Research Article

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Experimental-numerical studies of the effect of cell structure on the mechanical properties of polypropylene foams

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Abstract: The effects of the cell size and distribution on the mechanical properties of polypropylene foam were simulated and analyzed by finite element modeling with ANSYS and supporting experiments. The results show that the reduced cell size and narrow size distribution have beneficial influences on both the tensile and impact strengths. Decreasing the cell size or narrowing the cell size distribution was more effective for increasing the impact strength than the tensile strength in the same case. The relationship between the mechanical properties and cell structure parameters has a good correlation with the theoretical model.

Keywords: foam, cell structure, mechanical property, finite element analysis, injection foam molding

1 Introduction

Nowadays, microcellular polymer foam materials have attracted much attention due to their advantages such as lightweight, low material usage, high strength-to-weight

ratio, and good thermal insulation properties relative to the solid or macrocellular foam materials (1–7). For example, the PP foam material, in addition to the above characteristics, also has some unique advantages compared with some thermoplastic foams, such as higher temperature stability, excellent chemical resistance, and low material costs. However, one of the major defects of PP foam is lack of mechanical strengths. Many works have proved that the mechanical properties of foam materials are affected by the structural parameters of cells, such as the cell size and cell shape (8–11). Recently, a growing number of researchers have conducted experimental tests of polymer foam materials subjected to tensile or impact loads. However, it is difficult to get a more complete understanding of the relationship between the cell structure of polymer foam materials and their mechanical properties. As it is well-known that, developing numerical models can predict the mechanical properties of foam materials and decrease the required experimental measurements as well as the fabrication cost. Numerical simulation methodology has been widely used in kinds of mechanic analyses, due to its efficiency, reliability, and economy. Hence, many efforts have been made in the evaluation and advancement of polymer foams possessing improved mechanical properties using finite element analysis (FEA) (12–15). Gilchrist and Mills (12) used the FEA model to study the impact response of low-density polystyrene foam and found that when there was no crack growth, the predicted deformation fields were the same as those in high-speed videos. The predicted stresses were close to experimental values. Major crack growth, in some indentation impacts, caused the force to be significantly lower than that predicted. Fereidoon and Taheri (13) used Abaqus software to analyze the influence of microstructure on the energy absorption properties of open-cell polymer foam through a three-dimensional (3D) finite element method. The effect of the cavity size and density on the stress–strain behavior of PP open-cell foam was discussed. Most obturator PP foam was usually nonperiodic, heterogeneous, and disordered. Therefore, in the numerical simulation, it was necessary to include

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microstructure defects and a large number of element models to simulate the material crushing process. Li *et al.* (16) had developed this model for two-dimensional cell solids with irregular cell shape and uneven cell wall thickness, which were two common defects in such cell solids. Some researchers (17–20) have also carried out scale finite element simulation to study the quasi-static compressive behavior of porous materials. They provided an effective method to quantitatively and qualitatively simulate the compressive stress of cell materials. However, most previous works' focus was less on representing the stress–strain behavior of PP foams with closed cell structure near the cells and thereby the relationship between the microstructure of PP foams and the tensile and impact properties. Hence, it is essential to investigate the effect of cell structure on the mechanical properties of foams with the more appropriate methods. The present work is most importantly aimed at studying the stress–strain behavior of PP foams near the cells by 3D finite element modeling with ANSYS and supporting tests and thus identify the relationship between the mechanical properties and cell structure parameters of PP foams.

2 Experimental

2.1 Materials

Pelleted isotactic PP (grade T30S; density 0.91 g/cm³; MFR 3.7 g/10 min; melt temperature 167°C; tacticity 95.0–96.5%) and PE (grade 1F7B; density 0.92–0.94 g/cm³; MFR 21.6 g/10 min; melt temperature 120°C) commercial products from Sinopec, were selected for this study. Azodicarbonamide (AC) was used as the chemical blowing agent (CBA), which decomposes from 195°C to 200°C and has a gas yield of 210–250 mL/g. Zinc oxide (ZnO) and zinc stearate (ZnSt) as CBA activators were commercially available (all purchased from Sinopharm Chemical Reagent Co., Ltd).

2.2 Preparation of foamed PP materials

The blowing agent masterbatch was prepared by the blending of AC and low-density PE in a twin-screw extruder. An approximate AC/low-density PE ratio of 1:9 (w/w) was used. The activator masterbatch was

Table 1: Injection molding process parameters

Process parameters	Ranges
Mold temperature (°C)	40–90
Melt temperature (°C)	150–180
Packing pressure (% injection pressure)	50–60
Packing time (s)	5–15
Filling time (s)	4
Cooling time (s)	25

prepared by mixing zinc oxide (ZnO) and zinc stearate (C₃₆H₇₀O₄Zn) into the PE matrix in a twin-screw extruder, and the activator masterbatch/PE ratio was 1:9 (w/w). An approximate ZnO/C₃₆H₇₀O₄Zn ratio of 75:25 (w/w) was used. The prepared masterbatch was dried at 80°C for 12 h before injection processing. Foamed standard test bars (200 mm × 10 mm × 4.4 mm) based on the Chinese standard GB/T1843-2008 were molded through a two-step molding process under various process conditions in an injection molding machine (EM120-V, Zhende Plastic Machinery Co., Ltd). The machine used in this work has a maximum injection pressure of 150 MPa, a maximum screw speed of 200 rpm, and a maximum clamp force of 80 tons. The injection molding process parameters in detail are listed in Table 1. In this study, the CBA masterbatch and activator masterbatch were used at 15 and 5 wt%, respectively (22). A thermally regulated injection mold was utilized in this work. The PP foams having different cell sizes and cell size distributions were obtained by changing the mold temperature.

2.3 Characterization

A scanning electron microscope (SEM) was used to determine the size and distribution of cells. The samples were immersed in liquid nitrogen and then ruptured to expose their cell morphology, and the fractured surfaces were gilded before the characterization of the foam structure. The SEM images of foamed samples were analyzed with Image-Pro Plus software (Media Cybernetic) to quantitatively assess cell size. The area and number of cells in SEM images could be calculated by Image-Pro Plus software to obtain the average size of the cells. At least 100 cells in the SEM micrograph of each sample were used to evaluate the mean cell size and size distribution. A cell size distribution coefficient (S_d) is used to represent the cell size distribution in foamed materials, which can be

calculated based on the equation of standard deviation, as follows (5):

$$S_d = \left\{ \left(\sum_{i=1}^n (D_i - D)^2 / n \right) \right\}^{1/2}, \quad (1)$$

$$V_f = 1 - \frac{\rho_f}{\rho}, \quad (2)$$

where n is the number of counted cells, D_i is the single cell diameter, D is the average diameter of cells, V_f is the foaming ratio, ρ_f is the foamed material density, and ρ is the pure material density.

2.3.1 Mechanical measurement

Tensile strengths were determined according to the Chinese standard GB/T1040.1-2006 by the tensile testing machine (Instron8510). Tests were performed with a constant cross-head speed of 20 mm/min at 24°C. Impact tests were conducted according to the Chinese standard GB/T1843-2008 at 24°C on different cell size foam samples with a drop-weight impact test machine. Before the impact test, we

will make a U-shaped blunt end (2 mm depth, 1 mm radius) in the center of the sample. Test five samples of each sample and calculate the mean and standard deviation. The relationship between mold temperature and cell structural parameters is exhibited in Table 2.

3 Results and discussion

3.1 Dependence of the mechanical properties on the cell size

Figures 1 and 2 illustrate the effect of the cell size on the mechanical properties, and the reduced cell size is found to have a beneficial influence on both the tensile and impact strengths. The impact strengths of the foams increased with reducing cell size. The mechanical properties showed a moderate change with an increase in tensile strength, and the impact strength showed more sensitivity to the cell size than the tensile strength. The increase in impact strength was attributed to the cells acting as crack arresters. There is about a 30% increase in the impact strength from 3.398 to 4.388 kJ/m² when the cell size is reduced from 87 to 31 μm under the same volume expansion ratio and the same cell size distribution (as shown Figure 1). PP/OMMT composites have about 15.4% increase in the impact strength from 6.533 to 7.54 kJ/m² when the cell size reduced from 35.4 to 22.1 μm under the same volume expansion ratio and the same cell size distribution (as shown Figure 2).

Table 2: Cell structural parameters of the PP foams obtained at different mold temperatures

Parameters	Values			
Mold temperature (°C)	25	45	65	85
Cell size (μm) (standard deviation = 2 μm)	31	46	73	87
Mold temperature (°C)	30	60	90	120
S_d (μm) (standard deviation = 2 μm)	14	32	57	80

Figure 1: Relationships of the average cell size and (a) the tensile and (b) impact strengths of the PP foams with the same volume expansion ratio.

Figure 2: Correlation of mechanical behaviors and cell size for foamed PP/OMMT composites: (a) tensile strength and (b) impact strength (21).

Figure 3 shows typical SEM images of the PP foams with various cell sizes, and it illustrated that the cell size plays a big role in the mechanical strengths. From the SEM images, the average cell diameter and cell size distribution coefficient of the foams were measured with the software Image-Pro Plus. From these figures, it can be

seen that the average cell diameter lies between 31 and 87 μm. The samples with larger cell sizes have relatively poor impact strength and reduced a certain range of tensile strength. These inferior strengths are mainly due to the stress concentration induced by their larger cell sizes and very irregular cell morphology. The larger cells

Figure 3: Freeze-fracture SEM images of the PP foams with various cell sizes. Scale bar: 100 μm. Average cell size: (a) 31 μm, (b) 46 μm, (c) 73 μm, and (d) 87 μm.

Figure 4: Relationships of the cell size distribution and (a) the tensile and (b) impact strengths of the PP foams with the same volume expansion ratio.

present in the foamed samples act as cracks or defects during testing resulting in tensile strength and impact resistance reduction in the samples (21). By contrast, the foams with very fine cells exhibited better mechanical properties.

3.2 Dependence of the mechanical properties on the cell size distribution

The effects of the cell size distribution on the mechanical properties were obtained from the tensile and impact

tests, and the results are presented in Figures 4 and 5. As expected, both the tensile and notched impact strengths of the PP foams increased with the narrowing cell size distribution. There is a 43.61% increase in the impact strength from 3.398 to 4.88 kJ/m^2 when the cell size distribution reduced from 80 to 14 μm under the same volume expansion ratio and the same average cell size (as shown Figure 4). There is a 43.61% increase in the impact strength from 3.398 to 4.88 kJ/m^2 when the cell size distribution reduced from 80 to 14 μm under the same volume expansion ratio and the same average cell size (as shown Figure 4). PP/OMMT composites has about 22.87% increase in the impact strength from 3.398 to 4.88 kJ/m^2 when the cell

Figure 5: Correlation of mechanical behaviors and cell dispersion (S_d) for foamed PP/OMMT composites: (a) tensile strength and (b) impact strength.

Figure 6: Freeze-fracture SEM images of the PP foams with various cell size distributions. Scale bar: 100 μm . Cell size distribution: (a) 14 μm , (b) 32 μm , (c) 57 μm , and (d) 80 μm .

size distribution reduced from 13.4 to 2.75 μm under the same volume expansion ratio and the same average cell size (as shown Figure 5), while the observed increase in tensile strength is moderate.

Figure 6 shows typical SEM images of the PP foams with various cell size distributions. From the SEM images, the poly-dispersity of the foams were measured with the software Image-Pro Plus. The highest mechanical strengths were observed containing the narrowest cell size distribution, and the lowest mechanical strengths were observed on

the widest cell size distribution. The impact and tensile strengths in the case of narrow distributions were higher than those with wide cell size distributions (22). The uniform stress distribution and homogeneous deformation could make these foamed samples more rigid due to their narrow cell size distributions.

The main results of the mechanical tests are summarized as follows: (1) the larger cell size or wider cell size distribution reduces both the tensile and impact strength of PP foams due to the stress concentration and (2) the

Figure 7: The cells are modeled as the spheres with two fixed diameters in two ideal cubes: (a) $r = 2 \text{ mm}$ and (b) $r = 1 \text{ mm}$.

Figure 8: Three-dimensional stress analysis of foamed samples with small (a, c, e and g) and large (b, d, f and h) cell sizes: (a and b) along x direction, (c and d) along y direction, (e and f) along z direction, (g and h) along the x, y, and z directions.

Figure 9: Sphere model of the foamed samples with different cell size distributions: (a) $S_d = 1$ and (b) $S_d = 0$.

impact strength showed more sensitivity to the cell size and cell size distribution than the tensile strength.

3.3 Three-dimensional stress analysis around the spheres model with different cell sizes based on ANSYS

The basic unit of the foamed samples is assumed to be an ideal cube. The cells in a basic unit are modeled as spheres (Figure 7). For convenience, several assumptions have been made in this work: (1) two kinds of the cells are modeled as spheres with two fixed diameters, 2 and 1 mm, respectively, (2) the cells were isotropic under stress, and (3) the cell walls were elastoplastic bodies.

Figure 8 shows the stress distribution around the spheres along the x -, y -, and z -directions. It can be seen from Figure 8a, c, and e that the stresses for the small spheres along the positive x -, y - and z -axis are 9.4, 47.08, and 0.23 MPa, respectively. Figure 8b, d and f shows that the stresses for the large spheres along the positive x -, y -, and z -axis are 10.06, 49.30, and 1.07 MPa, respectively. Therefore, the higher total stress around the large sphere is apt to cause stress concentration when compared with the small sphere. It can be seen from Figure 8g and h that the stress for the large sphere is always higher than that for the small sphere in any direction, which further indicates that large spheres are more prone to cause local stress concentration. The stress analysis reveals reasonable agreement between the experimental and the predicted results under a three-dimensional stress state. Consequently, the cells with relatively small sizes could counteract stress concentration in the foamed samples and thus improve the tensile and impact strengths of the PP foams.

The stresses along the z -direction are 0.23 MPa for small cells and 1.07 MPa for large cells, respectively. The spheres in the model can be regarded as notches in the samples under tensile loading. For the specimen with a large cell size and a small number of cells (large spheres) as shown in Figures 1 and 2, it shows relatively thick cell walls. The cells can be taken into account in case of the notch at relatively thick plates. The situation is similar to the thick plate model (22,23). In the sample, a plane state of strain similar to that of the thick plate was produced. The cell deformation was strongly constrained in the z -direction. It is a state of plane strain considering volume effect, which leads to low crack propagation resistance and low tensile or impact strength (24,25). The situation is reversed for the specimen with small cell size and a large number of cells, where a plane stress state was produced. Small and uniform cells (small spheres) can deform almost freely in the z -direction, the stress state is similar to that of the thin plate according to the fracture mechanics (26). This stress state contributed to the corresponding high crack propagation resistance and high tensile or impact strength.

3.4 Three-dimensional stress analysis around the spheres model with different cell size distributions based on ANSYS

The basic unit of the foamed samples is regarded as an ideal cube. Similarly, for the sake of simplicity, several assumptions have been made: [1] three cells in the unit are modeled as spheres having three different radii, 0.5, 1, and 1.5 mm, respectively (Figure 9). The three cells in unit b are modeled as spheres having the same radius ($r = 1.15$ mm). The volumes of the three spheres in the unit

Figure 10: Three-dimensional stress analysis of foamed samples with wide (a, c, e and g) and narrow (b, d, f and h) cell size distributions: (a and b) along x direction, (c and d) along y direction, (e and f) along y direction, (g and h) along the x, y, and z directions.

are equal to that in unit b. [2] The cells were isotropic under stress, and [3] the cell walls were elastoplastic bodies.

Figure 10 shows the stress distribution around the spheres along the x , y , and z directions. It can be seen from Figure 10a, c and e that the stresses for the spheres with wide size distribution along the positive x -, y -, and z -axis are 17.01, 51.671, and 5.6717 MPa, respectively. Figure 10b, d and f show that the stresses for the spheres with narrow size distribution along the positive x -, y -, and z -axis are 5.6717, 39.628, and 1.436 MPa, respectively, which implies that the higher total stress in the vicinity of the spheres with wide size distribution is apt to cause stress concentration when compared with those with narrow size distribution. It can be seen from Figure 10g and h that the stress for the spheres with wide size distribution is always higher than that for the spheres with narrow size distribution in any direction, which further indicates that the spheres with wide size distribution are more prone to cause local stress concentration. Accordingly, the cells with relatively narrow size distribution could counteract stress concentration in the foamed samples and thus improve the tensile and impact strengths of the foamed composites. Therefore, the prediction of the model coincides with the mechanical behavior of the PP foams under a three-dimensional stress state.

4 Conclusions

The effects of the cell size and size distribution on the tensile and impact properties of the foamed PP materials were simulated by finite element modeling with ANSYS. The reduced cell size and narrowed cell size distribution have beneficial influences on both the tensile and impact strengths. There is about a 30% increase in the impact strength from 3.398 to 4.388 kJ/m² when the cell size reduced from 87 to 31 μ m under the same volume expansion ratio of the foamed PP materials. 43.61% increase in the impact strength from 3.398 to 4.88 kJ/m² was observed when the cell size distribution reduced from 80 to 12 μ m under the same volume expansion ratio and the same average cell size. The tensile strength of the foamed PP materials showed a relatively small increase compared to the impact strength. The effects of the cell size and cell size distribution on the mechanical properties of the foamed PP materials were simulated and analyzed by the finite element model with ANSYS. The relationship between the mechanical properties and cell structure parameters was correlated well with the theoretical model under a three-dimensional stress state.

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