# Foam Extrusion Characteristics of Thermoplastic Resin with Fluorocarbon Blowing Agent. II. Polystyrene Foam Extrusion

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## Synopsis

The foam extrusion characteristics of three different grades of polystyrene resin were investigated. For the study, cylindrical dies with various values of length-to-diameter ratio, entrance angle, and reservoir-to-capillary diameter ratio were used. Fluorocarbon blowing agents were used, and mixtures of citric acid and sodium bicarbonate were used as nucleating agent. It was found that the die temperature, shear rate, the type and concentration of blowing agent, and die geometry affect the quality of the extruded polystyrene foam. Foam density and open cell fraction were used in determining the quality of extruded foams. We have found that the extrudate swell ratio is correlatable to foam density, independent of the die temperature employed. However, the die temperature has been found to be a very sensitive processing variable governing the quality of extruded foams.

## INTRODUCTION

Polystyrene foam extrusion with fluorocarbon blowing agent has been practiced for some time in industry, for example, in foam sheet extrusion operations. Several investigators[1–3] have discussed the effects of processing variables on the mechanical properties and/or the quality of extruded polystyrene foam sheets, and others[4,5] have discussed the importance of the choice of proper blowing agents to the control of the quality of polystyrene foams.

The viscosity of polystyrene increases very rapidly as the temperature decreases, and therefore the extrusion die temperature commonly encountered in polystyrene foam extrusion is much higher (by 30–50°C) than in low-density polyethylene foam extrusion. Due to the rigid structure of polystyrene compared to the branched low-density polyethylene, the melt elasticity (or melt strength) of polystyrene is lower, in general, than that of low-density polyethylene. Therefore, the thermocollapse of bubbles during the expansion of extrudate is very sensitive to the cooling condition in polystyrene foam extrusion.[6] And the solubility of specific fluorocarbon blowing agents in polystyrene melts is quite different from that in low-density polyethylene melts and, thus, the amount of blowing agent required for obtaining polystyrene foams of good quality is much less than that required for low-density polyethylene foams. For instance, about 5–8 wt % of dichlorodifluoromethane (FC-12) is used in extruding polystyrene, whereas 10–15 wt % is used in extruding low-density polyethylene. It is also well known that mixtures of citric acid and sodium bicarbonate are used as the nuc-

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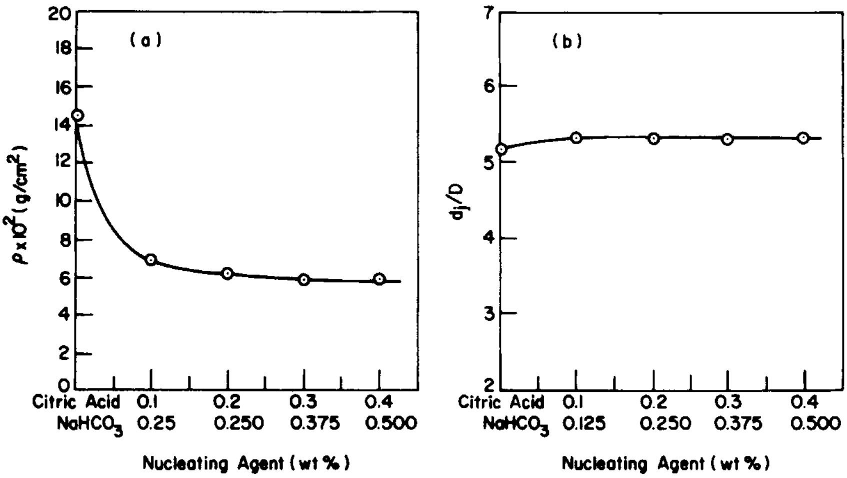


Fig. 1. Foam density and extrudate swell ratio vs. nucleating agent concentration (wt %) for the STYRON 678/8 wt % blend of FC-11 and FC-12. The die temperature is 130°C and apparent shear rate is 160 $s^{-1}$. The die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

leating agent in polystyrene foam extrusion, whereas talc is used as the nucleating agent in low-density polyethylene foam extrusion.

It is clear, then, that the information generated in extruding low-density polyethylene, reported in Paper I of this series,[7] may be of little help in understanding the foam extrusion characteristics of polystyrene. For this reason, we have conducted an experimental investigation into the effects of the processing and material variables, and also the die design variables, on the foam extrusion characteristics of polystyrene. In this paper, we shall report the highlights of our findings.

## EXPERIMENTAL

Three different grades of polystyrene, STYRON 678, STYRON 685D, and Amoco R2, were used. The molecular characteristics and rheological properties of these resins are given in our earlier paper.[8]

As blowing agent, trichlorofluoromethane (FC-11) and dichlorodifluoromethane (FC-12) were used, alone and in a 50–50 mixture by weight. As nucleating agent, mixtures of citric acid and sodium bicarbonate were used.

Note that FC-11 is highly soluble in polystyrene, and thus tends to make coarse-celled foam, because cell growth is increased by diffusion of gas into existing cells. On the other hand, compared to FC-11, FC-12 has a low solubility in polystyrene and thus tends to favor the formation of fine-celled foams.[9] Therefore, the use of mixtures of FC-11 and FC-12 is expected to offer additional latitude in adjusting the solubility of blowing agents, thus enabling one to better control the quality of the polystyrene foam produced.

The apparatus and experimental procedure employed are the same as that described in Paper I of this series.[7]

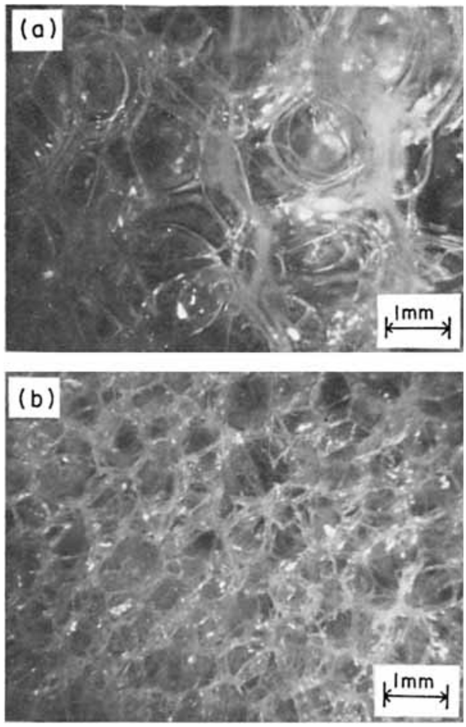


Fig. 2. Photomicrographs describing the effects of nucleating agent (mixture of citric acid and $NaHCO_3$) on cell size for the STYRON 678/4 wt % blend of FC-11 and FC-12: (a) without nucleating agent; (b) with nucleating agent (mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$). The die temperature is 150°C, and apparent shear rate is 160 $s^{-1}$. The die employed has: $L/D = 2, D_R/D = 8$, and $\alpha = 60°$.

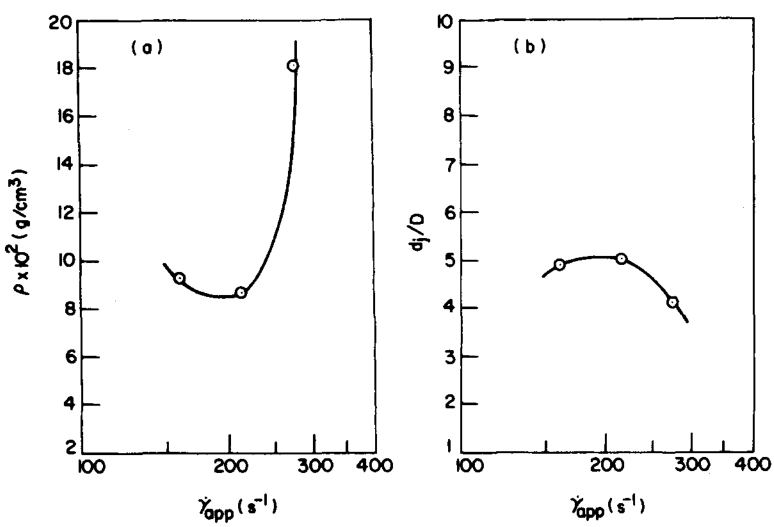


Fig. 3. Foam density and extrudate swell ratio vs. apparent shear rate for the STYRON 678/4 wt % blend of FC-11 and FC-12/0.3 wt % citric acid and 0.375 wt % $NaHCO_3$. The die temperature is 150°C. The die employed has: $L/D = 2, D_R/D = 8$, and $\alpha = 60°$.

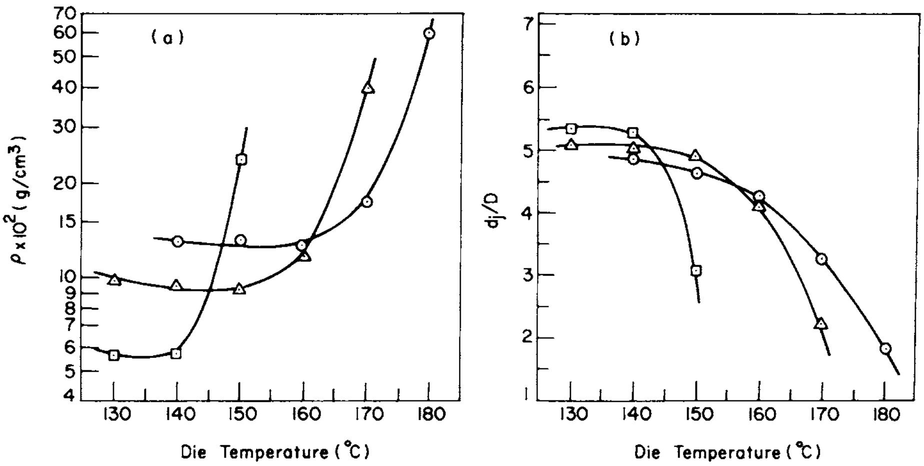


Fig. 4. Foam density and extrudate swell ratio vs. die temperature for the STYRON 678/0.3 wt % citric acid and 0.375 wt % $NaHCO_3$ system at $\dot{\gamma}_{app}$ = 160 $s^{-1}$, with various concentrations of FC-11/FC-12 blend (wt %): (⊙) 2; (△) 4; (⊡) 8. The die employed has: $L/D = 2, D_R/D = 8$, and $\alpha$ = 60°.

## RESULTS AND DISCUSSION

### The Effect of Nucleating Agent on Foam Density and Extrudate Swell

Figure 1 gives plots of foam density ($\rho$) and extrudate swell ratio ($d_j/D$) vs. the concentration of citric acid/sodium bicarbonate for the STYRON 678 and FC-11/FC-12 system. It is seen that, initially, $\rho$ decreases and $d_j/D$ increases as the concentration of nucleating agent increases and, then, both $\rho$ and $d_j/D$ level off. In other words, there exists a minimum amount of nucleating agent (about 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$) that may be required for providing the effective foaming of polystyrene.

One may surmise that a nucleating agent allows one to achieve fine cell sizes and closed-cell morphology. Figure 2 shows photographs demonstrating the difference in cell size obtained *without* and *with* nucleating agent. It is seen that the use of nucleating agent has indeed increased the number of cells and decreased the cell size.

### The Effect of Shear Rate on Foam Density and Extrudate Swell

Figure 3 gives plots of $\rho$ and $d_j/D$ vs. apparent shear rate ($\dot{\gamma}_{app}$) for the STYRON 678 and FC-11/FC-12 system, with a fixed concentration of nucleating agent (0.3 wt % of citric acid and 0.375 wt % of $NaHCO_3$). It is of great interest to observe in Figure 3(a) that as $\dot{\gamma}_{app}$ increases, $\rho$ initially decreases and, then, increases very rapidly. The reason for this observation is that, as $\dot{\gamma}_{app}$ increases, the less effective is the cooling of extrudate at ambient temperature and, thus, the thermocollapse of bubbles in the extrudate increases with $\dot{\gamma}_{app}$. When cells collapse, there is *less* extrudate swell, because the blowing agent escapes from the extrudate. This is clearly demonstrated in the measurement of the $d_j/D$ ratio shown in Figure 3(b).

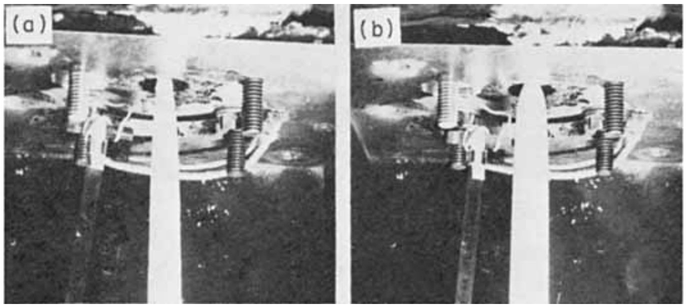


Fig. 5. Photographs describing the effect of die temperature on extrudate swell at: (a) $T = 160°C$ and $\dot{\gamma}_{app} = 160\ s^{-1}$; (b) $T = 150°C$ and $\dot{\gamma}_{app} = 160\ s^{-1}$. The system is STYRON 678/4 wt % blend of FC-11 and FC-12/0.3 wt % citric acid and 0.375 wt % $NaHCO_3$. The die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

In reference to Figure 3, it is clear that, unless one controls the amount of nucleating agent added, the permissible range of shear rate for producing low-density foams of polystyrene with acceptable quality is very limited. Throughout the rest of this paper, we present results that were obtained at a fixed shear rate ($\dot{\gamma}_{app} = 160\ s^{-1}$) and a fixed concentration of nucleating agent (0.3 wt % citric acid and 0.375 wt % $NaHCO_3$).

## The Effect of Processing Variables on Foam Extrusion Characteristics

Figure 4 gives plots of $\rho$ and $d_j/D$ vs. die temperature for the STYRON 678 and FC-11/FC-12 system, with various concentrations of blowing agent. It is seen that $\rho$ increases and the $d_j/D$ ratio decreases rapidly when the die tem-

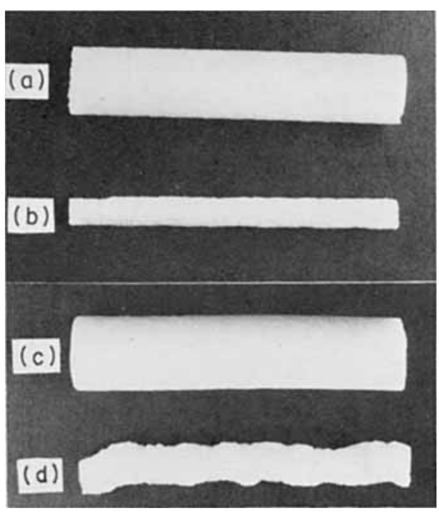


Fig. 6. Photographs of extrudates describing the effect of die temperature and FC blowing agent concentration on the final extrudate diameter of STYRON 678: (a) 4 wt % FC-11/FC-12 blend at 150°C; (b) 4 wt % FC-11/FC-12 blend at 170°C; (c) 8 wt % FC-11/FC-12 blend at 140°C; (d) 8 wt % FC-11/FC-12 blend at 150°C. The nucleating agent used is a mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$ and the apparent shear rate is $160\ s^{-1}$. The die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

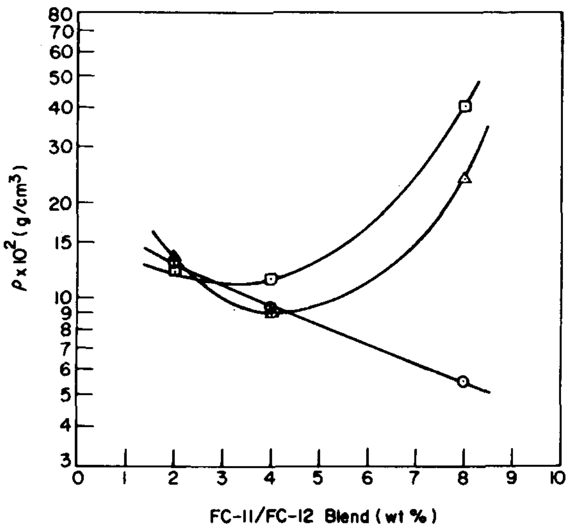


Fig. 7. Effect of FC-11/FC-12 blowing agent concentration on foam density at various die temperatures (°C): (⊙) 140; (▵) 150; (⊡) 160. The resin used is STYRON 678, the nucleating agent used is a mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$, and the apparent shear rate is 160 $s^{-1}$. The die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

perature passes a certain critical value and that, as the blowing agent concentration increases, the critical die temperature decreases. Note in Figure 4 that, below the critical die temperature, $\rho$ decreases, and $d_j/D$ increases as the blowing agent concentration increases. In other words, one must control both the blowing agent concentration and the die temperature in order to produce polystyrene foams of acceptable quality.

Earlier, Burt[5] reported plots of foam density vs. die temperature for the polystyrene and FC-12 system, with various blowing agent concentrations. Figure 4(a) given above is similar to Burt's observation.

Figure 5 shows photographs of extrudates as they expanded outside the die at two different die temperatures. Note that the capillary diameter of the die used is 3.175 mm. It is seen in Figure 5 that the extrudate diameter is increased as the die temperature is decreased from 160°C to 150°C and that the extrudate continuously expands as it flows downward under the influence of gravity. The continuous expansion of extrudate seen in Figure 5 is due to the bubble growth in the extrudate.

Figure 6 shows photographs of the extrudates that were obtained under different die temperatures. It is seen that, at a given blowing agent concentration, cells collapse and extrudate swell is reduced when the die temperature exceeds the critical value.

Figure 7 shows the effect of blowing agent concentration on foam density at various die temperatures. This figure is obtained by cross plotting the information given in Figure 4(a). This figure illustrates clearly how both the blowing agent concentration and the die temperature affect the foam density.

Figure 8 gives plots of $\rho$ vs. $d_j/D$ for the STYRON 678 and FC-11/FC-12 system, at various values of blowing agent concentration and die temperature. This figure is obtained from the information given in Figures 4(a) and 4(b). A few

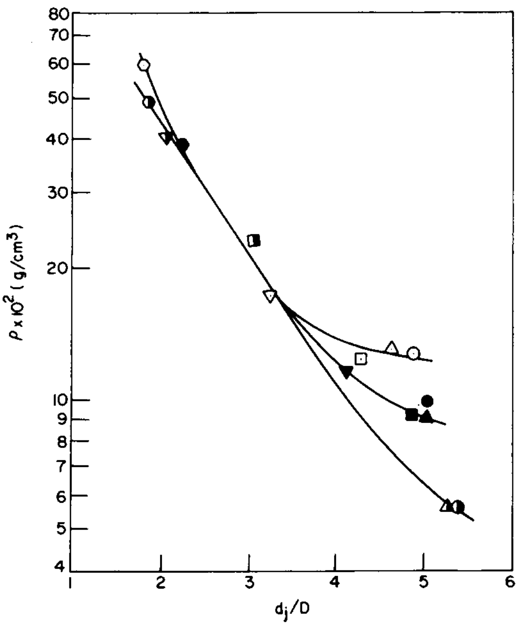


Fig. 8. Foam density vs. extrudate swell ratio for the STYRON 678/blend of FC-11 and FC-12 system. (a) 2 wt % FC-11/FC-12 blend at various die temperatures (°C): (⊙) 140; (△) 150; (⊡) 160; (▽) 170; (⊙) 180. (b) 4 wt % FC-11/FC-12 blend at various die temperatures (°C): (●) 130; (▲) 140; (■) 150; (▼) 160; (●) 170. (c) 8 wt % FC-11/FC-12 blend at various die temperatures (°C): (◑) 130; (▲) 140; (◨) 150; (▼) 160; (◑) 170. The die employed has: $L/D$ = 2, $D_R/D$ = 8, and $\alpha$ = 60°.

interesting observations may be made regarding the results given in Figure 8: (1) at a fixed concentration of blowing agent, $\rho$ correlates well to the $d_j/D$ ratio, independent of the die temperature employed; (2) when the die temperature is below a critical value (i.e., when closed-cell structures are obtained), $\rho$ decreases

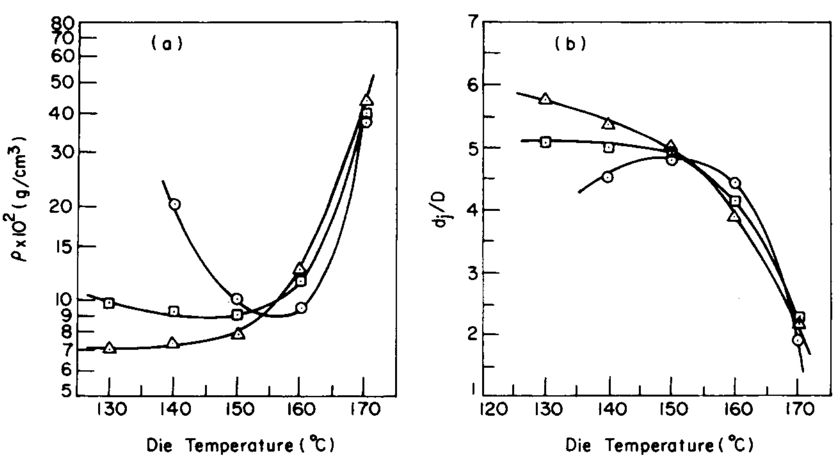


Fig. 9. Foam density and extrudate swell ratio vs. die temperature for the STYRON 678/0.3 wt % citric acid and 0.375 wt % $NaHCO_3$ system at $\dot{\gamma}_{app}$ = 160 s$^{-1}$, with various types of FC blowing agent: (⊙) 4 wt % FC-11; (△) 4 wt % FC-12; (⊡) 4 wt % FC-11/FC-12 blend. The die employed has: $L/D$ = 2, $D_R/D$ = 8, and $\alpha$ = 60°.

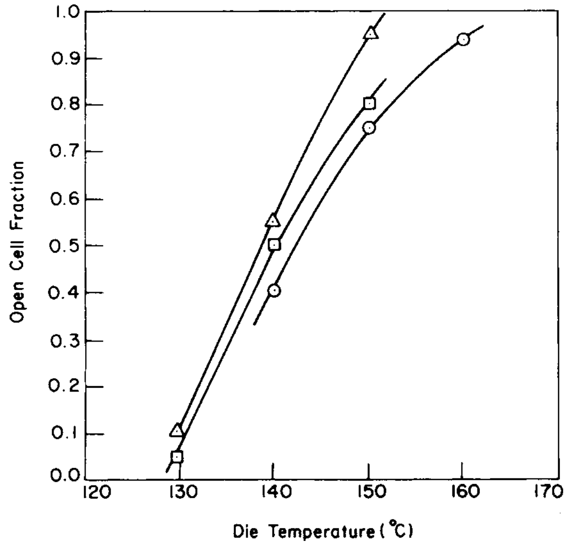


Fig. 10. Open cell fraction vs. die temperature. The system is STYRON 678/mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$, with various types of FC blowing agent: (⊙) 4 wt % FC-11; (▵) 4 wt % FC-12; (⊡) 4 wt % FC-11/FC-12 blend. The apparent shear rate is 160 $s^{-1}$, and the die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

with increasing blowing agent concentration, with $d_j/D$ constant. This implies that the foam specimens containing 8 wt % blowing agent would have more gas volume than those containing 4 wt % or 2 wt % blowing agent.

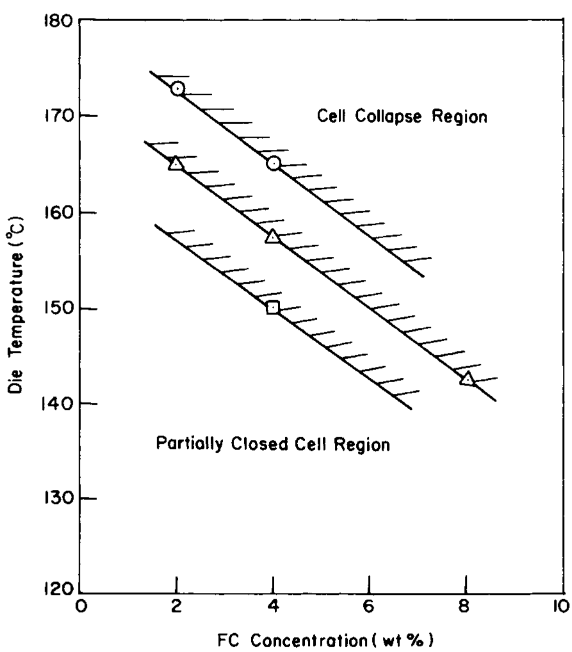


Fig. 11. Die temperature vs. FC concentration, describing the processing conditions that produce closed-cell foams and the region where cell collapse occurs. (⊙) STYRON 678/FC-11 system; (▵) STYRON 678/blends of FC-11 and FC-12 system; (⊡) STYRON 678/FC-12 system. The apparent shear rate is 160 $s^{-1}$. The die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

TABLE I
Summary of Open Cell Fraction of Polystyrene Foams Obtained at Various Processing Conditions[a]

| Die temp (°C) | FC concn (wt %) 2.0 | 4.0 | 8.0 |
|---|---|---|---|
| | | (a) STYRON 678/FC-11 system | |
| 140 | — | 0.40 | — |
| 150 | — | 0.75 | — |
| 160 | — | 0.93 | — |
| | | (b) STYRON 678/FC-12 system | |
| 130 | — | 0.10 | — |
| 140 | — | 0.56 | — |
| 150 | — | 0.95 | — |
| | | (c) STYRON 678/mixture of FC-11 and FC-12 | |
| 130 | — | 0.05 | 0.10 |
| 140 | 0.40 | 0.50 | 0.60 |
| 150 | 0.70 | 0.80 | — |
| 160 | 0.90 | — | — |

[a] The nucleating agent used is a mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$; the apparent shear rate is 160 $s^{-1}$; the die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

Figure 9 describes the effect of the type of fluorocarbon blowing agent on the foam density and extrudate swell ratio, at various die temperatures. It is seen that, in the use of FC-11, foam density is very high at 140°C and decreases rapidly as the die temperature is increased to 150–160°C and, then, increases very rapidly as the die temperature is increased above 160°C. It should be remembered that FC-11 is a good solvent for polystyrene and, therefore, at low temperatures (say, at 140°C) gas bubbles of FC-11 come off very slowly from homogeneous mixtures of polystyrene and FC-11, giving rise to high foam densities. On the other hand, having a low boiling point (−29.9°C) and being a poor solvent for polystyrene, FC-12 tends to come off easily from mixtures of polystyrene and FC-12 at low

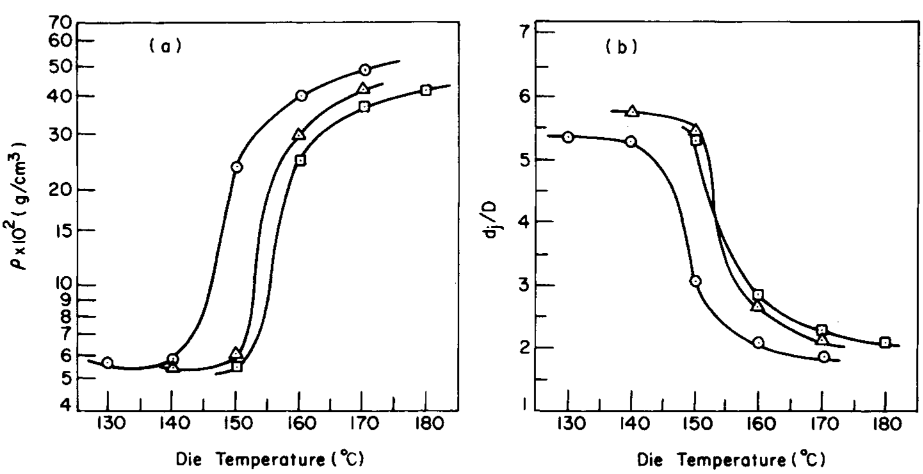


Fig. 12. Foam density and extrudate swell ratio vs. die temperature for various grades of polystyrene resin: (⊙) STYRON 678; (▲) Amoco R2; (⊡) STYRON 685D. The blowing agent used is 8 wt % blend of FC-11 and FC-12, the nucleating agent used is a mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$, and the apparent shear rate is 160 $s^{-1}$. The die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

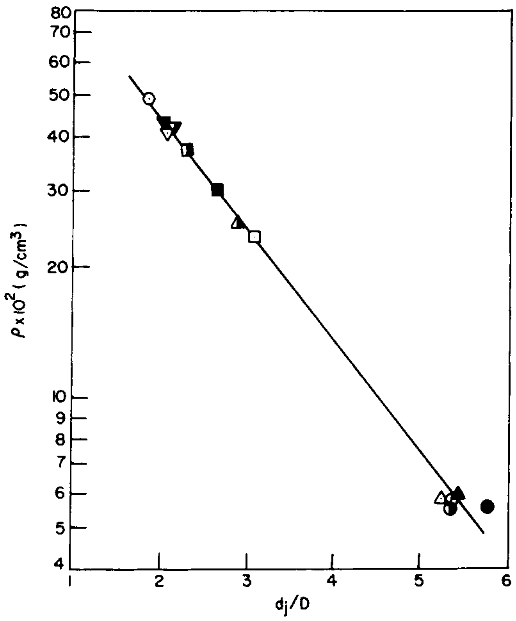


Fig. 13. Foam density vs. extrudate swell ratio. (a) STYRON 678/8 wt % blend of FC-11 and FC-12 at various die temperatures (°C): (⊙) 130; (△) 140; (⊡) 150; (▽) 160; (⊙) 170. (b) STYRON 685D/8 wt % blend of FC-11 and FC-12 at various die temperatures (°C): (●) 140; (▲) 150; (■) 160; (▼) 170. (c) Amoco R2/8 wt % blend of FC-11 and FC-12 at various die temperatures (°C): (◑) 150; (▲) 160; (◨) 170; (▼) 180. The nucleating agent used is a mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$, and the apparent shear rate is 160 $s^{-1}$. The die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

temperatures, giving rise to low foam density. The use of a mixture of 50–50 wt % FC-11 and FC-12 yields a reasonable density of extruded polystyrene foam over the temperature range 130–150°C. Figure 10 shows that, under the identical extrusion condition, FC-12 gives rise to higher open cell fraction than either a mixture of FC-11 and FC-12, or FC-11 alone. This suggests that the use of mixtures of FC-11 and FC-12 may allow one to have a better control of the cell morphology and the foam density than the use of either FC-11 or FC-12 alone.

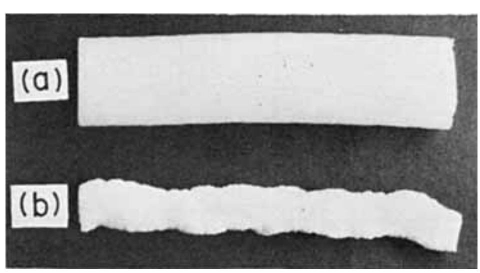


Fig. 14. Photographs of extrudates: (a) Amoco R2/8 wt % blend of FC-11 and FC-12 at 150°C; (b) STYRON 678/8 wt % blend of FC-11 and FC-12 at 150°C. The nucleating agent used is a mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$, and the apparent shear rate is 160 $s^{-1}$. The die employed has: $L/D = 2$, $D_R/D = 8$, and $\alpha = 60°$.

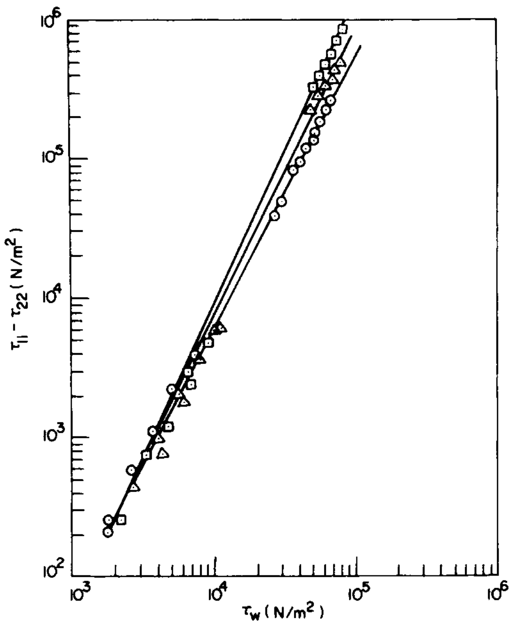


Fig. 15. First normal stress difference vs. shear stress: (⊙) STYRON 678; (△) Amoco R2; (⊡) STYRON 685D.

Earlier, Burt[5] reported plots of foam density vs. die temperature for polystyrene containing either FC-11 or FC-12. Figure 9(a) given above is similar to Burt's observations.

Figure 11 describes, in terms of the die temperature and the blowing agent concentration, operating guides for producing closed-cell structures of polystyrene foam when FC-11, FC-12, or a mixture of FC-11/FC-12 (50/50 by wt %) is used as blowing agent. Note in Figure 11 that, for each type of blowing agent, the region *above the shaded area* represents the processing conditions that yield cell collapse, which is undesirable from the standpoint of producing low-density foams of polystyrene. The region *below the shaded area* in Figure 11 represents the processing conditions that yield partially closed cell structure. The open cell fractions obtained under various processing conditions are given in Table I.

## The Effect of the Rheological Properties on Foam Extrusion Characteristics

Figure 12 gives plots of $\rho$ and $d_j/D$ vs. the die temperature for three different grades of polystyrene, namely STYRON 678, STYRON 685D, and Amoco R2, each containing 8 wt % of FC-11/FC-12 mixture. Figure 13 gives a correlation between $\rho$ and the $d_j/D$ ratio, which is seen to be independent of the grade of resin and the die temperature employed. It is seen in Figure 12(a) that the highest permissible die temperatures that allowed us to produce low-density foams were 140°C for STYRON 678 and 150°C for STYRON 685D and Amoco R2. Figure 14 shows photographs illustrating the effect of the molecular parameters (or

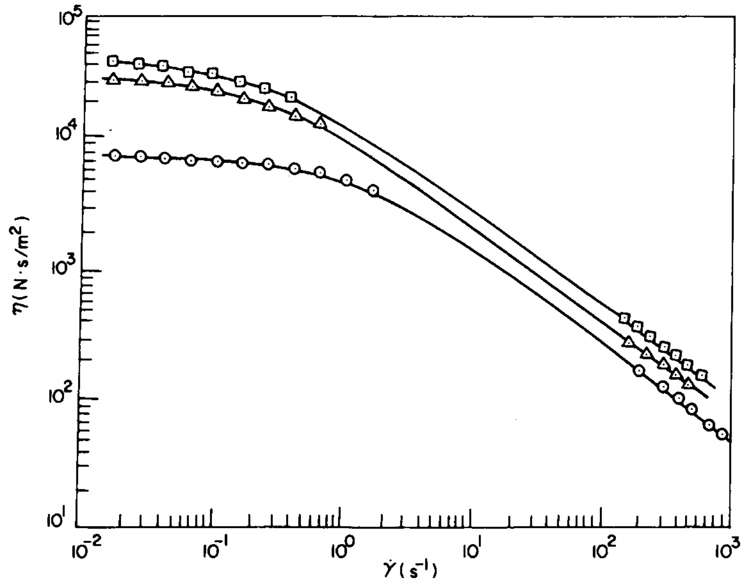


Fig. 16. Viscosity vs. shear rate at 200°C for the three polystyrenes employed. Symbols are the same as in Figure 15.

rheological properties) of the resins on extrudate swell under the same processing conditions.

As discussed in Paper I of this series,[7] the foam extrusion characteristics of thermoplastic resins are intimately related to the rheological properties of the resins, especially the elastic property. Figure 15 gives plots of first normal stress difference ($\tau_{11} - \tau_{22}$) vs. shear stress ($\tau_w$), and Figure 16 gives plots of viscosity ($\eta$) vs. shear rate ($\dot{\gamma}$), for the three polystyrenes employed. It is seen in Figure 15 that the STYRON 678 has the lowest melt elasticity, which is also reflected in the lowest $d_j/D$ ratio given in Figure 12(b). It should be remembered that, when the melt viscosity is low, premature foaming may occur inside the die. The reasons why, for instance, the STYRON 678 at 150°C gives such a high density foam and, hence, such poor foam quality [see Fig. 12(a)] may be: (1) the viscosity of the mixture of STYRON 678 and FC-11/FC-12 is low enough to permit bubble formation to occur inside the die; (2) the elasticity of STYRON 678 may *not* be high enough to slow down bubble growth in the extrudate and, therefore, cells might have collapsed. It is concluded, therefore, that both the melt viscosity and the melt elasticity play important roles in controlling the foam extrusion characteristics of polystyrene.

## The Effect of Die Design Variables on Foam Extrusion Characteristics

We have investigated the foam extrusion characteristics of polystyrene by varying the capillary length-to-diameter ($L/D$) ratio (0, 2, 4, and 8), the die entrance angle (15°, 30°, and 60°), and the reservoir-to-capillary diameter ($D_R/D$) ratio (2 and 8). Over the range of these die design variables investigated, we have found that only the $L/D$ ratio plays a significant role in influencing the foam extrusion characteristics of polystyrene.

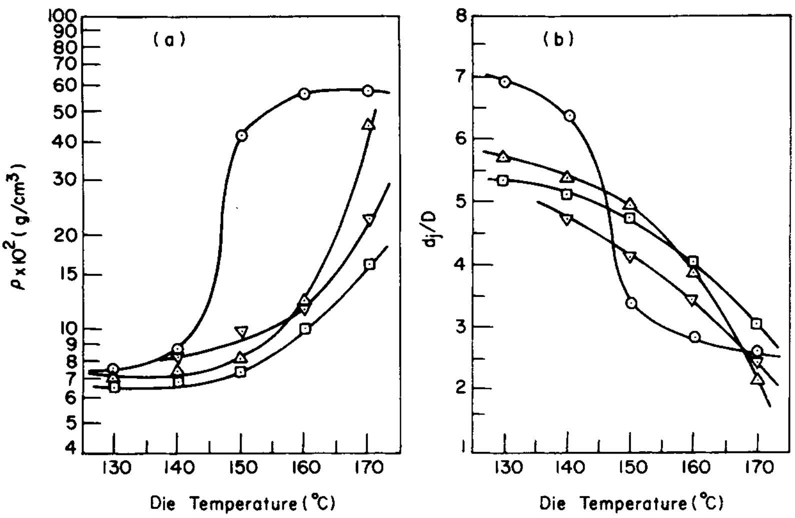


Fig. 17. Foam density and extrudate swell ratio for different values of capillary length-to-diameter ($L/D$) ratio: (⊙) 0; (△) 2; (⊡) 4; (▽) 8. The die entrance angle is 60° and the reservoir-to-capillary diameter ($D_R/D$) ratio is 8. The system is STYRON 678/4 wt % FC-12/mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$, and the apparent shear rate is 160 $s^{-1}$.

Figure 17 gives plots of $\rho$ and $d_j/D$ vs. die temperature for the STYRON 678 and FC-12 system, with different values of capillary length-to-diameter ($L/D$) ratio. It is seen in Figure 17(b) that, at die temperatures at and below 145°C, the $d_j/D$ ratio decreases with increasing $L/D$, which is consistent with the observations reported in the literature dealing with homopolymer melts.[10] Note further that the $d_j/D$ ratio for the die having an $L/D$ ratio of 0 decreases very rapidly as the die temperature increases from 140°C to 150°C. This represents appreciable cell collapse occurring in the extrudate, which is reflected in the rapid increase in foam density as indicated in Figure 17(a).

It is also seen in Figure 17(b) that the $d_j/D$ ratio for the die having an $L/D$ ratio of 2 decreases rapidly as the die temperature increases above 155°C. This again is attributable to the cell collapse that might have occurred in the extrudate. This is also reflected in $\rho$, as shown in Figure 17(a). That is, at the die temperature at and above 160°C the foam density for the die having an $L/D$ ratio of 2 is greater than that for the dies having $L/D$ ratios of 4 and 8.

In reference to Figure 17(b), the $d_j/D$ ratio for the die having an $L/D$ ratio of 8 is smaller than that for the dies having $L/D$ ratios of 2 and 4, at die temperatures between 130°C and 160°C. Note in Figure 17(a) that the foam density for the dies having $L/D$ ratios of 2, 4, and 8 has no significant difference for die temperature in the same range.

Figure 18 describes an operating guide for the extrusion of the STYRON 678 and FC-12 system, in terms of the die temperature for various values of $L/D$ ratio, for obtaining extruded polystyrene foams with a partially closed cell structure. In order to facilitate our discussion here, the open cell fraction in polystyrene foams obtained with the dies having various values of $L/D$ ratio (0, 2, 4, and 8) is listed in Table II, and plots of die pressure vs. die temperature for the mixture of STYRON 678 and FC-12, with $L/D$ ratio as parameter, are given in Figure 19. It is seen in Figure 19 that the die pressure increases with decreasing die

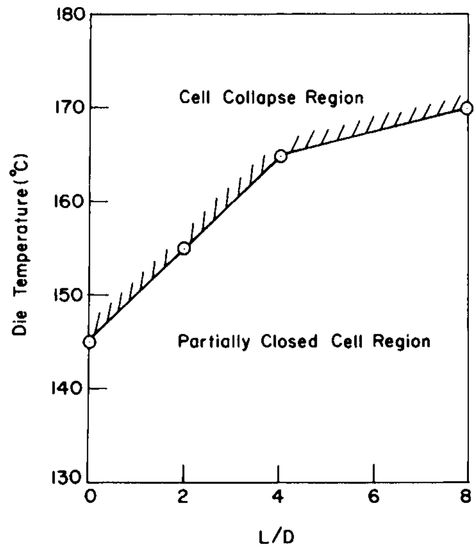


Fig. 18. Die temperature vs. capillary length-to-diameter ratio, describing the processing conditions that produce closed cell foams and the region where cell collapse occurs. The system is STYRON 678/4 wt % FC-12/mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$, and the apparent shear rate is 160 $s^{-1}$.

temperature and with increasing *L/D* ratio. It is of interest to note that the die pressure at the die temperature 130°C, with all the dies employed, is much greater than the vapor pressure (ca. 200 psi) of 5 wt % FC-12 in polystyrene.[11] Under such situations, we expect that *little* premature foaming would occur inside the die during extrusion. This indeed is borne out to be the case, as reflected in the relatively low open cell fraction in the extrudate (see Table II). In the use of a die having large *L/D* ratio, too low a die temperature would require excessively large pressure drops, which will then limit the extrusion rate. Therefore, the choice of a die having small *L/D* ratio is most desirable in order to obtain polystyrene foams with low open cell fraction, provided that the die temperature is kept sufficiently low to prevent premature foaming inside the die.

## CONCLUDING REMARKS

On the basis of the results presented above, it is quite clear that the die tem-

TABLE II
Open Cell Fraction of Polystyrene Foams Affected by the *L/D* Ratio of Extrusion Die[a]

| Die temp (°C) | *L/D* ratio | | | |
|---|---|---|---|---|
| | 0 | 2 | 4 | 8 |
| 130 | 0.10 | 0.10 | 0.17 | — |
| 140 | 0.56 | 0.55 | 0.45 | 0.15 |
| 150 | — | 0.95 | 0.70 | 0.45 |
| 160 | — | — | 0.90 | 0.80 |

[a] The system employed is STYRON 678/4 wt % FC-12/mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$; the apparent shear rate is 160 $s^{-1}$; the die employed has $D_R/D = 8$ and $\alpha = 60°$.

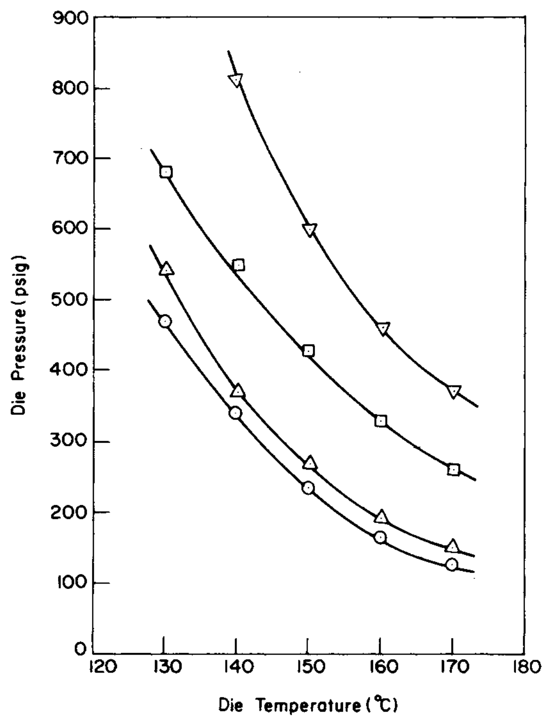


Fig. 19. Die pressure vs. die temperature for the dies having $\alpha = 60°$, $D_R/D = 8$, and different $L/D$ ratios: (⊙) 0; (▲) 2; (⊡) 4, (▽) 8. The system is STYRON 678/4 wt % FC-12/mixture of 0.3 wt % citric acid and 0.375 wt % $NaHCO_3$, and the apparent shear rate is 160 $s^{-1}$.

perature, the shear rate, the type and concentration of fluorocarbon blowing agent, and the die geometry affect the quality of extruded polystyrene foams. We have found that the die temperature is one of the most sensitive processing variables, and it must be chosen judiciously, in conjunction with the die design variables and the material variables, in order to obtain a good quality polystyrene foam.

To the best of our knowledge, STYRON 678 has not been used as a foam extrusion grade polystyrene, whereas both STYRON 685D and Amoco R2 have widely been used for this purpose in industry. We have found, however, that STYRON 678 can give rise to as good a foam quality as STYRON 685D and Amoco R2 by a proper choice of the die temperature and the type and concentration of fluorocarbon blowing agent. We have found that STYRON 678 requires a lower die temperature than STYRON 685D and Amoco R2, to produce low-density foam having a closed cell structure.

Although in our study we have used cylindrical extrusion dies, most of the results presented above would be directly applicable to polystyrene sheet foam extrusion, which uses annular dies. The advantage of using cylindrical dies lies in that one can easily obtain information on the extrudate swell ratio, which is then correlatable to foam density. This would not have been easy, if not impossible, if we had used annular dies.

In a future study, we shall investigate bubble growth in sheet foam extrusion under biaxial stretching, at various cooling conditions.

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