Tensile property of thin microcellular PC sheets prepared by compression molding

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Abstract. Thin microcellular polycarbonate (PC) sheets have been prepared by compression molding. Tensile tests were performed on microcellular PC sheets prepared under different conditions, and results show that foaming time plays the main role on the tensile property. The cellular structure prepared in this process has been shown to have a significant effect on the corresponding tensile property of microcellular PC foams. For these foams, Single Blend model can be used to predict the effect of the relative density on the relative strength, but the experiment data of the tensile modulus is much lower than that predicted by Square-Relationship Model. The effect of cell size on the tensile property of microcellular PC foams was also investigated, and found that the cell size can affect the tensile property, which is different from the result of Kumar. In order to make the tensile property predictable, some mathematical formulas were also simulated.

Keywords: mechanical properties, microcellular, polycarbonate, simulation

1. Introduction

Due to the special structure of microcellular foams, they can be used in many areas, such as packaging, insulation, bone substitute material, military aircraft and microelectronic application. In the microcellular foam application, the mechanical property is a very important factor to consider.

There is considerable literature on the mechanical properties of conventional foams [1–8], particularly in the book edited by Gibson and Ashby [2], but too limited reports on that of microcellular foams. Since the microcellular foam was successfully prepared by Suh and his co-workers [9–11] in Massachusetts Institute of Technology, some researchers have focused on the tensile property of microcellular foam. Waldman [12] reported that the tensile strength of microcellular polystyrene (PS) foam follows a linear relationship with the specific density, but much higher than that of the structural foam when Young's modulus is kept constant.

Kumar and Van der Wel [13] found that the tensile strength of polycarbonate (PC) microcellular foam was lower than that predicted by the law of mixture, and Young's modulus was larger than that of structural foam. Collias and Baird [14] studied the tensile toughness (the area under the stress-strain curve) of microcellular foams of PS, PC and Styrene-Acrylonitrile (SAN) copolymer. They concluded that microcellular PS foam shows limited improvement in the tensile toughness, but microcellular SAN and PC foams show deterioration in tensile toughness. Later on, Sun *et al.* [15] carried out mechanical tests both in compression and tension, and they drew a conclusion that Young's modulus and strength are closely related to the relative density. Youn and Suh [16] found that the flexural toughness of polyester microcellular foam increases by a factor of 3 for 30% bubble volume fraction compared to the neat polyester, although the strength is about the same. Aroka [17] investigated the effect of the cell size and shape on the

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compressive yield stress of microcellular PS foam, and found that the compressive strength of foam increases with the increase of cell size, and their data are higher than those predicted by an anisotropic foam model. Recently there has been some research dealing with the effect of relative density on the mechanical property of microcellular composite foams [18, 19], however, they only related mechanical property with the relative density, but fewer reports are available on the effect of processing parameters and cell size on the tensile property.

The objective of this paper is twofold. One is to assess the importance of processing parameters which affect the tensile property. These processing parameters include foaming time, foaming pressure and foaming temperature. The other is to investigate the effect of cellular structure, that is, the relative density and the cell size, on the tensile property, and compare the experimental data with the values predicted by Gibson and Ashby [2].

2. Experimental

2.1. Materials

The polycarbonate (PC) sheets used in this work were commercial-grade product with a thickness of 0.178 mm, purchased from GE Corporation. Low density polyethylene (LDPE) pellet from Sinopec Beijing Yanshan Chemical Corporation Factory (Beijing, China), with a melt index 2 g/10 min at 190°C, was used as received. Commercial-grade azobisformamide (AC) from Wuhan Hanhong Chemical Reagent Corporation of China (Wuhan, China), was used as blowing agent. The amount of gas yielded, which mainly consists of nitrogen, carbon monoxide, carbon dioxide and ammonia, is about 200–220 ml/g. Dicumyl peroxide (DCP), Sinopharm Chemical Reagent Corporation, Ltd. (Shanghai, China), was used as received. Analytical-grade zinc oxide (ZnO) from Shanghai Shiyi Chemical Reagent Co.Ltd. (Shanghai, China), was used as activate agent for AC decomposition.

2.2. Microcellular PC foam preparation

The preparation of microcellular PC foam consists of two processing steps. First, according to the formula, 200 g LDPE, 40 g AC, 5 g DCP and 20 g ZnO were mixed in a two-roll mill as a gas source for PC foaming. Second, the PC sheets and the

mixed LDPE were placed in a 250×250×2 mm mold together and loaded in a hydraulic hot press under experimental conditions.

After the required foaming time and other conditions were reached, the pressure was released and the mold was taken out of the hot press immediately. Then we unloaded the mold, quenched it to room temperature within 30 s; and removed the microcellular PC foam from the mold. Thus, the microcellular PC samples were ready for property characterization after being kept at room temperature for at least 2 days.

2.3. Microcellular PC foam characterization

The cell size of the foamed samples was calculated according to the image observed under a Nikon YS2 optical microscopy (using a 100× amplify camera lens), following the procedure described previously by Kumar *et al.* [20] and Equations (1) and (2).

$$V_f = \frac{\pi D_c^3 N_f}{6} \quad (1)$$

$$N_0 = \frac{N_f}{1 - V_f} \quad (2)$$

where V_f is the volume fraction of the foamed material, D_c is the average cell size measured from the photographs, N_f is the cell density relative to the foamed material, and N_0 is the cell density relative to the neat material.

The specific density of foamed samples was measured according to the method used by Yuan [19], and concrete procedure was shown in ASTM-792 standard. When the specific density was less than 1.0, the foamed samples were immersed into water by the help of a thin copper sheet. The specific density and relative density are calculated by Equations (3) and (4), respectively.

$$\rho_f = 0.9975 \cdot \frac{M_a}{M_w} \quad (3)$$

$$\rho_r = \frac{\rho_f}{\rho_0} \quad (4)$$

where ρ_0 , ρ_f is the specific density of the unfoamed and foamed material, respectively; M_a and M_w are the weight of the samples measured in air and water, respectively; ρ_r is the relative density.

The microcellular PC sheets were machined into dumbbell-shape specimens with a gage length of 50 mm (ASTM D638 type II specimen), the specimen thickness varied with the expansion of foam. For each sample, at least five samples were tested and the average data are reported in this article. The tensile test was carried out at room temperature using a Shimadzu AG-A all-purpose testing machine (Japan) equipped with a 1000 lb load cell at a constant crosshead rate of 50 mm/min.

3. Results and discussion

3.1. Tensile behavior of unfoamed and microcellular PC sheets

Figure 1 shows the typical stress-strain curves of unfoamed and microcellular foamed PC sheets, they can be divided into three regions: in the first region stress increases steeply with the increase of strain; the central region in which stress remains constant and strain varies quickly; and the last region where stress varies with the increase of strain up to fracture. The relative density decreases when PC sheet is microcellularly foamed, the tensile strength at break, the elongation at break evidently decreases and the yield point becomes faint. This is because the gas acts as a plasticizer. The experimental data that reflect the effect of processing parameters on the tensile property, such as tensile strength, tensile modulus, specific strength, breaking elongation, are listed in Table 1 and are discussed as follows.

Figure1. The stress-strain curves of unfoamed and microcellular PC sheets (foaming time is 10 min, foaming pressure is 20 MPa, foaming temperature is 130°C)

3.1.1. The effect of processing parameters on tensile strength

From Figure 2, it can be seen that the tensile strength decreases with the increase of each processing parameter. However, when foaming time varies, the tensile strength changes more than the ones in other foaming conditions. Hence, combined with Table 1, it can be concluded that foaming time plays the main role on the tensile strength. Under the pressure of 18 MPa, 20 MPa and 22 MPa as shown in Figure 2a, the tensile strength is evidently affected by foaming time, and decreases with the increase of foaming time. The foaming pressure can also affect the tensile strength as shown in Figure 2b, when foaming pressure increases, the

Table 1. The experimental data of the microcellular PC sheets prepared under different processing conditions

Foaming time [min]	Foaming pressure [MPa]	Upper-plate temperature [°C]	Cell size [μm]	Standard deviation [μm]	Cell density N_0 [10^8 cells/cm ³]	Relative density	Tensile modulus [MPa]	Tensile strength [MPa]	Breaking elongation [%]
0	0	0	0	0	0	1.000	2157.5	66.1	185.70
7	18	140	9.2	1.12	2.18	0.912	951.1	60.6	153.82
8	18	140	4.5	0.974	27.84	0.876	925.2	59.4	145.30
9	18	140	6.6	0.844	8.22	0.874	877.2	58.8	143.06
10	18	140	7.1	0.966	6.37	0.804	825.9	56.9	134.80
11	18	140	10.3	1.28	4.15	0.747	771.3	51.3	133.54
12	18	140	10.8	2.19	2.53	0.767	680.8	47.2	131.82
10	12	140	9.0	0.842	7.46	0.896	970.0	60.2	123.49
10	14	140	8.0	1.59	16.09	0.874	879.9	58.6	125.49
10	16	140	7.4	0.982	17.64	0.872	833.4	58.0	127.05
10	18	140	7.1	0.966	23.32	0.864	825.9	57.5	134.80
10	20	140	6.8	0.965	22.78	0.857	784.9	56.9	127.21
10	22	140	6.2	1.27	33.86	0.844	766.3	55.2	123.55
10	20	130	4.3	0.718	23.87	0.927	906.8	58.8	131.22
10	20	135	5.6	0.768	16.61	0.857	822.5	57.9	123.40
10	20	140	6.8	0.965	10.30	0.795	784.9	56.9	127.21

Figure 2. The effect of processing parameters on tensile strength of microcellular PC sheets

tensile strength decreases gradually. But the effect of upper-plate temperature and lower-plate temperature on the tensile strength is too limited as shown in Figures 2c and 2d. This is perhaps due to the decrease of relative density and the growth of cell. When foaming time, foaming temperature and lower-plate temperature increase, the relative density decreases and the cell size increases. Thus, the foamed microcellular PC can stand less stress. As for the effect of foaming pressure on the tensile strength, although cell size decreases with the increase of foaming pressure, the decreased relative density plays the main role in the tensile strength. The result is the same to that reported by Gibson [2], the tensile strength is proportional to the relative density. And the foaming time plays more important role in the decreased relative density than other foaming conditions in our considered experimental conditions. So the tensile strength decreases with the increase of foaming parameters, especially with the increase of foaming time.

3.1.2. The effect of processing parameters on tensile modulus

As shown in Figure 3, tensile modulus decreases with the increase of each processing parameter, and foaming time affects tensile modulus to larger extent, the variation trend is similar to that of tensile strength. When foaming time increases, tensile modulus decreases to the lowest point as shown in Figure 3a; and as the other three processing parameters increase, tensile modulus decreases to different points as shown in Figures 3b, 3c and 3d. The reason is similar to that of the tensile strength, the tensile modulus is also a function of the relative density. The relative density decreases with the increase of processing parameters; and decreases much more with the foaming time than with other foaming conditions. In addition, the dissolved gas acts as a plasticizer when performing tensile test. So the tensile modulus also decreases with the increase of each processing parameter, especially with the increase of the foaming time.

Figure 3. The effect of processing parameters on tensile modulus of microcellular PC sheets

3.1.3. The effect of processing parameters on specific strength

In this paper, the specific strength, which is affected by processing parameters in a complex manner, is defined as the ratio of tensile strength to relative density. The specific strength of non-foamed PC sheet is 66.1 MPa, in most cases, it becomes larger when PC sheets are in microcellular foamed state, as shown in Figure 4. When foaming time and lower-plate temperature increase, the specific strength increases to a certain value and then decreases as shown in Figures 4a and 4d. But when the foaming pressure and upper-plate temperature increase, the specific strength increases as shown in Figures 4b and 4c. This result satisfies the initial aim of inventing microcellular foam. After microcellular foaming, the mechanical property decreases less compared to the decreased relative density, so the specific strength of PC sheet is increased after microcellular foaming.

3.1.4. The effect of processing parameters on elongation at break

Elongation at break is an important parameter to assess whether the microcellular foam is toughened or not, and the elongation at break of non-foamed PC sheet is 185.70% in our experiment. From Figure 5 we can see that the elongation at break of microcellular PC sheets is decreased, it agrees with the result of Kumar and Van der Wel [13]. When foaming time increases, the elongation at break decreases to larger extent under the pressure of 18 MPa, 20 MPa and 22 MPa, but the elongation at break varies differently with the increase of each processing parameter. This result may be caused by the decreased relative density and the deterioration of microcells. The relative density decreases with the increase of processing parameters, the elongation at break decreases. When the microcells generated are larger than certain size, they can result in the embrittlement of the foamed sample. Hence, the reduced elongation at break after microcellular foaming in this research may be the result of larger cell size.

Figure 4. The effect of processing parameters on specific strength of microcellular PC sheets

Figure 5. The effect of processing parameters on breaking elongation of microcellular PC sheets

3.2. The effect of relative density on tensile property

In order to investigate the effect of relative density on tensile property clearly, some microcellular PC sheets with the same cell size and the different relative density were tested by using universal tensile tester. Figure 6 shows the effect of the relative density on the tensile strength and the tensile modulus of microcellular PC sheets, whose cell size is in the range of 5.0~6.0 μm and the relative density is in the range of 0.65~0.98. As shown in Figure 6, the relative tensile strength and the relative tensile modulus increase with the increase of relative density. We have compared our experimental data with that predicted by the Square-Relationship model and Single Blend model [21]. The two models are represented by Equations (5) and (6).

$$E_r = \rho_r^2 \quad (5)$$

$$\sigma_r = \rho_r \quad (6)$$

where E_r is the relative tensile modulus of microcellular foam (E_f/E_0), E_f is the tensile modulus of microcellular foam [MPa], E_0 is the tensile modulus of non-foamed polymer [MPa]; σ_r is the relative

tensile strength of microcellular foam (σ_f/σ_0), σ_f , tensile strength of the foam [MPa]; σ_0 , tensile modulus of the non-foamed polymer [MPa].

The comparisons between experimental data and predicted value are shown in Figure 6. The experimental data of the relative strength at break approximately fits well with the curve predicted by Single Blend model for the relative density is in the range of 0.65~0.98, but the relative modulus is evidently smaller than that predicted by Square-Relationship Model, this may come from the origin material property and its cell size. In order to accurately predict the tensile strength and the tensile modulus relationship with the relative density, the experimental data between the tensile property and the relative density were simulated, and Equations (7) and (8) are fit to our experimental data well.

$$E_r = 0.8021\rho_r^2 - 0.6041\rho_r + 0.2987 \quad (7)$$

$$\sigma_r = 2.5278\rho_r^2 - 3.2232\rho_r + 1.7521 \quad (8)$$

3.3. The effect of cell density on tensile property

There have been fewer reports about the effect of cell size on the tensile property. Only Kumar and Weller [22] investigated the effect of cell size on the tensile behavior of microcellular PC, and found that the cell size had no effect on the tensile behavior. Since the microcellular foams exhibit some special properties compared to the conventional foams with the same specific density, we assume that the cell size should have the effect on the tensile property. Thus, we selected the microcellular PC foam samples with the same relative density and the different cell size, and measured their tensile property.

Figure 7 shows the effect of cell size on the tensile strength and the tensile modulus of microcellular PC sheets, whose relative density is in the range of 0.86~0.87 and cell size is in the range of 3~14 μm . As shown in Figure 7, the relative tensile strength and the relative tensile modulus decrease with the increase of cell size, which doesn't agree with Kumar's conclusion [22]. The disagreement may be the result of the different way of preparing the microcellular PC foam. When the cell size becomes larger as shown in Figure 8 and the relative density keeps constant, each bubble can stand less stress

Figure 6. The effect of relative density on tensile property of microcellular PC sheets

Figure 7. The effect of cell size on tensile property of microcellular PC sheets

Figure 8. The photograph of optical microscope of microcellular PC; (a): smaller cell and (b): larger cell

when stress was put on microcellular foams; and when the cell size becomes larger and the relative density keeps constant, the decreased cell density results in fewer bubbles that can share stress put on microcellular foam, so relative tensile strength and relative tensile modulus decrease with the increase of cell size.

In order to predict the effect of cell size on the tensile strength and the tensile modulus, we also simulated the relationship between cell size and tensile property, and Equations (9) and (10) are fit to experimental data well.

$$E_r = \frac{0.667}{D_c^{0.3125}} \quad (9)$$

$$\sigma_r = \frac{1.2489}{D_c^{0.2207}} \quad (10)$$

From the results discussed above, the cell size does affect the tensile property under our experimental conditions, and the relative tensile strength and relative tensile modulus are a function of $1/D_c$. In order to predict the tensile strength and tensile modulus on the basis of relative density and cell size, the relationship between cellular structure and tensile property can be expressed in Equations (11) and (12):

$$\frac{E_f}{E_0} = A \cdot \left(\frac{\rho_f}{\rho_0} \right)^m \cdot \left(\frac{1}{D_c} \right)^n \quad (11)$$

$$\frac{\sigma_f}{\sigma_0} = B \cdot \left(\frac{\rho_f}{\rho_0} \right)^i \cdot \left(\frac{1}{D_c} \right)^j \quad (12)$$

where A, B are fitting constants; m, n, i, j are constants related to material. And these formulas can accurately express the relationship between the cellular structure and the tensile property.

4. Conclusions

In this paper, tensile tests were performed on the thin microcellular PC sheets prepared under different conditions. The results show that foaming time plays the main role on the tensile property. The cellular structure prepared by compression molding has been shown to have a significant effect on the corresponding tensile property of the microcellular PC foams. We have investigated the effect of the cellular structure on the tensile property, and found that Single Blend model can be used to predict the effect of the relative density on the relative strength for microcellular PC foams, but the experimental data of the tensile modulus is much lower than that predicted by Square-Relationship model. The cell size can affect the tensile property to some extent in our experiment. In order to accurately express the relationship between the cellular structure and the tensile property, semi-empirical models were proposed to fit the experimental data well.

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