The Die Swell through Converging Slits

INTRODUCTION

In the extrusion of molten polymers, die swell has attracted much attention. The cross section studied was mainly uniform,[1–5] but commercial dies usually have channels with nonuniform cross sections. Particularly for extrusion of sheet such as a fish-tail die, the cross section varies considerably with the flow direction.

In order to predict the properties of the films or sheets extruded, the die swell through a converging slit or a diverging slit must be considered. For calendering, the nip part also can be considered as a sort of die which consists of a converging slit and a diverging slit, with a moving boundary.

Cogswell has analyzed theoretically the converging flow and proposed equations which predict the die swell from capillary data.[6] Chee et al. determined the die swell through successive capillaries with different radii.[7]

In 1966, Nakajima and Shida correlated quantitatively the die swell with elastic recoverable strain owing to the viscoelasticity of polymers,[8] and many articles have been presented.[1–5] Most assumed a fully developed flow and the storage of energy in the shear flow. After the extrusion of the fluid from the die, the energy is recovered by axial contraction, namely, the die swell. Chapoy et al. described the two mechanistic origins (die entrance or die passage) of the die swell by mathematical models and showed that the resulting equations were similar.[9]

In this article it is assumed that the total recoverable energy at the die exit consists of the energy relaxed through the die from the entrance and the energy stored in shear field. Several slit dies with different gaps are arranged in series in order to form stepwise converging channels, and the pressure drops and the die swell ratios are measured. The observed swell ratios are compared with the values calculated from the rheological parameters measured with a capillary rheometer.

EXPERIMENTAL

The HDPE used was a grade of Chubu Chemical #3000. Its density at room temperature was 0.947 and its melt index was 5.0. The melt viscosity was determined by means of a capillary rheometer at 180°C, and its shear moduli were calculated from Bagley's entrance correction (G_{en}) and from the swell ratio (G_{ex}). The viscosity and the shear moduli data are shown in Figure 1.

For relaxation of the stress, the solidified extrudate was annealed in a hot silicone bath of 150°C.

TABLE I
Dimensions of Slits

Die designation	Length L, mm	Width W, mm	Gap H, mm
W_1	3.04	17.3	1.00
W_2	4.05	17.3	0.60
W_3	2.05	17.3	0.33

TABLE II
Comparison between Observed and Calculated Swell Ratios

$\Delta P \times 10^{-6}$, dyn/cm^2	Swell ratio	
	Obsd.	Calcd.[a]
6.63	1.197	1.22
9.36	1.218	1.29
11.5	1.245	1.33

[a] From eq. (1).

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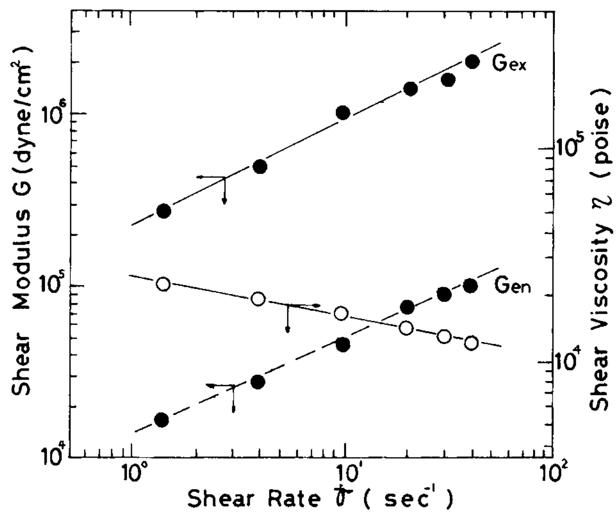

Fig. 1. Rheological properties of HDPE at 180°C.

Its thickness was measured with a micrometer; the position corresponded to 10 mm from the die exit. The swell ratio was defined as the ratio of extrudate thickness to slit gap.

The dimension of the slits are shown in Table I. Figure 2 shows a schematic diagram of our combined converging slit die.

THEORY

The analysis was based on the following assumptions: (1) The polymer was incompressible. (2) Viscoelasticity was described according to a simple Maxwell model. (3) The mean axial normal stress was equal to the first normal stress difference. (4) The shear rate was represented by the volumetrically average shear rate. (5) The flow was isothermal. (6) The swell toward the transverse direction of a slit was neglected.

Our proposed model was the following:

1. At the die entrance, energy stored in elongation was[5,10]

$$W_e = G_{en}(\lambda^2 - 1/\lambda^2)$$

2. Through the die, energy relaxed was

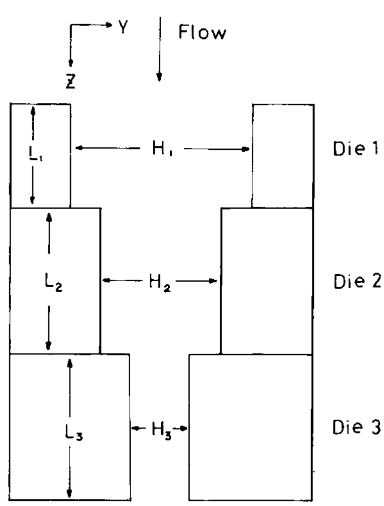

Fig. 2. Schematic diagram of our converging slit die.

$$W_r = G_{en}(\lambda^2 - 1/\lambda^2)e^{-t/\tau}$$

3. Through the die, energy stored in shear was[5]

$$W_s = \tfrac{1}{2}G_{en}S_r^2 = \tfrac{1}{2}\eta^2/G_{en}\dot{\gamma}^2$$

4. At die exit, energy recovered by contraction was[5,10]

$$W_c = \tfrac{1}{2}G_{ex}(\lambda^2 - 1/\lambda^2)$$

From the energy balance,

$$W_r + W_s = W_c$$

The process which stored and recovered energy in the stepwise converging die was as follows: The stored energy in elongation was

$$\sum_{i=1}^{n} W_{ri} = \sum_{i=1}^{n} G_{eni}(\lambda^2{}_i - 1/\lambda^2{}_i)\, e^{-(t/\tau)_i}$$

and the stored energy in shear was

$$W_s = \tfrac{1}{2}\eta^2/G_{en}\dot{\gamma}^2$$

The recovered energy was

$$W_c = \tfrac{1}{2}G_{ex}(\lambda^2 - 1/\lambda^2)$$

so that

$$\sum_{i=1}^{n} W_{ri} + W_s = W_c \tag{1}$$

where G = shear modulus, η = shear viscosity, $\dot{\gamma}$ = shear rate, t = residence time through slit ($2L/H\dot{\gamma}$), τ = relaxation time (η/G_{ex}), λ = extension ratio (H_{i-1}/H_i), H = slit gap, L = slit length.

At a given shear rate, all parameters of eq. (1) are known except λ in the right hand, and λ phenomenally means the die swell ratio at the final die exit. Therefore, die swell ratio can be predicted from eq. (1).

RESULTS AND DISCUSSION

The pressure drops and the volumetric flow rate through a converging die are shown in Figure 3. In combined die, the solid lines are calculated ones, i.e., the sum of each single die's data. It was shown that the pressure drops at a given volumetric flow rate through combined slits were nearly equal to the sum of the pressure drops through the individual slits. This result suggested that the converging flow patterns were almost independent of other slits.

The swell ratio is plotted against the mean shear rate in Figure 4. The swell ratio increased with shear rate and depended only on the final die. This suggested that the shear history upstream through the converging die had little effect on the ultimate swell.

The swell ratio observed and those calculated by eq. (1) are compared in Table II. The calculated swell ratios were somewhat greater than the observed ones, but the difference did not exceed 6%.

The shear history had little effect on either viscous or elastic behavior in the case of our slow flow rate. Therefore, most of the stored energy was relaxed at the die exit. The residence time through a slit was ~1.3 sec in this study, and it exceeded considerably the calculated relaxation time of 0.15 sec. The energy stored by the elongation at the die entrance was calculated to be nearly 8×10^7 dyn/cm^2, but it was relaxed through the slit to ~40 dyn/cm^2 at the exit. The energy stored by the elongation at the die entrance was approximately 98% of the total energy, but at the exit it decreased to ~0.1%.

If the residence time is shortened, some energy may be retained because of incomplete relaxation. However, in our die, when the shear rate exceeded 40 sec^{-1}, the extrudate became distorted (it waved and folded). Thus, accurate die swell could not be determined under these conditions.

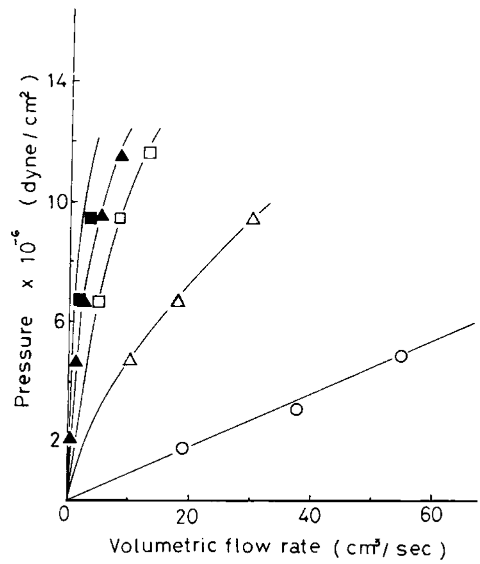

Fig. 3. Pressure drops and volumetric flow rate through a converging die. The notations in the figure correspond to those shown in Table I: In the combined die, the upper die is listed first: (○) W_1; (△) W_2; (□) W_3; (▲) $W_2 + W_3$; (■) $W_1 + W_2 + W_3$.

CONCLUSIONS

Under our experimental conditions of slow flow rate (less than 40 sec^{-1}), the die swell through the converging slit die, which was combined stepwise, depended almost entirely on the final die, and little effect of the shear history on both viscosity and elasticity was observed. Incomplete relaxation of stored energy should be considered in the case of high flow rate.

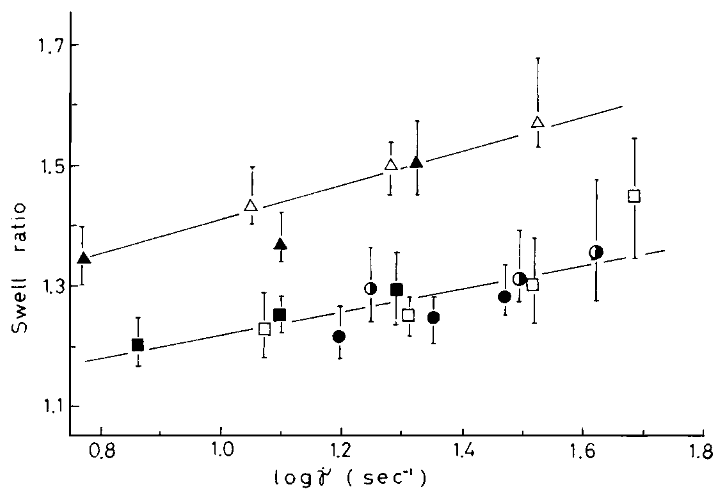

Fig. 4. Relationship between swell ratio and logarithm of shear rate. The notations in the figure correspond to those shown in Table I: (△) W_2; (▲) $W_1 + W_2$; (□) W_3; (◑) $W_1 + W_3$; (●) $W_2 + W_3$; (■) $W_1 + W_2 + W_3$.

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