Influence of Die Angles on Pressure Drop during Extrusion of Rubber Compound

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ABSTRACT: The factors affecting pressure losses during extrusion of polymer melts are discussed in the present article. The rheological properties of an unvulcanized rubber compound were examined by using a Monsanto processability tester (MPT) under experimental conditions of temperatures varied 90 to 120°C and shear rates from 10^2 to 10^3 s^{-1}. Furthermore, a set of dies with different entry angle (2α) was selected to identify the effects of die angles on pressure losses in capillary extrusion of the sample fluid. It was found that the total pressure drop (ΔP) decreased when $2\alpha < 75$ degrees, and then increased with increasing 2α. The ΔP reached the minimum value when 2α is around 75°. It suggests that the natural converging angle of the sample fluid be about 75° under the experimental conditions, according to the research results presented in previous work. © 2001 John Wiley & Sons, Inc. J Appl Polym Sci 80: 1150–1154, 2001

Key words: rubber compound; capillary rheometry; extrusion; die angle; pressure drop

INTRODUCTION

When polymer melt enters into a small channel from a reservoir, it is subjected intensive extrusion and shear, leading to forming an entrance converging flow due to the melt viscoelasticity and the contraction of the channel. In general, entry converging flow consists of elongation flow and shear flow. Consequently, obvious entry pressure losses will be produced. The effect of entrance convergence is an important factor for inducing unsteady flow during extrusion of polymer melts under given conditions. Entry converging flow has been an interesting topic in polymer processing rheology, because it influences directly the quality of extruded products and production rate of processing equipment. The mechanisms of the entry converging flow for polymer fluids have been discussed and the progresses in this field have been reviewed.[1–3] Apart from the melt viscoelasticity, the influence of channel geometry on the rheological performance of polymer melts is important. Han and Kim[4] observed the influence of reservoir diameter (D_P) on the melt elasticity in capillary flow of high density polyethylene, and found that the exit pressure first increased and then leveled off, as the D_P/D ratio was increased. This is similar to the author's results in his previous work.[5] Gibson and Williams[6] investigated the effects of the die angles and the bore diameter on the entry pressure drop with bulk molding compound, and proposed a model for prediction of the entry pressure losses. The results showed that there was a transition from constrained convergence with recirculation at a die semiangle of approximately 56°.

There is a vortex flow region at the front of the die inlet when converging flow is formed during

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extrusion of polymer fluids, especially in the case of flat entrance die (i.e., die angle is 180°). As a result, extra entry pressure losses are produced. To minimize the harmful effect of vortex flow at the die entry district on energy consumption, extrusion flow stability and extrudate quality, a die is usually connected with the extruder barrel by a conical transition region in polymer industry. Then, what is the best value of the die entrance angle?

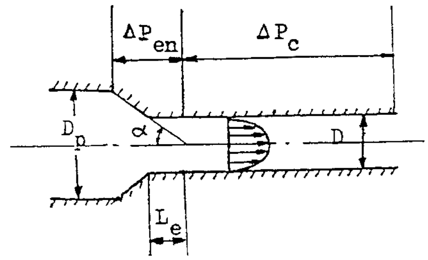

Figure 1 Diagram of polymer melts in die flow.

EXPERIMENTAL

Sample Material

The sample material used in this test was an industrial unvalcanized rubber compound. The main composition consisted of natural rubber (NR), styrene–butadiene rubber (SBR), sulfur, stearic acid, carbon black, etc. The NR/SBR ratio was 70/30. The partial physical properties were: hardness (SHA) 54 ± 2; plasticity (Williams) 0.5 ± 0.03; density 1.11 ± 0.02 g/cm^3; and Mooney viscosity ($ML_{1+4}^{100°C}$) 46.5.

Instrument and Methodology

The rheological properties of the sample were measured by means of a Monsanto processability tester (MPT), a constant rate type of capillary rheometer. In addition, a set of dies with various entry angles of 35°, 45°, 60°, 75°, and 90° were selected to investigate the effects of die angles on the pressure drop and rheological behavior during extrusion of the sample. The diameter and length/diameter ratio (L/D) for these dies were 1.2 mm and 16, respectively. The test temperatures were 90, 100, 110, and 120°C, and the apparent shear rates varied from 10 to 10^3 s^{-1}.

RESULTS AND DISCUSSION

Pressure Losses

Figure 1 shows polymer melt flow in a circular channel. As stated above, a great quantity of energy is consumed during die extrusion of polymer melts, owing to the viscoelasticity and the contraction of the channel, leading to producing obvious pressure losses. It is generally believed that the total pressure drop (ΔP) in die extrusion includes entry pressure drop (ΔP_{en}), pressure drop in die (ΔP_c) and exit pressure drop (ΔP_{ex}). That is

$$\Delta P = \Delta P_{en} + \Delta P_c + \Delta P_{ex} \quad (1)$$

Because ΔP_{ex} is relatively small, in general, the former two terms in eq. (1) are only discussed. For a short die (i.e., L/D is very small), ΔP_{en} is a major part of ΔP. Generally, ΔP_{en} is a function of temperatures, shear rates (or shear stress), and channel geometry, such as the shape of across section, diameter, and entry angle, for a given polymer material. There will be, therefore, a certain relationship between ΔP_{en} and the above parameters. Liang et al.[7] studied the rheological behavior of polymer melts in a conical duct flow. On the basis of the hypothesis that the melt entry flow obeys the power law, a mathematical model for describing a relationship between the viscoelastic parameters of the melts, processing variables and ΔP_{en} was proposed by using a tensor analysis method, as follows:

$$\Delta P_{en} = 2KLnZ\left(2K_1\dot{\gamma}_w^n + \frac{1}{2}KK_2\dot{\gamma}_w^m\right) + K_1\dot{\gamma}_w^n[1 - (1/Z)^{3n}]/3nK \quad (2)$$

where m and n are the flow behavior indices for elongation flow and shear flow, respectively; Z is the diameter ratio between reservoir and die (i.e., channel contraction ratio, $Z = D_P/D$). $\dot{\gamma}_w$ is the wall shear rate that is defined as

$$\dot{\gamma}_w = \frac{3n + 1}{4n}\dot{\gamma}_a \quad (3)$$

where $\dot{\gamma}_a$ is the apparent shear rate that is given by:

$$\dot{\gamma}_a = \frac{32Q}{\pi D^3} \quad (4)$$

Table I Rheological Parameters of the Sample Melt

Temperature (°C)	K_1 (10^4 Pa · s)	n	K_2 (10^4 Pa · s)	m
90	6.13	0.2843	3.10	0.7262
100	4.66	0.3219	4.65	0.6189
110	4.32	0.3298	6.90	0.5281
120	3.87	0.3303	8.18	0.4836

where Q is the volume flow rate. In addition, parameter K in eq. (2) is a function of the half entry natural converging angle (α_o). That is,

$$K = \frac{1}{2} tg\alpha_o \tag{5}$$

Table I lists some rheological parameters of the sample measured under experimental conditions. It can be seen that n and K_2 increase while m and K_1 decrease with a rise of temperature, suggesting that the viscosity and elasticity of the sample reduce with a rise of temperature.

Influence of Temperature on ΔP

Figure 2 demonstrates the dependence of the total pressure drop on temperature in extrusion of the sample when apparent shear rate is 100 s^{-1}. With a rise of temperature the values of ΔP are decreased, and the decrease of ΔP reduces with increasing 2α. This means that the sensitivity of pressure losses to temperature is weakened with the addition of the die angles. This is because the length of the connecting zone between reservoir and die is decreased with increasing the die angle when the channel contraction ratio is fixed, leading to reduction of the residual time of the melt in the die. Consequently, the dependence of pressure losses on temperature is relatively reduced.

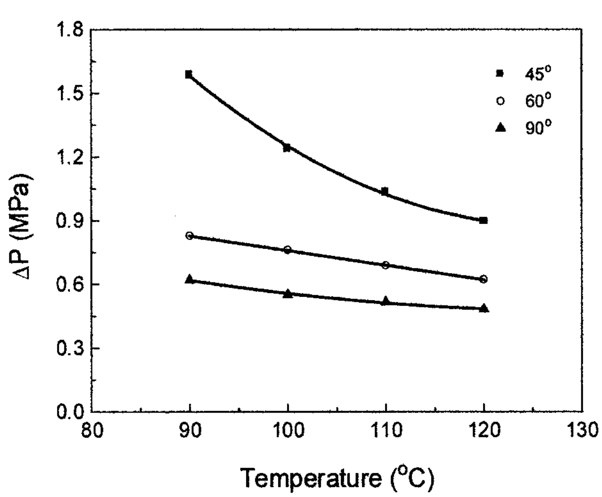

Figure 2 Dependence of ΔP on temperature ($\dot{\gamma}_a$ = 100 s^{-1}).

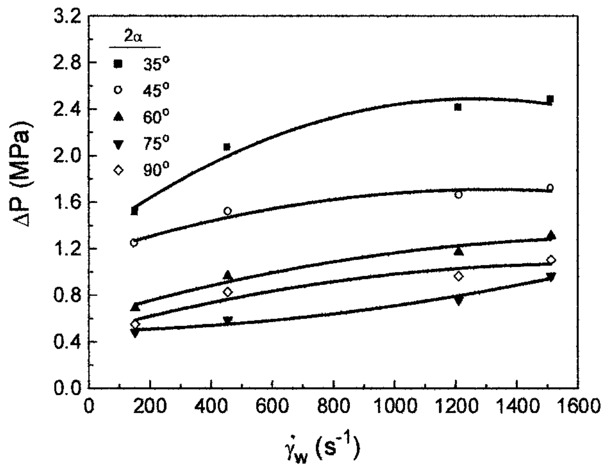

Figure 3 ΔP as a function of shear rate (100°C).

Dependence of ΔP on Shear Rates

Figure 3 shows the relationship between the total pressure drop and shear rate during extrusion of the sample in the dies with various entry angles at temperature of 100°C. It can be seen that ΔP increases with the increase of $\dot{\gamma}_w$. At the same shear rate, the values of ΔP decrease with the addition of the die angles when $2\alpha < 75°$. In addition, when 2α is greater than 45°, ΔP increases relatively gently with increasing $\dot{\gamma}_w$. It seems that the sensitivity of pressure losses to shear rates or shear rate dependence is weakened with the increase of the die angles.

For given a polymer melt and channel, when temperature is constant, the addition of flow rate not only enhances the entry flow, but also strengthens the shear flow within the die. Thus, the energy consumption increases correspondingly during extrusion of the melt, resulting in obvious pressure drop. Furthermore, as stated above, the length of the connecting zone between the reservoir and die is decreased with increasing the die angle when the channel contraction ratio is fixed, leading to reduction of the residual time of the melt in the die. Consequently, the shear rate dependence of pressure losses is relatively reduced.

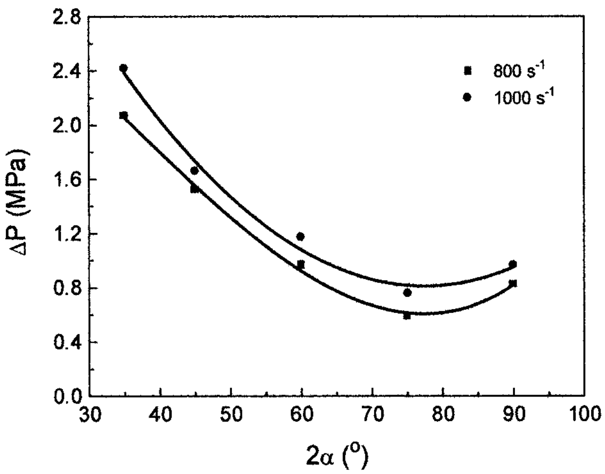

Figure 4 Effect of 2α on ΔP (100°C).

Effect of 2α on ΔP

Figure 4 displays the dependence of the total pressure drop on the die angles during extrusion of the sample at temperature of 100°C. It can be seen that ΔP decreases quickly with increasing 2α when 2α is smaller than 75°. But ΔP increases with increasing 2α when 2α is greater than 75°. It can be also seen in Figure 4 that ΔP reaches minimum value at $2\alpha = 75°$. From the viewpoint of minimum energy theory, fluid always flows along the direction of minimum pressure. This means that the energy consumption is minimal when the die angle is equal to the natural convergence angle of the fluid. Thus, the above results suggest that the natural converging angle for this fluid be about 75° at the die inlet. In previous work,[8,9] the authors investigated the effects of the die angles on the flow properties and die-swell behavior during extrusion of rubber compounds by using a capillary rheometry. The results showed that the shear viscosity and die-swell ratio also achieved minimum values when 2α is about 75°.

When 2α is smaller than $2\alpha_o$, the length of the connecting region between the reservoir and die, L_c, is relatively long for given channel contraction ratio. In this case, L_c decreases with increasing 2α, the energy consumed in the entry flow is decreased, leading to reduced ΔP. When 2α is greater than $2\alpha_o$, the elongation flow is enhanced apart from shear flow, and the vortex flow may occur at the front region of the die inlet. Consequently, the dissipation and storage of energies in the entry flow increase with increasing 2α, resulting in increasing the ΔP. Therefore, the die angle should be designed to be equal or close to the natural entry converging angle of the material to be processed to reduce energy consumption in production.

DISCUSSION

The natural entry converging angle is an important characterization of viscoelasticity for non-Newtonian fluids. Figure 5 illustrates the entry flow pattern and natural converging angle during extrusion of viscoelastical fluids. For polymer melts, when the reservoir diameter is much greater than that of the die (i.e., $Z \gg 1$), the half angle of natural convergence at the die entrance can be approximately expressed as:[10]

$$\alpha_o = tg^{-1}\left[\frac{2}{3e}\left(\frac{2}{n+1} + \frac{\xi}{1-n}\right)\right] \tag{6}$$

where ξ is the constant related to the wall adhesion property of fluid, n is the flow behavior index, e is the Bagley entry correction factor for characterizing the melt elasticity, which is defined as:

$$e = \frac{\Delta P_{en}}{2\tau_w} \tag{7}$$

where τ_w is the wall shear stress.

Equation (6) shows that the natural entry convergence angle is a function of the viscoelastical parameters (e, n, ξ) of polymer fluids under given conditions. In other words, the values of $2\alpha_o$ mainly depend upon the molecular structure of polymeric materials and flow conditions. Because e and ξ decrease but n increases with a rise of temperature, and e increases while n decreases with increasing shear rate, $2\alpha_o$ will increase somewhat with a rise of temperature and decrease slightly with the increase of shear rate.

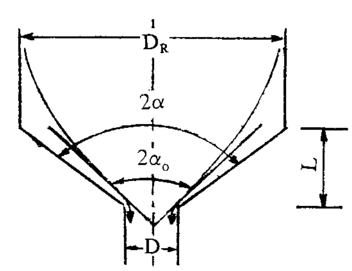

Figure 5 Sketch of entry flow in extrusion of polymer melts.

CONCLUSION

During extrusion of polymer melts, an entry converging flow is formed due to the melt viscoelasticity and the contraction of channel. Consequently, large pressure drop is produced under given operation conditions. In general, the values of pressure drop are related to not only the melt viscoelasticity, but also the extrusion operation conditions (e.g., temperature and flow rate) and the channel geometry, such as contraction ratio, length/diameter, and entrance angle. For a short die extrusion of polymer melts, the influence of entry flow on the total pressure losses is quite important. In this case, the effect of die angles on pressure drop is correspondingly significant.

The effect of the die angles on the pressure drop during extrusion of a rubber compound has been investigated. The results show that the values of ΔP reach minimum when 2α is around 75°. This means that the natural convergence angle at the die entry for this sample be about 75° under these test conditions, suggesting that the optimal die angle is when it is equal (or close) to the $2\alpha_o$ of the fluid. Generally, the values of $2\alpha_o$ for polymer melts mainly depend upon the molecular configuration and the composition of the sample materials, in additional to the processing variables in extrusion and the channel geometry.

REFERENCES

1. Liang, J. Z. ASME 1995, FED-231/MD-66, 35.
2. White, S. A.; Gotsis, A. D.; Baird, D. G. J Non-Newton Fluid Mech 1987, 24, 121.
3. Binding, D. M. J Non-Newton Fluid Mech 1988, 27, 173.
4. Han, C. D.; Kim, K. U. Polym Eng Sci 1971, 11, 395.
5. Liang, J. Z. Plast Rubber Compos Process Appl 1993, 19, 311.
6. Gibson, A. G.; Williams, G. A. Polym Eng Sci 1985, 25, 980.
7. Liang, J. Z.; Sun, X. L.; Tang, G. J. Proceedings of China-Japan Int Confer on Rheol, Beijing, 1991, p. 190.
8. Liang, J. Z.; Huang, Y. Q.; Tang, G. J.; Ness, J. N. Plast Rubber Compos Process Appl 1992, 18, 311.
9. Liang, J.-Z. J Mater Process Technol 1995, 52, 207.
10. Liang, J. Z. Acta Mech Sinica 1990, 22, 79.