Studies on High-Speed Melt Spinning of Noncircular Cross-Section Fibers. II. On-Line Measurement of the Spin Line, Including Change in Cross-Sectional Shape

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ABSTRACT: On-line measurement was performed in the high-speed spinning of flat, hollow, and circular fibers of poly(ethylene terephthalate), paying particular attention to the change in cross-sectional shape along the spin line. The diameter profiles of hollow and circular fibers were essentially identical, whereas the deformation of flat fiber shifted to the region closer to the spinneret. The necklike deformation of hollow and circular fibers started at the takeup velocity of 5 km/min. In the case of flat fibers, presence of the necklike deformation was confirmed at 4 km/min, and extremely steep diameter attenuation was observed at 5 km/min. The spin-line tension of the flat fiber was also larger than that of circular fibers. Combined measurements of fiber velocity and thickness enabled us to evaluate the aspect ratio of the flat fiber and hollow ratio of the hollow fiber in the spin line. These two factors were found to decrease steeply near the spinneret. Accordingly, the thinning of the spin line and the change in cross-sectional shape appeared to proceed independently. © 2001 John Wiley & Sons, Inc. J Appl Polym Sci 80: 1582–1588, 2001

Key words: poly(ethylene terephthalate); melt spinning; noncircular fiber; on-line measurement

INTRODUCTION

In the high-speed melt-spinning process, fiber structure development through the molecular orientation and orientation-induced crystallization occurs along with the formation of the shape of fibers. The mechanism of shape and structure formation can be clarified through the on-line measurement of the spin line at various distances from the spinneret. Observation of the high-speed spin line, however, is quite difficult because of the fineness of the running filament and the fluctuation of its position. Therefore, many experimental techniques have been developed for the on-line measurement of the spinning behavior.

It is well known that abrupt diameter attenuation, i.e., necklike deformation, occurs in the high-speed spin line. This phenomenon was first reported by G. Perez, who captured poly(ethylene terephthalate) (PET) fibers from the spin line and measured their diameter under an optical microscope.[1] On-line measurement of the diameter profile of high-speed spin line was first conducted by Shimizu et al.[2] using a back-illumination diameter monitor. Experimental techniques for on-line measurement of the detailed shape of necklike deformation have also been developed, and it was confirmed that the elongational strain rate at the necklike deformation reaches several tens of re-

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ciprocal milliseconds.[3,4] Velocity and temperature of the spin line were also measured using a laser doppler velocimeter[5,6] and infrared (IR) radiation gauge,[7,8] respectively. More recently, on-line measurement of the birefringence development was accomplished paying particular attention to the birefringence development in the necklike deformation.[9]

In the steady-state spinning of circular fibers, fiber diameter and velocity can be converted using the equation of continuity. If the density of the spin line is assumed to be constant, fiber velocity is inversely proportional to its cross-sectional area. The same principle can be applied to the steady-state spinning of noncircular fibers; however, direct on-line measurement of the cross-sectional area is difficult. Another important feature in the melt-spinning process of noncircular fibers is that the shape of the nozzle hole cannot be transferred to the cross-sectional shape of as-spun fibers. Investigation of the mechanism of the deformation of cross-sectional shape is an important subject for the production of fibers with designed shape. Change of the cross-sectional shape along the spin line was analyzed by Kim and colleagues[10,11] through the observation of fiber samples captured from the spin line. It should be realized, however, that the cross-sectional shape changes easily during the course of fiber sampling.

This study conducted on-line measurement of the fiber velocity and thickness of the spin line of flat and hollow fibers and analyzed the change of cross-sectional shape along the spin line.

EXPERIMENTAL

Melt Spinning

The polymer materials used for the high-speed melt spinning was the PET chip kindly supplied by Teijin Ltd. A slit nozzle with width and gap of 4.3 and 0.1 mm was used for the preparation of flat fibers. The spinneret for the hollow fibers had three arc slits. The slits have a gap of 0.15 mm and are arranged on a 2-mm-diameter circle. The polymer melt extruded from these slits connected each immediately below the spinneret and formed a hollow fiber. The details of the spinning conditions are described in the previous article.

On-line Measurement

A laser doppler velocimeter (TSI, LS50) was used to evaluate the change of fiber velocity along the spin line. The use of the polymer containing titanium oxide facilitated the higher efficiency of data acquisition. A short scan time of 1 ms was adopted for the measurement, as extreme data fluctuation was expected for the region in which the necklike deformation occurs. The measurement was performed at 10–210 cm below the spinneret, with an interval of 10 cm. The velocity versus frequency histogram was prepared from the acquired 2000 data. The mean velocity for each position was calculated from the histogram.

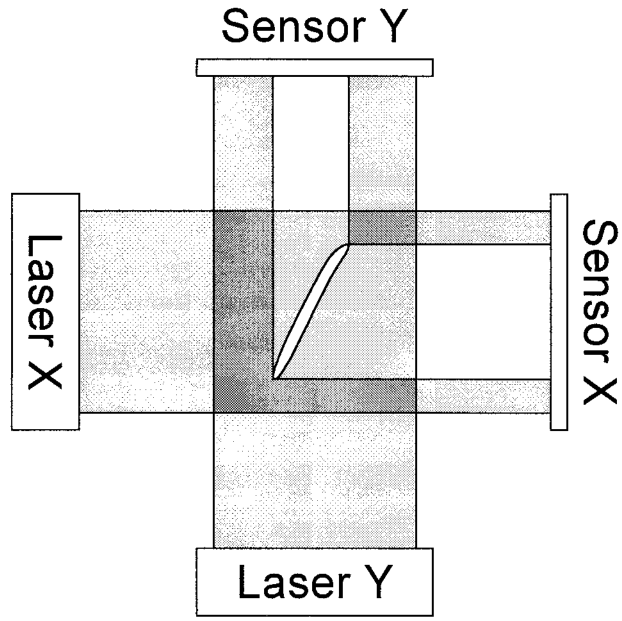

Figure 1 Schematic diagram of two-dimensional diameter monitor.

Two types of diameter monitor were used to measure thickness along the spin line. A two-dimensional diameter monitor (TSI, Holix GAGE XY5007) was used for the on-line measurement of the long-axis length of flat fibers. The diameter monitor has two sets of perpendicularly aligned optical systems designed to measure fiber thickness, as shown in Figure 1. The projection lengths of the cross-sectional shape in Cartesian coordinates X and Y can be obtained using this measuring device. A back-illumination diameter monitor (Zimmer OHG, model 460 A/10) was used to measure the outer diameter of the hollow fibers.

Tension of the spin line was measured using a three-point-bending tension meter (Eiko Sokki RF4000D) equipped with air-bearing rollers. The measurement was performed for the solidified part of the spin line, i.e., from 210 to 270 cm below the spinneret, with an interval of 10 cm.

Characterization of Cross-sectional Shape

The cross-sectional area of the spin line A was calculated from the measured velocity V using the equation of continuity:

$$A = \frac{W}{\rho V} \tag{1}$$

where W is the throughput rate and ρ the density of polymer.

If the cross-sectional shape of the spin line of flat fibers is assumed to be rectangular, the cross-sectional area can be given by

$$A = lt \tag{2}$$

where l and t are the lengths of long and short axes of the rectangular shape. Also, if the long axis is sufficiently longer than the short axis, the long-axis length of the rectangular cross section can be approximated by the following equation:

$$l = \sqrt{X^2 + Y^2} \tag{3}$$

The parameters for the cross-sectional shape of rectangular fiber, l and t, were calculated using eqs. (1), (2), and (3). The aspect ratio l/t was adopted as a characteristic parameter describing the cross-sectional shape of flat fibers.

To confirm the validity of eq. (3), an as-spun flat fiber with an aspect ratio of ~ 10 was rotated in the two-dimensional diameter monitor, and the change of output signals was recorded as shown in Figure 2. Even though two signals measured from two different directions varied with the rotation of the fiber, the long-axis length calculated using eq. (3), also shown in Figure 2, was not affected by the rotation. Therefore, it was confirmed that the long-axis length of flat fiber in the spin line can be evaluated regardless of the rotation angle of the fiber.

The cross-sectional area of the hollow fiber can be described as follows:

$$A = \frac{\pi}{4}(D_o^2 - D_i^2) \tag{4}$$

where D_o and D_i are the outer and inner diameters of the hollow fiber. Using the result of velocity measurement, the inner diameter D_i was calculated from eqs. (1) and (4). The hollow ratio $(D_i/D_o)^2$ was adopted for characterization of the shape of hollow fibers.

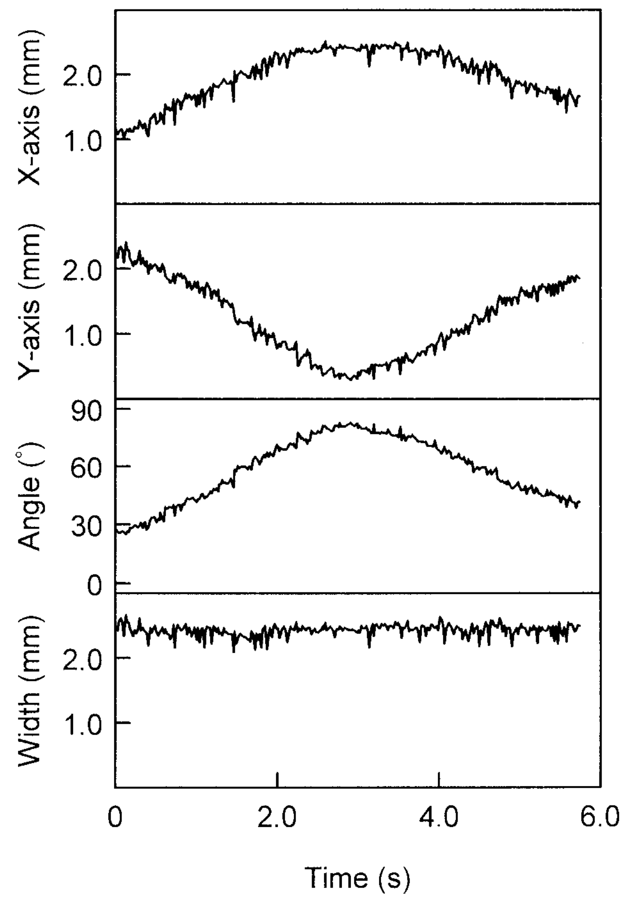

Figure 2 Change of output signal from two-dimensional diameter monitor with rotation of flat fiber. Calculated rotation angle and fiber width are also plotted.

In the measurement of the outer diameter of the hollow fibers using the back-illumination diameter monitor, the variation of inner diameter possibly affects the measured value, as the incident laser light can pass through the center part of the fiber despite its circular shape. Therefore, off-line diameter measurements of the hollow fibers with a hollow ratio of 0.2–0.4 and solid circular fibers were conducted. The output signal was plotted against the outer diameter measured with an optical microscope as shown in Figure 3. Regardless of the change in hollow ratio, the output signals for the hollow fibers and circular fibers are on the same straight line, which passes through the origin. Therefore, it was confirmed that the diameter monitor can provide the signal on the outer diameter of hollow fibers despite the back-illumination principle. The use of polymer

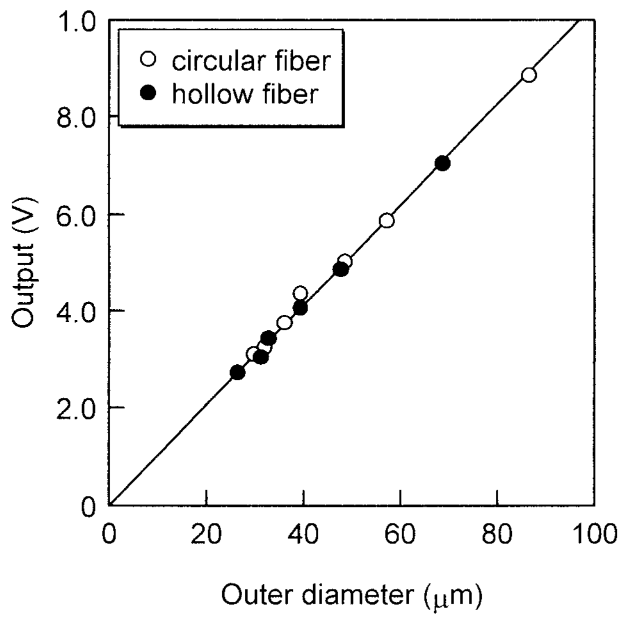

Figure 3 Calibration of output signal from diameter monitor against outer diameter of circular and hollow fibers measured using optical microscope.

containing titanium oxide might have prevented the transmission of light at the center of the fiber.

Measurements designed to characterize the cross-sectional shape of noncircular fibers were performed only at the takeup velocity of 1 km/min, as it was found in the previous article[12] that the takeup velocity does not have a significant effect on the cross-sectional shape of the as-spun noncircular fibers.

RESULTS AND DISCUSSION

Velocity and Tension Profiles

Velocity profiles of flat, hollow, and circular fibers in the spin line are presented in Figure 4. The diameter profiles of hollow and circular fibers were found to be essentially identical within a range of experimental error. By contrast, deformation of the flat fiber spin line shifted to the region closer to the spinneret. This result indicates that cooling of the spin line was enhanced by the change in cross-sectional shape from circular to flat. In both the flat and hollow fibers, necklike deformation was observed in the high-speed region, as in the case of circular fibers. The necklike deformation of hollow and circular fibers started at 5 km/min, with both fibers exhibiting similar deformation behavior. In the case of flat fibers, however, the necklike deformation was found to start at 4 km/min. At 5 km/min, the position of necklike deformation shifted closer to the spinneret, and an extremely steep velocity increase was observed. It has been reported that the necklike deformation usually accompanies orientation-induced crystallization during the spinning process.[13] In the previous article, we reported that the edge of the flat fiber began to crystallize at 4 km/min, whereas crystallization of the hollow and circular fibers began at 5 km/min.

The results of the tension measurement for the flat and circular fibers are shown in Figure 5. After solidification of the spin line, tension is known to increase linearly with an increase in the distance from the spinneret. The slope corresponds to the accumulation of the air-friction force along the spin line. In comparison with the result for the circular fibers, the rectangular fiber

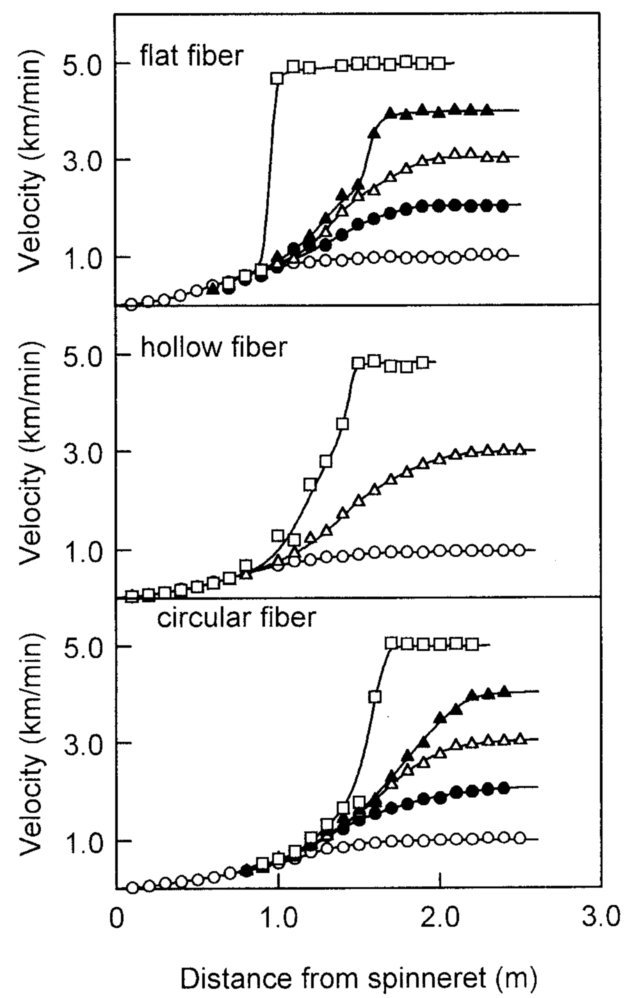

Figure 4 Velocity profiles of flat, hollow, and circular fibers in the spin line.

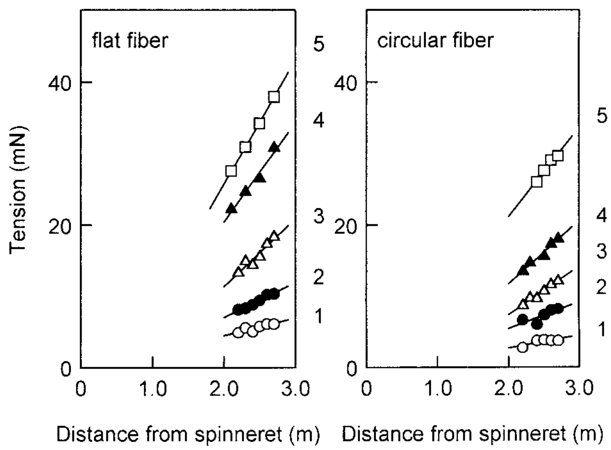

Figure 5 Change of spin-line tension along spin line of flat and circular fibers. Takeup velocity (km/min) indicated.

showed a significantly larger value. The slope also was larger in the case of flat fibers, indicating that a larger air-friction force was acting on the spin line of flat fibers.

The enhancement of cooling and air friction for flat fibers is probably attributable to the larger surface area per unit volume of the material. Even though the outer surface area of the hollow fiber is larger than that of the circular fiber, because of inclusion of air in the center, the hollow ratio of < 0.2, observed in the previous article, corresponds to the increased surface area of less than 10%. In addition, empirical equations for the melt-spinning process suggest that the cooling and air-friction effects vary with 0.3–0.4 power of the fiber diameter.[13] Therefore, a 10% increase in fiber diameter corresponds to only 2% increased cooling and air-friction efficiency. This is the reason for almost identical thinning and air-friction behavior of the hollow and circular fibers.

By contrast, the surface area of the flat fibers is more than two times larger than that of the circular fibers. Furthermore, the change in cross-sectional shape from circular to rectangular with a high aspect ratio may yield some additional effects for the enhancement of cooling and air friction.

In the previous paper, we reported that there was no meaningful effect of the change in the cross-sectional shape on the development of fiber structure in as-spun fibers in all the takeup velocity range examined. With regard to measured velocity and tension profiles, however, the spinning behavior of the flat fiber is substantially different from that of hollow and circular fibers. Considering that the structure formation is basically controlled by the elongational stress applied at the solidification of the spin line, these two results suggest that the effects for the enhancement of cooling and air friction cancel each other and that the stress at the solidification position eventually became similar despite the significant difference in the cross-sectional shape of the fibers.

Cross-sectional Shape

Variations in the cross-sectional shape of flat and hollow fibers along the spin line are presented in Figures 6 and 7. The measured velocity and thickness (i.e., long-axis length for the flat fibers and outer diameter for the hollow fibers) are plotted in the graph at the top. Characteristic parameters describing the cross-sectional shape of the noncircular fibers (i.e., the aspect ratio for flat fibers and the hollow ratio for hollow fibers) are plotted against the distance from the spinneret in the graph at the bottom.

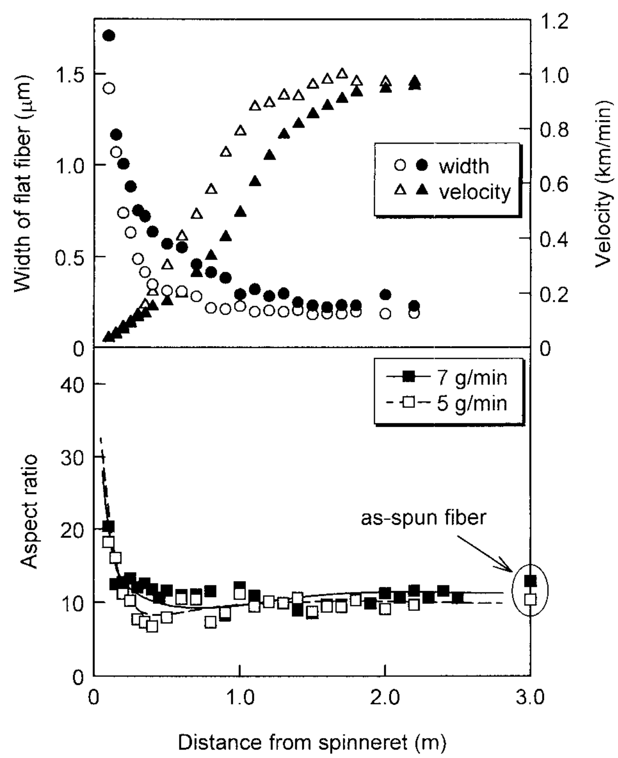

Figure 6 Measured velocity and width profiles of flat fiber spin line. Aspect ratio calculated from measured values are also shown. Open marks (○, △, □) and closed marks (●, ▲, ■) are for throughput rate of 5 and 7 g/min, respectively.

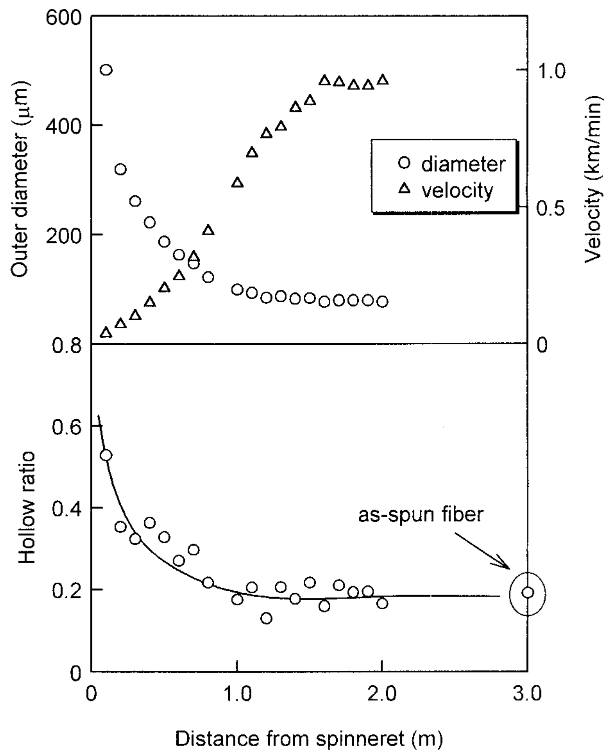

Figure 7 Measured outer diameter and velocity profiles of hollow fiber spin line. Hollow ratios calculated from measured values also shown.

In both cases, the thickness of the spin line more steeply decreased near the spinneret than the increase in spin-line velocity. Accordingly, aspect ratio and hollow ratio decreased steeply near the spinneret and settled to a constant value before the fiber reached 50 cm from the spinneret, in the case of flat fibers, and 100 cm in the case of hollow fibers. The characteristic parameters measured in the down stream of the spin line were in fair agreement with those from off-line observation under a microscope. The slightly lower aspect ratio compared with the off-line data for the flat fibers may be due to the warping of the flat shape in the spin line.

It is interesting to note that the thinning behavior of the spin line and the change in cross-sectional shape appear to proceed independently. The maximum strain rate was achieved at ~ 90 and 130 cm in the flat and hollow fiber spin lines, respectively. The change in cross-sectional shape occurred in the region much closer to the spinneret. The increased throughput rate yielded a slightly higher characteristic parameter for the cross-sectional shape. At the same time, change of cross-sectional shape continues to a position slightly farther from the spinneret. This result indicates that the change in cross-sectional shape is strongly affected by the temperature (i.e., viscosity) of the spin line. Because the change in cross-sectional shape proceeds toward a circular shape and is strongly affected by temperature, it can be concluded that the major factor responsible for the change in cross-sectional shape is the surface tension and the key factor in preventing the change is the viscosity.

It should be noted that there is a slight indication of an increase in aspect ratio at ~ 80 cm. In the film process, aspect ratio increases extrusion in the process of draw down because the center of the film is elongated in the mode of planar elongation.[14] If the same mechanism can be applied to flat fibers, an increase in the aspect ratio can occur in the spin line, as suggested by Kim and colleagues.[10]

CONCLUSIONS

The diameter profiles of hollow and circular fibers were essentially identical because of the small hollow ratio and small effect of the change in outer diameter on cooling and air-friction behaviors. The deformation of flat fiber shifted to the region closer to the spinneret because of the enhanced spin-line cooling. The necklike deformation of hollow and circular fibers was found to start at a takeup velocity of 5 km/min, whereas the presence of the necklike deformation was confirmed at 4 km/min; extremely steep diameter attenuation was observed at 5 km/min in the case of flat fiber spinning. Air-friction force acting on the spin line of the flat fibers was found to be larger than that of circular fibers. Changes in the aspect ratio of the flat fibers and the hollow ratio of the hollow fibers along the spin line could be evaluated by combining the fiber velocity and thickness data. These two factors decreased steeply near the spinneret, and the thinning of the spin line and the change in cross-sectional shape appeared to proceed independently. It was concluded that the major factor forwarding the change in cross-sectional shape is the surface tension and that preventing the change is the viscosity.

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