Foam Extrusion Characteristics of Thermoplastic Resin with Fluorocarbon Blowing Agent. III. Foam Sheet Extrusion of Polystyrene and Low-Density Polyethylene

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Synopsis

An experimental study was conducted on the extrusion of polystyrene and low-density polyethylene foam sheets, using fluorocarbon blowing agents and a tubular die. The effects of the type and concentration of blowing agent, die temperature, and takeoff speed on foam extrusion characteristics were investigated. They are foam density, tensile modulus, and cell morphology. It has been found that die temperature greatly influences the open cell fraction and foam density and that the takeoff speed greatly influences cell orientation, which, in turn, has a profound influence on the tensile modulus of the foam sheets produced.

INTRODUCTION

The foam sheet extrusion process has been used commercially for the past two decades. The most commonly used foam sheets on the market today are polystyrene and low-density polyethylene. Polystyrene foam sheets are widely used in food packaging applications (e.g., meat and fruit trays and fast food containers), and polyethylene foam sheets are used in packaging applications (e.g., protecting fragile electronic equipment and dishware).

However, the published literature has very little fundamental information on the processing–property–cell morphology relationships in foam sheet extrusion. Most of the publications deal with the type and choice of process equipment,[1-5] the properties and the choice of blowing agents,[6-8] and relationships among the foam density, cell geometry, and mechanical properties.[9-11]

Using the slit/capillary rheometer, Han and Ma[12,13] have investigated the effects of the type and concentration of blowing agent and, also, of melt temperature on the rheological properties of mixtures of molten polymer and fluorocarbon blowing agent. They have reported that the viscosity of mixtures of molten polymer and fluorocarbon blowing agent is decreased as either the concentration of blowing agent or the melt temperature is increased, and that trichlorofluoromethane (FC-11) reduces the viscosity of molten polymer to a greater extent than dichlorodifluoromethane (FC-12) does.

Journal of Applied Polymer Science, Vol. 30, 3297–3316 (1985)
CCC 0021-8995/85/083297-20$04.00

Han and Ma[14,15] have, also, made serious efforts to investigate the fundamental aspects of the foam extrusion characteristics of polystyrene and low-density polyethylene, using a cylindrical die. They have pointed out that either a decrease in die pressure or an increase in die temperature gives rise to premature foaming inside the die and consequently high open cell fraction in extruded foams, and that when the die temperature is increased above a critical value, the cells collapse and the foam density increases dramatically. They have suggested that, in order to produce good quality foams (i.e., uniform closed-cell foams with low density), the geometry of die, the processing conditions, the type and concentration of blowing agent, and the molecular characteristics (hence the rheological characteristics) of polymers be chosen judiciously.

The unique feature of the foam sheet extrusion process that employs a tubular-film die is that very wide foam sheets, having biaxially oriented cells, can be produced. On the other hand, if a flat-film die is used, one obtains cells that are oriented uniaxially, giving rise to corrugated foam sheets.

As part of our continuing efforts towards enhancing our understanding of the physical phenomena occurring in the foam extrusion processes, we have very recently carried out an experimental investigation of foam sheet extrusion, using a tubular die. In this paper, we shall report the highlights of our findings.

EXPERIMENTAL

We have constructed a laboratory-scale foam sheet extrusion line, as schematically shown in Figure 1. It has: (1) a feeding system consisting of a single-screw extruder, a blowing agent metering system, and two static mixers with hot-oil temperature control units; (2) a tubular die similar to a blown-film die; (3) a cooling mandrel; (4) a slitting knife; (5) a stand for orientation mandrel; (6) a takeoff stand; (7) a winder. The feeding system that delivers mixtures of blowing agent and molten polymer is the same as that described in a paper by Han and Ma,[12] as is the operating procedure.

Referring to Figure 1, upon exiting the tubular die, the mixture of molten polymer and blowing agent expands considerably in all directions, thus increasing the diameter of the tubular bubble. The bubble is then pulled over a water-cooled mandrel, maintained at 25°C by circulating cold water through the flow channels drilled inside the mandrel. The tubular bubble is then slit into two sheets, and wound onto rolls. A fairly balanced ori-

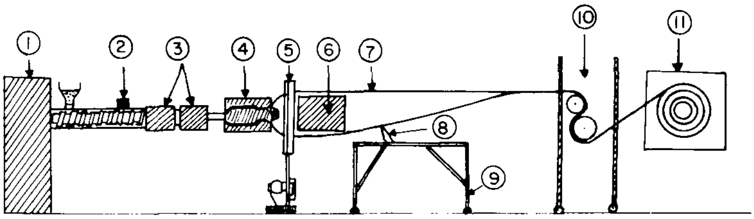

Fig. 1. Schematic of the Foam extrusion line: (1) extruder; (2) blowing agent injection port; (3) static mixers; (4) tubular die; (5) stand for orientation mandrel; (6) cooling mandrel; (7) foam sheet; (8) slitting knife; (9) stand for slitting knife; (10) takeoff stand; (11) winder.

entation of cells can be achieved by controlling the takeoff speed in the machine direction, because the stretching (or orientation) in the cross direction is determined, once the size of the cooling mandrel is chosen. Note that both the blowup ratio and the takeoff speed influence the density and the thickness of the foam sheets produced.

The die design, especially the geometry of the flow channel in the vicinity of the die lips, is one of the most important parts of the foam extrusion line, because the occurrence of foaming inside the die must be prevented. The inner diameter of the tubular die used in our study was 2.54 cm and the opening of the die lip was 0.508 mm for extruding low-density polyethylene and 0.457 mm for extruding polystyrene. The diameter of the cooling mandrel used was 7.62 cm, and thus the blowup ratio of the blown foam sheets was 3.0.

In the present study, polystyrene (Dow Chemical, STYRON 678) and low-density polyethylene (El Paso Polyolefin, REXENE 143) were used. As blowing agent, we used fluorocarbons, namely, trichlorofluoromethane (FC-11), dichlorodifluoromethane (FC-12), and dichlorotetrafluoroethane (FC-114). As nucleating agent, talc was used for extruding low-density polyethylene, and mixtures of citric acid and sodium bicarbonate for extruding polystyrene.

Throughout this study, the throughput (hence the shear rate) was kept almost constant. The processing and material variables investigated are summarized in Table I for polystyrene and in Table II for low-density polyethylene.

TABLE I

Processing and Material Variables Investigated for the Polystyrene Foam

(a) Effect of die temperature[a]

Die temp (°C)	Throughput (g/min)	Die adaptor pressure (psig)	Extruder pressure (psig)
140	33	850	1750
150	35	700	1500
160	36	590	1150

(b) Effect of blowing agent concentration[b]

FC-12 (wt %)	Throughput (g/min)	Die adaptor pressure (psig)	Extruder pressure (psig)
3	33	780	1700
4	35	700	1500
5	36	620	1280

(c) Effect of the type of blowing agent[c]

Type of blowing agent	Throughput (g/min)	Die adaptor pressure (psig)	Extruder pressure (psig)
FC-11	36	600	1300
FC-12	37	620	1280
FC-114	35	550	1200

[a] 4 wt % FC-12.

[b] Die temperature = 150°C.

[c] 5 wt % blowing agent and die temperature = 150°C.

TABLE II

Processing and Material Variables Investigated for the Low-Density Polyethylene

(a) Effect of blowing agent concentration[a]

FC-114 (wt %)	Throughput (g/min)	Die adaptor pressure (psig)	Extruder pressure (psig)
5.0	43.2	500	1250
7.5	43.6	500	1200
10.0	41.8	400	1100

(b) Effect of die temperature[b]

Die temp (°C)	Throughput (g/min)	Die adaptor pressure (psig)	Extruder pressure (psig)
100	43.6	500	1200
110	44.0	400	890
120	46.1	350	850

(c) Effect of the type of blowing agent[c]

Type of blowing agent	Throughput (g/min)	Die adaptor pressure (psig)	Extruder pressure (psig)
FC-12	43.2	500	1250
FC-114	43.2	500	1250
FC-11/FC-12 (50/50)	42.8	350	1050

[a] Die temperature = 100°C.
[b] 7.5 wt % FC-114.
[c] 5 wt % blowing agent and die temperature = 100°C.

During our experiment, foam samples were collected for measurements of cell size and its distribution, foam density, and the mechanical properties of the foam sheets produced. The foam density was measured by following ASTM D-1622-63, the tensile properties by following ASTM D-638-71, the open cell fraction by following ASTM D-2856-70, and the cell orientation by exposing foam samples in an oven.

RESULTS AND DISCUSSION

Foam Sheet Extrusion of Polystyrene

Figure 2 describes the effect of takeoff speed on foam density, with the concentration of blowing agent as parameter. Figure 3 does the same with die temperature as parameter, and Figure 4 with the type of blowing agent as parameter. It is seen in Figures 2–4 that the foam density first decreases, and then increases, as the takeoff speed is increased. Note that, with other processing variables fixed, an increase in takeoff speed brings about a decrease in the thickness of the foam sheets produced. It should be pointed out that, in the foam extrusion of thermoplastic resins, the rate of cooling (i.e., the heat transfer necessary for solidifying the molten polymer) has a profound influence on foam quality (i.e., cell size and open cell fraction). At the same time, thermoplastic foams, especially low-density foams, are

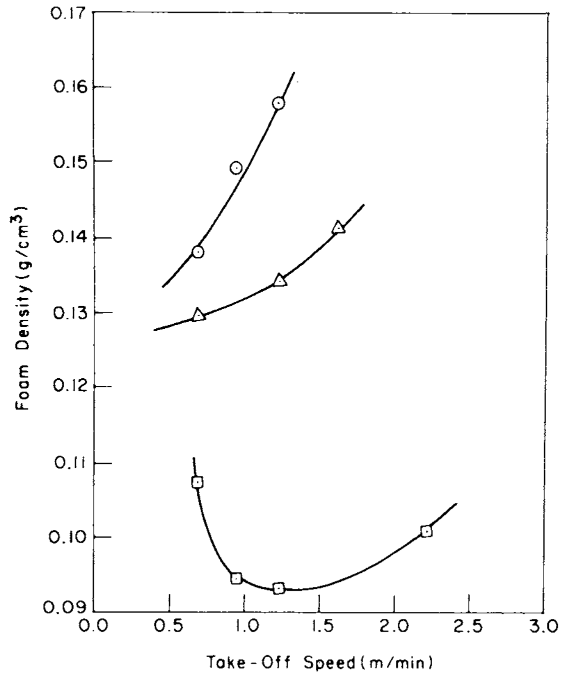

Fig. 2. Foam density vs. takeoff speed for the STYRON 678/ 0.3 wt % citric acid/0.375 wt % $NaHCO_3$ system, with various FC-12 concentrations (wt %): (⊙) 3.0; (△) 4.0; (⊡) 5.0. The die temperature is 150°C and the apparent shear rate is 285 s^{-1}.

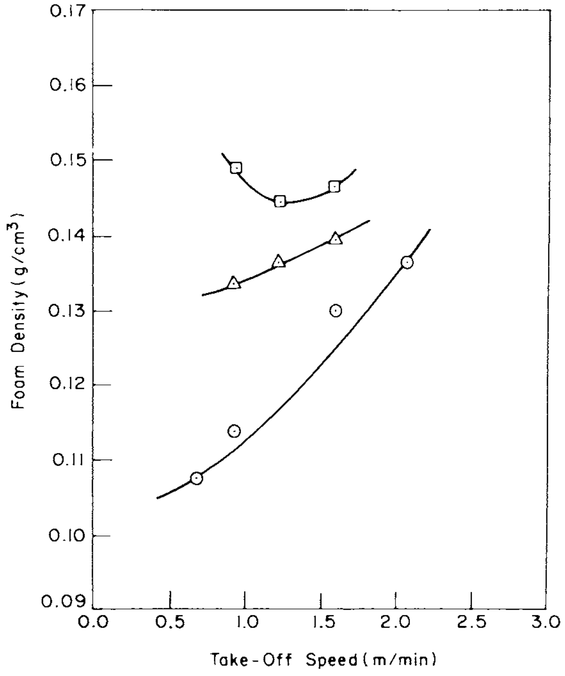

Fig. 3. Foam density vs. takeoff speed for the STYRON 678/ 0.3 wt % citric acid/0.375 wt % $NaHCO_3$/4 wt % FC-12 system, at various die temperatures (°C): (⊙) 140; (△) 150; (⊡) 160. The apparent shear rate is 285 s^{-1}.

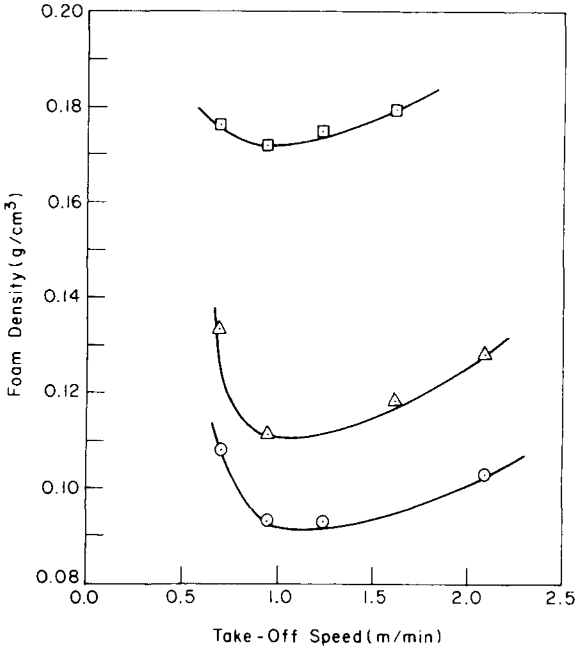

Fig. 4. Foam density vs. takeoff speed for the STYRON 678/ 0.3 wt % citric acid/0.375 wt % $NaHCO_3$ system, with different types of blowing agent: (⊙) 4 wt % FC-12; (△) 4 wt % FC-11/ FC-12 = 50/50 mixture; (□) 4 wt % FC-11. The die temperature is 150°C and the apparent shear rate is 285 s^{-1}.

good thermal insulators. Therefore, the higher foam density observed at low takeoff speeds (i.e., thicker foam sheets) may be, in part, due to the fact that the center of the foam could not be cooled fast enough to below the glass transition temperature of the polymer, giving rise to partial cell collapse. As pointed out by Han and Ma,[14,15] cell collapse increases foam density.

On the other hand, the diffusion of ambient air into the cells will help expand the foam sheet, because it enhances the expanding power of the blowing agent. The amount of ambient air that can diffuse into the foam sheet depends on the foam thickness and on the time available, during which the foam sheet is exposed to cooling air. The latter is determined by the extrusion rate and takeoff speed. Note that thicker foams have smaller surface-to-volume ratios available for the ambient air to diffuse into the foam sheet. Therefore, the higher foam density observed at low takeoff speeds may also be due to the decreased expanding power of the blowing agent.

In order to facilitate our discussion here, we have prepared plots of foam density versus foam thickness in Figures 5–7, using Figures 2–4. Note in Figures 5–7 that the concentration of blowing agent, die temperature, and the type of blowing agent were each used as parameters. It is clearly seen that the foam density first decreases, and then increases, with increasing thickness of foam sheet. This trend can be explained in terms of the interpretation given above.

It is seen in Figure 7 that the foams obtained with FC-11 have higher

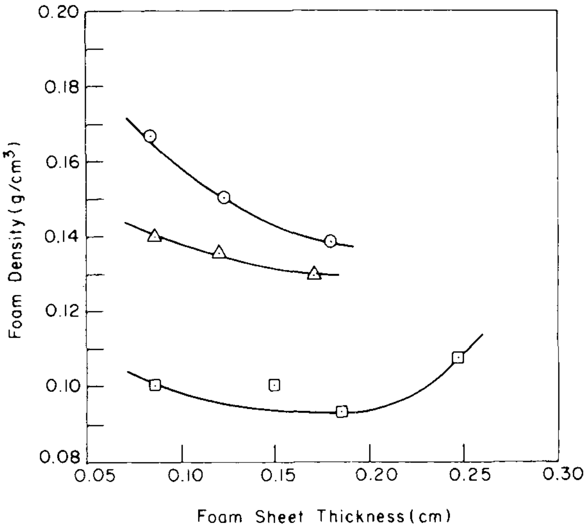

Fig. 5. Foam density vs. foam thickness at various FC-12 concentrations. Symbols are the same as in Figure 2.

densities than those obtained with FC-12. This is because FC-11 is a good solvent for polystyrene. Therefore, for instance at the die temperature of 150°C, the gas bubbles of FC-11 will come off very slowly from the mixtures of molten polystyrene and FC-11, giving rise to large bubbles and thus high-density foams. On the other hand, FC-12 is a poor solvent for polystyrene and has a low boiling point (−29°C) and therefore gas bubbles will come off fast from mixtures of polystyrene and FC-12, resulting in low-density foam. It is also seen in Figure 7 that the use of mixtures of FC-11 and FC-12 gives rise to foam densities lying between those when using FC-11 and

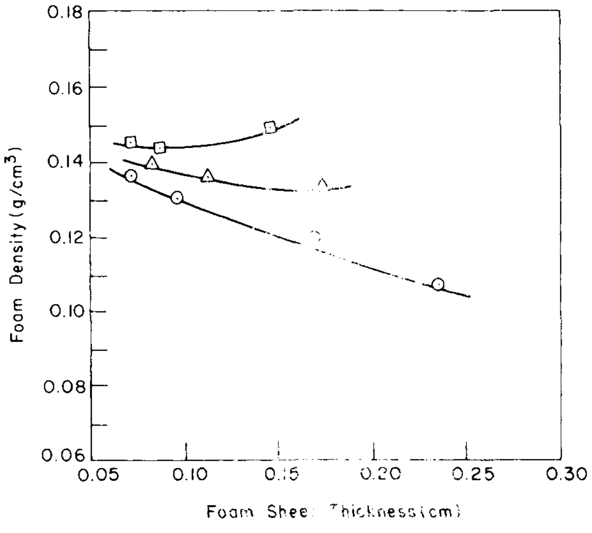

Fig. 6. Foam density vs. foam thickness at various die temperatures. Symbols are the same as in Figure 3.

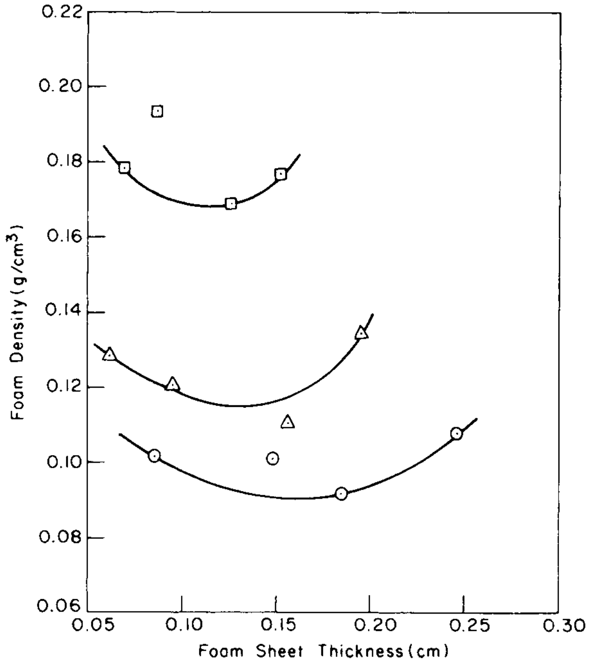

Fig. 7. Foam density vs. foam thickness for different types of blowing agent. Symbols are the same as in Figure 4.

FC-12 alone. Note that, at the same blowing agent concentration, FC-11 has a lower molar volume for expansion than FC-12.

Figure 8 describes the effect of takeoff speed on the machine direction (MD) and cross direction (CD) shrinkages, with the concentration of blowing agent as parameter. Figure 9 does the same with die temperature as parameter, and Figure 10 with the type of blowing agent as parameter. It is

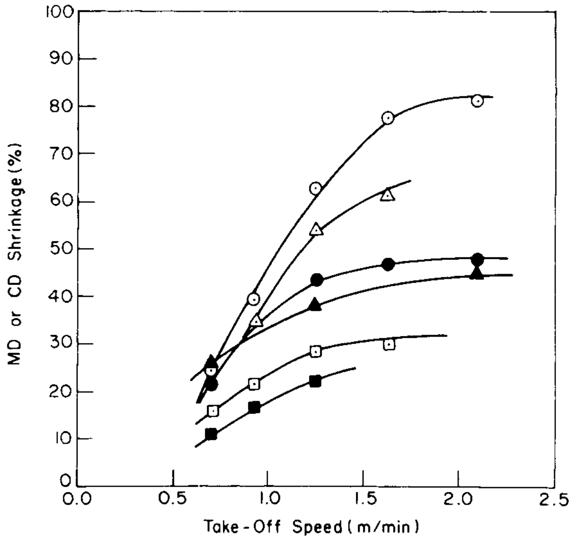

Fig. 8. MD (open symbols) or CD (closed symbols) shrinkage vs. takeoff speed at various FC-12 concentrations. Symbols are the same as in Figure 2.

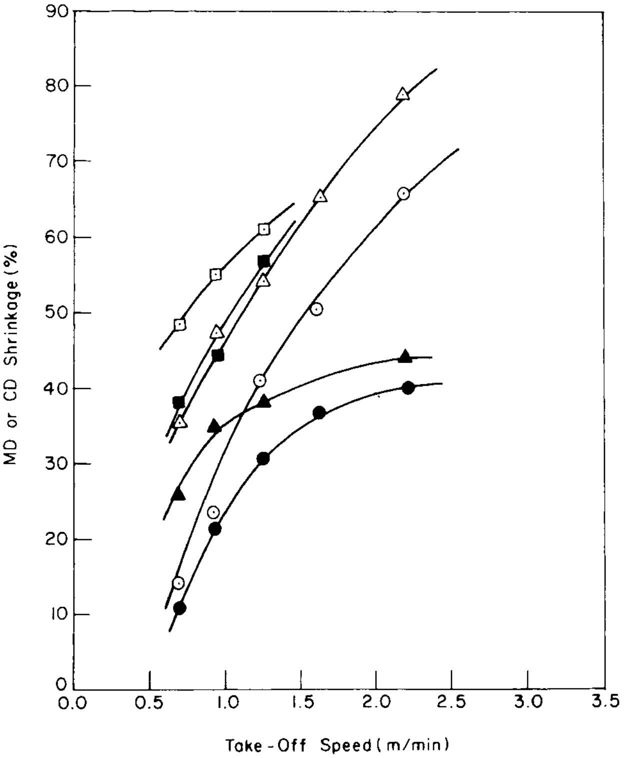

Fig. 9. MD (open symbols) or CD (closed symbols) shrinkage vs. takeoff speed at various die temperatures. Symbols are the same as in Figure 3.

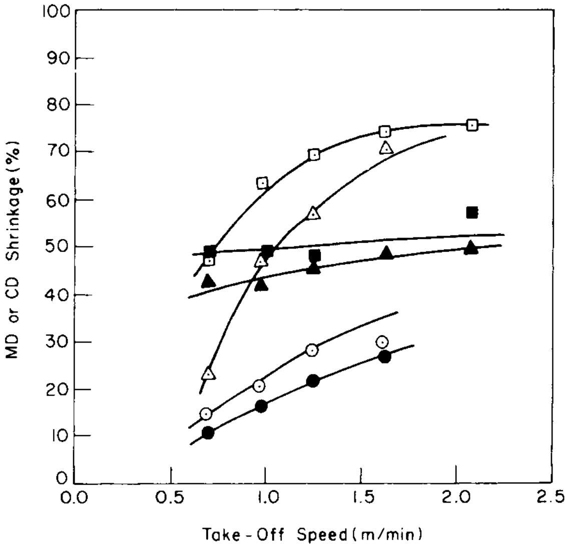

Fig. 10. MD (open symbols) or CD (closed symbols) shrinkage vs. takeoff speed for different types of blowing agent. Symbols are the same as in Figure 4.

seen that the MD shrinkage increases fast as the takeoff speed increases; however, the CD shrinkage first increases very slowly and then levels off at a value of about 50%.

It has been suggested that the cell orientation in a foam sheet be defined by the ratio of MD shrinkage (Sh_1) to CD shrinkage (Sh_2), and that the cell geometry be defined by the following expression[10]:

$$a(1 - Sh_1) = b(1 - Sh_2) = D \tag{1}$$

Where a and b are the average dimensions of the cell in the MD and CD, respectively, and D is the diameter of the cell before its orientation. Gliniescki[3] reported that foam sheet having a free shrinkage of approximately 60% in the MD is most desirable for thermoforming. Therefore, depending on the throughput of the extruder (i.e., shear rate in the die), the die opening and takeoff speed must be varied in order to control the cell orientation in the foam sheets extruded.

Figures 11–13 show the effects of blowing agent concentration on foam density, MD shrinkage, and MD tensile modulus, respectively, with takeup speed as parameter. It is seen that, at a fixed takeup speed, an increase in blowing agent concentration decreases the foam density, tensile modulus, and MD shrinkage. The increase in MD tensile modulus with increasing takeoff speed is due to the fact that, as the takeoff speed is increased, the cells become more oriented in the MD. Figure 14 shows photomicrographs describing the cell orientation in a foam sheet as the takeoff speed is increased.

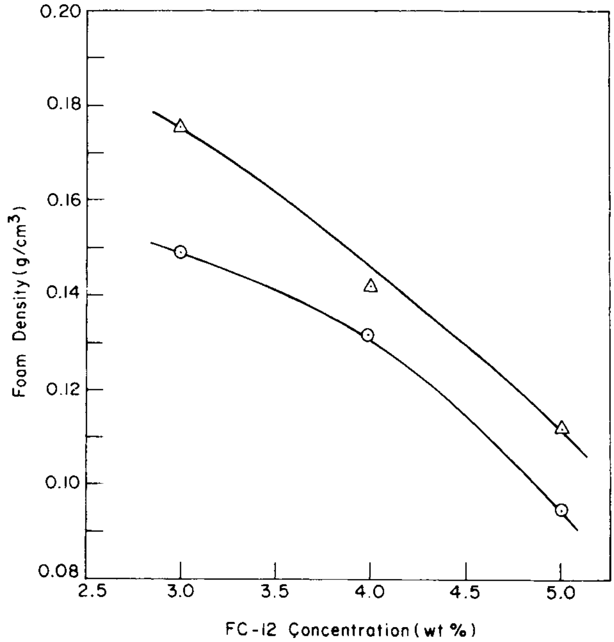

Fig. 11. Effect of FC-12 concentration on foam density for the STYRON 678/0.3 wt % citric acid/0.375 wt % NaHCO$_3$ system, at two different takeoff speeds (m/min): (⊙) 0.94; (△) 1.62. The die temperature is 150°C and the apparent shear rate is 285 s^{-1}.

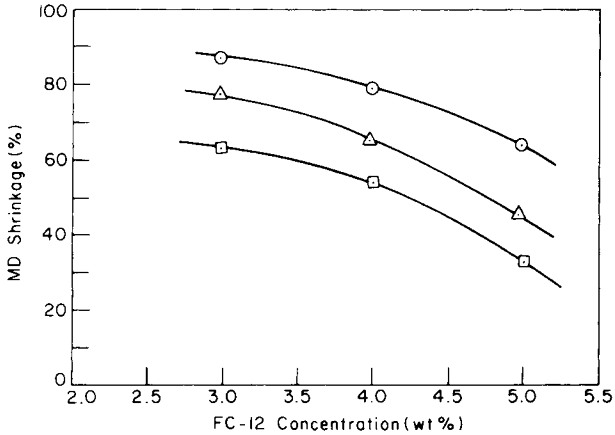

Fig. 12. Effect of FC-12 concentration on MD shrinkage for the STYRON 678/0.3 wt % citric acid/0.375 wt % $NaHCO_3$ system, at various takeoff speeds (m/min): (□) 1.23; (△) 1.62; (⊙) 2.20. The die temperature is 150°C and the apparent shear rate is 285 s^{-1}.

Figure 15 shows the effect of die temperature on foam density at various takeoff speeds. It is seen that the foam density increases with increasing die temperature. Earlier, Burt[6,7] reported that using a rapidly expanding blowing agent, such as FC-12, one would obtain an essentially constant foam density with increasing temperature until the viscosity exceeds a critical value. However, the recent study by Ma and Han[15] indicated that

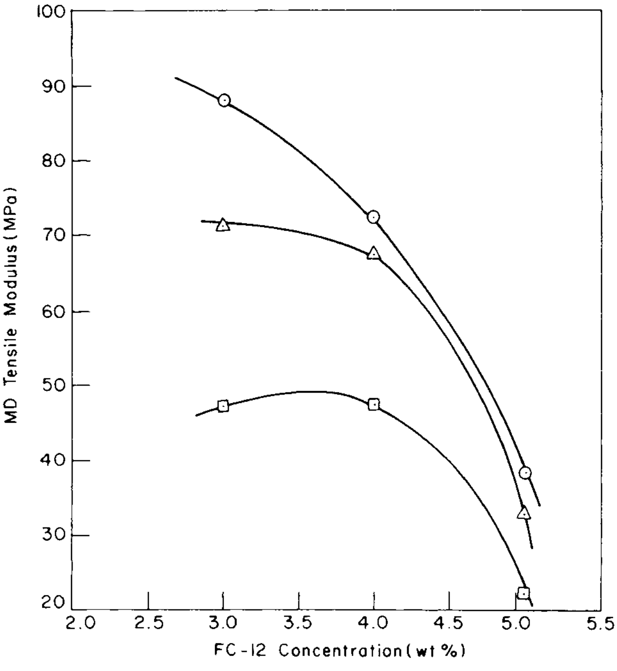

Fig. 13. Effect of FC-12 concentration on MD tensile modulus for the STYRON 678/0.3 wt % citric acid/0.375 wt % $NaHCO_3$ system, at various takeoff speeds (m/min): (□) 0.69; (△) 0.94; (⊙) 1.23. The die temperature is 150°C and the apparent shear rate is 285 s^{-1}.

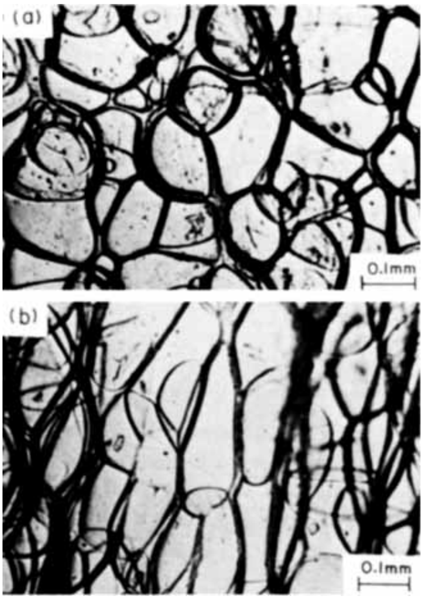

Fig. 14. Photomicrographs describing the effect of takeoff speed on cell orientation for the STYRON 678/0.3 wt % citric acid/0.375 wt % NaHCO$_3$/4 wt % FC-12 system. The takeoff speed is: (a) 0.94 m/min; (b) 2.20 m/min. The die temperature is 150°C and the apparent shear rate is 285 s^{-1}.

the foam density increased slightly as the die temperature increased from 140 to 160°C. This could have been due to the fact that, as the melt temperature was increased, the viscosity of the melt was decreased, giving rise to a melt strength insufficient for bubble stability. It should be pointed out that, as the melt temperature is increased, the die pressure is decreased, which then affects the open cell fraction. Figure 16 gives plots of open cell

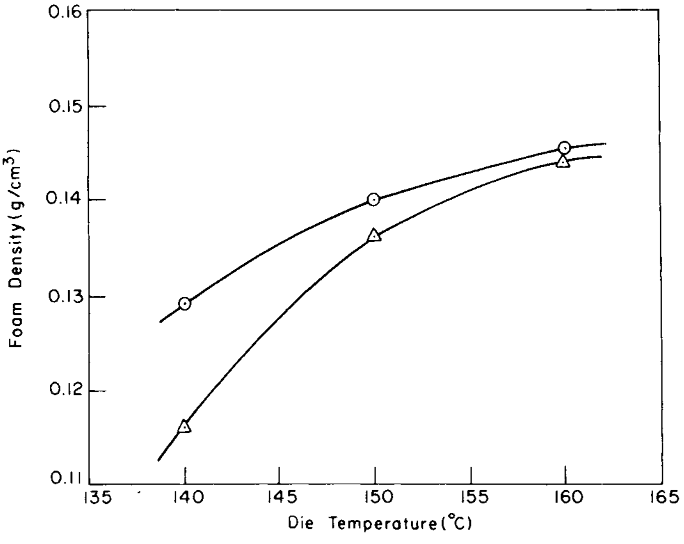

Fig. 15. Effect of die temperature on foam density for the STYRON 678/0.3 wt % citric acid/0.375 wt % NaHCO$_3$/ 4 wt % FC-12 system, at two different takeoff speeds (m/min): (△) 1.22; (⊙) 1.62. The apparent shear rate is 285 s^{-1}.

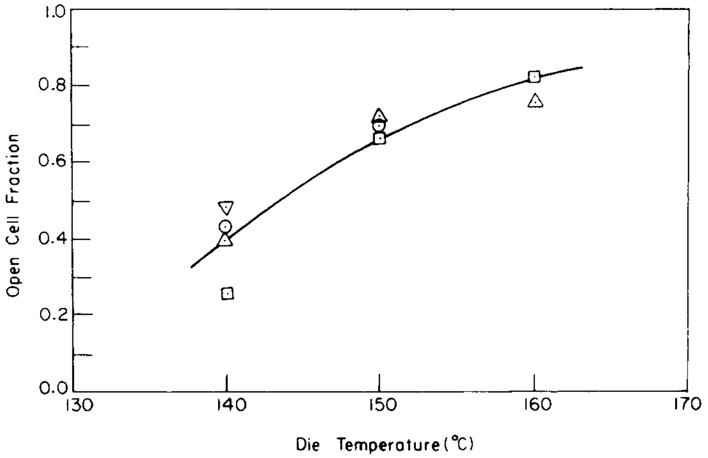

Fig. 16. Effect of die temperature on open cell fraction for the STYRON 678/0.3 wt % citric acid/0.375 wt % $NaHCO_3$/ 4 wt % FC-12 system, at various takeoff speeds (m/min): (⊙) 0.69; (△) 0.94; (⊡) 1.23; (▽) 2.20. The apparent shear rate is 285 s^{-1}.

fraction vs. die temperature. It is seen that open cell fraction is increased considerably as the die temperature is increased from 140 to 160°C.

The effects of die temperature on the MD shrinkage and MD tensile modulus at various takeoff speeds are shown in Figures 17 and 18. The observed increase in MD shrinkage and MD tensile modulus with increasing die temperature is attributable to the increased foam density and to the elongation of cells as the die temperature was increased. Note that the foams extruded at 150°C have higher density and, also, greater cell orientation than those extruded at 140°C (see Figs. 3 and 9), and therefore they have a higher MD tensile modulus. On the other hand, although the foams extruded at 160°C have higher density and greater cell orientation than those extruded at 150°C, the MD tensile modulus of the foams extruded at 160°C is lower than those extruded at 150°C. Croft[16] reported that, at the

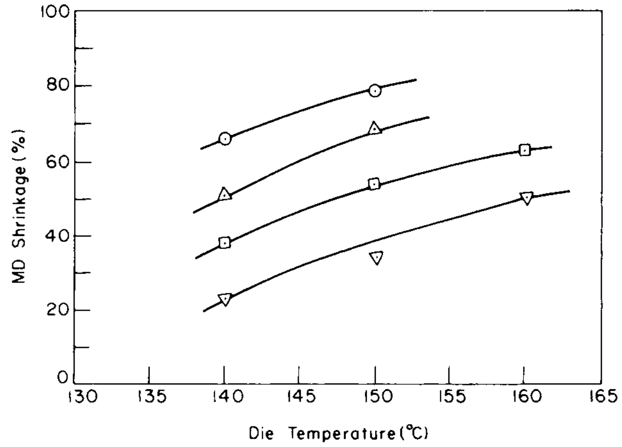

Fig. 17. Effect of die temperature on MD shrinkage for the STYRON 678/0.3 wt % citric acid/0.375 wt % $NaHCO_3$/ 4 wt % FC-12 system, at various take-off speeds (m/min); (▽) 0.94; (⊡) 1.23; (△) 1.62; (⊙) 2.20. The apparent shear rate is 285 s^{-1}.

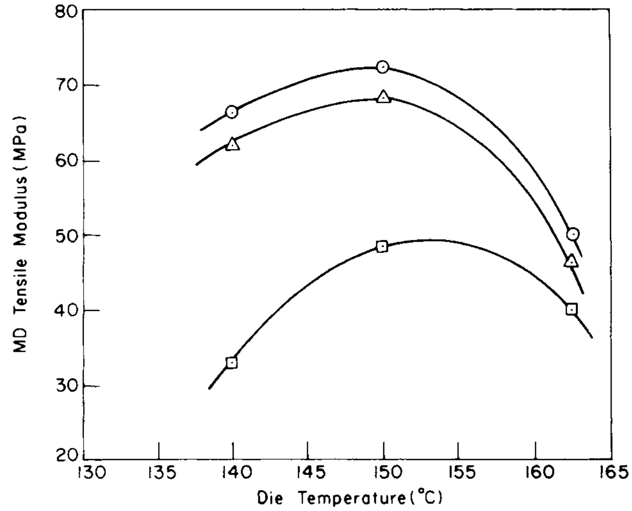

Fig. 18. Effect of die temperature on MD modulus for the STYRON 678/0.3 wt % citric acid/0.375 wt % $NaHCO_3$/ 4 wt % FC-12 system, at various takeoff speeds (m/min): (⊡) 0.69; (△) 0.94; (⊡) 1.23. The apparent shear rate is 285 s^{-1}.

same foam density, the foams with small cell sizes have higher tensile properties than those with large cells. Also, Meinecke and Clark[9] reported that foams with high open cell fractions have low tensile properties. Therefore, the low values of the MD tensile modulus observed at 160°C may be in part due to high open cell fractions and the large cell size, as shown in Figures 16 and 19, respectively.

It is a well-known fact today that the foam density, cell size and cell geometry influence the mechanical properties, such as tensile strength, shear

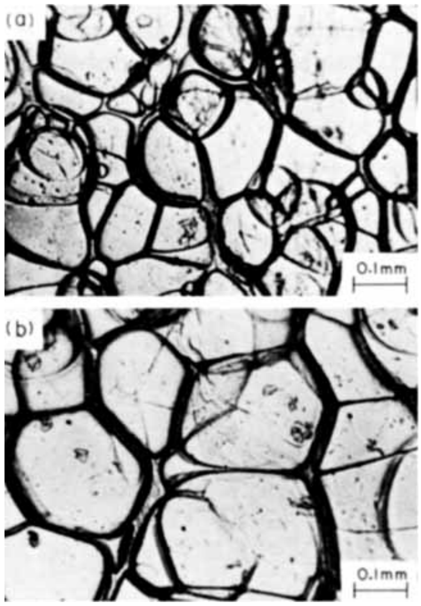

Fig. 19. Photomicrographs describing the effect of die temperature on cell size of the STYRON 678/0.3 wt % citric acid/0.375 wt % $NaHCO_3$/4 wt% FC-12 system. The die temperature is: (a) 150°C; (b) 160°C. The apparent shear rate is 285 s^{-1}.

strength, and compressive strength of polystyrene foam sheets. It has been demonstrated that, for isotropic foams, their tensile property may be correlatable to density by the following empirical expression[10]:

$$\text{property} = A\,(\text{density})^{B} \tag{2}$$

in which A is a scale factor that depends on cell structure, cell geometry, and temperature, and B a power-law index. Kanakkanatt[17] discussed the mechanical anisotropy of open-cell foams by using a modified Gent–Thomas model.

Employing the Halpin–Tsai theory[18] for composite materials, Mehta and Clombo[10] derived the following semiempirical expression:

$$\frac{E_{f1}}{E_{f2}} = \frac{1 + \dfrac{\Phi_g}{0.5[(1 - \mathrm{Sh}_1)/(1 - \mathrm{Sh}_2)]^2}}{1 + \dfrac{\Phi_g}{0.5[(1 - \mathrm{Sh}_2)/(1 - \mathrm{Sh}_1)]^2}} \tag{3}$$

where E_{f1} and E_{f2} are the MD and CD moduli of the foam, Φ_g is the cell volume fraction, and Sh_1 and Sh_2 are the MD and CD shrinkage, respectively. We found that our experimental data were not correlatable by eq.(3). This may be attributable in part to the inhomogeneity of the cells and, also, in part to the high level of cell orientation in our foam samples. We believe, however, that eq.(3) would be useful for foam samples having low level of cell orientation.

Figures 20 and 21 give plots of MD tensile modulus vs. foam density, with the blowing agent concentration and the type of blowing agent used in turn as parameter. In these figures, the solid lines represent the correlation obtained with the least-squares method.

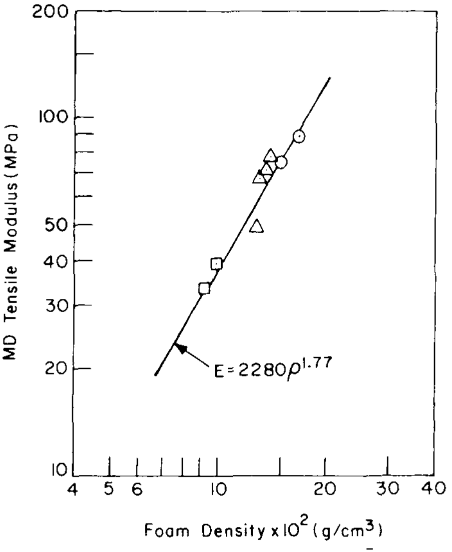

Fig. 20. MD tensile modulus vs. foam density at various FC-12 concentrations (wt %): (⊙) 3.0; (△) 4.0; (⊡) 5.0. The die temperature is 150°C and the apparent shear rate is 285 s^{-1}.

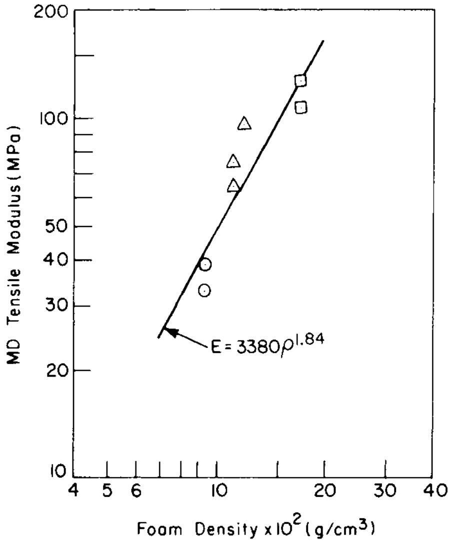

Fig. 21. MD Tensile modulus vs. foam density for different types of blowing agent: (⊙) 4 wt % FC-12; (△) 4 wt % FC-11/ FC-12 = 50/50 mixture; (□) 4 wt % FC-11. The die temperature is 150°C and the apparent shear rate is 285 s^{-1}.

Foam Sheet Extrusion of Low-Density Polyethylene

We also investigated the effects of processing variables, namely, takeoff speed, blowing agent concentration, die temperature, and the type of blowing agent on foam density, mechanical properties, and cell morphology of low-density polyethylene foam sheets. We obtained results very similar to those described above for polystyrene. Because of the limitations of space, we shall present below only some representative results.

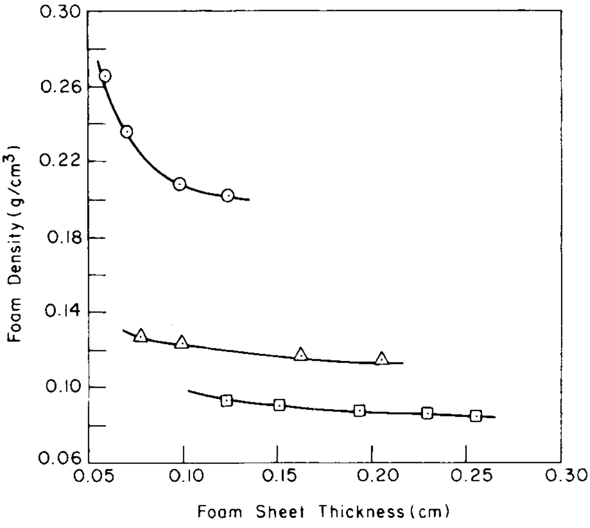

Fig. 22. Foam density vs. foam thickness for the Rexene 143/1 wt % talc system, with various FC-114 concentrations (wt %): (⊙) 5.0; (△) 7.5; (□) 10.0. The die temperature is 100°C and the apparent shear rate is 169 s^{-1}.

Figure 22 gives plots of foam density vs. foam sheet thickness, with blowing agent concentration as parameter, Figure 23 with die temperature as parameter, and Figure 24 with the type of blowing agent as parameter. It is seen in Figure 22 that, for 5 wt % of FC-114, the foam density decreases rapidly as the thickness decreases, but, for higher concentrations (i.e., 7.5 and 10 wt % of FC-114), the variation in foam density is very small. The cell size in the polyethylene foam sheets was found to be much larger than that in the polystyrene ones and, consequently, the MD orientation of the cells was very pronounced.

The effect of die temperature on foam density is shown in Figure 25. It is seen that the foam density increases very rapidly when the die temperature increases from 100 to 120°C. This may be due to the fact that, as the die temperature was increased, the blowing agent vaporized from the mixture of molten polymer and blowing agent before reaching the die exit, giving rise to bubble collapse as well as the escape of the blowing agent from the extrudate. Therefore, it is very important to control the die temperature in order to obtain low-density foam sheets.

The effect of blowing agent concentration on foam density at various takeoff speeds is given in Figure 26. It is seen that the foam density decreases with increasing blowing agent concentration. It is of special interest to note in Figure 24 that the FC-12 gives rise to lower foam density than the FC-114. A similar observation was made earlier by Han and Ma.[14] Burt[6] reported, however, that FC-12 and FC-114 give rise to almost the same foam densities for blowing agent concentrations up to 0.4 g mol/kg resin, and FC-114 gives rise to lower foam densities than does FC-12 at higher concentrations.

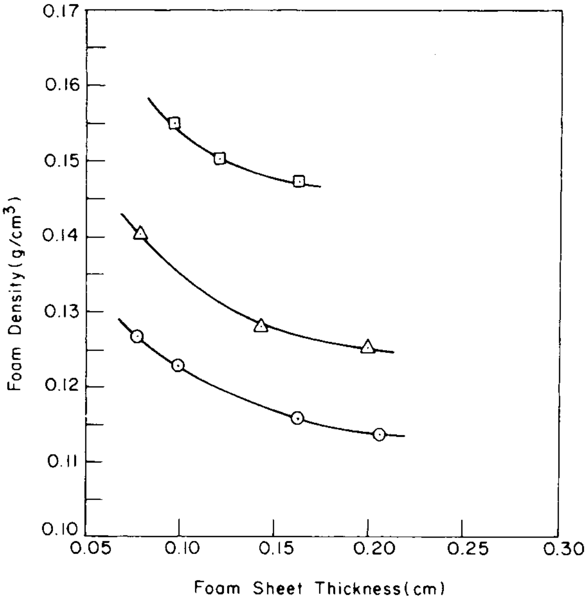

Fig. 23. Foam density vs. foam thickness for the Rexene 143/1 wt % talc/7.5 wt % FC-114 system, at various die temperatures (°C): (⊙) 100; (△) 110; (⊡) 120. The apparent shear rate is 169 s^{-1}.

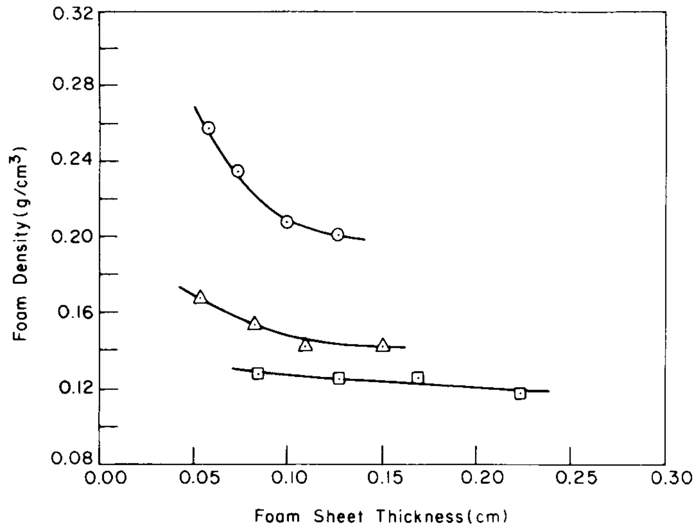

Fig. 24. Foam density vs. foam thickness for the Rexene 143/1 wt % talc system, with different types of blowing agent: (⊙) 5 wt % FC-114; (△) 5 wt % FC-12; (⊡) 5 wt % of FC-11/FC-12 = 50/50 mixture. The die temperature is 100°C and the apparent shear rate is 169 s^{-1}.

Figure 27 describes the effect of extrusion rate (i.e., apparent shear rate in the die) on foam density. It is seen that the foam density is decreased as the apparent shear rate is increased. This may be attributable to the fact that, as the apparent shear rate is increased, (1) the viscosities of mixtures of molten polymer and blowing agent are decreased, thus promoting the nucleation of gas bubbles, and (2) the die pressure is increased, thus preventing the premature foaming inside the die.

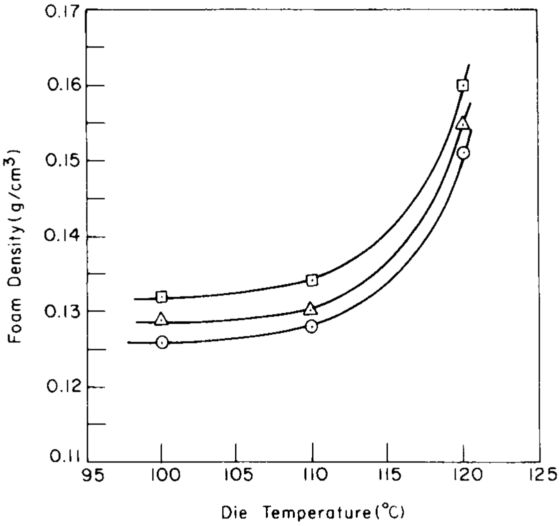

Fig. 25. Effect of die temperature on foam density for the Rexene 143/1 wt % talc/7.5 wt % FC-114 system, at various takeoff speeds (m/min): (⊙) 0.94; (△) 1.22; (⊡) 1.69. The apparent shear rate is 169 s^{-1}.

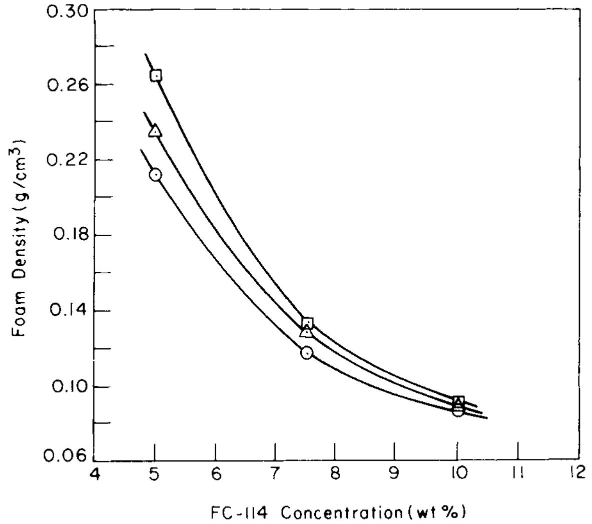

Fig. 26. Effect of FC-114 concentration on foam density for the Rexene 143/1 wt % talc system, at various takeoff speeds (m/min): (⊙) 0.94; (△) 1.22; (□) 1.63. The die temperature is 100°C and the apparent shear rate is 169 s^{-1}.

CONCLUDING REMARKS

Many factors are involved in controlling the properties of foam sheets produced by extruding mixtures of thermoplastic resin and fluorocarbon blowing agent. The present study shows the effects on the cell morphology and properties of foam sheets of die temperature, the type and concentration of blowing agent, shear rate, and takeoff speed. It has been found that takeoff speed has a profound influence on the cell orientation and that the cooling of extrudate affects the foam density. From the point of view of

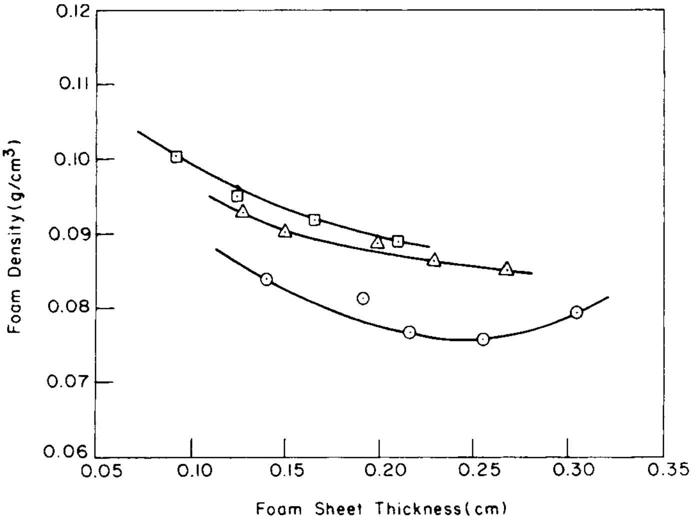

Fig. 27. Foam density vs. foam thickness for the Rexene 143/1 wt % talc/10 wt % FC-114, at various shear rates (s^{-1}): (□) 128; (△) 169; (⊙) 226. The die temperature is 100°C.

choosing optimum processing and material variables for producing low-density foam sheets, the following observations are worth noting: (1) The foam density may first decrease and then increase as the takeoff speed increases; (2) the cell orientation and MD tensile modulus increase with increasing takeoff speed; (3) the foam density and open cell fraction increase with increasing die temperature; (4) an increase in foam density and cell orientation increases the tensile modulus of the foam sheets; (5) FC-12 gives rise to foam densities lower than does FC-114 in producing low-density polyethylene foam sheets.

In order to improve and predict the properties of foam sheets, a better understanding of the relationships among processing variables, cell size, cell structure, and mechanical properties is essential. In the future, we will put efforts into developing a mathematical model simulating the foam sheet extrusion process, including the effects of the solubility and diffusivity of blowing agent in molten polymer, the heat transfer between the foam sheet being extruded and the cooling air, and the rheological properties of mixtures of molten polymer and blowing agent.

This study was supported in part by the National Science Foundation under Grant CPE-8403287, for which the authors are very grateful.

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Received July 5, 1984
Accepted December 17, 1984