Influence of the Cross-Sectional Shape on the Structure and Properties of Polyester Fibers

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ABSTRACT: The effects of the fiber cross-sectional shape on the structure and properties of polyester fibers were investigated. Fully drawn yarn (FDY) polyester fibers (167 dtex and 48 filaments) were produced under the same spinning conditions used in a spinning plant. The only difference between the fibers was their cross-sectional shapes. Four different cross-sectional shapes were chosen for the experimental work: round, hollow-round, trilobal, and hollow-trilobal. The crystallinity and values of the maximum stress, maximum strain, modulus, yield stress, shrinkage in boiling water, and unevenness of the fibers were determined. The difference in the cross-sectional shapes influenced the modulus, maximum strain, yield stress, and shrinkage in boiling water. No effects on the crystallinity and maximum stress were observed. The results suggested that the hollow fibers had higher amorphous orientation than the full fibers. The hollow-round fiber had the highest unevenness value. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 103: 2615–2621, 2007

Key words: crystallization; fibers; mechanical properties; polyesters

INTRODUCTION

The cross-sectional shape is one of the most important morphological features of fibers. Today, a round fiber cross section is the most common shape manufactured by synthetic-fiber producers. However, in fiber applications, a round cross section is not always preferred.

The development of melt-spun fibers with noncircular cross sections started in the 1960s. The first attempt was to mimic the gloss of expensive silk fibers by changing the cross section to a trilobal shape. Since then, various types of noncircular fibers have been developed to add functionality and aesthetics to synthetic fibers. At present, the trilobal cross section is the most widely used for silklike fabrics.[1,2]

The cross section of a synthetic fiber that is produced by the melt-spinning method can be easily varied by changes in the spinneret hole shape.[3] Fibers with a noncircular cross-sectional shape show properties different from those of fibers with a circular cross-sectional shape, including the bending stiffness, coefficient of friction, softness, luster, comfort, pilling, bulkiness, handle, and performance.[4–6]

Hollow fibers produced in various geometries such as circles, triangles, trilobals, and squares are examples of simple, noncircular fibers. They are widely used for reverse osmosis, hemodialysis, gas separation, microfiltration, pervaporation, water-cleaning systems, and the fabrication of cushions, carpets, and garments.[7,8] The difference between the spinning processes of hollow fibers and round fibers is due to an additional dimensional variable (inner radius).[6,9] Compared with ordinary fibers of the same linear density, hollow fibers are stiffer, bulkier, warmer because of the inclusion of air, and more resistant to bending and have a more opaque appearance caused by the diffused reflection of light.[10,11]

The spinning behavior can change significantly if the cross-sectional shape of the nozzle is varied because heat-transfer and air-friction effects for the noncircular cross-sectional fibers are not the same as those for circular fibers. These effects may lead to the alteration of the structure and properties of as-spun fibers.[1,12]

The research performed on fiber cross-sectional shapes has generally been focused on the melt-spinning process. Among the numerous publications concerning hollow fibers, only a small number of theoretical investigations[9] can be found. Most of the reports have been supported by experimental investigations. Most of the publications[6–9,12,13] concerning hollow fibers have included hollow-round polypropylene fibers. Numerous researchers[1,6,7,11,13,14] have used a three- or four-segmented arc-type die in their studies. Others[8,12] have used an annular die with a system injecting fluid into the inner core.

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TABLE I
Properties of the PET Polymer and Chips

Inherent viscosity of the dry chips	0.641 dL/g
Moisture of the dry chips	40 ppm
Freefall viscosity	0.627 dL/g
Carboxyl end groups	37.8 mmol/kg
Density of the polymer melt	1.18 g/cm^3
Density of the chips	1.38 g/cm^3
Melting temperature of the polymer	260°C
Molecular weight of the polymer	20,000 g/mol
Weight of TiO_2	0.3%

Beyreuther and Hofmann[15] presented comments on the experimental values of the wall thickness of hollow poly(ethylene terephthalate) (PET) fibers. Oh et al.,[6] who compared the numerical simulation of dimensional changes with experimental results, simulated the dynamics of the spinning process of hollow polypropylene fibers with a finite element method. Lee et al.[13] investigated the hollowness of polypropylene fibers in a continuous drawing process. Rovere and Shambaugh[8] modeled the hollow-fiber-formation process with momentum, energy, and continuity equations. In their study, the results were compared with online measurements of the outside diameters of hollow polypropylene fibers. Takarada et al.[1] investigated the effect of changes in the cross-sectional shapes on the structure and properties of PET fibers. They produced flat and hollow fibers and compared their structures with those of circular fibers. Rwei,[7] who used circular and triangular spinnerets for producing hollow fibers, reported the effect of die swelling on the formation of hollow polypropylene and poly(butylenes terephthalate) fibers. Takarada et al.[14] performed online measurements of the fiber velocity and thickness of the spin line of flat, hollow, and circular PET fibers. Rovere et al.[12] compared the mechanical and thermal properties of hollow polypropylene fibers with those of solid ones. Petrulis[9] studied a mathematical model and some theoretical relations for the structural properties of hollow polyamide and polypropylene fibers and compared them with solid ones. Oh[11] studied dimensional changes and profile development of hollow PET fibers, changing the spinning variables through a finite element method and experimentation.

This article reports the results for round and trilobal fibers produced in both full and hollow forms and presents experimental results comparing full and hollow cross sections. The publications found in the literature were mostly focused on the hollow-round cross-sectional shape. The hollow-trilobal cross-sectional shape was not fully studied. Also, in most of the publications, the properties of hollow fibers were not compared with those of the full fibers produced under the same spinning conditions

This work includes not only round cross-sectional shapes but also trilobal cross-sectional shapes. Round, trilobal, hollow-round, and hollow-trilobal fibers were produced by the melt spinning of PET, and the effect of the change in the fiber cross-sectional shape on the structure and physical properties of the produced fibers was investigated.

EXPERIMENTAL

The polymeric material used for the melt-spinning process was semidull PET chips. The properties of the PET polymer and chips used in this work are presented in Table I.

Four types of spinnerets were prepared to obtain different cross sections. Two spinnerets were for the full fibers, with the nozzle holes having round and trilobal shapes. The other two were for the hollow fibers, and the nozzle holes also consisted of round and trilobal shapes. The nozzle holes in the spinnerets that were designed for hollow-round fibers had three segmented arc slits, and those for hollow-trilobal fibers had three segmented V-type slits. The cross-sectional shapes of the nozzle holes in each spinneret are illustrated in Figure 1.

There are factors such as the viscosity, mass throughput rate, spinning temperature, take-up speed, and quenching conditions that affect the final pro-

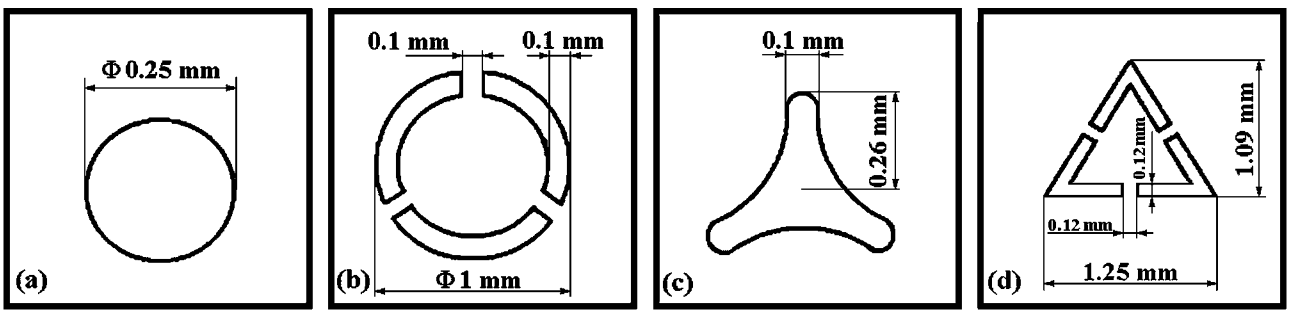

Figure 1 Cross-sectional shapes of the nozzle holes in the spinnerets: (a) round, (b) hollow and round, (c) trilobal, and (d) hollow-trilobal.

TABLE II
Melt-Spinning Conditions

Spinning pressure	150 bar
Spinning temperature	286°C
Mass throughput rate	91.85 g/min
Quench air speed	0.55 m/s
Quench air temperature	22°C
Temperature of godets (entrance/exit)	80/130°C
Draw ratio between godets	1.5
Take-up speed	5500 m/min
Pressure at intermingling	3.5 bar
Quantity of intermingling	14–15 n/m
Spin length	85 cm

perties of melt-spun fibers. Some researchers[1,6,8,11,12] have investigated the effects of various processing parameters. In this article, only the effect of the fiber cross-sectional shape is evaluated, and all other variables were kept constant in the production line. In other words, we consider hollow and full fibers with a constant cross-sectional area. This approach means that the polymer throughput and take-up speed were constant for each sample. For all the fibers, the melt-spinning-process conditions are presented in Table II.

The Fully drawn yarn (FDY) polyester fibers (167 dtex and 48 filaments) were produced by the extrusion of polymer chips from the orifices of the special spinnerets with four different cross-sectional shapes under the same melt-spinning conditions. The photographs of the cross-sectional shapes of the produced fibers taken by a JEOL model 840 scanning electron microscope (Japan) are presented in Figure 2.

The crystallinity and some physical properties such as the maximum stress, maximum strain, modulus, yield stress, unevenness, and shrinkage in boiling water were measured to study the influence of the cross-sectional shape on the fiber structure and properties. All the measurements, except shrinkage in boiling water, were carried out under standard

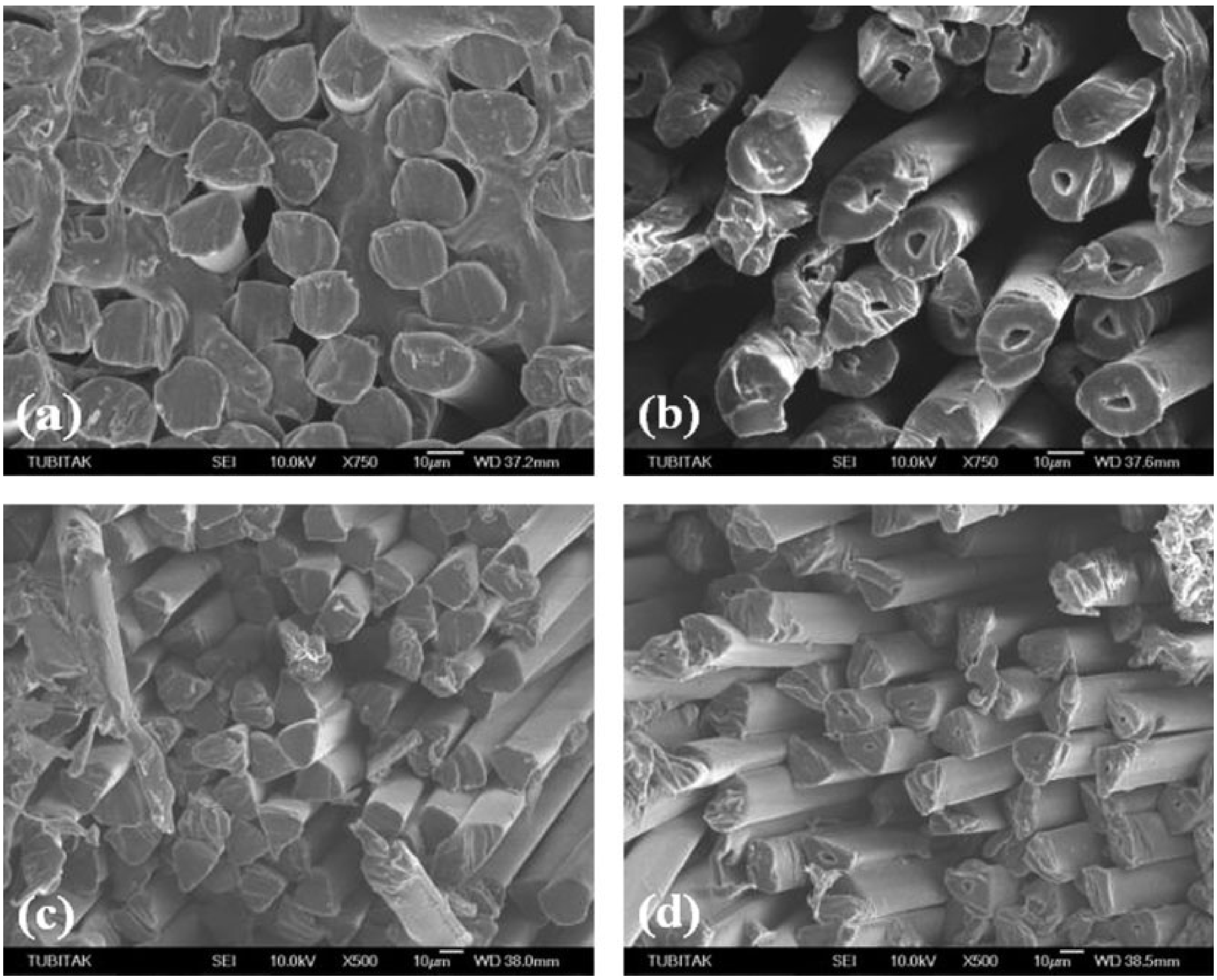

Figure 2 Cross-sectional shapes of the fibers: (a) round, (b) hollow-round, (c) trilobal, and (d) hollow-trilobal.

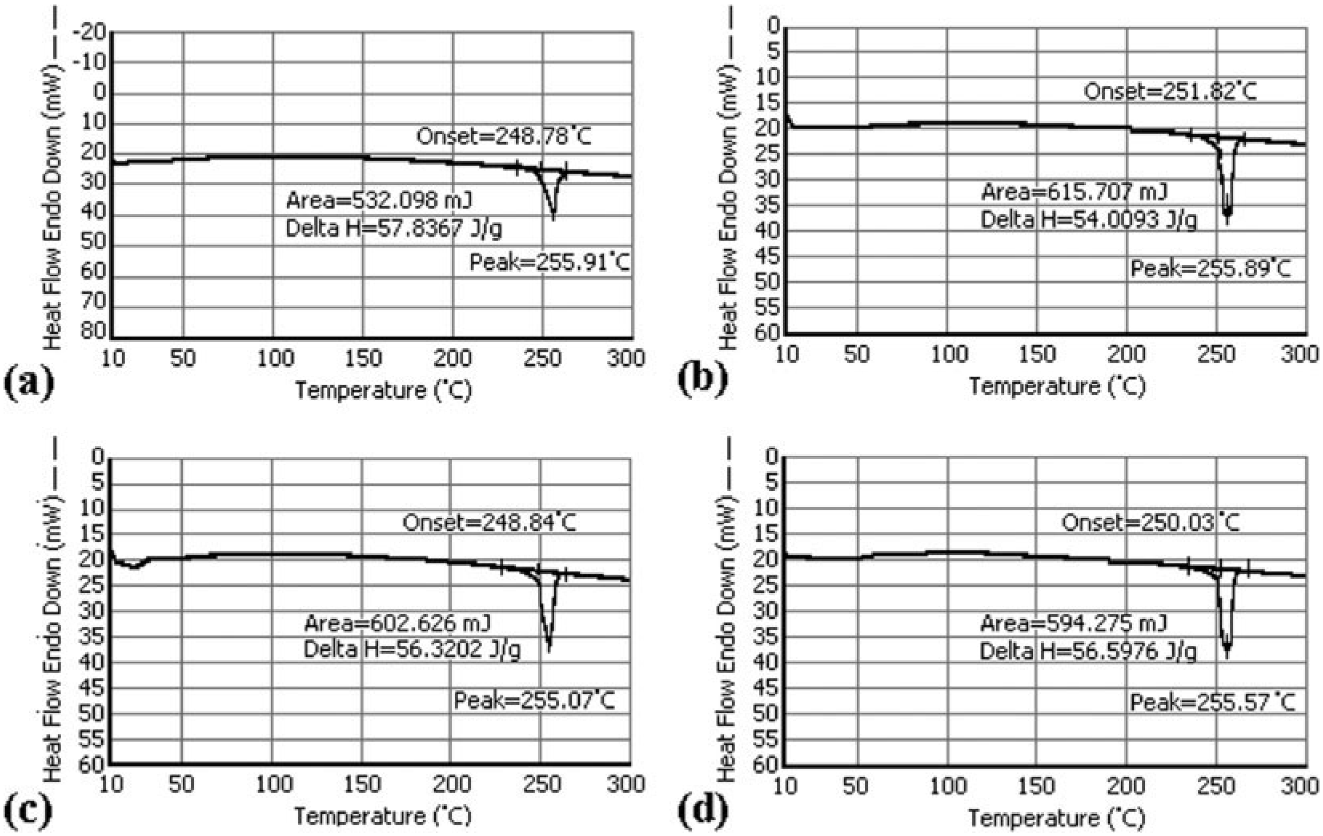

Figure 3 DSC curves of the fibers: (a) round, (b) hollow-round, (c) trilobal, and (d) hollow-trilobal.

atmospheric conditions of 65 ± 2% relative humidity and 20 ± 2°C.

The heat of fusion (enthalpy) and melting point of the fibers were measured via the heating of the samples from 10 to 300°C at 10°C/min on a Perkin-Elmer/Pyris 1 differential scanning calorimeter according to ASTM E 1356-03. The crystallinity of the fibers was determined with the following commonly used relation:[4]

$$\text{Crystallinity} = \frac{\text{Heat of fusion of the fiber}}{\text{Heat of fusion of the pure crystal for PET (140 J/g)}} \quad (1)$$

The tensile tests of the fibers were performed on a Textechno-Statimat-Me tensile tester according to DIN 2062. The distance between the jaws was 500 mm, and the gauge speed was 1500 mm/min. The stress and strain were determined at the maximum point of the stress–strain curve. Young's modulus was calculated from the initial slope of the stress–strain curve. The yield stress was determined with the Coplan method.[16] The test was repeated five times for all cross-sectional shapes.

The unevenness test was performed on an Uster Tester 3 according to DIN 53817-1. The test speed was 100 m/min, and the test period was 1 min. The test was repeated three times for all cross-sectional shapes.

The shrinkage test in boiling water was performed on a Texturmat-Me tester according to DIN 53866-12. The test was performed with a strand length of 14 m for 10 min at 95°C. The test was repeated three times for all cross-sectional shapes.

RESULTS AND DISCUSSION

The data for the enthalpy and melting point of the fibers are given on differential scanning calorimetry (DSC) curves in Figure 3. In the DSC curves of the fibers, only the endothermic peak (due to the melting temperature) was observed. The melting temperatures of the all fibers consisting of different cross-sectional shapes were identical (ca. 255°C). The value of the enthalpy, a function of the interchain forces, was highest for the round fiber and lowest for the hollow-round fiber.

The average stress–strain curves of the fibers are given in Figure 4. The stress–strain curves of the full and hollow fibers are different. The stress–strain curves, however, are similar in shape for the round and trilobal cross-sectional shapes of both the full and hollow fibers. The curves show that the hollow fibers were stiffer and more resistant to plastic defor-

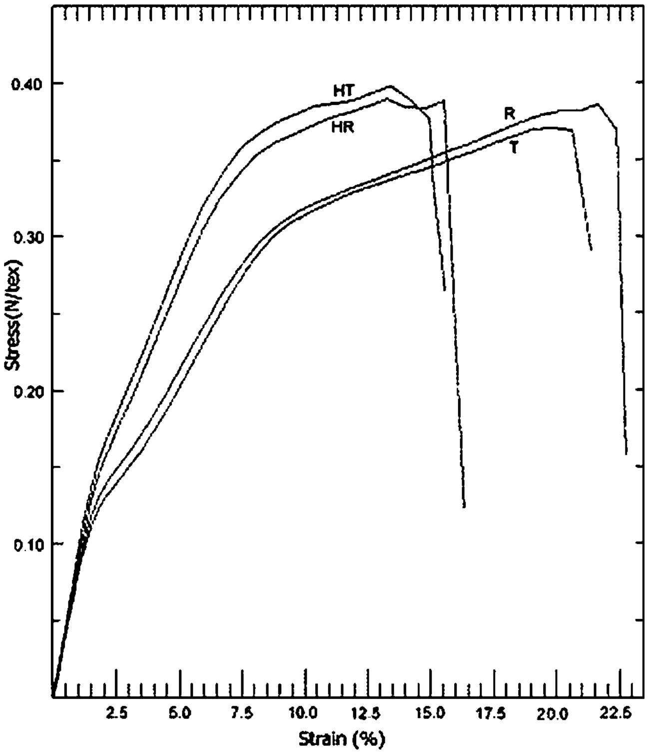

Figure 4 Average stress–strain curves of the fibers (R = round, HR = hollow-round, T = trilobal, HT = hollow-trilobal).

mation, whereas the full fibers had a tough material property.

The crystallinity, which was calculated with eq. (1), maximum stress, and yield stress according to the fiber cross-sectional shape are presented in Figure 5. Similar values of the maximum stress and crystallinity were obtained for all cross-sectional shapes. The yield stresses, however, were different for the different cross-sectional shapes. The hollow fibers had higher yield stresses than the full fibers.

The maximum strain and modulus values according to the fiber cross-sectional shape are presented in Figure 6. The effect of the fiber cross-sectional shape on the maximum strain can be readily observed. The hollow fibers had considerably lower values for the maximum strain than the full fibers. The round cross-sectional shape showed higher (ca. 11%) extension for both full and hollow fibers. The effect of the fiber cross-sectional shape on the modulus was harmonious with the effect of the fiber cross-sectional shape on the maximum strain. The hollow fibers had higher values for the modulus.

The shrinkage in boiling water and unevenness values according to the fiber cross-sectional shape are presented in Figure 7. The shrinkage in boiling water showed no regular pattern according to the fiber cross-sectional shape. For the same cross-sectional shape, the hollow fibers had greater shrinkage values in boiling water than the full fibers. When the

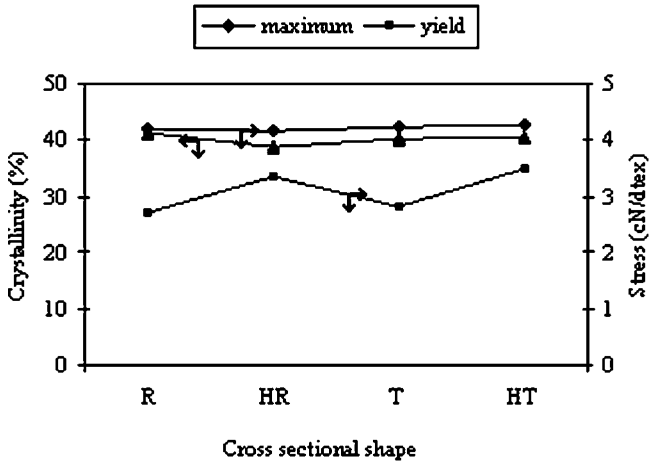

Figure 5 Comparison of the crystallinity and stress with respect to the cross-sectional shape (R = round, HR = hollow-round, T = trilobal, HT = hollow-trilobal).

effect of the fiber cross-sectional shape on the unevenness was investigated, it was observed that the unevenness percentage was higher than 1 for only the hollow-round fiber. The others had low and similar values for unevenness.

The formation of structures of as-spun fibers is mainly controlled by the elongational stress at the solidification point. This stress is dominated by the contribution of inertia and air-friction forces if the take-up speed is sufficiently high. The effect of the inertia force is independent of the cross-sectional shape, but the change in the cross-sectional shape of the fiber should lead to significant changes in the cooling behavior and air-friction force acting on the fiber surface.[1,14] The outer surface of the hollow fiber is larger than that of the round fiber for the same fiber thickness, as in this work. The enhancement of cooling and air friction is attributable to the larger

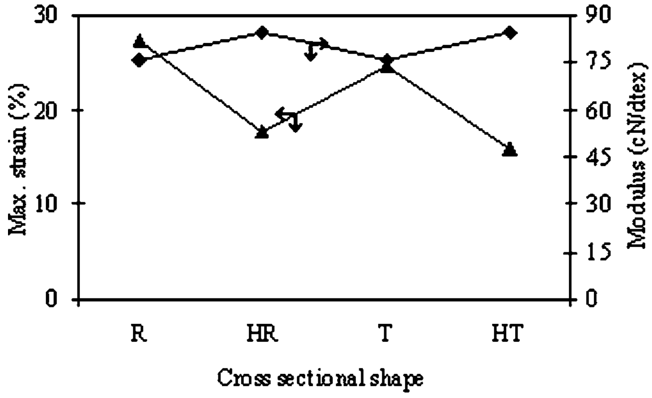

Figure 6 Comparison of the maximum strain and modulus with respect to the cross-sectional shape (R = round, HR = hollow-round, T = trilobal, HT = hollow-trilobal).

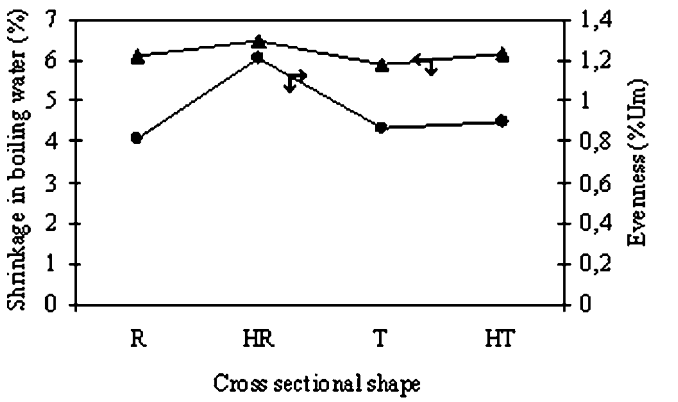

Figure 7 Comparison of the shrinkage in boiling water and unevenness with respect to the cross-sectional shape (R = round, HR = hollow-round, T = trilobal, HT = hollow-trilobal).

surface area per unit of volume of the material. If the same process conditions are defined, a larger surface area can increase the air-friction force. However, a larger surface area also enhances the cooling and shortens the distance from the spinneret to the solidification point, and this leads to the reduction of the air-friction force. In other words, the effects of enhanced cooling and air friction cancel each other, and therefore the air-friction force at the solidification point is not changed much by the change in the cross-sectional shape.[1] Consequently, the stresses at the solidification point eventually become similar despite the significant difference in the cross-sectional shapes of the fibers. It has been reported in previous studies[1,14] that orientation-induced crystallization of hollow and round fibers starts at a take-up speed of 5 km/min. We found in this work that there were no clear differences between the values for the crystallinity and maximum stress of different cross-sectional shapes. The reason may be the take-up speed of the fibers, which was 5500 m/min (Table II). The crystallinity of the hollow-round fiber was only about 7% lower than that of the round fiber. These results mean that the changes in the cross-sectional shapes of the fibers had only a small effect on the formation of the structure in the FDY melt-spinning process.

Although the effect of the cross-sectional shapes of the fibers on the crystallinity and maximum stress is not clear, the values for the modulus, maximum strain, and yield stress have been influenced. In fact, the modulus of the fiber is determined by the chemical structure of the polymer and the molecular orientation of the amorphous regions. The more highly oriented the molecules are along the fiber axis, the more chains bear the load, and the stiffer the fiber is. These changes in the molecular structure as the fiber is drawn result in increased initial modulus and decreased extension to break. The same arguments can be applied to the strength, but the presence of defects may control the ultimate stress. The yield stress depends also on the orientation imparted by the spinning process.[4,17] These results are harmonious with the higher enthalpy value of the round fiber, despite the similar melting temperature of the hollow-round fiber. This situation suggests that increasing entropy due polymer molecules coiled upon themselves must be considered.

During the spinning process, the take-up stress (0.36 cN/dtex), measured at the take-up point of the hollow fibers, was higher than that (0.19 cN/dtex) of the full fibers. When the take-up speed, the polymer output, and the cooling conditions are kept unchanged, the fiber assumes a highly oriented amorphous structure because the take-up stress exceeded a limit value (0.30 cN/dtex).[2] These results suggested once more that the hollow fibers had higher amorphous orientation (the orientation of the molecule chains in the amorphous region) than the full fibers. The boil-off shrinkage is also measured as a function of the take-up stress at the take-up point, while all spinning conditions are kept identical. When the take-up stress exceeds a certain limit value, the boil-off shrinkage starts to rise.[2] Furthermore, when the hollow fibers are heated above the glass-transition temperature, as in the shrinkage test in boiling water, because of the larger total surface area, the heat transfer to the fiber and hence the shrinkage force would be higher than those of the full fibers.

CONCLUSIONS

The hollow fibers had lower maximum strain values and higher values for the modulus, yield stress, take-up stress, and shrinkage in boiling water than the full fibers. The full fibers were tough and ductile, whereas the hollow fibers were stiffer and more resistant to plastic deformation. The values for the maximum strain and shrinkage in boiling water of the round fibers were higher than those of the trilobal fibers for both the hollow and full fibers. The hollow-round fiber had the highest value for unevenness and the lowest value for crystallinity.

The change in the cross-sectional shapes had only a small effect on the crystallinity and maximum stress of the fibers produced in the FDY melt-spinning process.

The hollow-round fiber had lower enthalpy and entropy and hence higher take-up stress and amorphous orientation than the round fiber.

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References

1. Takarada, W.; Ito, H.; Kikutani, T.; Okui, N. J Appl Polym Sci 2001, 80, 1575.
2. Nakajima, T. Advanced Fiber Spinning Technology; Woodhead: Cambridge, England, 1994.
3. Hudson, S. Theory and Practice of Fiber Formation; NCSU: United States, 1995.
4. Warner, S. B. Fiber Science; Prentice Hall: Upper Saddle River, NJ, 1995.
5. Bueno, M. A.; Aneja, A. P.; Renner, M. J Mater Sci 2004, 39, 557.
6. Oh, T. H.; Lee, M. S.; Kim, S. Y.; Shim, H. J. J Appl Polym Sci 1998, 66, 1209.
7. Rwei, S. P. J Appl Polym Sci 2001, 82, 2896.
8. Rovere, A. D.; Shambaugh, R. L. Polym Eng Sci 2001, 41, 1206.
9. Petrulis, D. J Appl Polym Sci 2004, 92, 2017.
10. Wada, O. J Text Inst 1992, 83, 322.
11. Oh, T. Polym Eng Sci 2006, 46, 609.
12. Rovere, A. D.; Grady, B. P.; Shambaugh, R. L. J Appl Polym Sci 2002, 83, 1759.
13. Lee, M. S.; Oh, T. H.; Kim, S. Y.; Shim, H. J. J Appl Polym Sci 1999, 74, 1836.
14. Takarada, W.; Ito, H.; Kikutani, T.; Okui, N. J Appl Polym Sci 2001, 80, 1582.
15. Beyreuther, R.; Hofmann, H. Chem Fiber Int 1997, 47, 54.
16. Morton, W. E.; Hearle, J. W. S. Physical Properties of Textile Fibres; Textile Institute: London, 1975.
17. Ward, I.; Cansfield, D.; Carr, P. In Polyester 50 Years of Achievement: Tomorrow's Ideas and Profits; Brunnschweiler, D.; Hearle, J. W. S., Eds.; Textile Institute: Manchester, England, 1993.