JOURNAL OF APPLIED POLYMER SCIENCE VOL. 15, PP. 1091-1097 (1971)

Rheology of Shaped Fiber Formation

CHANG DAE HAN, *Department of Chemical Engineering, Polytechnic Institute of Brooklyn, Brooklyn, New York 11201*

Synopsis

A rheological interpretation is given for the formation of shaped fibers whose cross section is different from the spinnerette shape. For the study, a rectangular die having an aspect ratio of 6 was constructed, with dimensions 0.1 in. by 0.6 in. Measurements were then taken of the distributions of wall normal stresses at two adjacent walls of the rectangular duct. The measurements show the nonuniform distributions of wall normal stresses over the long and short sides of the rectangle, which is in accord with the nonuniform distributions of extrudate swell on both sides of the rectangle. Explanations are then given for the observed fact that extrudate swell is more pronounced at the long side than at the short side.

INTRODUCTION

In recent years, the fibers having various cross sections other than circular, for instance, elliptical, have been manufactured.[1,2] They are called "shaped fibers" in the fibers industry. One of the most interesting facts is that the shape of finished filaments can be made quite different from that of the spinnerette hole, depending upon the rheological properties of the materials being extruded and spinning conditions, such as jet stretch and coagulating bath concentration, etc. It is known, for instance, that fibers of an elliptical cross section having various aspect ratios can be produced from a rectangular spinnerette hole (see Fig. 1). Here, the aspect ratio is defined as the ratio of major to minor axis. However, very little appears to have been mentioned quantitatively to account for such changes in extrudate cross section.

It is believed that the changes in extrudate cross section occur while the extrudate is still in the liquid state. This implies that the significant region lies within a relatively short distance from the spinnerette face. It is also this region where the extrudate swell occurs in the emerging stream. The distance at which maximum swell occurs depends on the velocity of the fluid in the spinnerette and also on a characteristic "recovery" time. It has been discussed in the literature that the extrudate swell occurs as a result of recovery of the elastic deformation imposed in the spinnerette hole[3,4,5] and that the extent of extrudate swell can be correlated to other elastic behavior of the material, such as the normal stress differences[6,7,8] and the exit pressures.[9] However, it is to be noted that most of the published

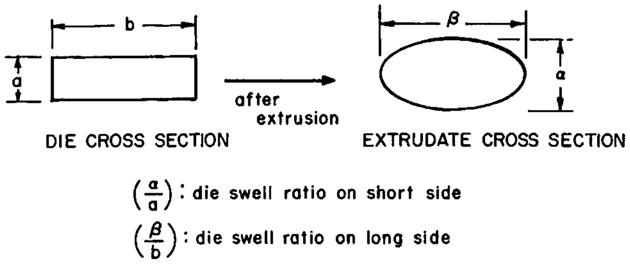

Fig. 1. Schematic representation of extrudate swell behavior in extrusion from a rectangular duct.

literature, including those referred to above, was concerned with the die swell phenomenon from a circular capillary.

Unlike the extrudate swell from a circular tube, the extrudate from a rectangular die swells nonuniformly at two adjacent sides (i.e., the long and short sides of the rectangle). There is more pronounced swell on the long side than on the short. One might be tempted to think that the surface tension force could be a contributing factor to the changes in extrudate cross section. However, one can easily show from a rough calculation that the magnitude of the surface tension force alone is much too small to be entirely responsible for the changes in extrudate cross section, at least for polymer melts.

It is the purpose of this paper to present experimental results showing that the nonuniform extrudate swell from a rectangular spinnerette hole is due to the nonuniform distributions of the wall normal stresses at two adjacent walls of the rectangle.

EXPERIMENTAL

Materials

The material used for the present study was polypropylene (Enjay Chemical Co., E115 Resin) with a melt index of about 5.0. Experimental runs were made at a melt temperature of 180°C.

Apparatus and Experimental Procedure

The apparatus consists of an extruder, a reservoir section which connects the outlet of the extruder to the inlet of the die section, and the rectangular die section. Polymer melt flows from the extruder into the reservoir section, which is 10 in. long by 1.125 in. in diameter. From here, melt flows into the rectangular slit of the die section. The slit has an aspect ratio of 6, with a short side of 0.1 in. and a long side of 0.6 in. The die is made of a 6-in. length of 5-in. diameter aluminum bar.

In Figure 2 is shown the detailed layout of the rectangular die section having three pressure tap holes on the long side and three pressure tap holes along the center line of the short side.

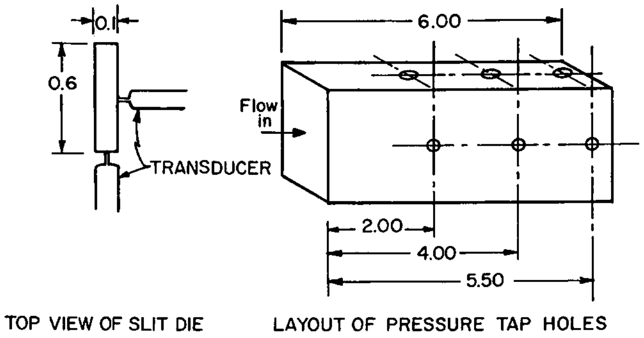

Fig. 2. Layout of pressure tap holes in rectangular duct die.

The pressure at the wall (i.e., the total wall normal stress) is measured with Dynisco melt pressure transducers. The electrical outputs, in millivolts, of the pressure transducers are read on a potentiometer which is balanced with the aid of a dc null detector.

The temperature is monitored at various positions in the reservoir and die sections with the aid of iron-Constantan thermocouples, and the temperature is controlled to within ±0.5°F by Thermistor-operated thermal regulators. The heating system itself consists of resistance wire wound on aluminum jackets for uniform heat distribution, and the entire system is well insulated.

RESULTS AND DISCUSSION

Typical pressure profiles are shown in Figure 3 for polypropylene melts at 180°C, measured at two adjacent walls of the rectangular die. (See Fig. 2 for the positions of the pressure tap holes.) It can be seen from Figure 3 that, if the last pressure measurement is extrapolated to the die exit, the pressure at the die exit shows nonzero gauge pressure, that is, above atmospheric. This pressure has been called the "exit pressure" in the author's earlier papers.[8–11]

Note that the pressure profiles in Figure 3 are at a given throughput rate. As has been shown in the author's papers,[8–11] wall normal stress increases with throughput rate, and this has been the case in the present study also. It is further to be noted from Figure 3 that the magnitude of the wall normal stress at the center of the long side of the rectangle is greater, at any position along the longitudinal direction, than that at the center of the short side. Figure 4 shows the schematic of the distributions of the wall normal stresses at two adjacent walls of the rectangular die.

In order to see if there is any correlation between the wall normal stress distributions and the extrudate swell behavior, samples of the extrudate were collected at the same shear rate as those at which the pressure measurements were taken. Figure 5 shows the photographs of the extrudate cross-section of polypropylene melt at 180°C. It is quite interesting to see from

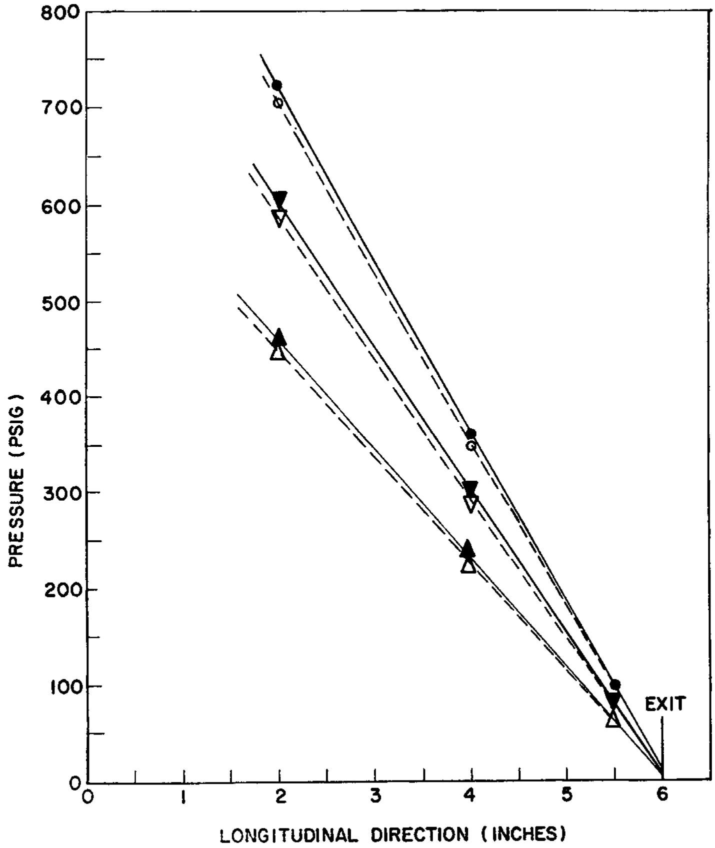

Fig. 3. Axial pressure profiles in a rectangular duct for polypropylene melt at 180°C: (—) long side at center; (---) short side at center; (●) (○) 67.8 cc/min; (▼) (▽) 45.5 cc/min; (▲) (△) 16.2 cc/min.

these photographs that the distributions of extrudate swell at two adjacent walls of the rectangle are very similar to the distributions of the wall normal pressure shown in Figure 4. This similarity leads one to the conclusion that the changes in extrudate cross section are due to the nonuniform distributions of wall normal stresses at the two adjacent walls of the rectangle. Earlier, Han[8,9] contended that the existence of both the exit pressure and die swell behavior are manifestations of the elastic behavior of viscoelastic fluids, by giving an argument based on the phenomenologic point of view. Han[9,12] further presented correlations between the exit pressures and die swell ratio in the flow of polymer melts through circular tubes. The results of the present study fortify once again the author's earlier contention that the exit pressure is indeed a manifestation of elastic behavior, the same as the die swell behavior is.

It is very interesting to examine the extrudate swell behavior at the corners of the rectangle. It is seen from Figure 5 that there is hardly any

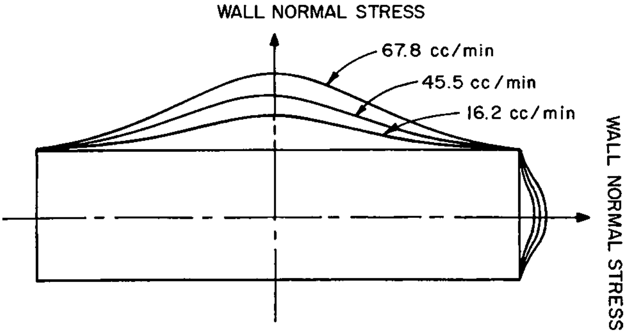

Fig. 4. Distributions of the exit pressures for polypropylene melt at 180°C.

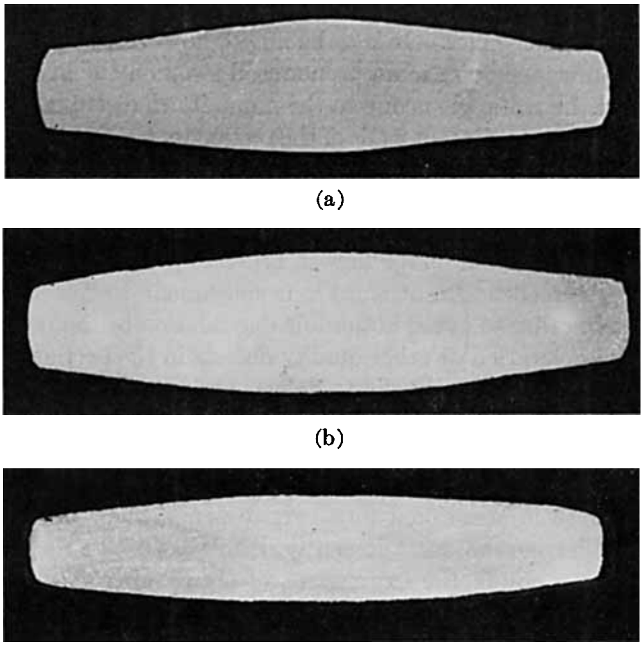

Fig. 5. Extrudate swell behavior for polypropylene melt: (a) $Q = 67.8$ cc/min; (b) $Q = 45.5$ cc/min; (c) $Q = 16.2$ cc/min.

rounding at the edges (the corners) of the rectangle. This suggests that the surface tension force is far too small to play any role in rounding the edges of the molten polymers. (The surface tension force would be the only important factor that could come into the picture for rounding the edges.) On the other hand, at the corners of the rectangle the shear rates are zero and so are the wall normal stresses, giving rise to no extrudate swell.

Hence the discussion given above applies to melt fiber spinning. The same will also apply to wet fiber spinning with the possible exception of the roundedness of the finished fiber corners. Recently, the author[13] carried out a wet-spinning study using a spinnerette of rectangular holes having an aspect ratio of 5. As a spin dope, an aqueous solution of polyacrylonitrile (PAN) consisting of approximately 10% polymer and 40% sodium thiocyanate (NaSCN) was spun into a coagulating bath of 12% NaSCN in water. The study showed that the cross section of the extrudate has smoothly rounded corners, which are very similar to the schematic shown in Figure 1, in contrast to the very sharp edges of the extrudate from melt extrusion (see Fig. 5). It is, however, no surprise to us to see this difference in the cross section between the melt-spun and wet-spun extrudates. The magnitude of the surface tension force between the spin dope and the coagulating bath solution in wet spinning is much greater than that between the molten polymer and the air in melt spinning, and thus some influence of the surface tension force is expected in rounding off the edges of finished fibers spun from rectangular holes. It is to be noted, however, that even in wet spinning the occurrence of a more pronounced swell on the long side than on the short of the rectangle is due to the nonuniform distributions of wall normal stresses at two adjacent walls of the rectangle.

Today, many dies of various shapes other than rectangular are designed for various melt processing purposes, for instance, combinations of wide thin slits and/or annuli. In designing such dies, there appears to be no quantitative consideration of the flow in order to predict the various flow properties of the melts. An attempt is usually made to "streamline" the flow passages in order to avoid noticeable degradation of the polymer that might cause discoloration or other quality defects in the product. Seldom is an effort made to design the die to deliver a given output of the proper shape with some specified pressure drop. Admittedly, the theoretical approach to this problem is not easy, because dealing with non-Newtonian viscoelastic fluids in flow through rectangular ducts, for instance, presents the problem of two-dimensional flow, whose complexity depends on the type of flow model one chooses. Recently, Han[14] has used a three-constant Oldroyd model to obtain the expressions of shear rates at two adjacent walls of a rectangular duct.

In summary, a rheological interpretation is given for the formation of shaped fibers, with an example of extruding polypropylene melts in a rectangular die. The present study shows that the nonuniform distributions of wall normal stresses at two adjacent walls of the rectangle give rise to nonuniform distributions of extrudate swell, and hence produce shaped fibers.

The work was supported in part by the Fibers Division, American Cyanamid Company, to which the author is grateful.

References

1. R. C. Forney, L. K. McCune, N. C. Pierce, and R. Y. Tompson, *Chem. Eng. Progr.*, **62,** No. 3, 89 (1966).
2. R. A. Buckley and R. J. Phillips, *Chem. Eng. Progr.*, **65,** No. 10, 41 (1969).
3. E. B. Bagley, S. H. Storey, and D. C. West, *J. Appl. Polym. Sci.*, **7,** 1661 (1963).

4. R. C. Kowalski, Elastic Behavior in Molten Viscoelastic Polymeric Materials, Ph.D. Dissertation, Polytechnic Institute of Brooklyn, 1963.

5. C. D. Han and L. Segal, *J. Appl. Polym. Sci.*, **14,** 2973 (1970).

6. A. B. Metzner, W. T. Houghton, R. A. Sailor, and J. L. White, *Trans. Soc. Rheol.*, **5,** 133 (1961).

7. W. W. Graessley, S. D. Glassock, and R. L. Crawley, *Trans. Soc. Rheol.*, **14,** 519 (1970).

8. C. D. Han, *J. Appl. Polym. Sci.*, **14,** 1775 (1970).

9. C. D. Han, M. Charles, and W. Philippoff, *Trans. Soc. Rheol.*, **14,** 393 (1970).

10. C. D. Han, M. Charles, and W. Philippoff, *Trans. Soc. Rheol.*, **13,** 455 (1969).

11. C. D. Han, and M. Charles, *Polym. Eng. Sci.*, **10,** 148 (1970).

12. C. D. Han, *A.I.Ch.E. J.*, **16,** 1087 (1970).

13. C. D. Han, unpublished work.

14. C. D. Han, paper presented at the 41st Annual Meeting of the Society of Rheology, Princeton, New Jersey, October 26–28, 1970.

Received December 1, 1970