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Factors affecting crimp configuration of PTT/PET bi-component filaments

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Abstract

In this paper, we explored factors that affect the crimp configuration of polytri-methylene terephthalate (PTT)/polyethylene terephthalate (PET) filaments. We selected three PTT/PET filaments that have approximately identical monofilament fineness but different cross-sectional shapes to study how crimp configuration is influenced by the elastic modulus ratio and differential shrinkage between PTT and PET components. The average elastic modulus ratio was obtained from the stress–strain curves and the cross-sectional measurements of the three PTT/PET filaments. The crimp curvature expressions of the three fibers were used to determine that the differential shrinkage of the two components, which was in the range of 6.8–10.01%. It was found that as the elastic modulus ratio (*m*) increased, the crimp curvature increases rapidly when the *m* increases from 0 to 0.5, and then approaches to a stable value when *m* is larger than 0.5. The crimp curvature increased continuously as the differential shrinkage increased. The crimp curvature of the PTT/PET filament with a dumbbell-shaped cross-section was higher than that of the other two fibers with gourd-shaped and round cross-sections.

Keywords

PTT/PET side-by-side fiber, crimp curvature, elastic modulus ratio, differential shrinkage

PTT/PET (polytri-methylene terephthalate/polyethylene terephthalate) side-by-side bi-component filament is a self-crimping conjugated polyester fiber with a high frequency of helical crimps, offering exceptionally good stretch, wrinkle recovery, and bulk to the yarns and fabrics. Side-by-side bi-component fibers were developed by imitating the unique structural property of wool fibers, which have dissimilar ortho-cortex and para-cortex adhering side by side. Much attention was given in the past to develop the theory of the formation of self-crimping in side-by-side fibers. Timoshenko[1] used the bi-metallic thermostat theory to explain the self-crimping behavior produced by the differential strain resulting from temperature changes, and the curvature was used to indicate the crimp configuration. Brown and Onions[2] investigated the crimp properties of wool fibers and applied Timoshenko's theory to construe self-crimps of wool fibers. Brand and Becker[3] found the inverse relationship between crimp curvature and fineness of wool fibers or synthetic bi-component fibers, and suggested that longitudinal changes and cross-section shapes of two components were the important factors affecting crimp numbers. El-Shiekh et al.[4] established the analytical relationship between the crimp radius and the features of individual components, including strain, area and elastic modulus. Gupta and George[5] presented a model for calculating the curvature of a bi-component fiber based on a theory of bending two coupled, thin elastic elements. Denton[6] developed simple and efficient expressions to describe the effect of fiber parameters on the crimp curvature of bi-component fibers with arbitrary cross-section shapes and component distributions.

As one of the side-by-side bi-component fiber, the crimp development within the PTT/PET filament is mainly due to the differential shrinkage of the PTT and PET components after heat treatment. Commercial PTT/PET bi-component fibers, such as Invista's T400,[7] contain components with different

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proportions by weight, and are manufactured by a conjugated melt-spinning process. Many factors, such as component volume ratio, differential shrinkage, elastic modulus ratio, and spinning parameters, can impact the self-crimping configuration of the PTT/PET fiber. It has been reported the different morphological and crystalline structures of bi-component fibers could be induced under the various processing conditions in the melting and cold-drawing process of PTT/PET components with different viscosities.[8,9] Rwei et al.[10] manufactured PET/CD (Cation Dyeable PET), PBT (polybutylene terephthalate)/PET and PTT/PET self-crimping filaments, and found that the fibers with triangular cross-sectional shapes were superior to those with round shapes in crimp potential, and the optimal volume ratio for making a self-crimping bi-component filament was 50/50. They also proved that the crimp ratio of PTT/PET filaments could be achieved as high as 40–45%, which was higher than that of PET/CD or PBT/PET bi-component fibers, and the crimp ratio and elongation of PTT/PET filaments increased dramatically after a wet-heat treatment.[11]

Based on the former researchers' experimental and theoretical work on side-by-side bi-component fibers and our recent work on PTT/PET fibers, we recognized that the elastic modulus ratio and differential shrinkage of PTT and PET are the two main factors that can affect the crimp properties of PTT/PET fiber. In this paper, we concentrated on how to determine the elastic modulus ratio and differential shrinkage of PTT and PET components in three PTT/PET filaments with different cross-sectional shapes, and how to analyze these two factors as well as the cross-sectional shape on crimp curvatures of PTT/PET fibers.

Materials

Three commercially available PTT/PET filament yarns were selected for the study (see Table 1). These filaments have the same monofilament fineness but different cross-sectional shapes.

Table 1. Specifications of PTT/PET bi-component filaments

Brand	CM800	ESS	X55
Producer	XINGAO (China)	HUVIS (Korea)	HYOSUNG (Korea)
Fabricate type	FDY*	FDY*	FDY*
Fineness	83.3 dtex	83.3 dtex	83.3 dtex
Filament number	32	36	36

*FDY is a fully drawn yarn.

The cross-section slices of the PTT/PET fibers were cut by a Y172 Hardy's cross-sectional device, and the slices were examined under the OLYMPUS CH-2 optical microscope with $\times 400$ magnification.

Figure 1 shows the change in crimp configuration of one PTT/PET filament before (Figure 1a) and after (Figure 1b) a wet-heat treatment. Specimens of 60–70 cm length were plunged in boiling water for 15 minutes in a XMT-6000 hot water bath (Shanghai Laboratory Instrument Co., Ltd. China), and then conditioned with a temperature of $20 \pm 1^\circ$C and a relative humidity of $65 \pm 1\%$ for 16 hours.

The stress-strain curves of the three filaments were measured by the YG061 yarn tensile testing instrument according to ASTM D2256.[12] For each filament, 20 50-mm-long specimens were tested at a speed of 500 mm/min with a load of 0.01 ± 0.001cN/tex.

Results and Discussion

Crimping model of PTT/PET bi-component filaments

The crimping configuration of a PTT/PET bi-component filament results from the differential shrinkage of the two components. Based on previous research findings, Denton[6] developed a simple means of estimating the crimping potential for a bi-component fiber by using the following equation:

$$\rho = \frac{1}{R} = \frac{A_2 A_0 u_2 \Delta}{A_0 I_0 + \left(m-1\right)\left(A_2 I_{2P} - \frac{1}{m} A_1 I_{1P} - \frac{m-1}{m} A_2^2 u_2^2\right)} \tag{1}$$

where ρ is the crimp curvature, R is the crimp curvature radius, Δ is the differential shrinkage between the two components, m is the ratio of the moduli E_1 and E_2. As denoted above, the cross-sectional areas of two components are A_1 and A_2, the distances from the centers of the two areas to the center of the whole cross-section are u_1 and u_2, the second moments of the two areas around the axes through their own centers are I_1 and I_2, and their second moments relative to the axis through the center of the whole section are I_{1P} and I_{2P}. Therefore, $A_0 = A_1 + A_2$, $I_{1P} = I_1 + A_1 u_1^2$, $I_{2P} = I_2 + A_2 u_2^2$, and $m = E_2/E_1$. Note that u_1 is needed for calculating I_{1P}.

Equation (1) indicates the factors affecting the crimp curvature of bi-component fibers include the elastic modulus ratio, differential shrinkage, cross-sectional areas, and the second moments of the two components. Usually, the cross-sectional areas and the second moments are determined by the shape of the spinneret holes and the spinning process. The elastic modulus ratio and the differential shrinkage are dictated by the material properties of the two components.

Figure 2 shows the optical microscope images and the schematic models of the cross-sectional shapes of three typical PTT/PET fibers, which allowed us to calculate the areas and the second moments of

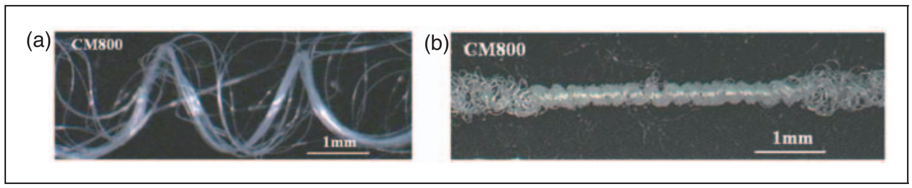

Figure 1. Crimp configuration of PTT/PET self-crimping fiber: (a) original fibers before wet-heat treatment, (b) fibers after wet-heat treatment.

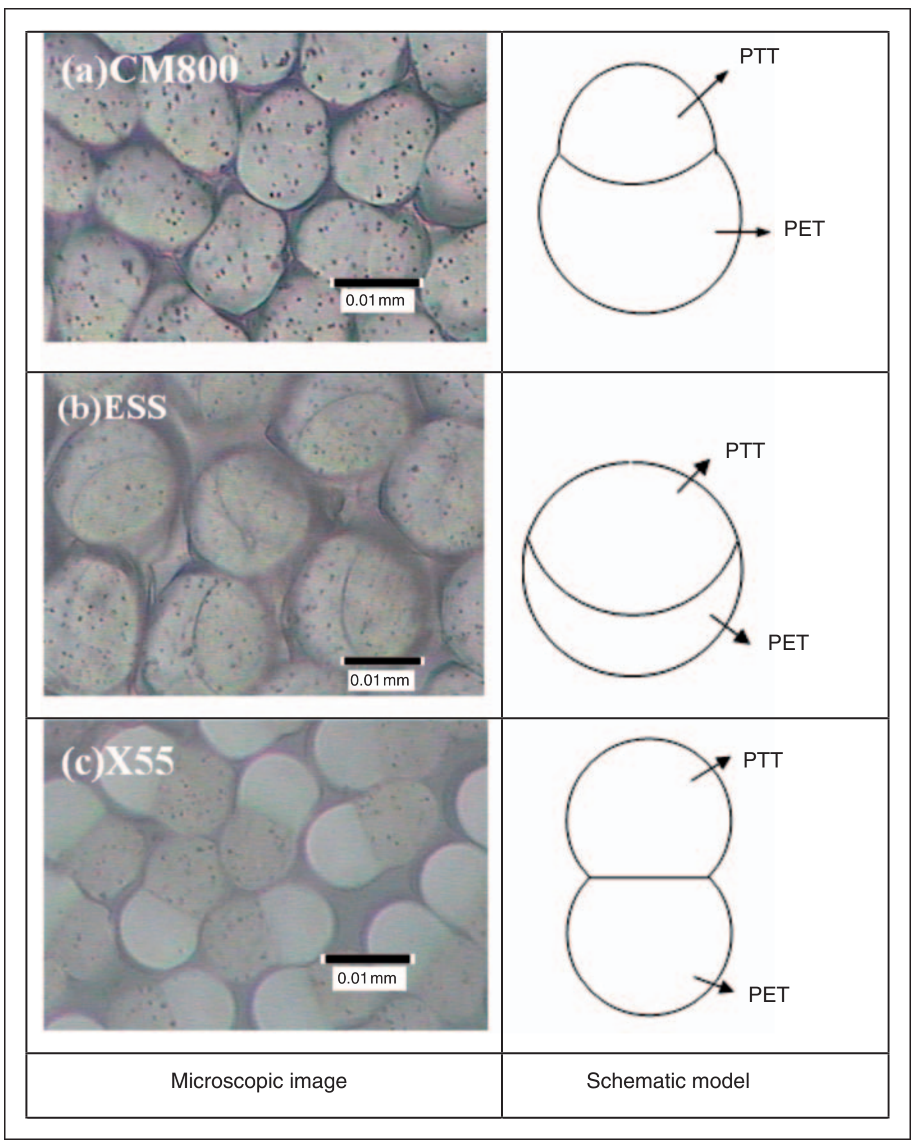

Figure 2. Cross-sectional shapes of CM800, ESS and X55 fibers.

the components. The parameters u_1 and u_2 could be measured from the optical microscope images of cross-section of PTT/PET fibers in Figure 2. And then based on the schematic model, the area and second moments of two components could be calculated, the results are listed in Table 2.

Therefore, three expressions of crimp curvatures of the three fibers (CM800, ESS, X5) can be deduced from Equation (1):

$$\left.\begin{aligned} \rho &= \frac{2.93\Delta}{25.5+(m-1)[6.69-5.83/m-5.25(m-1)/m]} = C\Delta \\ \rho &= \frac{6.92\Delta}{74.9+(m-1)[14.0-23.8/m-10.7(m-1)/m]} = C\Delta \\ \rho &= \frac{2.98\Delta}{28.4+(m-1)[7.1-7.1/m-5.32(m-1)/m]} = C\Delta \end{aligned}\right\} \tag{2}$$

where C is a coefficient that is dependent on m.

Elastic moduli of two components in PTT/PET filaments

In a bi-component fiber, one component on one side tends to shrink preferentially either during the manufacturing process or upon activation of texturizing or some equivalent process.[5] The difference in shrinkage lengths of the two components yields crimps. The tensile elastic modulus of a filament is defined as the slope of its stress-strain curve in its initial linear extension section. Usually, the ratio of elastic modulus of individual PTT and PET filaments is in the range of 0.2–0.4.[13] This ratio can be different in the PTT/PET bi-component filament because of the side-by-side bonding. The bonded ratio could be calculated by using the elastic moduli of the two components along with their cross-sectional areas in the fiber.

Figure 3 shows the stress-strain curves of the three heat-treated PTT/PET filaments. Take the stress–strain curve of CM800 as an example. The curve exhibits three distinct stages. Stage I (OA) is the extension for crimp removal, in which the filaments were stretched extensively by a small force, and the helical crimps were straightened without intrinsic filament extensions. In stage II (AB), the filaments began to be subjected to elastic deformation, and the elastic modulus of bi-component filament can be regarded as a constant, which can be obtained by measuring the slope of the curve in this stage. After the curve passes a yield point (B), it enters into the third stage, in which the filament continued to be elongated up to the rupture.

PTT and PET are both polyester polymers and hence have high compatibility in the side-by-side bi-component fiber, yielding a strong adhering interface between the two components. Let ε_1, ε_2 and ε, denote the strains of PET and PTT components, and the PET/PTT fiber, respectively. In the same convention, three sets of symbols, (F_1, F_2 and F), (A_1, A_2 and A) and (E_1, E_2 and E), are also used to denote the forces, the cross-section areas, and the elastic moduli for the two separate components and the fiber. Thus, we have

$$\frac{F_1}{A_1\varepsilon_1} = E_1 \tag{3}$$

$$\frac{F_2}{A_2\varepsilon_2} = E_2 \tag{4}$$

$$\frac{F}{A\varepsilon} = E \tag{5}$$

When F is applied to the PTT/PET fiber, both components are extended in the same rate as the

Table 2. The areas and second moments of two components in the cross-sections of PTT/PET fibers

Fiber	CM800	ESS	X55
Area of PET in cross-section A_1 (μm^2)	74.94	81.56	64.64
Area of PTT in cross-section A_2 (μm^2)	52.78	129.57	64.64
Second moments of PET I_{1P} (μm^4)	1217.39	1713.13	1098.05
Second moments of PTT I_{2P} (μm^4)	780.69	1836.03	1098.05

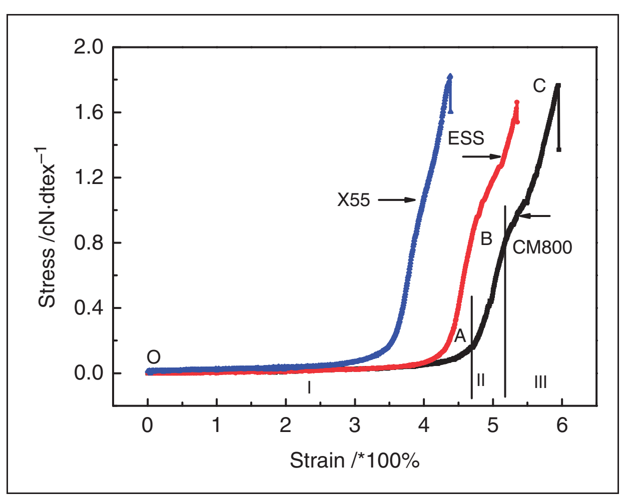

Figure 3. Stress–strain curves of three heat-treated PTT/PET filaments.

filament is, i.e., $\varepsilon_1 = \varepsilon_2 = \varepsilon$. It is obvious to have $A_1 + A_2 = A$ and $F_1 + F_2 = F$. After the simple substitutions, we obtain

$$E_1A_1 + E_2A_2 = E(A_1 + A_2) \tag{6}$$

The fibers' elastic moduli (E) obtained from the stress-strain curves were $1.928\,\text{cN}\cdot\text{dtex}^{-1}$, $2.351\,\text{cN}\cdot\text{dtex}^{-1}$ and $2.114\,\text{cN}\cdot\text{dtex}^{-1}$ for CM800, ESS and X55, respectively. The cross-sectional areas (A_1 and A_2) of PET and PTT components were listed in Table 2. By substituting E, A_1, and A_2 in Equation (6) with the data of any two of the three fibers, we can get the solutions for the two unknown variables, E_1 and E_2. As shown in Table 3, the data from three combinations of the fibers yield slightly different E_1s and E_2s, indicating that there is no obvious discrepancy in the degrees of orientation and crystallinity of PET and PTT components in these three bi-component fibers. On the other hand, we may use the average of three elastic moduli of PET and PTT components to represent the elastic moduli of PTT and PET in the side-by-side filament and to calculate their average specific value (m) as follows:

$$m = E_2/E_1 = 0.333$$

From Table 3, it was noticed that PTT component exhibits a lower modulus than PET component in a side-by-side fiber, which could be attributed to the helical crimp structure of the PTT/PET fiber.

Differential shrinkage between PTT and PET components

A pure PTT fiber usually has higher shrinkage than that of a pure PET fiber. However, when they adhere to each other in the PTT/PET fiber, the shrinkage behavior of the bi-component filament is different from that of anyone of the individual components. We have found that the ratio of the elastic modulus of PTT and PET is 0.333. The crimp curvature of these three fibers may be calculated by Equation (2), and the results are tabulated in Table 4 in the second column. The curvature had been calculated by using a standard helical line equation in our previous research.[14] The only unknown parameter is the differential shrinkageΔ. Based on Equation (2), Δs of the three fibers can be obtained and displayed in the fourth column, which range from 6.80% to10.01%.

The Δ values in the table indicate that the two components underwent a complete shrinkage after the bi-component filament was heat treated. The different shrinkage of the two components tended to decline if the temperature and time of heat treatment were not sufficient. The Δ is also associated closely with the interface area of two components in the bi-component fiber, which is a relatively complex topic that needs to be addressed in the future research. Among the three fibers, ESS has the highest Δ. This is due to the large contact area of the two components.

Other parameters, such as cross-sectional shape, fiber fineness and component ratio of bi-components fiber, are needed in the calculation of the crimp curvature using Equation (1) when the elastic modulus ratio m and the differential shrinkage Δ have been determined.

Effects of elastic modulus ratio and differential shrinkage on crimp curvature

Figure 4 displays the crimp curvatures of PTT/PET fibers with three different cross-sections (gourd, round, and dumbbell) when the elastic modulus ratio varies in the range of 0–1 and the differential shrinkage varies in the range of 0–10%. The crimp curvatures of the three PTT/PET fibers, CM800, ESS and X55, are highlighted by a black solid square in the figures.

Figure 4 demonstrates that crimp curvatures of the three bi-component fibers increase with the increase of their differential shrinkages regardless of the cross-section shapes. Similar results were reported in [8, 9]. It was found that the crimp contractions of the bi-component fibers made from PTT or modified PET polymers with different degrees of viscosity, increased

Table 3. Elastic moduli of materials

Elastic modulus	Equation sets: CM800 and ESS	ESS and X55	CM800 and X55	Average
E_1 (cN·dtex^{-1})	3.166	3.156	3.186	
E_2 (cN·dtex^{-1})	1.056	1.071	1.042	
$m = E_2/E_1$	0.3335	0.3394	0.3271	0.3333

Table 4. Differential shrinkage between PTT and PET components in the three fibers

Fiber	Constant coefficient C (mm^{-1})	Crimp curvature* ρ (mm^{-1})	Differential shrinkage Δ (%)
CM800	114	7.757	6.80
ESS	69.9	6.998	10.01
X55	96.8	8.488	8.77

*Calculated with a standard helical line equation.[14]

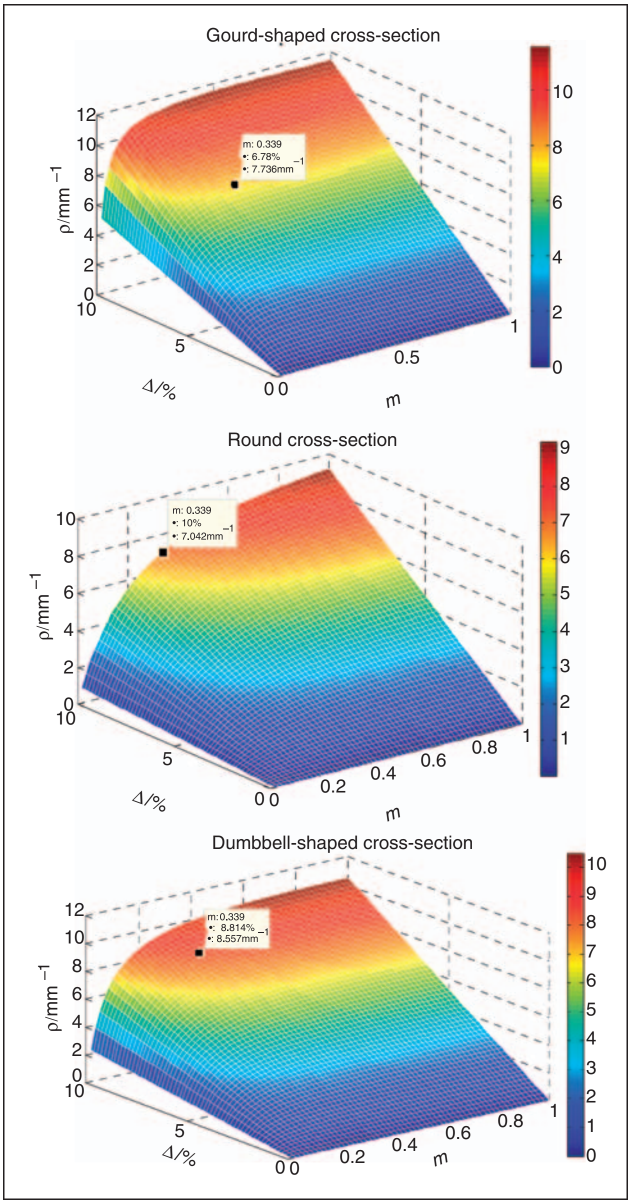

Figure 4. Crimp curvatures changing with elastic modulus ratio and differential shrinkage of PTT/PET fibers that have gourd, round and dumbbell-shaped cross-sections.

when the differential shrinkage between the two components increased. However, the differential shrinkage of the two components is restricted by the intrinsic properties of the material, and the crimp curvature of the fiber will be limited in a certain range. In addition to the differential shrinkage, the elastic modulus ratio also plays an important role in influencing the crimp curvature. The crimp curvature increases rapidly when the m increases from 0 to 0.5, and then approaches to a stable value when m is larger than 0.5.

The bi-component filament with the dumbbell-shaped cross-section has an advantage to achieve higher crimp curvature over the fibers with other two cross-sectional shapes. As shown by the highlighted data in Figure 4, the crimp curvatures of the three typical PTT/PET fibers have not reached their highest values. It is already known that changing the viscosity of the polymer or the spinning temperature and the draw ratio can improve the crimp curvature of a PTT/PET fiber [15]. The estimated values of differential shrinkage and elastic modulus ratio found in this research provide necessary information in designing new PTT/PET fibers. When the cross-section shape and components distribution of bi-component fiber are known, the crimp curvature can be calculated easily from Equation (1) without actual spinning experiments. Furthermore, the predicted parameters are useful for understanding the elastic elongation of the PTT/PET bi-component fiber.

Conclusions

This paper explored the two major factors that affect fiber crimp curvature of side-by-side PTT/PET fibers, elastic modulus ratio and differential shrinkage of the two components, based on the self-crimping theory. From the stress-strain curves of three PTT/PET fibers and their cross-sections, the average elastic modulus ratio of PTT and PET components was found to be 0.333. The crimp curvature expressions of the PTT/PET fibers were established, showing the differential shrinkage between PTT and PET components were in the range of 6.8–10.01%. It was also found that the elastic modulus ratio m has a significant influence on the crimp curvature only when m is in the range of 0 to 0.5, and the crimp curvature increased with the increase of components' differential shrinkages regardless of cross-section shapes. The bi-component fiber with a dumbbell-shaped cross-section has an advantage in getting a higher crimp curvature over fibers with a gourd-shaped or round cross-section.

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Conflict of interest statement

None declared.

References

1. Timoshenko SS. Analysis of bi-metal thermostats. *J Opt Soc Am* 1925; 11: 233–255.
2. Brown TD and Onions WJ. A theory for the development of wool fiber crimp on drying. *J Text Inst* 1961; 52: 101–108.

3. Brand RH and Backer S. Mechanical principles of natural crimp of fiber. *Textile Res J* 1962; 32: 39–49.
4. El-Shiekh A, Bogdan JF and Gupta RK. The mechanics of bi-component fibers. *Textile Res J* 1961; 41: 281–297.
5. Gupta BS and George W. A theory of self-crimping bicomponent filaments. *Textile Res J* 1975; 45: 338–349.
6. Denton MJ. The crimp curvature of bi-component fibers. *Text Inst* 1982; 73: 253–263.
7. Kotek R. Recent advances in polymer fibers. *Polym Rev* 2008; 48: 221–229.
8. Tae HO. Melt spinning and drawing process of PET side-by-side composite fibers. *J Appl Polym Sci* 2006; 101: 1362–1367.
9. Tae HO. Effects of spinning and drawing conditions on the crimp contraction of side-by-side Poly (trimethylene terephthalate) bi-component fibers. *J Appl Polym Sci* 2006; 102: 1322–1327.
10. Rwei SP, Lin YT and Su YY. Study of self-crimp polyester fibers. *Polym Engin Sci* 2005; 45: 838–845.
11. Wang K, Luo J, Xu GB and Wang FM. Stretching and elastic recovery of PTT/PET self-crimping filament. *Chin Synth Fiber* 2009; 38: 15–19.
12. ASTM D2256. *Standard test method for ensile properties of yarns by the single-strand method*. ASTM International, 2007.
13. Qian YH, Wang FM and Zhao L. *Development of PTT fiber and produce*. Beijing: China Textile Publishing House, 2006, pp.36–39.
14. Luo J, Xu GB and Wang FM. External configuration and crimp parameters of PTT (polytrimethylene terephthalate)/PET (polyethylene terephthalate) conjugated fiber. *Fiber Polym* 2009; 10: 508–512.
15. Shi MW and Xiao H. The crystallinity and orientation structures and crimp properties of PET/PTT bicomponent filament. *Chin Polym Bull* 2009; 22: 37–44.