Melt Spinning and Drawing Process of PET Side-by-Side Bicomponent Fibers

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ABSTRACT: The change of crimp contraction and shrinkage in the melt spinning and drawing process of polyethylene terephthalate (PET) side-by-side bicomponent fibers was studied. Regular PET and modified PET were selected to make a latent crimp yarn. The modified PET was synthesized to increase thermal shrinkage. The crimp contraction is mainly dependent on drawing conditions such as draw ratio, heat-set temperature, and drawing temperature. Difference in shrinkage between the PET and the modified PET causes the self-crimping of bicomponent fibers. Although changing the heat-set temperature and the drawing temperature can not affect dimensional change, the crimp contraction varies with those variables. As the heat-set temperature and the drawing temperature decrease, the crimp contraction increases. Difference in elongation also affects the crimp contraction in the effect of draw ratio. When the modified PET with neopentyl group was used for highly shrinkable part, the crimp contraction is greater in comparison with modified PET with dimethyl isophthalate. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 101: 1362–1367, 2006

Key words: side-by-side; bicomponent fibers; draw ratio; latent crimp; crimp contraction

INTRODUCTION

It has been developed progressively in the field of melt spinning process with a special function,[1–4] especially using polyethylene terephthalate (PET). New fiber[5] has the superior function and special applications in comparison with natural and regular homo fibers. The new fibers possess a very wide applicability for various textile products, such as clothing, furnishings, and technical textiles. There has been a great development in the technology of manufacturing them. Bicomponent melt spinning technology is mainly used to make the new fibers. Wool is a natural bicomponent fiber, and the side-by-side bicomponent fibers were developed to imitate the crimp property of wool.[6] The self-crimping property of wool results from its unique structure consisting of ortho-cortex and para-cortex adhering to each other, and it gives the stretch and recovery to woven fabric. Timoshenko[7] used bimetallic theory to describe the self-crimping behavior. Brown and Onions[8] applied Timoshenko's theory to fibers. Brand and Becker[9] have developed a more general theory that the crimp curvature is proportional to the differential length change and inversely proportional to the fiber thickness. Gupta and George[10] revealed the relation between the crimp curvature and the deformation of bicomponent fibers.

Fitzgerald and Kundsen[11] formulated the equations to explain the relation of fiber curvature, differential shrinkage, fiber thickness, and cross-sectional component distribution.

In this study, the crimp contraction and the thermal shrinkage in the bicomponent fiber consisting of two different PET were studied. Effect of drawing conditions on crimp contraction was examined. The modified PET comprising highly shrinkable part was selected to make latent crimp yarn.

EXPERIMENTAL

Polymer constituent

The polymers selected in this work were regular PET and modified PET. Both polymers are textile grade, and their specifications are presented in Table I. Here, co-PET means the modified PET.

Melt spinning and drawing

The side-by-side bicomponent melt spinning apparatus MST-II, manufactured by SYNTEX (UK), and the drawing apparatus DW-II, manufactured by Ishikawa Seisakusho (Japan), were employed to carry out the experiment. A spinneret plate with 36 bores, bore diameter of 0.30 mm and length to diameter ratio of 2, was employed. The spinning and drawing conditions are summarized in Table II.

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TABLE I
Specifications of PET Polymer Used for Bicomponent Fiber

	PET	co-PET-1	co-PET-2	co-PET-3
Intrinsic viscosity (dL/g)	0.64	0.66	0.68	0.66
Isophthalic acid (IPA)	–	8	6	0
Neopentyl glycol (NPG)	–	0	6	8

Crimp contraction

Under a tension of 45 mg/dtex, a sample of a bundle of yarns of 3333 dtex was obtained. The sample was heat-treated in hot water of 100°C for 20 min under a load of 0.45 mg/dtex, without causing tangling of the yarn, whereby a latent crimp was developed. After removing the load, the sample was cooled for 4 h and dried in the air. One minute after supplying a load of 1.8 mg/dtex to the dried sample, length L_1 of the yarns was measured. After measuring L_1, a load of 1.8 + 180 mg/dtex was applied to the sample, and after 1 min, length L_2 of the yarns was measured. The crimp contraction was calculated according to eq. (1), below, using the measured L_1 and L_2 values.

$$\text{Crimp contraction (\%)} = \{(L_2 - L_1)/L_2\} \times 100 \quad (1)$$

Birefringence

The retardation of the optical path of as-spun fibers was measured using a Nikon Optical-Pol polarizing microscope and was measured by compensator method. The wavelength was fixed to 546 nm. The birefringence was calculated using the following equation, where Δn is the birefringence, Γ the retardation of the optical path, and d the thickness of sample.[12,13]

$$\Delta n = \frac{\Gamma}{d} \quad (2)$$

Density

Density was measured on small loops of filaments with a density gradient column at 23°C, which con-

tains n-heptane and carbon tetrachloride. Volume fraction crystallinity (X_ν) was calculated from the measured filament density (ρ), using the following equation:

$$X_\nu(\%) = \frac{\rho - \rho_a}{\rho_c - \rho_a} \times 100 \quad (3)$$

where ρ_c and ρ_a are the densities of fully crystalline and amorphous polymers, respectively. For PET, ρ_c of 1.455 g/cm^3 and ρ_a of 1.335 g/cm^3 were used.[14]

Shrinkage

A sample of yarn of 3333 dtex was obtained. After supplying a load of 1.8 mg/dtex to the sample that caused no deformation, length L_i of the yarn was measured. The sample was immersed in boiling water for 30 min. After removing the load, the sample was cooled for 4 h and dried in the air. A load of 1.8 + 180 mg/dtex was applied to the sample, and after 1 min, the length L_f of the yarns was measured. The shrinkage was calculated according to eq. (4), below, using the measured L_i and L_f values.

$$\text{Shrinkage(\%)} = \{(L_i - L_f)/L_i\} \times 100 \quad (4)$$

RESULTS AND DISCUSSION

Figure 1 shows the cross section of as-spun bicomponent fiber and the side view of drawn fibers after boiling in hot water. There is curvature between PET and co-PET due to melt viscosity difference. After boiling, the latent crimp reveals, the number of curls increases, and the size of the crimp decreases.

Effect of draw ratio

Figure 2 is a plot of the crimp contraction with respect to the draw ratio. The crimp contraction increases with draw ratio. This is caused by a shrinkage difference due to the molecular chain orientation difference between PET and co-PET after drawing. The crimp contraction increases smoothly in the range of 30–42%, and the co-PET-2, including higher amount of comonomer, reveals the highest crimp contraction. Bicomponent fiber using co-PET-3 has greater crimp contraction than fiber using co-PET-1. Figures 3 and 4

TABLE II
Spinning and Drawing Conditions

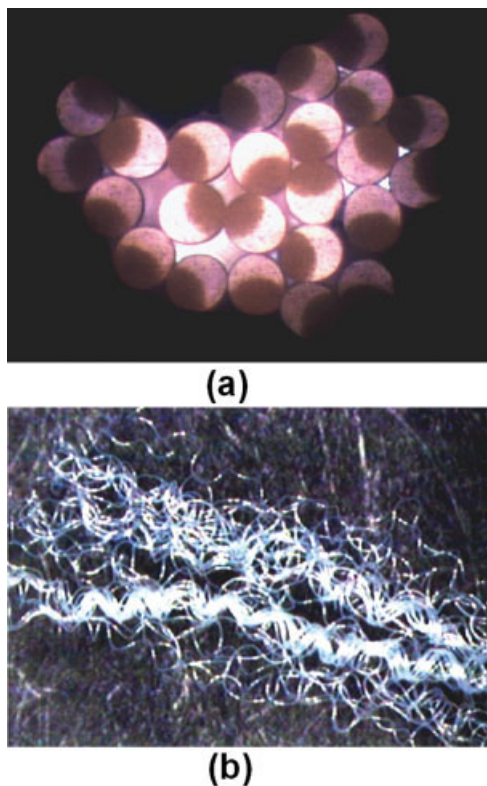| Variables	Conditions
Mass flow rate (g/min)	38.8
Spinning temperature (°C)	290
Take-up speed (m/min)	1500
Quench air speed (m/s)	0.45
Drawing temperature (°C)	80, 85, 90, 95
Draw ratio	2.7, 2.8, 2.9, 3.0, 3.1
Heat-set temperature (°C)	125, 135, 145, 155
Drawing speed (m/min)	600

Figure 1 Cross-section (a) of as-spun fiber (×400) and side view (b) of side-by-side latent crimp yarn after boiling (×40). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 3 Shrinkage of homofilament as a function of draw ratio.

show the shrinkage and shrinkage difference in the homofilament, which was spun at the same spinning conditions with bicomponent spinning. Shrinkage difference means the difference in shrinkage between PET and co-PET homofilaments. The shrinkage de-

creases with draw ratio, and the shrinkage difference slightly increases. An increased shrinkage difference between two polymers with draw ratio leads to increase in crimp contraction. The shrinkage and difference in shrinkage of co-PET-2 have largest value followed by co-PET-3. The chemical structure of neopetyl glycol (NPG) is more flexible than that of isophthalic acid (IPA), and thus, the shrinkage of co-PET-3 is greater than that of co-PET-1. However, the variation in shrinkage difference with draw ratio is relatively small in comparison with the change in crimp contraction. This may be due to the elongation difference between two components with respect to the draw ratio. Figures 5 and 6 are plots of the elongation at break and the elongation difference in homofilament. The elongation difference means the difference in elongation at break between PET and co-PET homo-
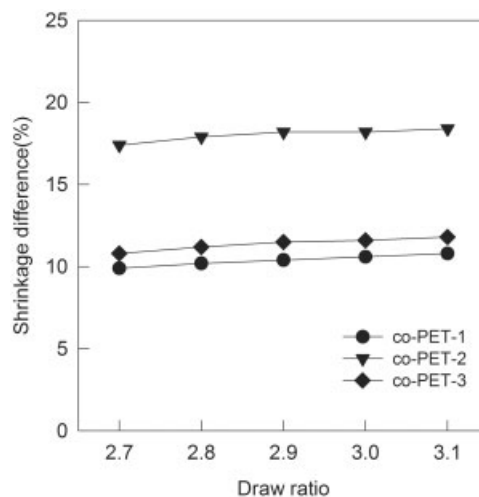

Figure 2 Crimp contraction as a function of draw ratio; spinning temperature: 290°C, spinning speed: 1500 m/min, drawing temperature: 80°C, heat-set temperature: 125°C.

Figure 4 Shrinkage difference between PET and co-PET as a function of draw ratio.
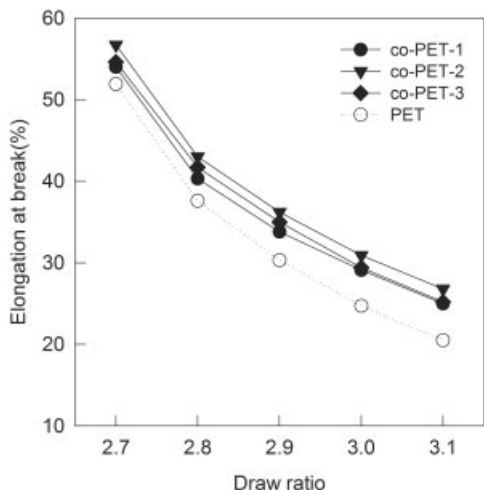
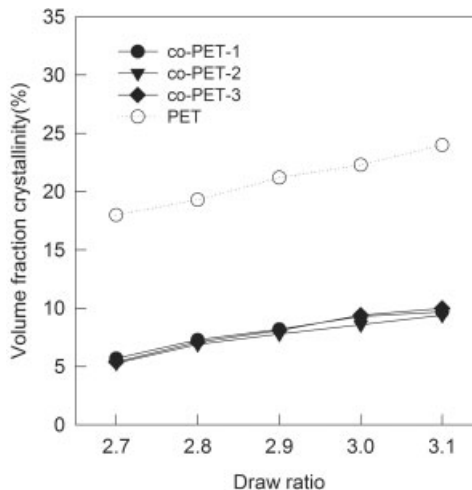**Figure 5** Elongation at break as a function of draw ratio.

Figure 7 Volume fraction crystallinity as a function of draw ratio.

filaments. The elongation at break of co-PET is greater than that of PET at the same draw ratio. The elongation at break decreases with draw ratio, and the elongation difference increases. It can be inferred from Figure 5 that the molecular chain of co-PET in the bicomponent spinning stretches larger than its original obtainable extension in the homofilament spinning. The extension difference adds the effect of draw ratio on crimp contraction in company with shrinkage difference effect. Figures 7 and 8 show the volume fraction crystallinity and birefringence of homofilament. Both volume fraction crystallinity and the birefringence increase with draw ratio, but an increase in crystallinity is small in comparison with birefringence increase. Birefringence is related to crystallinity, crystal orientation, and amorphous orientation.[13] In general, the crystallinity increases with draw ratio, but in the case of bicomponent filament, the increase of crys-

tallinity with draw ratio was not relatively large in the range of draw ratio selected in this experiment. This shows that the crimp contraction of bicomponent fiber is mainly affected by the amorphous orientation because the oriented amorphous molecule shrinks easily after boiling water treatment.

Effect of heat-set temperature

Figure 9 shows the crimp contraction as a function of heat-set temperature. Crimp contraction decreases with heat-set temperature. The change of heat-set temperature is not accompanied with dimensional change at a fixed draw ratio. Although there is no longitudinal dimensional change with the heat-set temperature, the change in crimp contraction is significant. The extension of molecular chain is the same at a fixed draw ratio, but the crimp contraction varies with heat-set
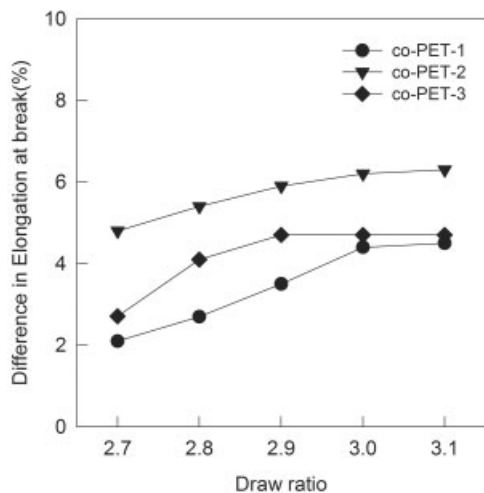

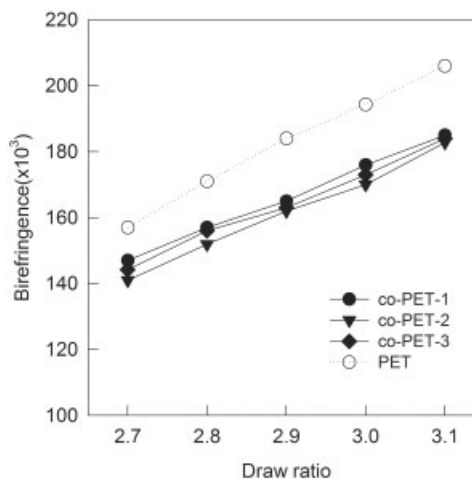**Figure 6** Difference in elongation at break between PET and co-PET as a function of draw ratio.

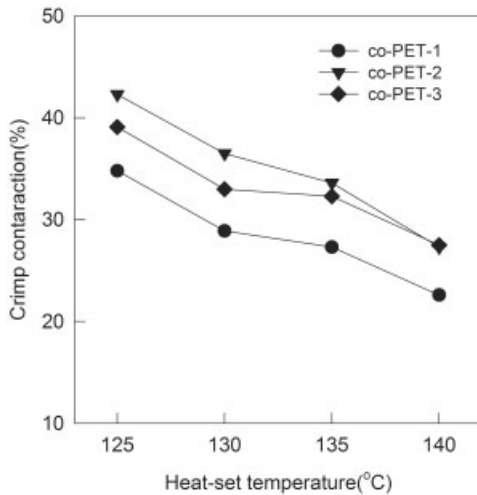**Figure 8** Birefringence as a function of draw ratio.

Figure 9 Crimp contraction as a function of heat-set temperature; spinning temperature: 290°C, spinning speed: 1500 m/min, drawing temperature: 80°C, draw ratio: 3.1.

temperature. This is due to the shrinkage difference with heat-set temperature. Figures 10 and 11 are plots of shrinkage and shrinkage difference with heat-set temperature. Shrinkage and its difference decrease with heat-set temperature. As the heat-set temperature increases, the crystal structure is stabilized, and the relaxation of amorphous oriented molecules is restricted. This leads to decrease in shrinkage difference, and induces the bicomponent fiber to lower crimp contraction yarn at higher heat-set temperature.

Effect of drawing temperature

The change of drawing temperature is not accompanied with dimensional change, but it affects the crimp contraction of bicomponent fibers. The crimp contraction decreases with drawing temperature (Fig. 12).
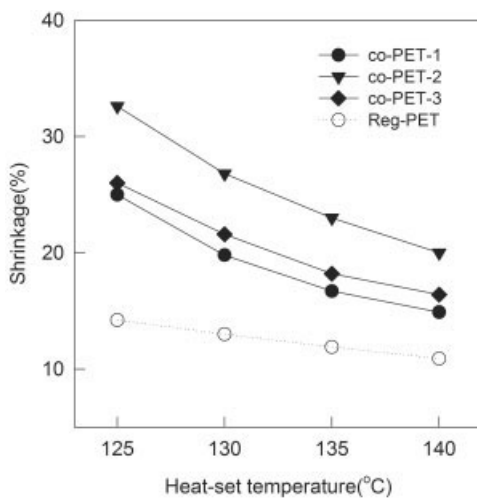

Figure 10 Shrinkage as a function of heat-set temperature.
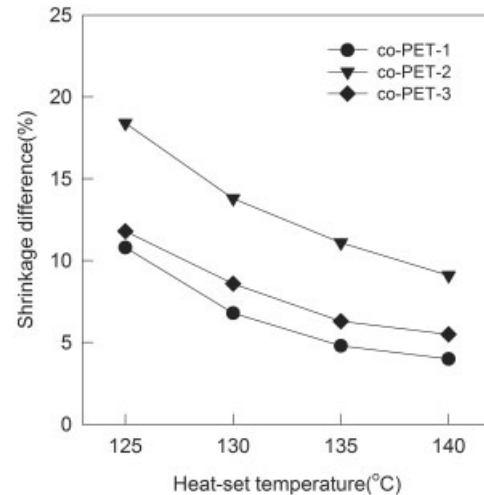

Figure 11 Shrinkage difference as a function of heat-set temperature.

Figures 13 and 14 are plots of shrinkage and difference in shrinkage with respect to drawing temperature. Shrinkage and difference in shrinkage decrease with drawing temperature. Decrease in difference in shrinkage with drawing temperature induces to decrease in crimp contraction. In a previous work of Tereda et al.,[15] when drawing was performed at over glass transition temperature, the shrinkage decreased with drawing temperature. The same trend is revealed in this experiment. Birefringence decreases with the drawing temperature (Fig. 15). Since the molecular chain has high mobility at a higher drawing temperature, the amorphous orientation is easy to relax. Thus, the birefringence decreases at a higher drawing temperature, and this leads to a decreased thermal shrinkage.
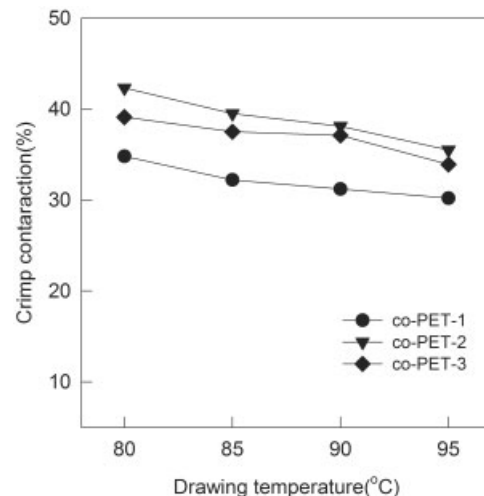

Figure 12 Crimp contraction as a function of drawing temperature; spinning temperature: 290°C, spinning speed: 1500 m/min, draw ratio: 3.1, heat-set temperature: 125°C.
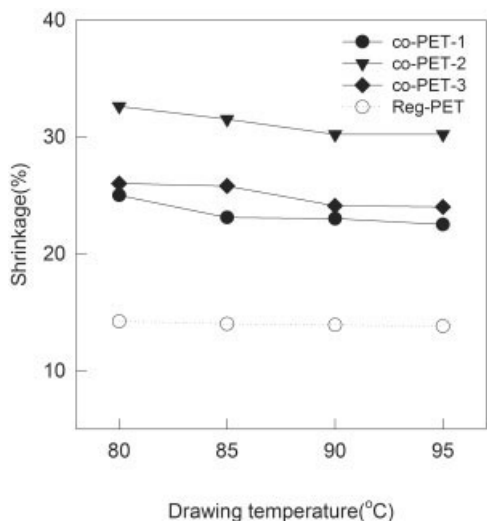
Figure 13 Shrinkage as a function of drawing temperature.

Figure 15 Birefringence as a function of drawing temperature.

CONCLUSIONS

The effect of process conditions on crimp contraction in the side-by-side bicomponent spinning, and drawing of PET and modified PET was studied. Draw ratio, heat-set temperature, and drawing temperature are the main effective process variables. Difference in shrinkage between two polymers is the main cause to induce crimp contraction. Difference in elongation affects crimp contraction in the effect of draw ra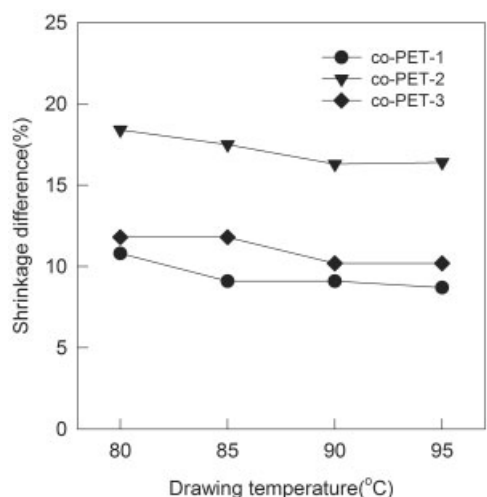tio. Although there is no dimensional change with heat-set temperature and drawing temperature, they have an influence on the crimp contraction. As the draw ratio increases, and the heat-set temperature and the drawing temperature decrease, the crimp contraction increases. Obtainable maximum crimp contraction is 42% at a draw ratio of 3.1, heat-set temperature of 125°C, and drawing temperature of 80°C. When the modified PET with neopentyl group was used for highly shrinkable part, the crimp contraction is greater in comparison with modified PET with dimethyl isophthalate.

Figure 14 Shrinkage difference as a function of drawing temperature.

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