CHAPTER 5

SUMMARY AND CONCLUSIONS

This research was encouraged to study the foamability of PP material that is well known as a semicrystalline polymer and the crystallinity of this polymer is found to be a problem in the foaming process because this stiff phase inhibits the diffusion of gas during the gas saturation step, especially in the solid-state batch foaming process. This foaming process was used to generate the microcellular structure in the PP matrix (Moplen EP380T SW-844) due to the profit of the process which could be facilitated to investigate the foamability of the polymer with various sample thicknesses. In order to solve the difficulty of the PP foaming by the solid-state process, the utilizing of plasticization performance of some solvents (hexane, chloroform, and THF) which have the comparable solubility parameters closed to that of the polymer was conducted to the process. Chloroform was selected to use in the batch process due to the highest swelling degree of the polymer sheets among all studied solvents at the various time ranges. In the batch foaming experiments, the polymer sheets were allowed to be swollen by chloroform prior to the gas saturation step for the time required (8 hours) and expanded at various temperatures (25, 50, 100, 155, and 165 °C) for 3 seconds then the physical and mechanical properties of foamed products were investigated compared to those of un-foamed sheets and non-solvent foams. The decreasing in crystallinity of the polymer sheet was an evidence to show the advantage of solvent performance on the foamability of PP. Namely, when the polymer was treated by the solvent, the solvent molecules which located between the polymer chains can act as a plasticizer, which made the polymer chains far apart so the polymer matrix becomes softer. At this condition the matrix contributed more nucleation area for high nucleation site as the resulted in the high density (10^8 to 10^{10} cells/cm^3) of 3-8 μm of cell size were generated in the matrix with the density reduction about 10-60 percentage as the increment of foaming temperatures compared to those of un-foamed sheet. Although, the high temperature (near the melting point of the polymer) is essential for foaming the semicrystalline polymer such as PP but using our approach the microcellular foams could be achieved at low foaming temperatures (25 °C or 50 °C). While foaming without the swelling step, the process required a higher foaming temperature (100 °C to 165 °C) in order to obtain the same amount of cell density. Because of the limit of different heat transfer through different thicknesses of polymer sheets, the influence of the processing condition on the foamability of thick PP sheets could be observed. The results showed that the high density of cells could be more easily nucleated in the thinner sheets compared to that of the thicker one. In addition, foaming of the thick PP sheets with the swelling step could facilitate to get the required cellular morphology even when they were processed at low foaming temperature. Although, the tensile properties of the microcellular PP foams seemed to be inferior as the void fraction increased compared to that of un-foamed sample, but foaming with and without the swelling step provided the foams with a superior notched-impact property with the microcellular structure. This was because the presence of high cell density with micro-cell size in the matrix could act as a crack arrestor [146]; therefore when the foamed samples absorbed the impact energy then the interior microcellular structure could uniformly dispersed the energy in the matrix as resulted in high impact strength PP foams. The impact properties of the foams were found to be higher than that of un-foamed samples about 2-7 times and the values were increased as the foaming temperatures increased.

The continuous foaming processing of PP material is found to be difficult to maintain the volume expansion ratio and the shape of final PP foams. This is because polypropylene has a weak melt strength during the molten state. When the polymer is melted it could not resist to the extension force as results in the rupture of cells and the deterioration of final expansion ratio. Therefore, in order to receive a high volume expansion ratio and fine-celled structure, the controlling of cell nucleation and growth is very important for the continuous foaming process. Because the cellular structure can be generated through the thermodynamic instability of the foaming process; therefore, the required foaming conditions (such as foaming temperature and pressure) can be gained by using the special foaming system incorporation with an optimum pressure drop rate die. Consequently, the tandem extrusion foaming system was selected to promote the low-density and fine-celled PP foams. This is due to the second extruder of the system provides a mixing and initial cooling for the polymer melt and the heat exchanger provides further cooling for the polymer melt to suppress cell coalescence. Moreover, using long-chain branched PP with high-melt-strength (HMS) the cell coalescence was more effectively prevented compared to the linear PP. Again, the most important characteristics of this material are high elastic response, two-step viscosity at low frequencies (shear rate), and various relaxation processes in the nonlinear relaxation modulus. Therefore, an introduction of this material is an exceptional method to overcome the weak melt strength behavior without any disadvantages such as the decomposition and aggravation of physical properties. For continuous foaming experiment, low-density and fine-celled PP foams were produced with a high-melt-strength branched PP material (Honam SMS-514) using the tandem extrusion system. In the process, CO_2 gas with various amounts (1, 3, and 5 wt%) was used to blown the polymer melt and very fine particles of talc with various amounts (0.8, 1.6, and 2.4 wt%) was introduced to the polymer matrix in order to generate high amount of nuclei and very small cell size. The medium pressure drop rate die was selected from the 8 competitive die geometries which provided three pressure drop levels (6.9 MPa, 13.8 MPa, and 20.7 MPa). The foamability of these dies was firstly observed through the experiment of Lee *et al.* [16] to determine a suitable one for foaming of Honam SMS-514. However, the length of the selected die was cut to obtain the optimum pressure drop for producing the required low-density PP foams with this material. The experimental results showed that this material could be processed in the range of 140 °C to 180 °C. This could be accepted that this material exhibited high melt strength to resist the extension force even it was processed at a temperature which was higher than the melting temperature (168 °C) and the cooling system of the tandem system could facilitate the expansion at high temperature. The investigation of the expansion ratio of this polymer revealed that the expansion behavior of the polymer was influenced by the gas loss phenomenon at high temperature and the crystallization of the polymer at low temperature as could be seen from the shape of the expansion ratio curve. Moreover, the die pressure was found to be a function of the CO_2 contents; the die pressure decreased as the content of CO_2 increased. Consequently, the optimum temperatures (the foaming temperature at the maximum expansion ratio) were shifted to lower temperatures when the CO_2 content was increased due to the plasticization effect of the increased CO_2 content. Therefore, the maximum expansion ratio was obtained when a high amount of CO_2 was used. In addition, cell nucleation behavior was affected by the content of CO_2 when foaming without the nucleating agent (talc) and the cell density increased as the content of CO_2 was increased and 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 at 5 wt% of CO_2. Although, the thermodynamic instability via a rapid pressure drop is utilized to promote a large number of nuclei, but the final cellular structure is usually unacceptable without the addition of nucleating agent; the cell size is too large and the cell density is too small. Therefore, talc particles were used to serve as solid surface for heterogeneous nucleation in this research. Furthermore, the processing pressure was decreased as the presence of nucleating agent in the polymer/gas solution. As the results, the changes of cell density and cell size were obviously observed when foaming with talc incorporation with the small amount of CO_2 (1 wt% and 3 wt%). But the maximum expansion ratio seemed to slightly decrease 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. HMS branched PP material could suppress the weak melt strength of PP foam production. The optimum processing condition was promoted by using optimum pressure drop rate die incorporation with 0.8 wt% of nucleating agents and 5 wt% of CO_2. The cell coalescence phenomenon could be prevented using the tandem extrusion foaming system. At this condition, the PP foams with expansion ratios up to 14-fold with 10^7-10^9 cells/cm^3 were successfully achieved.