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A Study of Shaped Fiber Formation

CHANG DAE HAN and JONG YOO PARK, *Department of Chemical Engineering, Polytechnic Institute of Brooklyn, Brooklyn, New York 11201*

Synopsis

An experimental study has been carried out to investigate the effects of spinning conditions on the shape of fibers spun through noncircular spinnerette holes, namely, rectangular holes, trilobal holes, and round holes with lugs. For the study, bench-scale apparatuses of wet spinning and melt spinning were used which had been constructed in connection with an earlier study by Han. In the wet-spinning experiment, the spin dope used was an aqueous solution of polyacrylonitrile (PAN) consisting of approximately 10% polymer and 40% sodium thiocyanate (NaSCN), and the spin dope was spun into aqueous solutions of NaSCN. In the melt-spinning experiment, polystyrene was used. The variables investigated were: size and shape of the spinnerette hole, coagulating bath concentration, throughput rate, and jet stretch. It has been found in wet spinning that, for a given shape of spinnerette hole, the fiber shape is most strongly affected by jet stretch and relatively little by the bath concentration and throughput rate. Also determined in the wet-spinning experiment was the maximum jet stretch at which thread breakage occurs. It has been found that the maximum jet stretch decreases as bath concentration is increased.

INTRODUCTION

During the past decade the fiber industry has produced fibers having a variety of cross sections other than circular (so called "shaped fibers"), for instance, elliptical and star-shaped fibers.[1,2] What is most intriguing in making shaped fibers is that a desired shape of fiber can be produced from spinnerette holes whose shape is quite different from that of the fiber itself. As may be surmised, there are many variables which may play an important role in the change of shape of a fiber's cross section.

For instance, it has been known to us that fibers of an elliptical shape having various aspect ratios can be produced from the same rectangular spinnerette hole, by judiciously choosing spinning variables such as jet stretch, bath concentration, etc. In addition, equally as important as, if not more important than, the spinning variables are the rheological properties of the spin dope itself. It has been a well-established fact that fiber-forming materials possess viscoelastic properties and that these are very important in understanding the flow behavior of the material both in the spinnerette holes and just outside them, where much deformation of the elongating threadlines occurs.

Because of the complexity of the problem, a rigorous analysis of the processes involved in producing shaped fibers has not been available in the literature as yet. Therefore, the development of shaped fibers appears to have largely depended on trial and error. Hence, understandably much of the technology in this field has been kept as proprietary information by the various fiber manufacturers.

Recently, Han[3] has presented some interesting experimental observations, which were then used to explain why, for instance, an elliptical fiber can be produced from a rectangular spinnerette hole. Han[3] contended that wall normal stresses, distributed nonuniformly along the long and short sides of the rectangle, can give rise to a nonuniform swelling of extrudate upon its exiting from the spinnerette holes and hence possibly yield an elliptical fiber cross section. It is to be noted that Han's primary concern was to relate the elastic properties of spinnable materials to the change in cross section.

Having realized that very little information is available in the literature on shaped fiber formation, the authors have undertaken an experimental program to investigate, by means of both wet and melt spinning, (1) the effect of shape and size of the spinnerette hole on the shape of extruded filaments and (2) the effects of spinning conditions such as jet stretch and bath concentration on the shape of fibers spun. Representative results from the study are presented and discussed in this paper.

EXPERIMENT

Apparatus

In the wet-spinning experiment, a bench-scale apparatus was used which had been constructed in connection with an earlier study by Han and Segal.[4,5] In the melt-spinning experiment, another bench-scale apparatus was used recently constructed by Han and Lamonte.[6] Details of the apparatuses have been given in papers referred to above,[4,6] but whereas in these earlier studies spinnerettes with circular holes were used, in the present study spinnerettes with noncircular holes were used. Basically, three different hole shapes were used. These were: rectangular holes, trilobal holes, and round holes with lugs. Sketches of the shape and dimensions of the spinnerette holes are given in Figures 1 and 2. These spinnerettes were made by DeGussa in Germany.

With respect to the rectangular holes, two spinnerettes were used: one was a nine-hole spinnerette having an aspect ratio of 3 (0.45 $\times$ 0.15 mm) and another was a seven-hole spinnerette having an aspect ratio of 5 (0.75 $\times$ 0.15 mm). These were used in the wet-spinning experiment in order to see how much the difference in the aspect ratio would affect the fiber shape. Other hole shapes chosen (trilobal holes and round holes with lugs) were used in both wet- and melt-spinning experiments to see how much the difference in hole shape would affect the fiber shape under various spin-

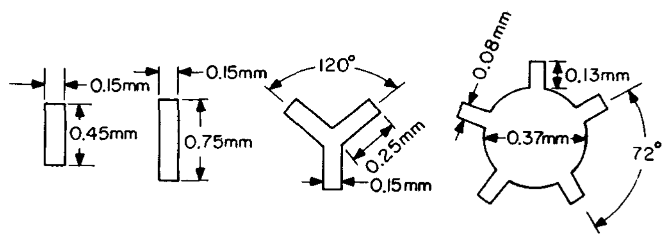

Fig. 1. Sketches of noncircular spinnerette hole shape used for the wet-spinning experiment.

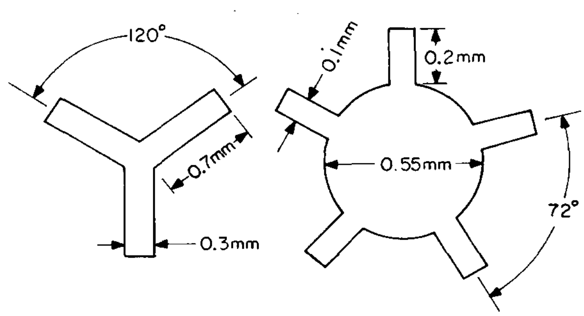

Fig. 2. Sketches of noncircular spinnerette hole shape used for the melt-spinning experiment.

ning conditions. It is known to us that all three types of hole shape used in this study have been used in some commercial spinning.

Materials and Experimental Procedure

The spin dope used for the wet-spinning experiment was an aqueous solution of polyacrylonitrile (PAN) consisting of approximately 10% polymer and 40% sodium thiocyanate (NaSCN). This dope was essentially the same as that used in previous studies by Han and Segal.[4,5] In the spinning experiment, the coagulation bath had aqueous solutions of NaSCN of varying concentrations: 0% (i.e., pure water), 5%, 10%, 15%, 17%, and 20%. Material used for the melt-spinning experiment was polystyrene, which was spun at 200°C.

For each of the bath concentrations in the wet-spinning experiment fiber was spun at various throughput rates (hence the initial velocity, V_0) and stretch rate (hence, take-up velocity, V_L). The throughput rate was varied by means of a Zenith variable-speed metering pump, and the stretch rate, by means of a variable speed take-up roll. For a fixed flow rate and stretch rate (i.e., a fixed stretch ratio), thread tension was measured on a Saxl tensiometer with a 0- to 25-g head. In order to accurately measure thread tension, multihole spinnerettes were used, since the tension per filament is too low to give a high accuracy of the tension measurement.

For each tension measurement, samples of fiber spun were collected. Fiber samples were later cross sectioned into very thin slices using a razor blade, mounted on slides, and examined under a microscope with known magnification. Then, photographs were taken of the fiber cross sections with the aid of a camera attached to the microscope.

RESULTS AND DISCUSSION

Shaped Fiber Formation in Wet Spinning

Thread tension was measured at a point about 50 cm away from the spinnerette face. Plots of tension versus jet stretch at various bath concentrations are given in Figure 3 for a rectangular spinnerette having an aspect ratio of 3, and in Figure 4, for a rectangular spinnerette having an aspect ratio of 5. It is seen in these figures that, for a given bath concentration, tension first increases as jet stretch is increased, and then it tends to level off before thread breakage occurs. Note that the last data point on each curve represents the maximum tension (or the critical value of tension) at which thread breakage occurred.

Another interesting observation that may be made from Figures 3 and 4 is the dependence of tension on bath concentration. That is, tension

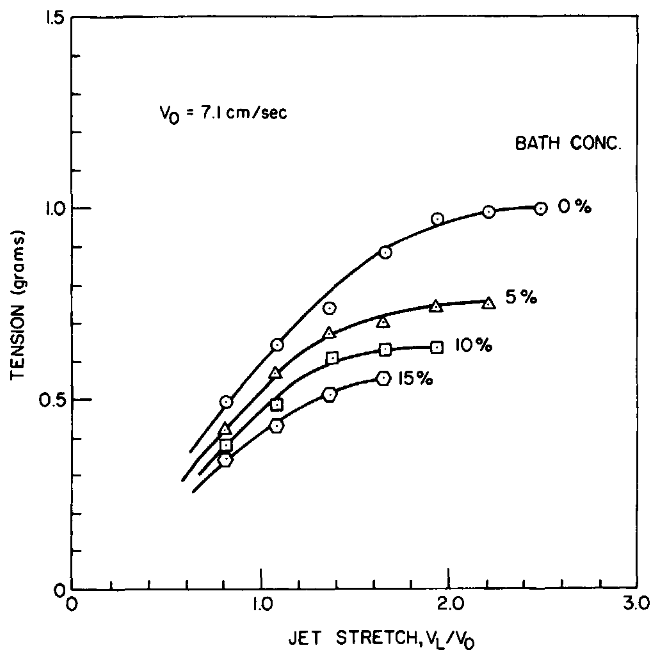

Fig. 3. Tension vs. jet stretch in wet spinning through rectangular holes having an aspect ratio of 3.

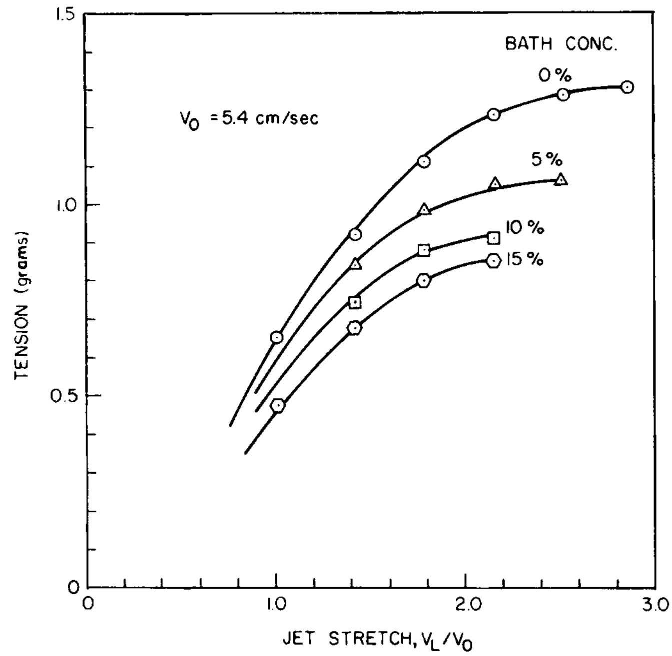

Fig. 4. Tension vs. jet stretch in wet spinning through rectangular holes having an aspect ratio of 5.

decreases as bath concentration is increased. In the experiment with 20% bath concentration, tension was too low to be accurately registered on the tensiometer (i.e., less than 1 g on a 0- to 25-g head). This observed dependence of thread tension on bath concentration is as expected, because the coagulation rate of the fiber spun will be decreased as the bath concentration is increased. Similar observations were made also for other throughput rates (i.e., different values of V_0). However, space limitation here does not permit us to present those results.

In order to observe the effect of bath concentration from a different point of view, plots of maximum tension versus bath concentration are given in Figure 5, and plots of maximum jet stretch versus bath concentration, in Figure 6. Maximum values of the tension and jet stretch are of particular interest to commercial fiber spinning. It is seen in Figures 5 and 6 that both the maximum tension and maximum jet stretch first decrease slowly as bath concentration is increased and then level off as bath concentration is further increased, say, above 15%.

When spinnerettes with trilobal holes and round holes with lugs were used (see Fig. 1), very similar observations were also made, as regards the dependence of jet stretch on thread tension and on bath concentration.

There are three variables which may affect the fiber shape when spun through noncircular spinnerette holes. There are: (1) jet stretch, (2) coagulating bath concentration, and (3) throughput rate. Figure 7 gives

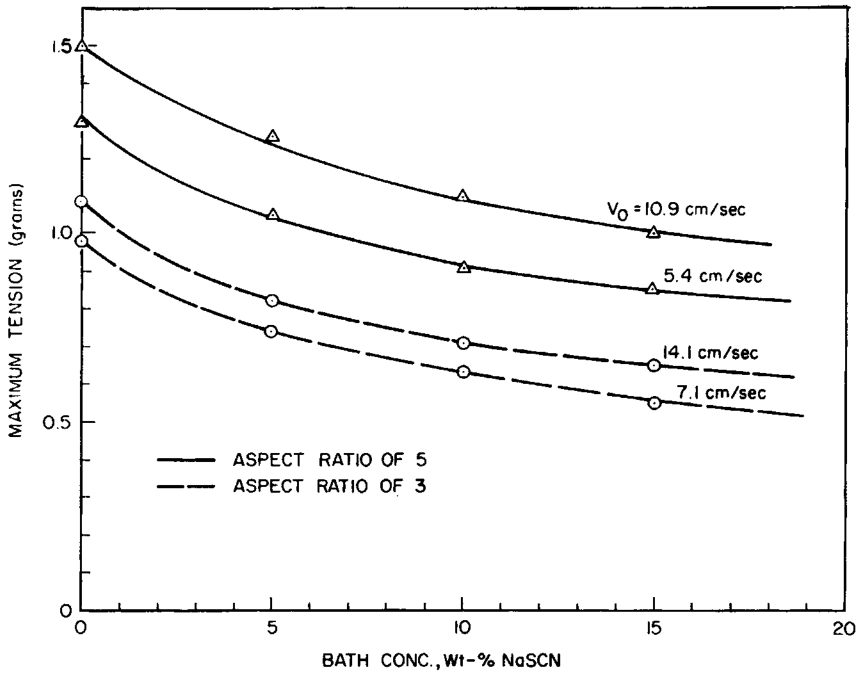

Fig. 5. Maximum tension vs. coagulating bath concentration.

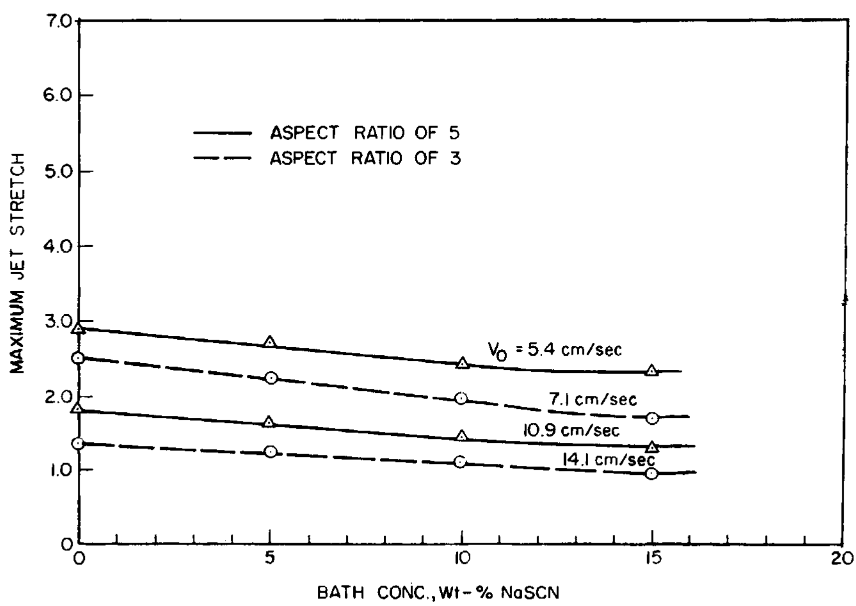

Fig. 6. Maximum jet stretch vs. coagulating bath concentration.

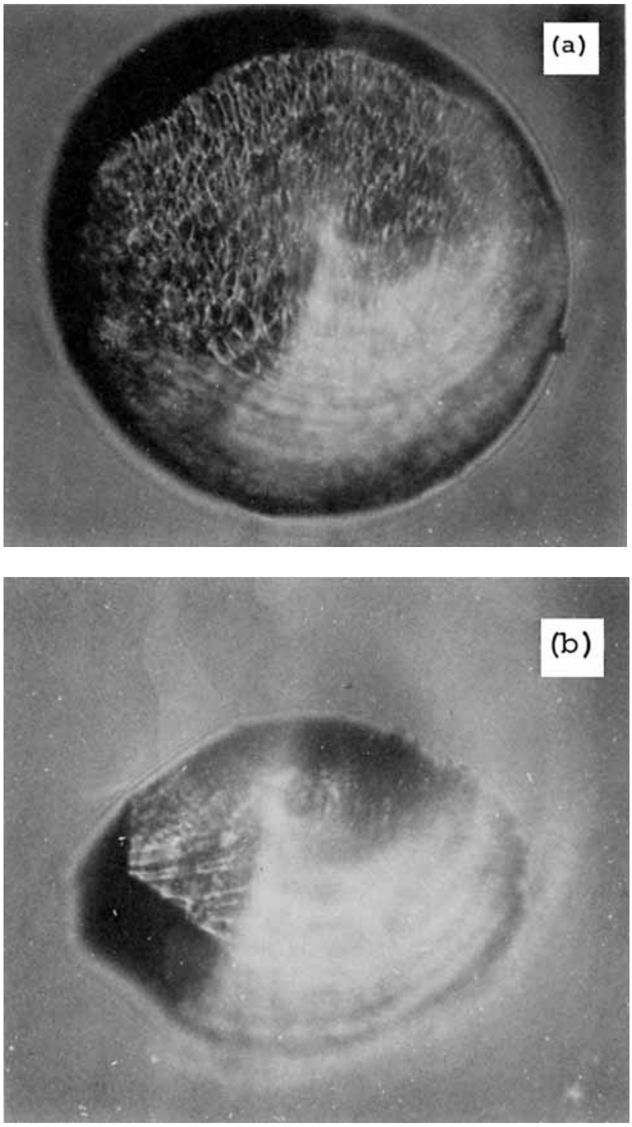

Fig. 7. Shape of fiber wet spun through rectangular holes having an aspect ratio of 5. Spinning conditions: bath concentration = 0% NaSCN (i.e., pure water); (a) $V_L/V_0 = 10.5$; (b) $V_L/V_0 = 20.5$.

pictures of fiber cross section spun through rectangular spinnerette holes having an aspect ratio of 5 (see Fig. 1b) into a water bath, at two different jet stretch ratios. It is seen that even a round fiber has been produced from a rectangular spinnerette hole at low jet stretch ratio and that the jet stretch ratio has a significant effect on fiber shape. Figure 8 gives pictures of fiber cross section spun into a 5% bath concentration, with the same spinnerette as that used in Figure 7. Figures 7 and 8 clearly indicate

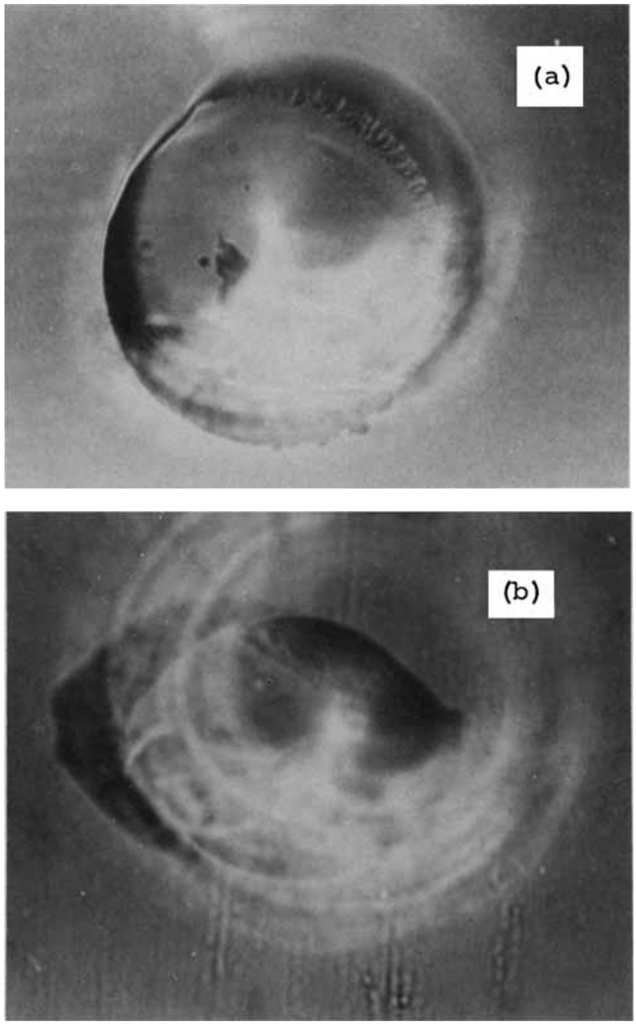

Fig. 8. Shape of fiber wet spun through rectangular holes having an aspect ratio of 5. Spinning conditions: bath concentration = 5% NaSCN; (a) V_L/V_0 = 10.5; (b) V_L/V_0 = 20.5.

that the difference in bath concentration does not affect the fiber shape noticeably. That is, the fiber shape does not resemble the spinnerette hole shape at low jet stretches and is little influenced by the bath concentration, but the resemblance increases as jet stretch increases.

Figure 9 gives pictures of fiber cross section spun through rectangular spinnerette holes having an aspect ratio of 3 (see Fig. 1a) into coagulating baths of 5% and 15% NaSCN, at different jet stretch ratios. Interestingly enough, over the range of jet stretch ratios investigated, the fiber shapes are all circular. In other words, the effect of jet stretch is not noticeable with the spinnerette having an aspect ratio of 3, whereas this was not the

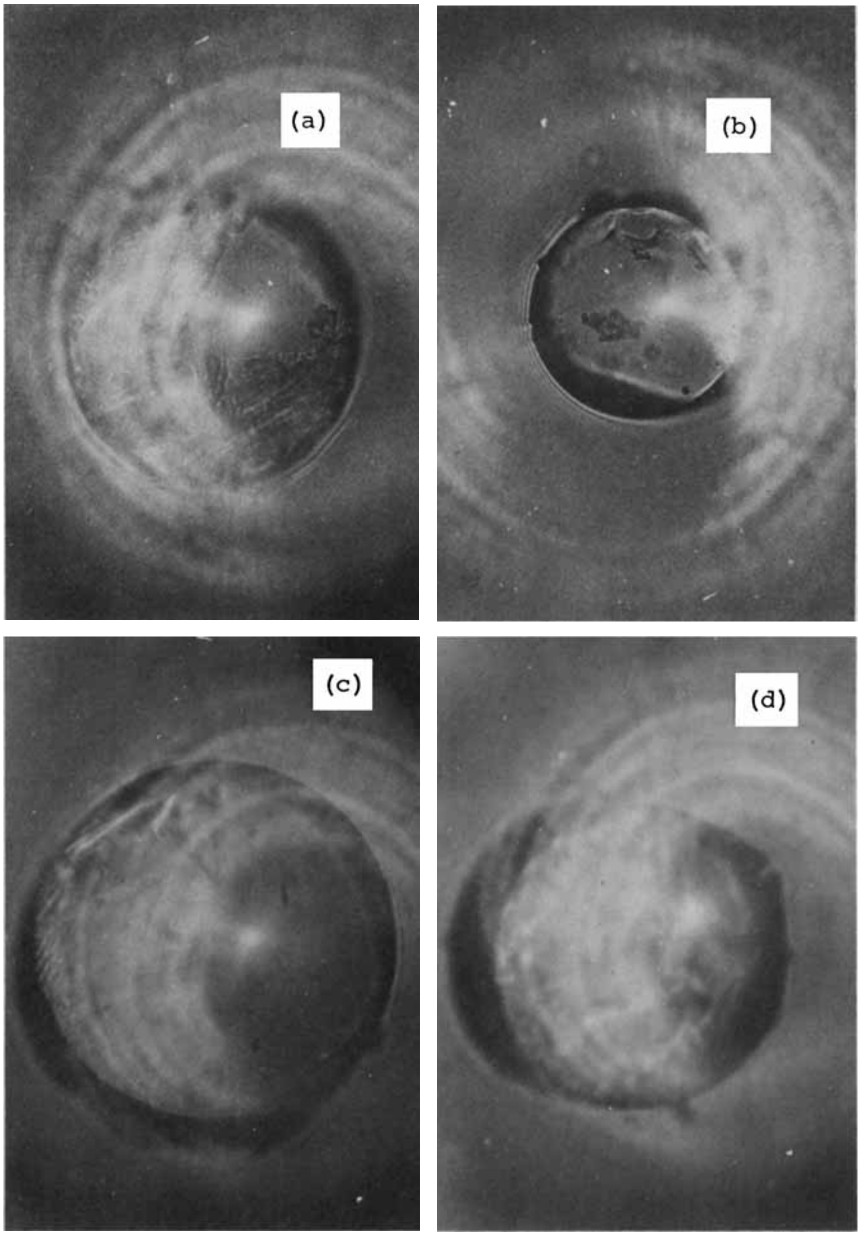

Fig. 9. Shape of fiber wet spun through rectangular holes having an aspect ratio of 3. Spinning conditions: (a) bath concentration = 5% NaSCN, V_L/V_0 = 5.5; (b) bath concentration = 5%, V_L/V_0 = 10.5; (c) bath concentration = 15%, V_L/V_0 = 5.5; (d) bath concentration = 15%, V_L/V_0 = 10.5.

case with the spinnerette having an aspect ratio of 5. This then indicates that when a rectangular hole shape is used, a large aspect ratio is to be chosen in order to produce fibers resembling the spinnerette hole shape. One may argue, however, that, had higher jet stretches been applied than the ones shown in Figure 9 in the spinning experiment with an aspect ratio of 3, fibers resembling the spinnerette hole shape might have been produced. However, as noted above in connection with the tension measurement, it was not possible, in practice, to further increase jet stretch due to the thread breakage.

Therefore, it may be said that in order to produce shaped fibers with a rectangular spinnerette hole, a proper choice of aspect ratio is very important so that, at some reasonably high jet stretch, fiber shape can be maintained resembling the spinnerette hole shape, yet avoiding possible thread breakage. It should be noted, however, that a choice of too large an aspect ratio is rather detrimental to the process because, for a specified fiber denier, an increase in aspect ratio means a decrease in the dimension of the short side of the rectangular hole, which can lead to subsequent thread breakage even at some moderate value of jet stretch. Therefore, there must be some optimum value of aspect ratio which would be most desirable from the processing point of view. Of course, such an optimum value would depend on the rheological properties of a spin dope, and to some extent it may depend on throughput rate, also.

The importance of jet stretch is also worth mentioning from the standpoint of molecular orientation in the fiber. It is a well-known fact that spin dope, which is viscoelastic in general, swells upon exiting from the spinnerette. Swelling of the liquid thread introduces some sort of molecular disorientation just outside the spinnerette face. However, stretching due to the applied tensile force can significantly influence the extent of molecular orientation while the liquid thread swells. In other words, a very high jet stretch can even eliminate the extrudate swell of a fiber, minimizing the chances of having molecular disorientation during swelling. This is an important step for controlling, to a certain extent, the mechanical properties of a finished fiber.

Now, in the use of noncircular spinnerette holes, the swelling behavior of a spun fiber is more complicated than that in circular holes. As recently pointed out by Han,[3] swelling of an extrudate from a rectangular hole, for instance, will be nonuniform, giving rise to most swelling at the center of the long side of the rectangle. Han[3] has attributed it to the nonuniform distribution of wall normal stresses of a spin dope in the spinnerette hole. He also noted that, in wet spinning, the surface tension force between the liquid thread being coagulated and the bath solution can be large enough to predominate over the normal stresses present in the liquid thread while it is being relaxed outside the spinnerette. When this happens, the fiber is still in the liquid state and tends to be circular due to the surface tension force. This appears, then, to explain the pictures shown in Figures 7 through 9.

Note, on the other hand, that at a very high jet stretch, the applied tension can be transmitted through the coagulated fiber in the bath to the liquid thread just outside the spinnerette face. In such an instance, the applied tension tends to overcome the surface tension force, giving rise

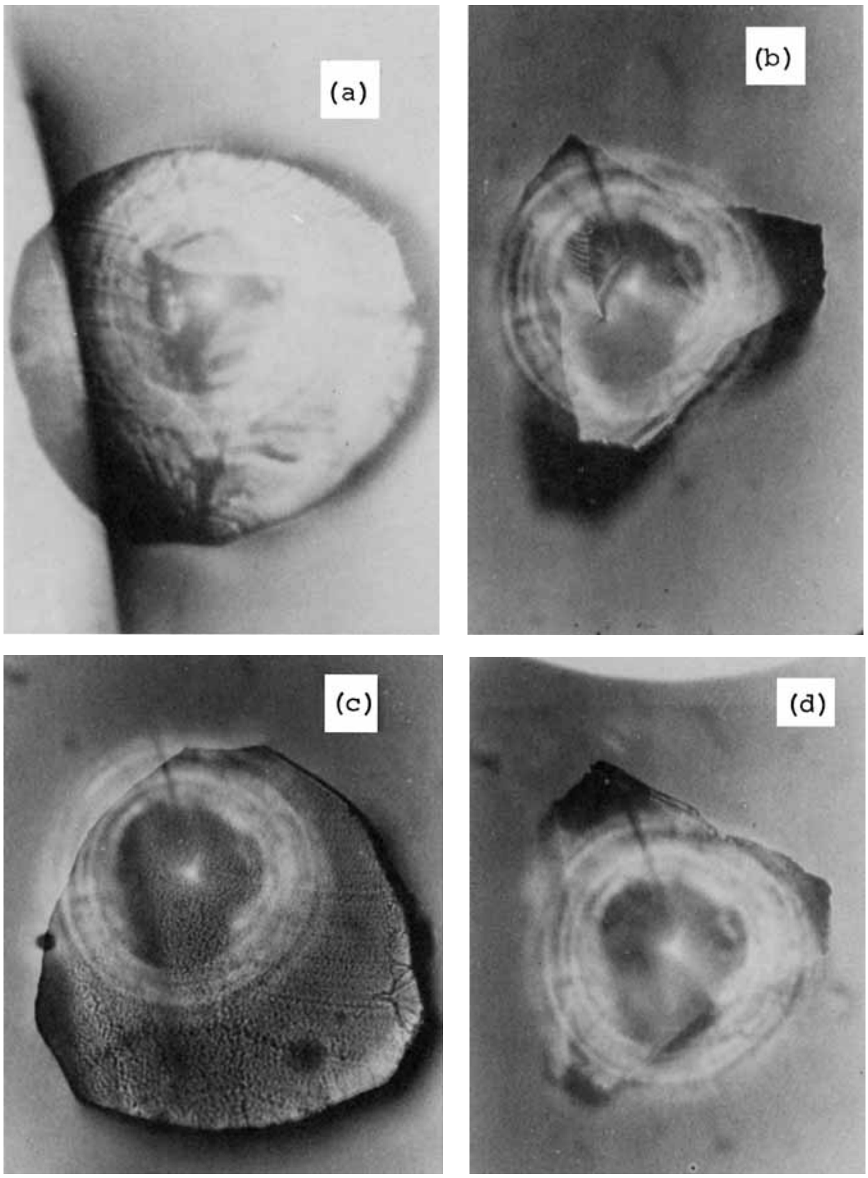

Fig. 10. Shape of fiber wet spun through trilobal holes. Spinning conditions: (a) bath concentration = 0% NaSCN, V_L/V_0 = 5.6; (b) bath concentration = 0% NaSCN, V_L/V_0 = 10.5%; (c) bath concentration = 10% NaSCN, V_L/V_0 = 5.6; (d) bath concentration = 10% NaSCN, V_L/V_0 = 10.5.

to a fiber shape resembling the spinnerette hole shape more closely. This would then explain why fibers spun from the rectangular spinnerette having an aspect ratio of 3 are more round than those spun through the spinnerette having an aspect ratio of 5, because at a comparable jet stretch,

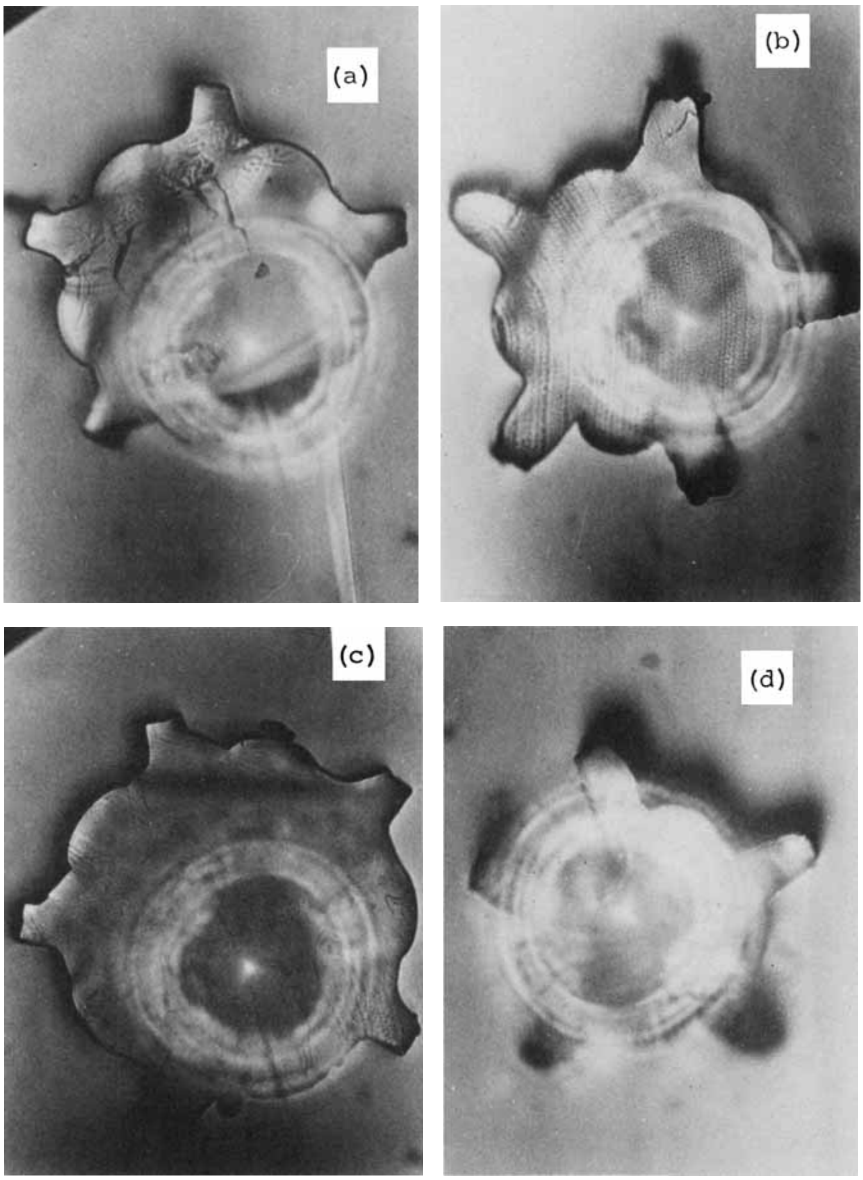

Fig. 11. Shape of fiber wet spun through round holes with lugs. Spinning conditions: (a) bath concentration = 0% NaSCN, V_L/V_0 = 5.6; (b) bath concentration = 0% NaSCN, V_L/V_0 = 10.5; (c) bath concentration = 10% NaSCN, V_L/V_0 = 5.6; (d) bath concentration = 10% NaSCN, V_L/V_0 = 10.5.

the smaller the aspect ratio, the more uniform the wall normal stresses would be and therefore the more readily the surface tension force can make the wet-spun fibers round. Therefore, it can be said that the surface tension force is primarily responsible for the roundness of the wet-spun fiber.

When fibers were spun through trilobal holes and round holes with lugs, it was found that the fiber shape also resembled the spinnerette hole shape more closely as jet stretch increased, being little influenced by the bath concentration. Some representative results are given in Figure 10 for fibers spun through trilobal holes and in Figure 11 for fibers spun through round holes with lugs.

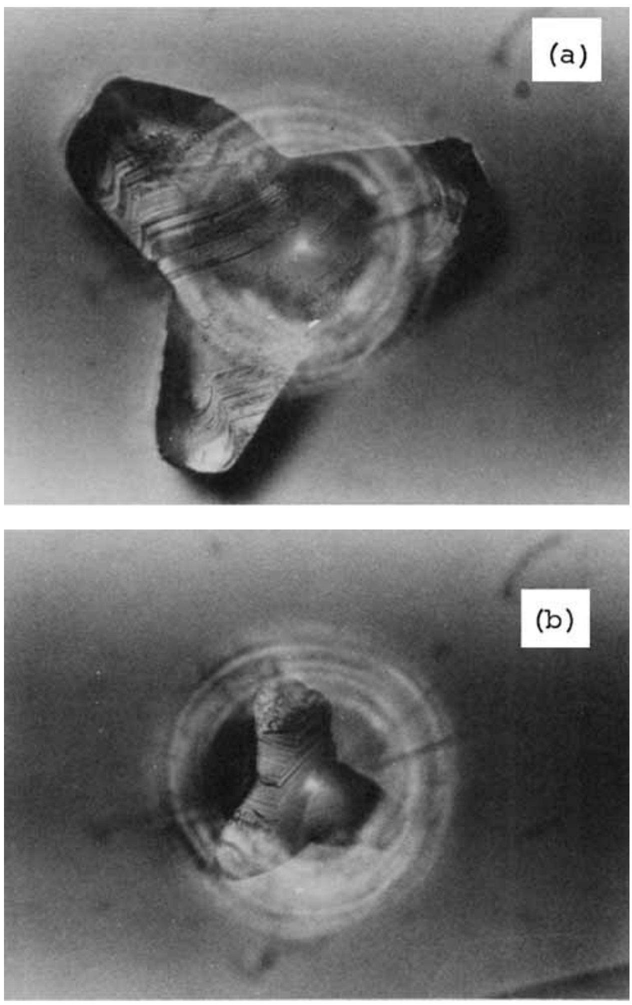

Fig. 12. Shape of fiber melt spun through trilobal holes. Spinning conditions: (a) $V_L/V_0 = 10.6$; (b) $V_L/V_0 = 30.5$.

Shaped Fiber Formation in Melt Spinning

Polystyrene was melt spun at 200°C through trilobal holes and round holes with lugs, vertically downward into ambient air, at various stretch rates. Some representative results of the fiber shape are given in Figure 12 for fibers spun through trilobal holes and in Figure 13, for round holes with lugs.

It is seen in Figures 12 and 13 that, unlike in wet spinning, the fiber shape in melt spinning is little influenced by stretch rate, although the cross-sectional area of the filaments gets smaller as the stretch rate is in-

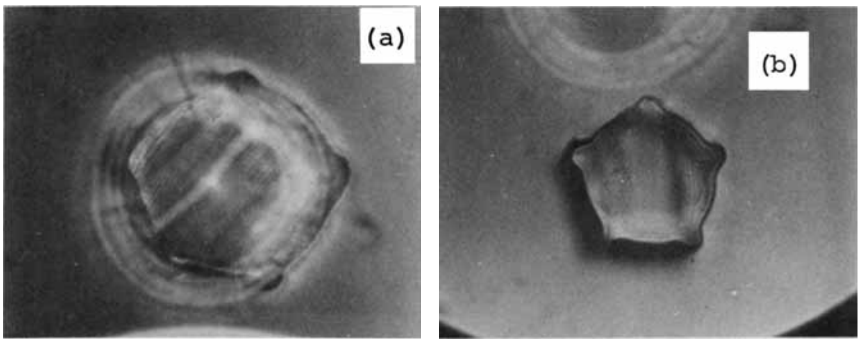

Fig. 13. Shape of fiber melt spun through round holes with lugs. Spinning conditions: (a) $V_L/V_0 = 10.6$; (b) $V_L/V_0 = 40.5$.

creased. In other words, the fiber shape resembles the spinnerette hole shape very much, being little influenced by stretch rate. Furthermore, it should be noted that the corners of the melt-spun fibers are hardly rounded. This is attributable to the large values of the normal stresses predominating over the surface tension force present in the molten filaments.

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