Formation of Hollow Fibers in the Melt-Spinning Process

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ABSTRACT: This article reports an investigation of the formation of hollow fibers in a melt-spinning process. Experimental results indicate that die swelling is largely responsible for a negative effect on hole formation. The factors that positively affect die swelling, including a decrease in temperature, a decrease in capillary length, and an increase in shear rate, are thus not recommended for the spinning of hollow fibers. For vinyl-type polymers such as polypropylene, in which the apparent elasticity leads to serious die swelling, the formation of hollow fibers is more complex than that of a typical condensation polymer. Our results further demonstrate that when hollow fibers are being made in a variety of shapes (but of the same denier), spinning a polygonal hollow fiber is significantly more unstable than spinning a circular one. Moreover, an asymmetric bridge along the polygonal contour leads to a melt twist and interrupts the entire spinning process. © 2001 John Wiley & Sons, Inc. J Appl Polym Sci 82: 2896–2902, 2001

Key words: die swelling; fissure length; melt fracture; hollow fibers; normal stress difference

INTRODUCTION

Consisting of a sheath of polymeric materials and one or more hollow spaces inside, hollow fibers have many unique properties and have found numerous applications as well.[1,2] For example, hollow fibers can provide great bulk with less weight and are often used to make insulated clothing or high-loft nonwoven materials. With the property of capillary rising, hollow fibers can be made highly absorbent. Other hollow-fiber applications include dialysis[3] in medicine and soil resistance in carpets.

There are different ways to manufacture hollow fibers,[4] such as, wet spinning, solution spinning, and melt spinning. In melt spinning, hollow fibers are generally spun via unique spinnerettes that are designed as reed stays with some open spots. For example, a single-hole hollow fiber is commonly spun via a spinnerette with a C-shaped cross section. The open gap along the C contour, commonly called the bridge, must exist to prevent the inner core of the C shape from collapsing. The melt stream, which does not shape a completely hollow space inside the spinnerette, flows and glues together in the still molten state directly under the spinnerette. They are thus known as gluing hollow fibers.

Engineers generally agree that the die swelling of a polymer melt enhances gluing under the spinnerette. Therefore, as widely assumed, design parameters that positively impact the die swelling facilitate the formation of hollow fibers. Die swelling is due to the elastic and thermal behavior of a polymer. Time and temperature significantly affect the swelling as the material stays within the die or passes the die lip. Critical parameters for enhancing the swelling include a decrease in capillary length, a decrease in process temperature, and an increase in shear rate. This article reports

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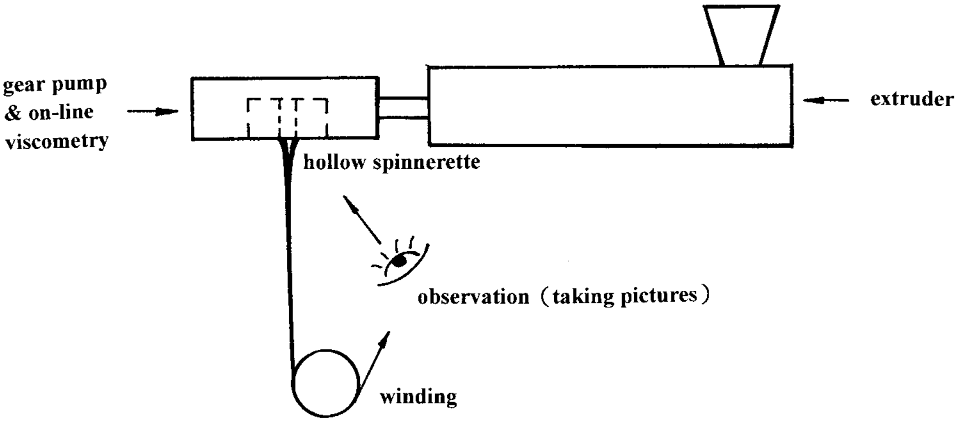
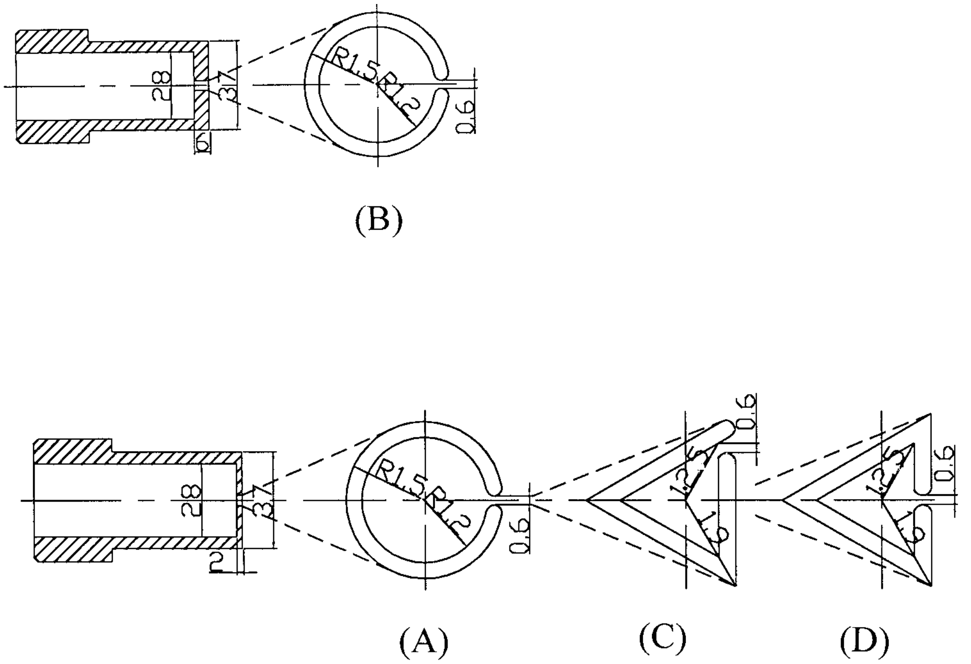


Figure 1 Schematic of the melt-spinning apparatus for observing the formation of hollow fibers.

an investigation of how hollow formation depends on these specific parameters. Also examined herein is the rheological effect of the melt flow, including the storage modulus (G') and first normal stress difference (N_1), on the hollow formation. The results of this study provide further insight into the mechanism by which hollow fibers form.

EXPERIMENTAL

Two types of fiber-grade polymers, polypropylene [PP; Taiwan Polypropylene Co., PD 973; melting temperature (T_m) = 180°C] and poly(butylene terephthalate) (PBT; DuPont Co., Crastin® S620; T_m = 220°C), were used. PP was selected as a representative of vinyl-type polymers, and PBT was chosen because it is a typical polycondensation polymer. Extrusion experiments were performed in a continuous single-screw extruder hooked with a spin pack (Fig. 1). A unique spinnerette designed for various hole formations (Fig. 2) was mounted onto the spin pack. Pulling at the ambient temperature without any additional quenching was applied for the spinning. The winding speed was maintained at 600 m/min for the entire experiment for the easy acquisition of a



(B)

(A) (C) (D)

Figure 2 Special spinnerette design for hollow fibers in circle and triangle shapes.

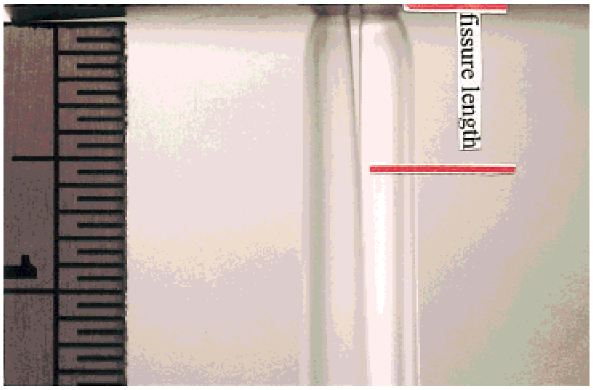


Figure 3 Typical formation of hollow fibers in the melt spinning of PP with spinnerette A at 220°C and a shear rate of 290 (1/s). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

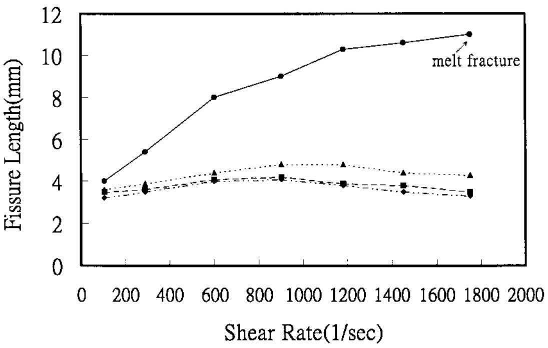


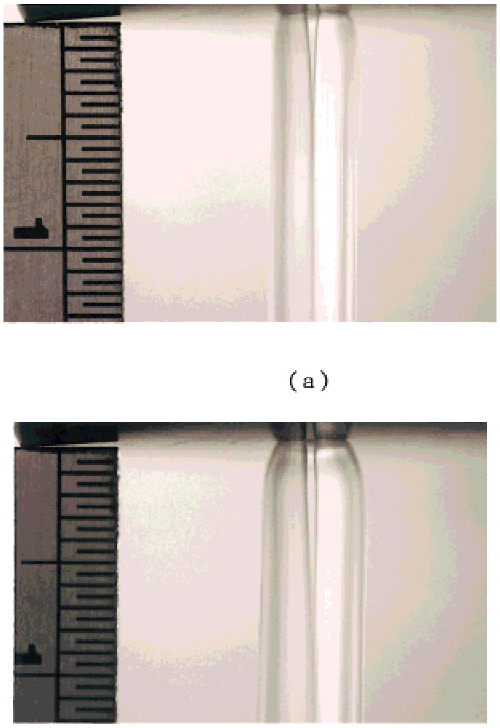
Figure 4 Fissure length as a function of the shear rate for spinning PP hollow fibers with spinnerette A at various temperatures: (●) 220, (▲) 240, (■) 260, and (◆) 280°C.

stabilized condition and simplification of the processing factors in the die-swelling study. The spun fiber after solidification was cut and collected 200 cm below the spinnerette. Before melt spinning, we dried one of the test polymers, PBT, to maintain its moisture level below 100 ppm.

The online measurements of temperature, flow rate, and pressure inside the spin pack were monitored and recorded. The shear rate employed herein was primarily the average bulk shear rate and was calculated with the Weissenberg–Rabinowitsch equation.[5] Photographs for recording the spinning process were obtained with a camera. Our observations focused mainly on the melt-gluing region, about 0.3–3 cm below the spinnerette. The joint distance, namely, the fissure length, could, therefore, be determined from the photographs. Finally, the offline rheological measurements of the polymer melt were taken in a parallel disk with an SR-5 rheometer from Rheometric Scientific Co.

RESULTS AND DISCUSSION

Figure 3 illustrates the gluing behavior for a typical spinning of a hollow fiber. Carefully tracing the fissure edge to its joint point allowed us to determine the fissure length. Figure 4 presents the dependence of the fissure length on the shear rate for PP at various process temperatures. According to the die-swelling hypothesis mentioned earlier, the fissure would glue easier and display a short fissure length if the die swelling increased. However, Figure 4 reveals that a decrease in the process temperature caused serious die swelling, subsequently increasing the fissure length. Moreover, increasing the shear rate at a


(a)

(b)

Figure 5 (a) After the melt spinning of PP hollow fibers with spinnerette A at 220°C and a shear rate of 104 (1/s), a clear fissure can be observed. (b) When the shear rate is increased to 903 (1/s), an increasing fissure length and a wider fiber diameter can be observed. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

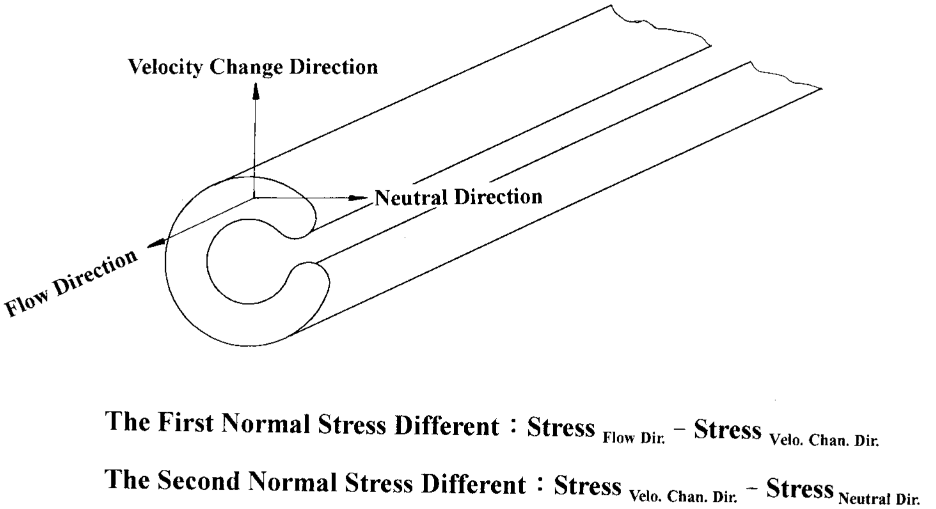


Figure 6 Illustration of the N_1 and N_2 directions in a hollow fiber spinning.

constant temperature caused serious die swelling and, subsequently, increased the fissure length too. These results contradict the die-swelling hypothesis. For clarification, closely examining the hole formation reveals an interesting phenomenon. Figure 5(a,b) illustrates the formation of hollow fibers at different shear rates. Figure 5(a), in which a low shear rate was applied, exhibits a shorter fissure length than Figure 5(b), in which a high shear rate was applied. More closely examining Figure 5(a,b) reveals that significant die swelling occurred in the *r* direction rather than the θ direction, as previously expected. This indicates that the swelling direction largely determines the formation of hollow fibers.

As generally known, die swelling in the *r* direction is associated with N_1, whereas swelling in the θ direction is related to the second normal stress difference (N_2). Tadmor and Gogos[6] and White and Roman[7] linked the recoverable shear strain, that is, a parameter composed of N_1 and the shear stress, to the die swelling in the *r* direction. As for swelling in the θ direction, although a theoretical approach is lacking, it has been practically applied to the die designs of profile extrusion,[8] in which the N_2 effect is considered. Figure 6 clearly indicates the geometric relationship between N_1 and N_2 in a hollow-formation process. Furthermore, Christiansen and Leppard[9] proposed that N_2 is proportional to N_1, and the former is probably an order of magnitude smaller than the latter. This finding suggests that die swelling in the *r* direction is more pronounced than swelling in the θ direction. Notably, swelling in the *r* direction can broaden the gap width of a hollow fiber by a factor of $2\pi\Delta R$, where ΔR refers to the radius difference of hollow fibers with various die swellings. The broadness gap surpasses the gluing effect induced by a relatively minor swelling in the θ direction. The overall increase in the gap width, therefore, leads to an increase in the fissure length. In sum, the die swelling increases the fissure length and negatively affects the formation of hollow fibers.

Interestingly, Figure 4 reveals that under the circumstances of a low temperature but a high shear rate, a melt fracture or, more generally, an extrudate distortion is observed. A critical flow rate often occurs, and the extrudate surface is no longer smooth; instead, a severe roughness appears on the surface as the hollow fiber is spun (Fig. 7). Although no single theory describes the phenomenon adequately, the molecular weight,

Figure 7 Melt fracture of a PP hollow fiber with spinnerette A at 220°C and a shear rate of 1800 (1/s). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

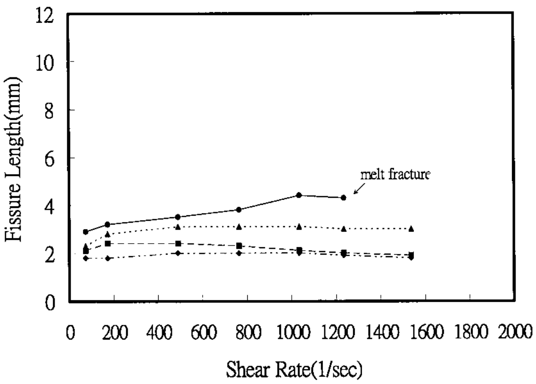


Figure 8 Fissure length as a function of the shear rate for spinning PP hollow fibers with spinnerette B at various temperatures: (●) 220, (▲) 240, (■) 260, and (◆) 280°C.

nature of elasticity, and die geometry appear to play important roles. The fracture with respect to different die geometries is discussed later.

For the further investigation of how die swelling affects the formation of hollow fibers, spinnerette B was designed with the exact same geometry as spinnerette A except for a longer capillary length. The capillary length was increased from 0.2 to 0.6 mm. Under normal circumstances, the die swelling decreases as the capillary is lengthened.[10,11] A general consensus appears to be that stress relaxation causes a decrease in swelling with increasing capillary length. The shear stress imposed on the melt while in the capillary may lead to disentanglement. However, the polymer melt flowing via a shorter capillary is much more entangled and does not have sufficient residence time to relax. The high entanglement density may possess a structure and generate a higher normal stress and higher die swelling at the exit. However, a long capillary provides a longer residence time for melt disentanglement; the normal stress and die swelling are, therefore, reduced. Comparing Figure 4 with Figure 8 reveals that the fissure length was dramatically reduced via spinnerette B, thus confirming that die swelling negatively affected the formation of hollow fibers. Notably, at 220°C the melt fracture was again observed, and the critical shear rate for the melt fracture decreased. This observation indicates that the severity of the melt fracture increases as the die is lengthened, which corresponds to the findings of other researchers studying the die swelling of linear polymers.[12]

Figure 9 illustrates the dependence of the fissure length on the shear rate for PBT and PP at processing temperatures of 260 and 220°C, respectively. The temperature applied herein for PBT and PP was about 40°C higher than T_m of each polymer. Figure 9 displays a distinct difference between PBT and PP in their fissure length and curve tendencies. PBT exhibits a tiny fissure length independent of the shear rate. However, as mentioned earlier, PP shows a significant fissure length that increases when the shear rate increases. Closely examining the viscoelastic behavior provides further insight into the die swelling effect on hole formation for different polymers. Figure 10(a,b) describes N_1 as well as the dynamic modulus for PP and PBT at various temperatures. Notably, PP is 2 orders of magnitude higher in the normal stress difference and 1–2 orders of magnitude higher in G'[13] than PBT. These results indicate that PBT, possessing insignificant elastic properties, would lead to a negligible die swelling for affecting its hollow-fiber formation. In addition to PBT, all condensation-type polymers, such as poly(ethylene terephthalate) and nylon, which generally have insignificant melt elasticity, behave similarly. In contrast, for vinyl-type polymers such as PP and PE,[14] because of their high portion of elasticity in the melt, the die-swelling effect significantly affects the formation of hollow fibers.

In fiber applications, a round cross section is not always preferred. Various geometries such as hollow triangles, hollow trilobals, and hollow squares are conventionally used in the carpet and apparel industries. Arranging the bridge position along the polygonal contour becomes critical in terms of manufacturing such a polygonal fiber. Figure 2(C,D) lists two specific designs for a hollow triangle. Triangle C was designed to locate the bridge in one of the corners, and the joint

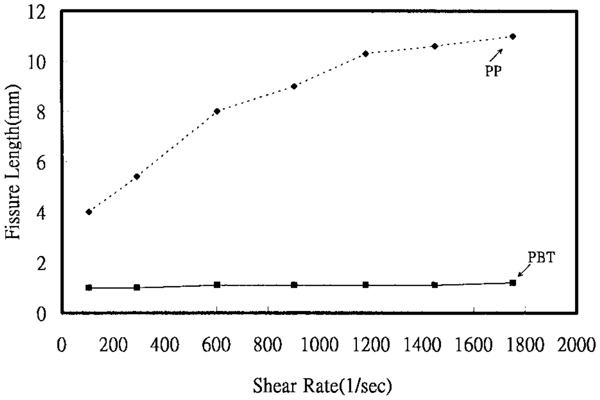


Figure 9 Fissure length as a function of the shear rate for hollow fibers made from PP and PBT with spinnerette A: (◆) PP at 220°C and (■) PBT at 260°C.

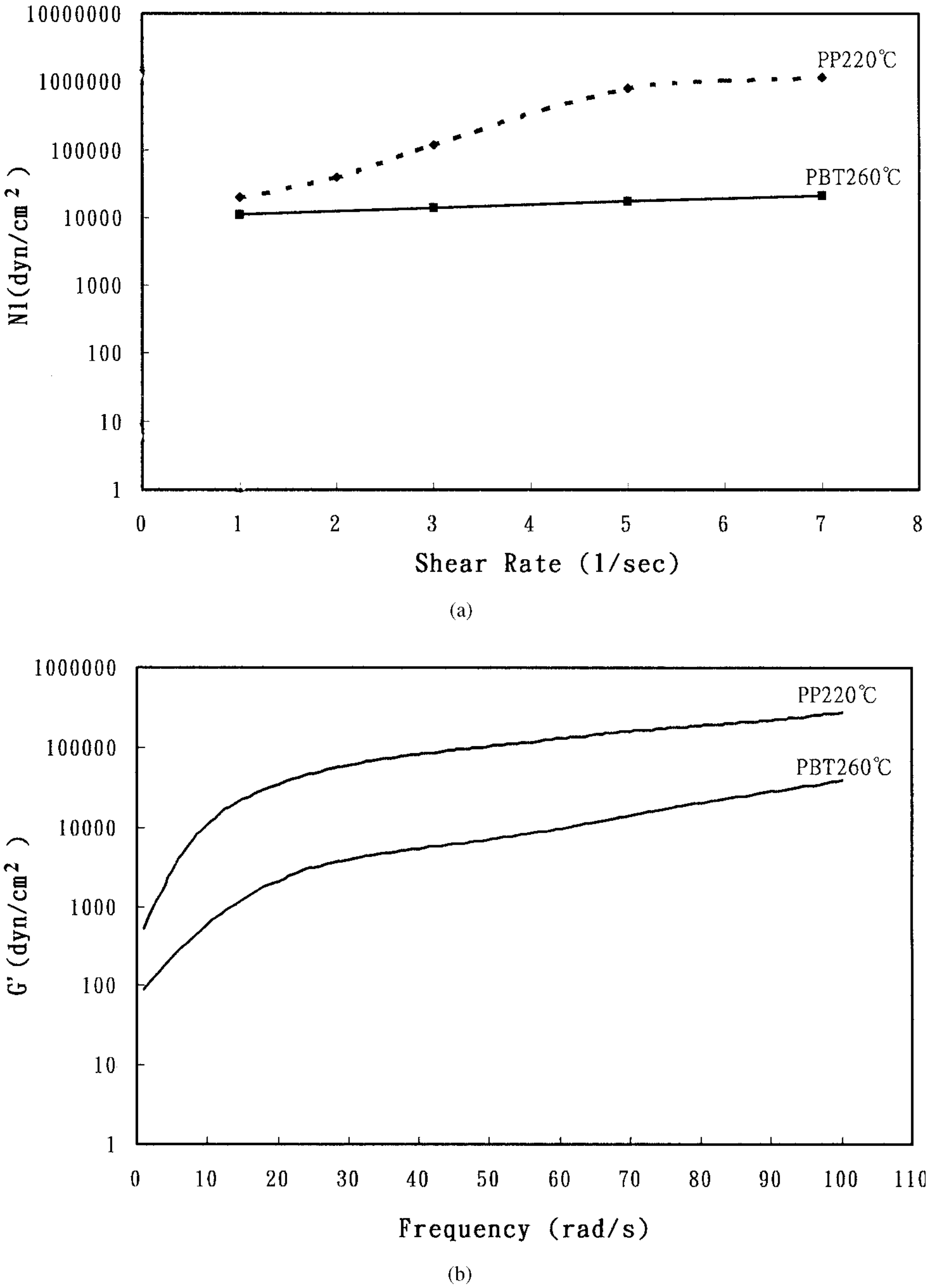


Figure 10 Elastic properties of PP and PBT: (a) N_1 in various shear rates and (b) G' at various frequencies.

position with a slight asymmetry was intentionally made. However, the bridge in triangle D was located in the middle of one triangle side to make the contour of the flow duck appear symmetric. Figure 11 reveals that the melt flow via the asymmetric bridge would cause a severe twist. The twist above the solidification point of the spin line will decrease the melt strength, which is expected to overcome the winding tension caused by air drag. Frequent breaks in the spin line, particularly in high-speed spinning, would thus occur and force termination of the entire spinning process. The melt twist induced by the asymmetric bridge also could be occasionally observed in a blocked spinnerette where the contaminations incidentally attached onto the wall of the flow duck to interfere with the symmetry of the extruded contour. In contrast to triangle C, triangle D with a symmetric bridge shows an untwisted profile. However, Figure 12 shows that a serious melt fracture would occur even at a low shear rate. Notably, the cross-section area of triangle D is similar to that of circular A for maintaining the same output and fiber denier. Compared with Figure 4, Figure 12 reveals that the critical shear rates for a melt fracture in a polygonal hollow fiber are markedly lower than those in a circular hollow fiber. In sum, for making hollow fibers with the same denier, spinning a polygonal hollow fiber is significantly more unstable than spinning a circular one.

CONCLUSION

This study investigated the formation of hollow fibers in a melt-spinning process. Of the basis of our results, we conclude the following:

1. On the basis of the effects of temperature, shear rate, and capillary length on hole formation, we believe that die swelling is largely responsible for the increase in the fissure length. In other words, die swelling negatively affects the formation of hollow fibers.
2. For vinyl-type polymers such as PP, because of its apparent elasticity leading to significant die swelling, the formation of hollow fibers is more difficult to achieve than a typical condensation polymer.

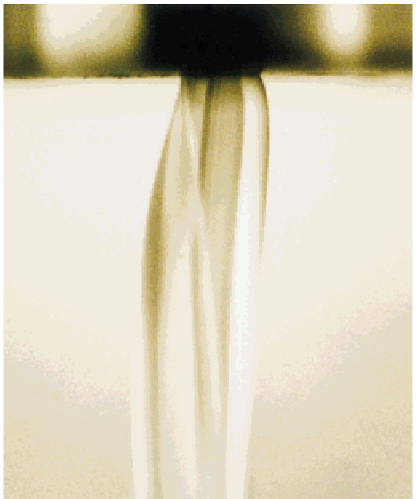


Figure 11 Melt-twist behavior of PP via spinnerette C at 220°C. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

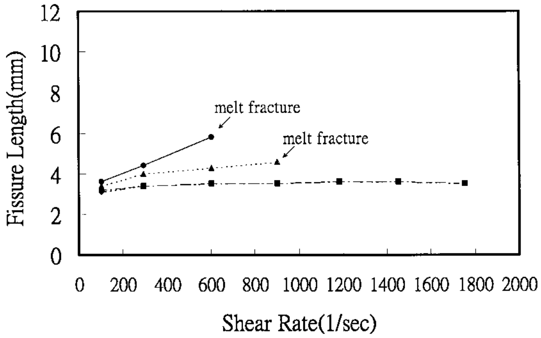


Figure 12 Fissure length as a function of the shear rate for spinning a triangular hollow fiber with spinnerette D: (●) 220, (▲) 240, (■) 260, and (♦) 280°C.

3. For making hollow fibers with various shapes but of the same denier, spinning a polygonal hollow fiber is markedly more unstable than spinning a circular one. Moreover, an asymmetric bridge along the polygonal contour leads to a melt twist and interferes with the entire spinning process.

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