrusion barrel, a metered amount of gas was delivered to the polymer melt. Injected gas diffused into the polymer matrix at a much higher rate because of convective diffusion induced in the extrusion barrel at elevated temperatures. The formation of a uniform solution of polymer and gas is essential in fine-celled foam processing since undissolved gas packets can generate undesirable large voids in the final foam morphology. Fine-cell nucleation was promoted using a rapid pressure drop rate nucleating die. Nucleated bubbles continued to grow to a desired final size during shaping at the die exit [5,13–15].

Polypropylene foam is considered to be a promising substitute for other thermoplastic foams in industrial applications due to its outstanding properties such as higher rigidity compared to other polyolefins, higher strength than polyethylene (PE), better impact strength than polystyrene (PS), higher service temperature range and good temperature stability compared to PE and PS, and low material cost. Despite these excellent properties, linear versions of PP have not been used much in the foaming industry due to their weak melt strength [16–24]. Because of the weak melt strength, cell walls separating cells or bubbles may not be strong enough to resist the extensional force and may rupture very easily during foaming. This results in severe cell coalescence in the final PP foam structure. When cells coalesce, not only are cell density and cell size uniformity deteriorated, but also volume expansion ratio is greatly decreased due to accelerated gas loss through opened cell walls. Therefore, using a long-chain branched resin is essential for producing low density fine-cell PP foams [16,17,20,21,24].

It is well known that the melt strength of a polymer can be enhanced by branching [16–24], crosslinking [9,25], controlling of processing temperature [26–29], control of molecular weight and molecular weight distribution [20,30,31], and blending of polymers and compatibilization of blends [18,31]. For example, in order to improve foamability, crosslinking of the polymer matrix can be induced to generate a partly solidified state which may contribute to strain-hardening [9,25]. However, extensively cross-linked foams are not recyclable [9,25]. Therefore, the easiest feasible method for promoting large expansion by increasing the melt strength of PP foams is to use branched PP materials [18–24]. Using long-chain branched PP with high melt strength and high melt extensibility, cell coalescence is more effectively prevented compared to linear PP [18–24]. The most important characteristics of long-chain branched PP for foaming are the high-melt-strength (HMS) properties, which can exhibit high elastic response, two-step viscosity at low frequencies (shear rates), and various relaxation processes in the nonlinear relaxation modulus. Therefore, introducing long chains may be the exceptional method to obtain excellent melt properties without any disadvantages such as decomposition, aggravation of physical properties, etc. In the foaming process of HMS PP, cell-population density and volume expansion can be enhanced due to a lower degree of cell coalescence in the cell growth stage [32,33]. Therefore, HMS branched PP material has been regarded as a good candidate for producing low-density, fine-celled foams. Furthermore, HMS PP can be recycled after processing.

In general, low density foams are produced using physical blowing agents such as hydrofluorocarbons (HFCs), volatile organic carbons (VOCs), or flammable hydrocarbons [34,35]. Due to increasing safety and environmental concerns over the use of flammable, volatile organic carbons, attention has shifted to using environmentally friendly gases such as carbon dioxide (CO_2) and nitrogen (N_2) [36]. Because these inert gases have higher diffusivity than those of long-chain blowing gases (i.e., butane, pentane), the maximum achievable expansion ratio was lower. However, CO_2 has been effectively used for producing fine-celled or microcellular foams with a small amount of nucleating agent such as talc [37–40].

Normally, nucleating agents are finely powdered to serve as solid surfaces for heterogeneous cell nucleation, and they remain solid or thermally stable during the foaming process. The condition for heterogeneous nucleation depends on the surface geometry and surface energies (between solid–liquid, solid–gas, and liquid–gas) [34]. If the free energy for gas cluster formation on the surface of a nucleating agent is less than that for homogeneous nucleation in the polymer melt, heterogeneous nucleation on the solid phase will occur. It is expected that nucleating agents play an important role in determining the cellular structure of thermoplastic foams. Unless a thermodynamic instability via a rapid solubility drop is utilized to promote a large number of nuclei, final foam structures are usually unacceptable without the addition of a nucleating agent; namely, the bubble size is too large and cell density is too small. In the PP foaming process, the addition of a nucleating agent was essential in achieving a good nuclear density. Moreover, it is expected that the high processing pressure and high pressure drop rate required to produce large cell density can be lowered by using a nucleating agent. It would be beneficial if the high nuclear density could be obtained at a lower pressure and pressure drop rate by adding a small amount of nucleating agent [37–40].

The objective of this study was to produce fine-celled (i.e., cell size smaller than 300 μm), low density (i.e., in the range of 4–30-fold) foams using the tandem foaming extruder system and environmentally benign CO_2. In this article, foaming behaviors of HMS PP foams have been investigated. Cell nucleation and expansion behaviors of extruded PP foams with various contents of CO_2 and nucleating agent were studied. In addition, the effects of processing conditions on the final foam morphologies have also been examined through the experiments.

EXPERIMENTAL

Materials

The plastic material used in this study was high-melt-strength (HMS) branched PP resin (Honam SMS-514, MFR = 2.4 g/s) supplied by Honam Petrochemical Corp. The melting temperature and crystallization temperature of the original polymer were investigated using a differential scanning calorimeter (DSC; DSC 2910, TA instrument) under N_2 atmosphere. The typical weight 3–5 mg of polymer pellet was randomly collected and heated up in the range of 25–230°C at 10°C/min in order to identify the melting temperature (T_m) and crystallinity of PP. After that, the sample was cooled down from 230°C to the initial temperature at 10°C/min in order to investigate the crystallization temperature (T_c) of the polymer. The DSC thermogram of this HMS PP is shown in Figure 1; the melting temperature was 168°C and crystallization temperature was 128°C. The crystalline fraction was calculated based on that of the completely crystallized PP polymer (209 J/g) [26,27]. The crystallinity of this polymer was approximately 38%. The blowing agent was CO_2 with 99.5% purity (supplied by BOC Gas Co.). The HMS branched PP resin was mechanically mixed with a different concentration of talc particles (mean particle size 7 μm). For example, if 0.8 wt% of talc content is desired, 960 g of branched PP resin is mixed with 40 g of 20 wt% talc-filled PP resin. Then, the 1000 g polymer blend will have 0.8 wt% talc embedded in it. The composition of talc content in PP was varied in the range of 0–2.4 wt%, and the amount of injected CO_2 was varied at 1, 3, and 5 wt%.

Experimental Setup

Figure 2 shows the tandem foaming extrusion system used in this study. It consists of a 5 hp extruder driver with a speed

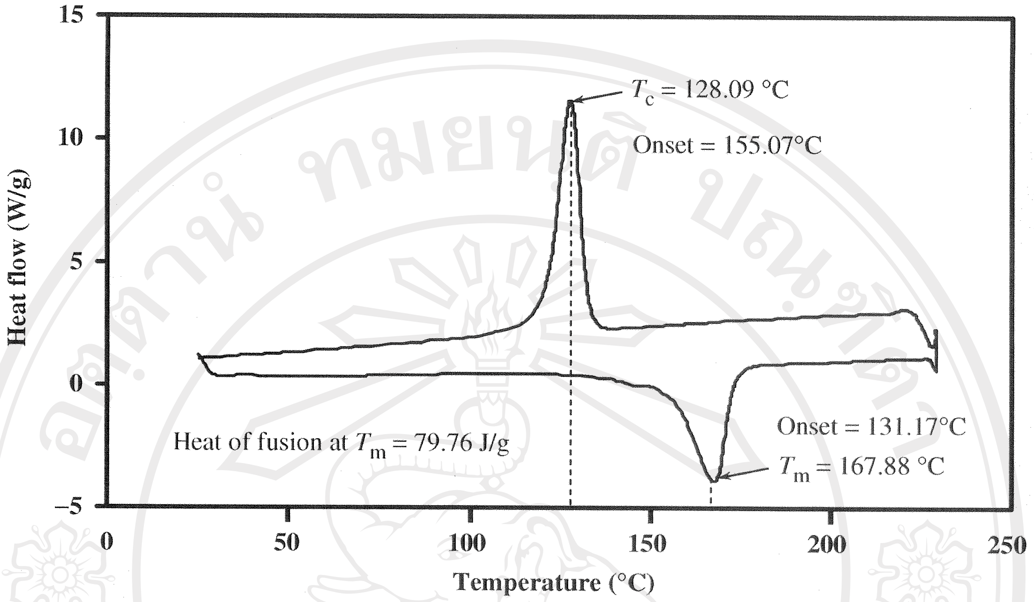


Figure 1. DSC thermogram of HMS-branched PP resin at the heating and cooling rate of 10°C/min.

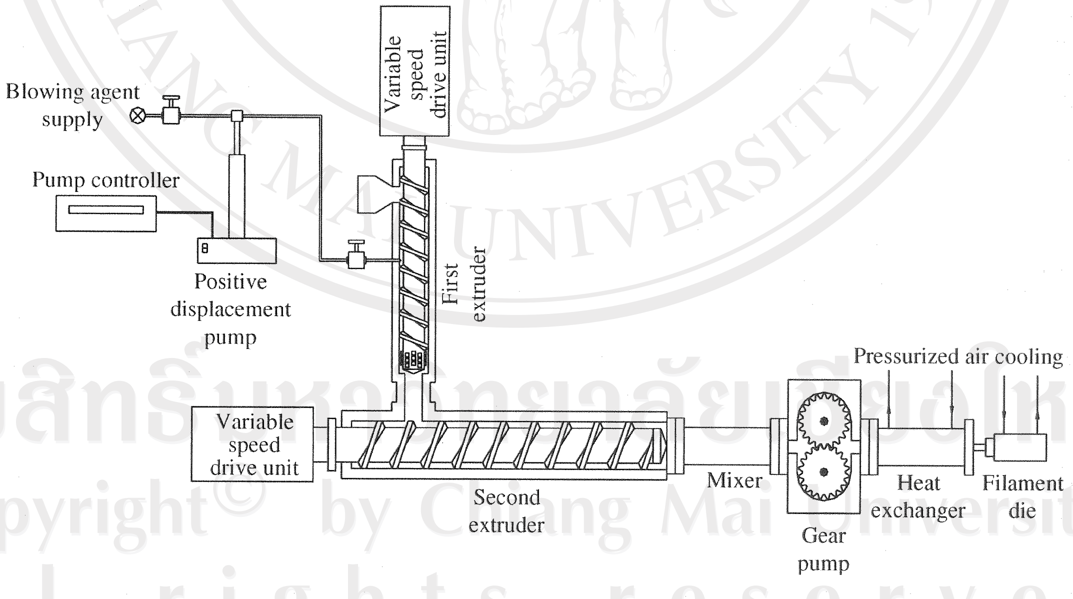


Figure 2. Schematic of a tandem foaming extrusion system setup.

control gearbox (Brabender: prep center), a first 3/4″ extruder (Brabender: 05-25-000) with a mixing screw, a second 1.5″ extruder with a built-in 15 hp variable speed drive unit (Killion: KN-150), a positive displacement pump for injecting the blowing agent into the polymer melt, a gear pump (Zenith PEP-II 1.2 cc/rev), a heat exchanger (for cooling the polymer melt) which contains homogenizing static mixers, a filament die with a length/diameter (*L*/*D*) ratio of 21.84 mm (0.86″)/0.94 mm (0.037″), and a cooling sleeve for precise control of die temperature. The first extruder is used for plasticizing polymer resin. The second extruder provides mixing and initial cooling for the polymer melt. The gear pump controls the polymer melt flow rate, independent of temperature and pressure changes. The heat exchanger provides further cooling for the polymer melt to suppress cell coalescence. Shaping and foaming are done in the filamentary die.

Experimental Procedure

The mixed-PP pellets with various talc contents (0.0, 0.8, 1.6, and 2.4 wt%) were first fed into the barrel through a hopper and were completely melted by the screw motion. A metered amount of blowing agent was then injected into the extrusion barrel by a positive displacement pump at a given weight percentage with the polymer stream. When gas was injected into the barrel, the remaining section of the first screw and second screw generated shear fields to completely dissolve gas in the polymer melt via convective diffusion. The single-phase polymer/gas solution went through the gear pump and was fed into the heat exchanger where it was cooled to the desired temperature. The cooled polymer/gas solution entered the die, and foaming occurred as pressure decreased near the die exit. While fixing all the other materials and processing parameters such as the screw speed, gear pump speed (i.e., 12 RPM), blowing agent content and barrel temperature (i.e., 160°C) in order to obtain a constant 12 g/min gas/polymer mixture flow rate, the synchronized melt and die temperatures were lowered step by step, and samples were randomly collected at each set temperature only after the system reached the equilibrium state.

The foamed samples were randomly collected at each processing condition and were characterized by using a scanning electron microscope (SEM, JEOL JSM-6060) to evaluate the morphology. The samples were dipped in liquid nitrogen and then fractured to expose the cellular morphology, and then the fractured surface was sputter-coated with gold. The microstructure was investigated by SEM. The volume expansion ratio and cell density were the structural foam parameters measured. The expansion ratios of foams were examined by measuring the weight and volume of the sample. The expansion ratio (υ_a) of each sample was calculated as the ratio of bulk density of pure PP (ρ_p) to bulk density of foamed sample (ρ_f) as shown in Equation (1) [33].

$$\upsilon_a = \frac{\rho_p}{\rho_f} \tag{1}$$

The void fraction (V_f) was calculated on the basis of the ratio of the bulk density of foamed sample (ρ_f) and un-foamed sample (ρ) as Equation (2) [41–43].

$$V_f = 1 - \frac{\rho_f}{\rho} \tag{2}$$

The blowing agent efficiencies (η) were determined as Equation (3), and the ideal volume expansion ratio (υ_t) was approximately calculated as Equation (4). The specific volume of CO_2 (υ_{gas}) at the crystallization temperature (T_c) of 131°C was $752.2\,cm^3/g$, and the specific volume of Honam SMS-514 resin (υ_a) at room temperature was $1.2408\,cm^3/g$, respectively [33]:

$$\eta = \frac{\upsilon_a}{\upsilon_t} \tag{3}$$

$$\upsilon_t = \frac{\text{Volume}_{(\text{Polymer})} + \text{Volume}_{(\text{gas})}}{\text{Volume}_{(\text{Polymer})}} = 1 + \frac{m_{gas}}{m_a} \times \frac{\upsilon_{gas}}{\upsilon_a} \tag{4}$$

The m_{gas} and m_a are the mass flow rate of gas (g/min) and PP (g/min), respectively. For example, for the injected CO_2 amount of 1 wt%, the ideal volume expansion was estimated as follows [33]:

$$\upsilon_t = 1 + 0.01 \times \frac{752.2(\text{cm}^3/\text{g})}{1.2408(\text{cm}^3/\text{g})} \approx 7.0622$$

Cell-population density (n) was calculated as the number of cells per unit volume with respect to the un-foamed polymer. The number of cells (n_b) in a defined area ($l \times l$), is determined, and then the total number of cells per cubic centimeter is calculated as follows [33]:

$$n = \left(\frac{n_b}{l^2}\right)^{3/2} \times 10^{12} \times \upsilon_a \tag{5}$$

As the calculated values from Equations (1) and (2), the average cell size (d) can be determined as Equation (6) [43]:

$$d = \sqrt[3]{\frac{6V_f}{\pi n(1 - V_f)}} \tag{6}$$

RESULTS AND DISCUSSION

In this research, the target volume expansion ratio is 10–30-fold, and the target cell population density is in the range of 10^6–10^9 cells/cm^3. The effects of blowing agent contents (i.e., 1, 3, and 5 wt%), talc contents (i.e., 0.0, 0.8, 1.6, and 2.4 wt%), and die temperatures (i.e., 140–180°C) on the expansion ratio and cell nucleation behaviors of HMS PP were investigated to determine the processing–morphology relationships. The effects of processing parameters on expansion ratios and cell morphologies of the final foams are also discussed. Figure 3 depicts pressure versus temperature profiles during the foaming process of HMS branched PP resin with various blowing agent contents and nucleating agent contents. Figures 4 and 5 show the volume expansion ratios versus temperature and the maximum volume expansion ratios, respectively, with respect to CO_2 content and talc content. The blowing agent efficiency versus temperature is shown in Figure 6. Cell morphology and cell density are summarized in Figures 7–10.

Effects of Processing Parameters on the Volume Expansion Ratio

Die Temperature

Figure 4 shows the expansion ratios versus die temperatures of foams with various CO_2 contents and talc contents. The typical mountain shaped curves [11,40] were observed, which clearly appeared when the CO_2 content was higher than 1 wt% for all talc contents. It can be explained that expansion behaviors were governed by gas loss at high temperatures because of high gas diffusivity. When the melt temperature was too high, most of the gas escaped through the hot skin layer of foam during the initial stages of expansion. This led to the presence of only a small amount of residual gas inside the cells, resulting in insufficient gas pressure for foam expansion (i.e., the force exerted by gas pressure was insufficient to overcome the melt strength).

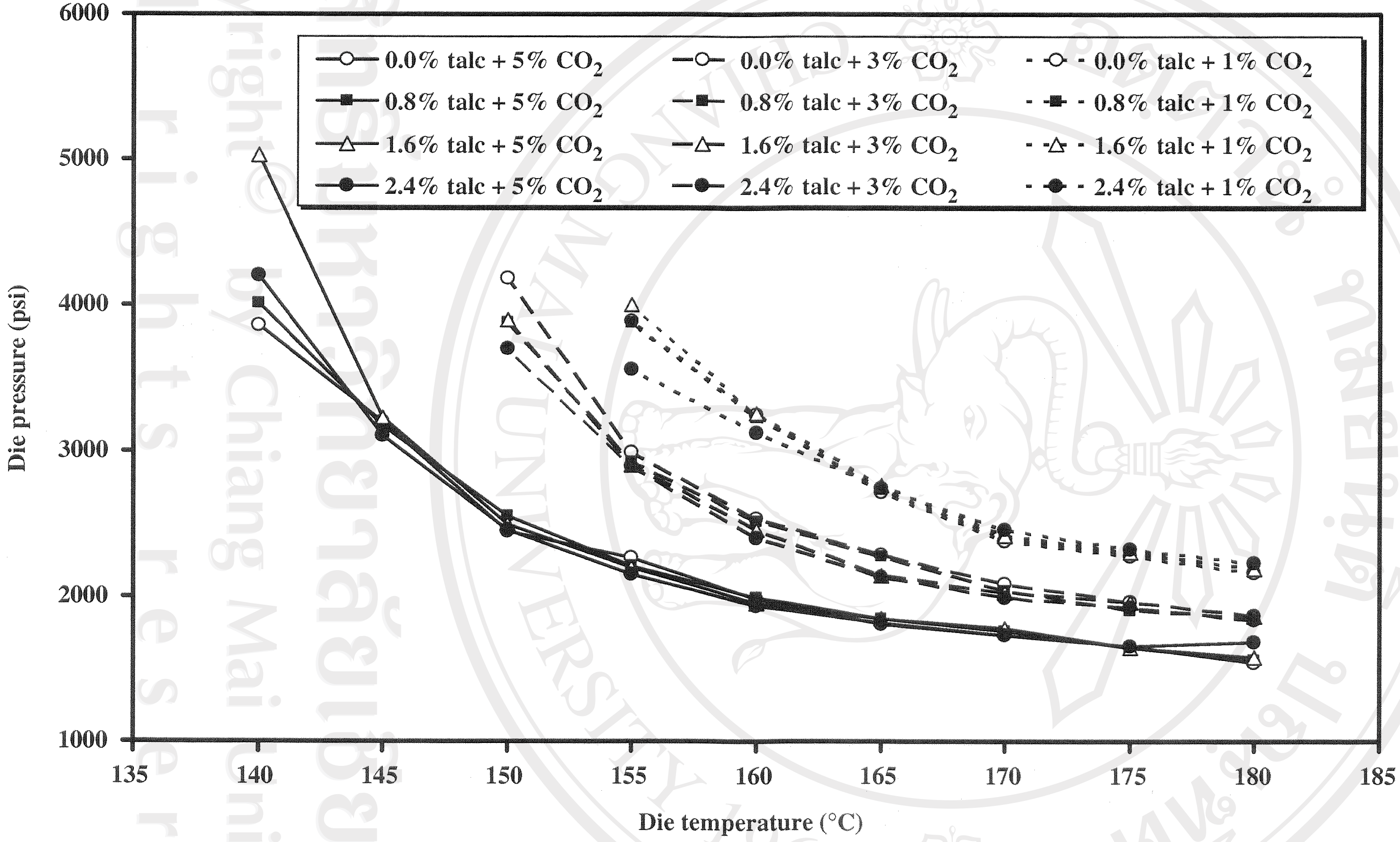


Figure 3. Die pressure and temperature profile of HMS-branched PP resin with 1, 3, and 5 wt% injected CO_2 and 0.0, 0.8, 1.6, and 2.4 wt% talc.

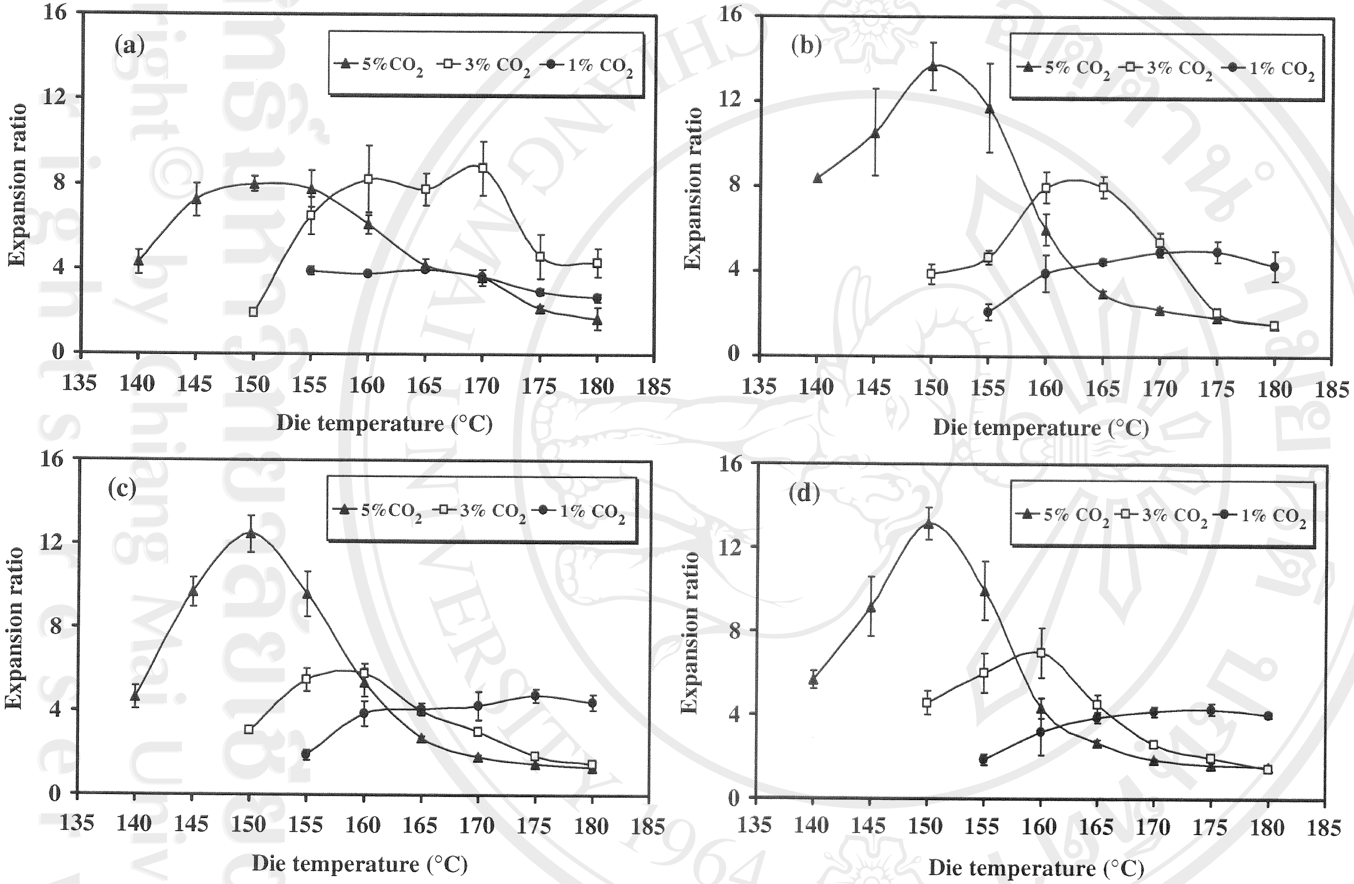


Figure 4. Expansion ratio of foamed HMS PP with 1, 3, and 5 wt% CO_2 at (a) 0.0 wt% talc, (b) 0.8 wt% talc, (c) 1.6 wt% talc, and (d) 2.4 wt% talc.

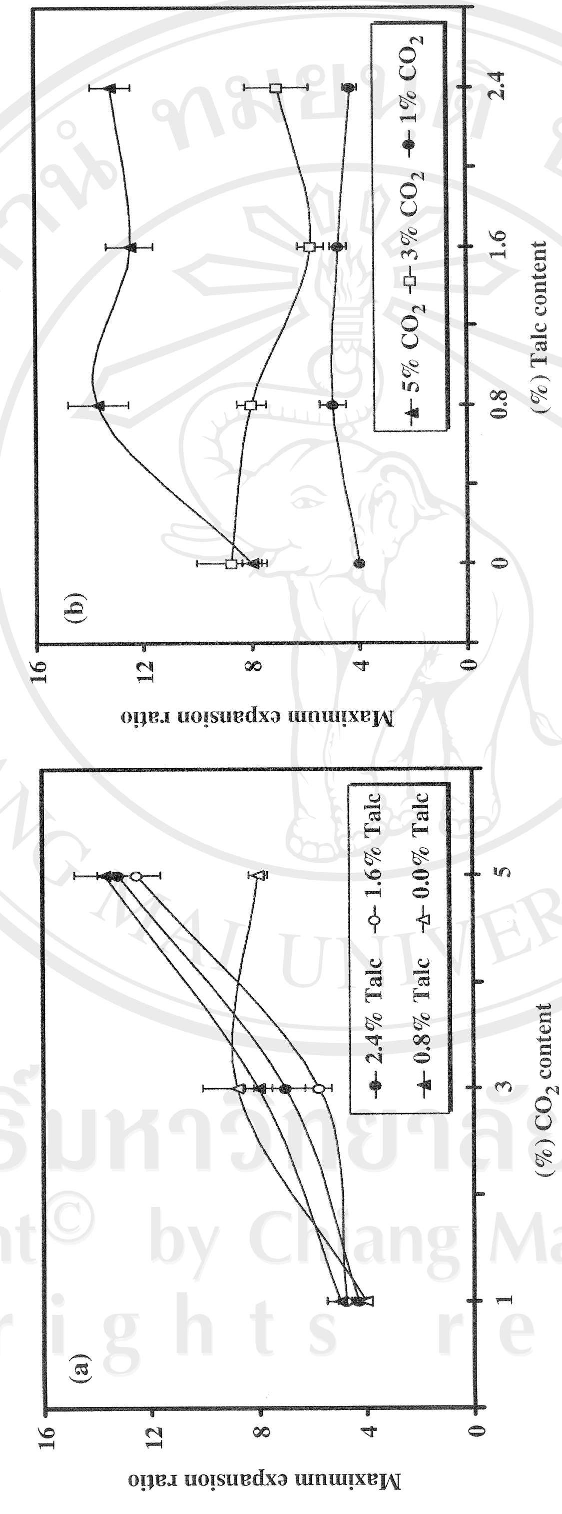


Figure 5. (a) Maximum volume expansion ratio vs CO_2 content and (b) maximum volume expansion ratio vs talc content.

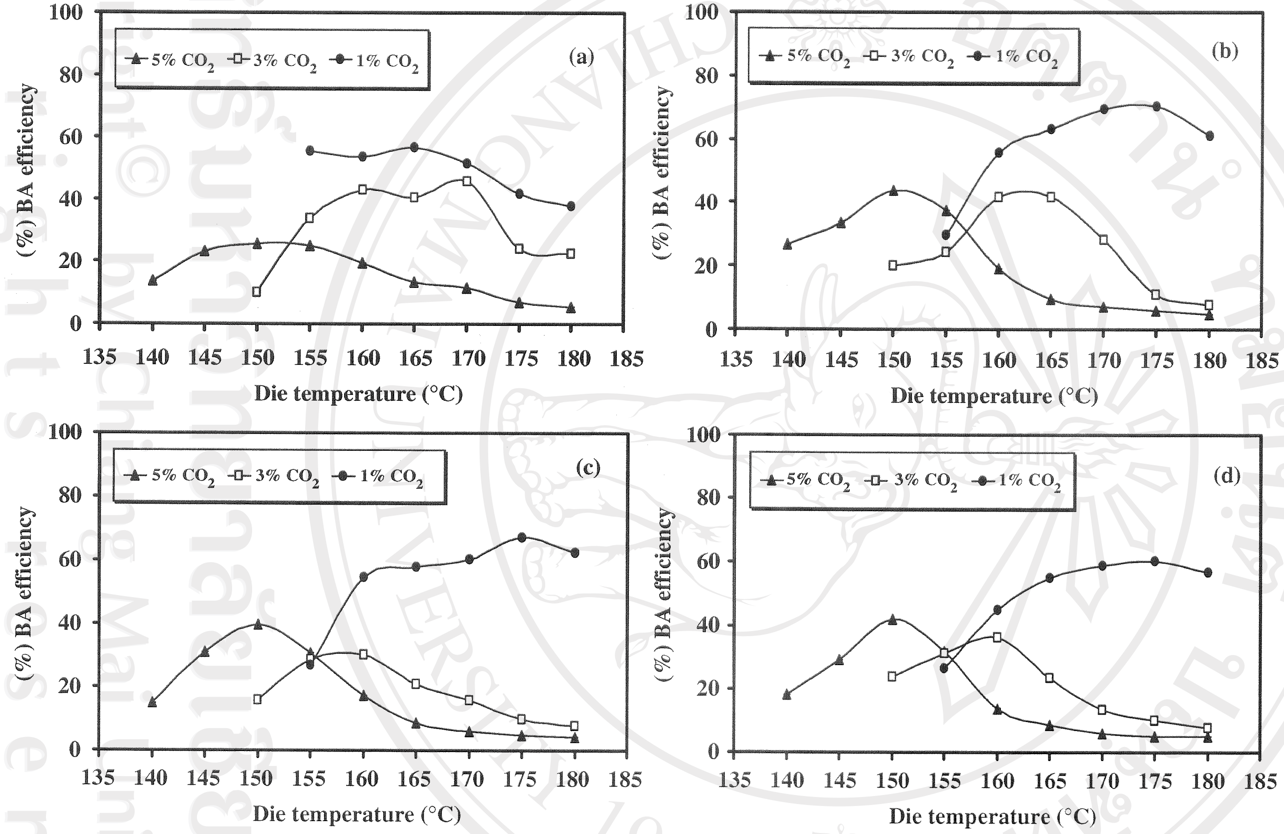
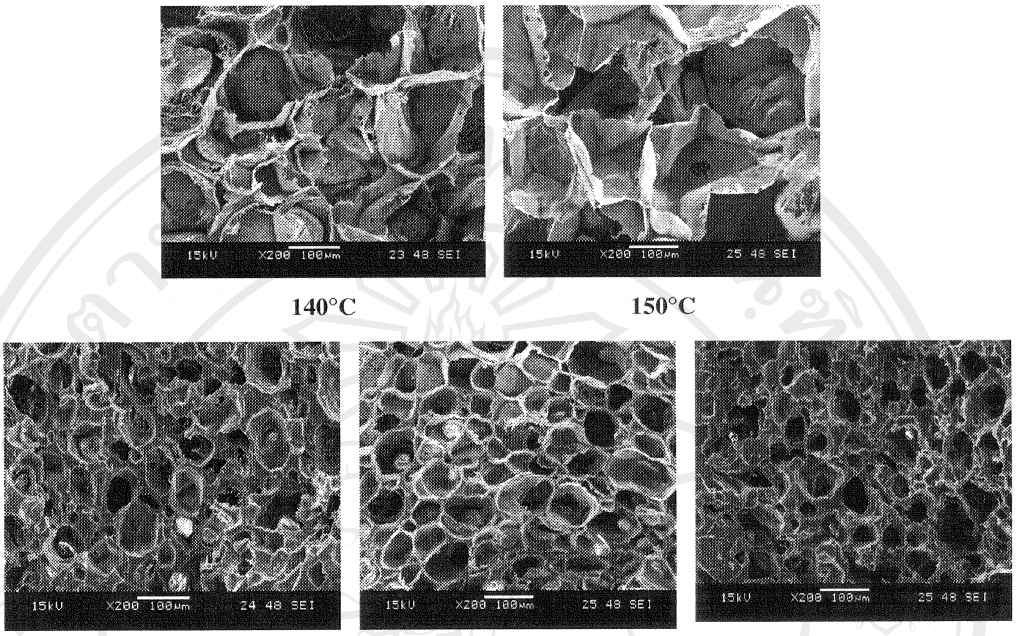


Figure 6. (%) Blowing agent (BA) efficiency of HMS-branched PP foaming with 1, 3, and 5 wt% CO_2 at (a) 0.0 wt% talc, (b) 0.8 wt% talc, (c) 1.6 wt% talc, and (d) 2.4 wt% talc.



140°C 150°C

160°C 170°C 180°C

Figure 7. Cell morphology of foamed HMS PP with 0.8 wt% talc and 5 wt% CO_2 at various die temperatures.

Therefore, the final expansion ratio was low at high temperatures. In addition, at low temperatures, expansion behaviors were governed by the stiffness of PP melt; the melt strength of PP due to crystallization is higher than that of gas pressure entrapped inside the cells. According to the result of thermal history analysis, polymer started to crystallize at 155°C, as shown in Figure 1. Therefore, foaming the PP with a small amount of CO_2 (i.e., 1 and 3 wt%) near the onset crystallization temperature was very challenging; the bubbles could not grow due to stiffened cell walls. This also resulted in low expansion ratios [11,40]. For 5 wt% CO_2 experiments, processing at much lower temperature was possible due to the plasticizing effect of residual gas inside the polymer melt. Consequently, the optimum temperature for a maximum expansion ratio was shifted to a lower temperature for all talc content experiments.

Blowing Agent Content

The optimum temperature shifted to lower temperatures when the amount of CO_2 was increased from 1 to 5 wt%. This shift in optimum temperature was due to the plasticizing effect of increased CO_2 content in the polymer matrix. Moreover, die pressure was decreased as CO_2

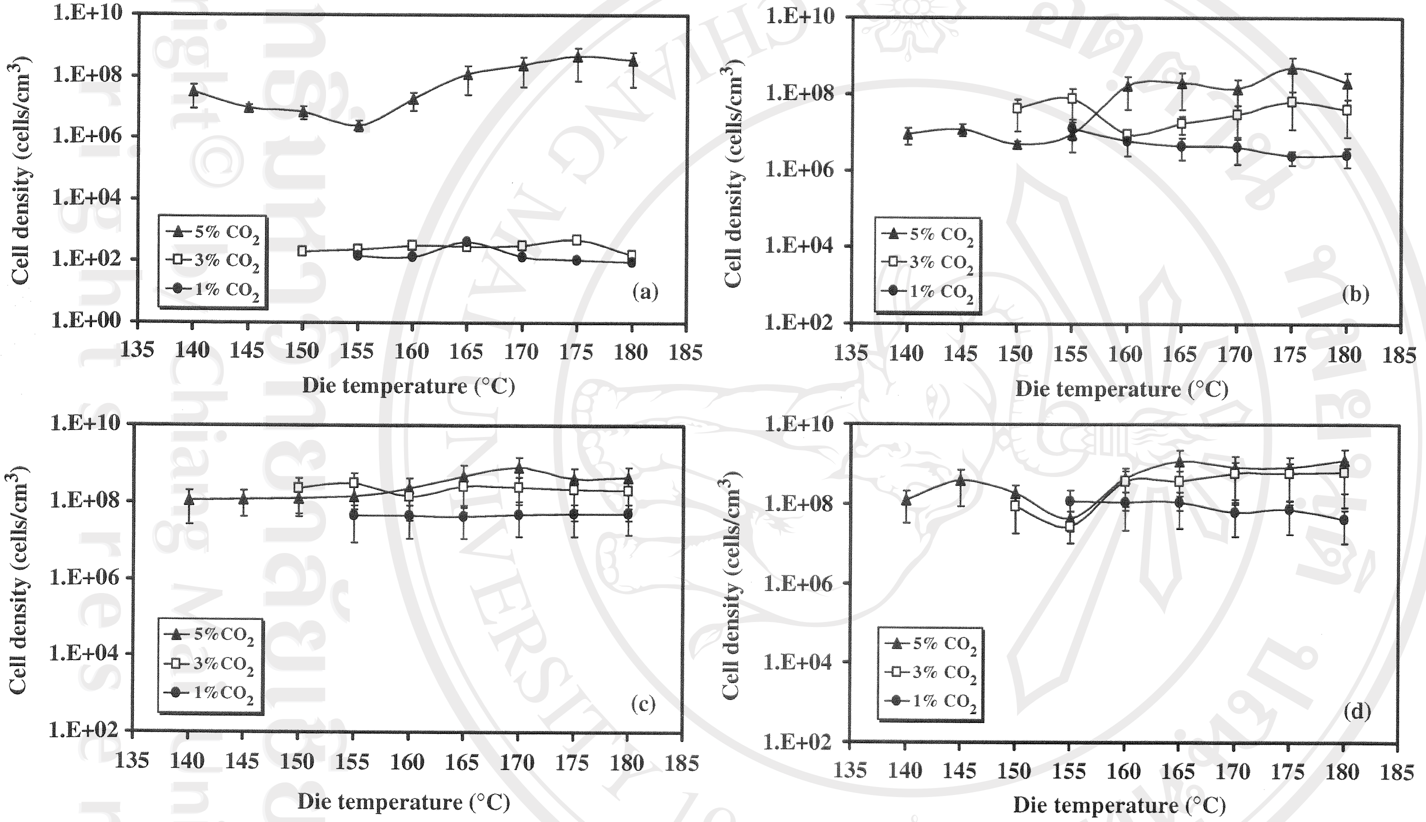


Figure 8. Cell density of foamed HMS PP with 1, 3, and 5 wt% CO_2 at (a) 0.0 wt% talc, (b) 0.8 wt% talc, (c) 1.6 wt% talc, and (d) 2.4 wt% talc.

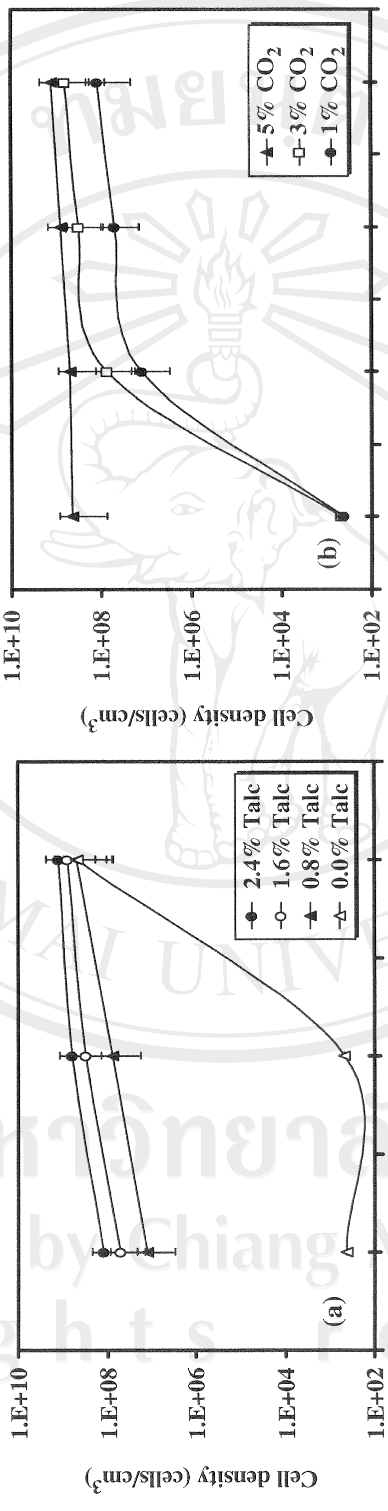


Figure 9. (a) Maximum cell density vs CO$_2$ content and (b) maximum cell density vs talc content.

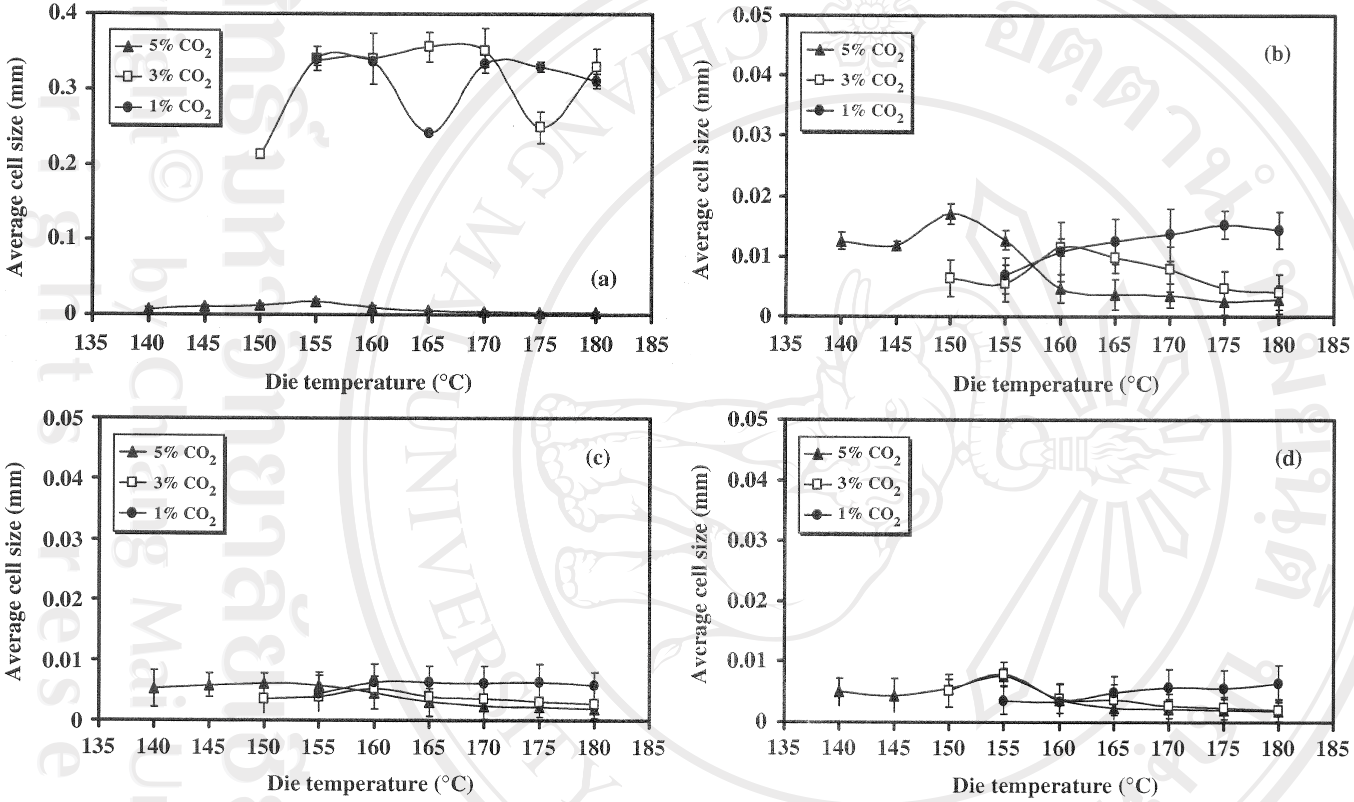


Figure 10. Average cell size of foamed HMS PP with 1, 3, and 5 wt% CO_2 at (a) 0.0 wt% talc, (b) 0.8 wt% talc, (c) 1.6 wt% talc, and (d) 2.4 wt % talc.

content was increased, as shown in Figure 3. The significant drop in processing pressure as the amount of injected CO_2 increased was due to the effect of the viscosity drop of molten polymer with CO_2. It was observed that the effect on expansion behavior of foams was not clear when foaming with a low content of CO_2 (1 wt%) for all talc contents (Figure 4(a)–(d)). The maximum expansion ratios were only 4–6-fold over the entire temperature range. As CO_2 content was increased to 3–5 wt%, mountain shaped curves were observed, and expansion ratios increased as CO_2 contents increased. The target expansion ratio of 10-fold was not achieved with 3 wt% CO_2 at all talc contents. But, maximum expansion ratios up to 12–14-fold were successfully obtained at 5 wt% CO_2 with a small amount of talc (i.e., 0.8–2.4 wt%), as shown in Figure 5.

The blowing agent efficiency was plotted against die temperature in Figure 6. At a high foaming temperature range (i.e., $>155°C$), the blowing agent efficiencies of 1 wt% at all talc contents were higher than those of 3 and 5 wt%. The maximum blowing agent efficiencies at 1 wt% CO_2 experiments were 58, 70, 68, and 60% for 0.0, 0.8, 1.6, and 2.4 wt% talc cases, respectively. The CO_2 efficiency with 0.8 wt% talc was the highest. At low temperatures, the blowing agent efficiencies of 5 wt% CO_2 experiments could reach up to 40% due to the effective prevention of gas loss. Even though the expansion ratio increased as CO_2 content increased, the gas efficiency decreased [35]. This may be due to enhanced gas loss caused by the increased plasticizing effect. The free volume increased as the viscosity of the molten polymer dropped when CO_2 was dissolved in the polymeric matrix. This effect increased as the amount of gas increased; likewise, the diffusivity of CO_2 in the swollen polymer matrix must have increased as well. Therefore, the chance of gas loss through the foam skin was increased at a high content of CO_2. Subsequently, the blowing agent efficiency would be lowered by foaming with a large amount of CO_2. This decreased efficiency phenomena at high content of gas implied that there would be a practical limit to the accomplishment of a high volume expansion ratio by enhancing and dissolving a large flow rate of CO_2. In addition, if the amount of CO_2 exceeds the solubility, injected CO_2 cannot completely dissolve in the matrix, and a much lower blowing agent efficiency would be achieved [35].

Nucleating Agent Content

When foaming without the nucleating agent, the volume expansion ratios were only 2–9-fold at all CO_2 contents (i.e., 1–5 wt%).

Therefore adding talc in the process enhanced volume expansion. Consequently, maximum expansion ratios of up to 14-fold were achieved by using 0.8 wt% talc and 5 wt% CO_2. While increasing the concentration of talc (i.e., >0.8 wt%), the maximum expansion ratio was slightly decreased, as shown in Figure 5. It seemed that too much talc worked negatively to enhance the expansion of foamed samples. It is believed that too much talc would increase the open cell fraction and thereby increase foam density. The reason did not seem to be clear, but it would be one of the following two reasons. First, since higher talc content resulted in higher cell density (and thereby a thinner cell wall), the chance of cell wall opening was increased in the case where there was not a high degree of branching. If this is the case, then an increased degree of branching prevents cell opening, and therefore the expansion ratio increases. Second, if the viscosity is too high, then the expansion ratio is decreased because of too high resistance in the cell wall. If this is the case, a decreased viscosity results in an increased expansion ratio. It can be said that the content of talc does not clearly play an important role on the expansion behavior of foamed samples, and the expansion ratio increased dramatically when small amounts of talc particles were introduced into the polymer melt especially at 5 wt% CO_2. In this experiment, the optimum expansion ratio (14-fold) was obtained with 0.8 wt% talc.

Effects of Processing Parameters on Cell Nucleation

Die Temperature

Figure 8 shows the cell density of foamed samples with various CO_2 and talc contents. The cell density was insensitive to die temperatures; especially at high temperatures, cell density was maintained high, as shown in Figure 7. This is due to the material having a high degree of branching to prevent cell coalescence. Cell-population densities of this material were in general 10^7–10^9 cells/cm^3 with this filamentary die. It can be concluded that the processing temperature did not significantly influence cell nucleation of foamed samples.

Blowing Agent Content

Cell population densities were significantly affected by the blowing agent content. For all talc contents, cell densities increased as

CO_2 contents increased. Cell density was dramatically increased from 10^2–10^3 to 10^8 cells/cm^3 (i.e., five orders of magnitude) as CO_2 content was increased from 1 to 5 wt% without talc (Figure 9(a)), while cell size was consequently decreased (Figure 10(a)).

But, at above 0.8 wt% talc, even though the cell densities increased gradually with the increase in talc content, the degree of improvement in cell density was less. This was also reflected in the cell size; the decrease in cell size was not significant. Therefore, when talc particles were introduced into the system, the effect of CO_2 content was less significant on cell density and cell size.

Nucleating Agent Content

When 5 wt% CO_2 was used, added talc did not affect the number of cells and bubble size. This indicates that the addition of talc was very effective for nucleation when foaming with CO_2 at low contents (1 and 3 wt%), but it did not play a significant role on cell nucleation at high contents of CO_2, as shown in Figure 9, which shows the plot of cell density as a function of CO_2 and talc contents, respectively. Therefore, it may be concluded that at low CO_2 and talc contents, cell density was strongly affected by both CO_2 and talc. When either CO_2 or talc content was high, cell nucleation was governed by the high concentration of one agent regardless of the content of the other. Again, from the results in Figures 9(b), it was also observed that the cell density tended to initially level off at 0.8 wt% talc concentration. The addition of talc content above 1.6 wt% did not improve the cell density and cell size because of the possible agglomeration of talc particles. A slight increase in cell density was achieved with the increase in talc content [39]. This means that excessive talc particles will be agglomerated while retaining the number of effective nucleation sites. Cell nucleation was not a function of die temperature, while it was affected by small talc concentration and high CO_2 content. Moreover, a large number of cells, up to 10^7–10^9 cells/cm^3 and fine cells (i.e., less than 0.02 mm), was easily achieved in all combinations with talc particles.

CONCLUSIONS

In this study, low density, fine-celled PP foams were successfully produced by using a recyclable HMS branched PP resin as a polymeric matrix to suppress cell coalescence. A filamentary die was selected to promote the optimum pressure and pressure drop rate at various die temperatures. CO_2 and talc were utilized as a blowing agent and a nucleating agent, respectively. The effects of varying CO_2 and talc contents on volume expansion and cell nucleation behaviors were investigated. The experimental results were concluded as the following:

1. The expansion behavior was governed by two mechanisms: at high temperatures, the gas loss phenomenon affected the expansion behavior of foams. At lower temperatures, crystallization of the polymer was the dominating factor on the expansion behavior. These phenomena were very clearly observed at high CO_2 contents (i.e., 3 and 5 wt%). Optimum temperatures tended to shift to lower temperatures because of the plasticization effect with the increased CO_2 content.
2. The expansion behavior was not clear at 1 wt% CO_2 for all talc contents, since the maximum expansion ratio was only 4–6-fold. Expansion ratios increased as CO_2 content increased, and the expansion ratios showed mountain shaped curves. The maximum expansion ratio of up to 12–14-fold was successfully obtained at 0.8 wt% talc and 5 wt% CO_2.
3. The blowing agent efficiency did not increase proportionally to the increase in CO_2 content. The maximum blowing agent efficiency of 70% was achieved at 1 wt% CO_2 and 0.8 wt% talc.
4. The CO_2 content played an important role on the cell nucleation behavior when foaming this polymer without talc particles. The cell density was noticeably increased as the CO_2 content was increased to 5 wt% while the bubble size decreased. The maximum number of cells, up to 10^7–10^9 cells/cm^3 and small cells (less than 0.02 mm), were easily achieved in this experiment. On the other hand, talc content showed obvious changes in cell density and cell size when foaming with small amounts of CO_2 (i.e., 1 and 3 wt%). But the maximum expansion ratio seemed to have decreased slightly as the talc content was increased. This could be due to one of two reasons: (1) this polymer had a low degree of branching and (2) its viscosity was too high. If these were the cases, an increase in the degree of branching and a decrease in viscosity would result in increased expansion ratio.
5. Expansion ratios of up to 14-fold and cell densities of up to 10^7–10^9 cells/cm^3 were successfully achieved when using 0.8 wt% talc and 5 wt% CO_2 in the tandem foaming extrusion system.

ACKNOWLEDGMENTS

The researchers appreciate the financial support from the Royal Thai Government in the form of a scholarship under the Staff Development Program at Naresuan University and a scholarship for research supported by the Graduate School of Chiang Mai University, Chiang Mai, Thailand. In addition, the authors thank the Honam Petrochemical Company for providing the materials.

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