

Effect of Spinning Speed on the Structure and Physical Properties of Filament Yarns Produced from Used PET Bottles

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ABSTRACT: In the previous work (S. Kiantash, MS Thesis, Amirkabir University of Technology, Textile Engineering Department, Tehran, Iran, 2002), the possibility of producing filament yarns from used PET bottles was investigated and the production was successfully carried out. To improve physical properties and to have a detailed understanding of the molecular structure, spinning variables such as the take-up speed (one of the most influencing factors) should be varied and studied. In the present work, continuous filament yarns from virgin PET chips and used PET bottles were produced at the two take-up speeds of 2500 and 3000 m/min. Optical birefringence, crystallinity (obtained from three methods including density, calorimetry, and FTIR), tenacity, breaking elongation, initial modulus, and shrinkage of yarns were measured and compared. Optical birefringence and crystallinity (ob-

tained from all three methods) of used samples show higher values compared with those of virgin samples produced at both take-up speeds. Consequently, the tenacity of used samples is higher and breaking elongation is lower. Generally, samples having bigger crystallinity present higher initial modulus and smaller shrinkage. However, results of initial modulus and shrinkage do not correspond to this assumption. As it was predicted, increasing the take-up speed resulted in an increase in the optical birefringence, crystallinity, tenacity, and initial modulus and a reduction in the breaking elongation of both virgin and used samples. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 103: 3972–3975, 2007

Key words: recycling; polyester; filament; spinning speed; bottle

INTRODUCTION

Polymers are used in a wide range of applications. After usage, these materials are degraded during a very long time and therefore this can create a big problem in environmental protection. Although polymers consist of only 7% of the total solid waste, due to low density, their volumetric fraction is 25–30%.¹ PET is one of the most important polymers whose application is increasingly growing. Consequently, researchers and scientists pay more attention to the recycling of PET.² PET is used in two main products: bottles and textile fibers. Bottles for drinks, drinking water, oil, detergent, etc., are usually made from bottle grade PET.³

The recycling methods applied for PET are as follows: mechanical recycling, chemical recycling, and energy recycling (burning).

Mechanical recycling is the most common and economic method. This method consists of collecting and separating bottles, grinding, and finally extrud-

ing them. Heat and stress applied during this method changes some physical properties of PET.^{4,5} It should be pointed out that PET chips or flakes have to be dried before extrusion, otherwise the molecular weight will be reduced from 1/2 to 1/3 of the initial molecular weight. The moisture content of PET should not exceed from 0.005% in melt spinning process.⁶ Production of staple fibers from used PET bottles has been reported but there is no published information about continuous filament yarns.⁷

Mannhart⁸ showed that melting reduces intrinsic viscosity (IV). Intrinsic viscosity of bottle grade PET is higher than that of fiber grade PET. Therefore, melting of used PET bottles prepares suitable viscosity for melt spinning.

EXPERIMENTAL

Virgin PET chips with the IV of 0.60 and density of 1.353 g/cm³ and used PET bottle flakes having the IV of 0.69 and density of 1.382 g/cm³ were used as the starting material in this study. An automatic pilot plant spinning machine was used for spinning filament yarns at the spinning temperature of 275°C and the take-up speeds of 2500 and 3000 m/min. Intrinsic viscosity of PET was measured using 40/60

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TABLE I
Density and Crystallinity of Yarn Samples

Spinning speed (m/min)	Density (g/cm ³)		Density loss (%) (compared to the starting material)		Crystallinity (X _d , %)	
	Virgin	Used	Virgin	Used	Virgin	Used
	2500	1.340 (0.046)	1.341 (0.004)	0.96	2.97	3.86
3000	1.347 (0.005)	1.355 (0.006)	0.44	1.95	9.21	15.26

Note, the numbers in brackets indicate standard deviation.

mixture of 1,1,2,2 phenol and tetra chloro ethane according to ASTM D 4603.

Measurement of density (ρ) was carried out using carbon tetrachloride with the density of 1.594 g/cm³ and toluene with the density of 0.867 g/cm³ at the temperature of (20 ± 4)°C. Density based crystallinity (X_d) was calculated from the following equation:

$$X_d = \frac{\rho - \rho_{am}}{\rho_c - \rho_{am}} \times \frac{\rho_c}{\rho}$$

where $\rho_{am} = 1.335$ g/cm³ and $\rho_c = 1.478$ g/cm³ are the density of amorphous and crystalline areas, respectively.⁹

Crystallinity of samples was also obtained from DSC method using a TA instrument. Calorimetry based crystallinity (X_{DSC}) was calculated from the following equation:

$$X_{DSC} = \frac{\Delta H_m - \Delta H_c}{\Delta H_{ref}} \times 100$$

ΔH_m refers to the measured melting enthalpy, ΔH_c is the crystallization enthalpy induced during DSC test and ΔH_{ref} refers to 100% crystalline polymer, which in the case of PET equals to 140 ± 20 J/g.¹⁰

Crystallinity index (CI) was obtained using a Nicolet FTIR instrument from dividing the amplitudes at the wavelengths of 868–1410 cm⁻¹.¹⁰

$$CI = \frac{A(868)}{A(1410)}$$

An interference Carl-Zeiss microscope was employed to measure optical birefringence and an Instron for evaluating the tensile properties. Shrinkage of yarns was measured using an oven at the temperature of 120°C.

RESULTS AND DISCUSSIONS

Density and crystallinity calculated from the density of samples are given in Table I. As it can be seen, higher the take-up speed results in higher density and crystallinity of both virgin and used samples. This increase is bigger in the case of used samples. Higher degradation of used PET during the melt spinning process, as it can be found in density loss of used PET, may prepare suitable conditions for improved order of molecular structure leading to higher crystallinity and density.

DSC thermographs of starting materials and yarns are illustrated in Figures 1 and 2.

Thermal properties obtained from DSC thermographs are summarized in Table II. Results indicate that crystallinity of used samples is higher than that of virgin samples at both take-up speeds. Higher level of take-up speed leads to higher crystallinity. Although the absolute values of crystallinity obtained

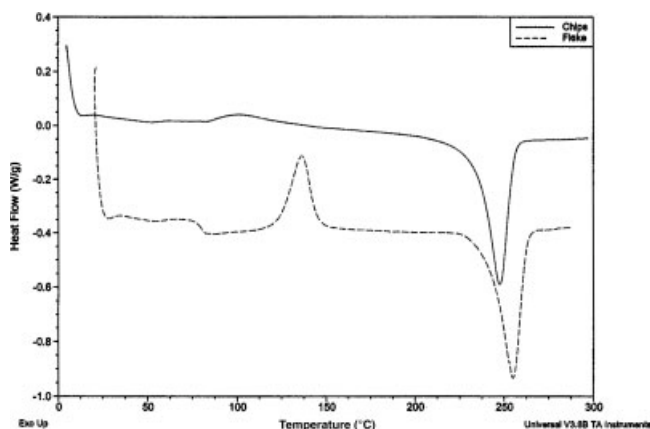


Figure 1 DSC diagrams of starting materials.

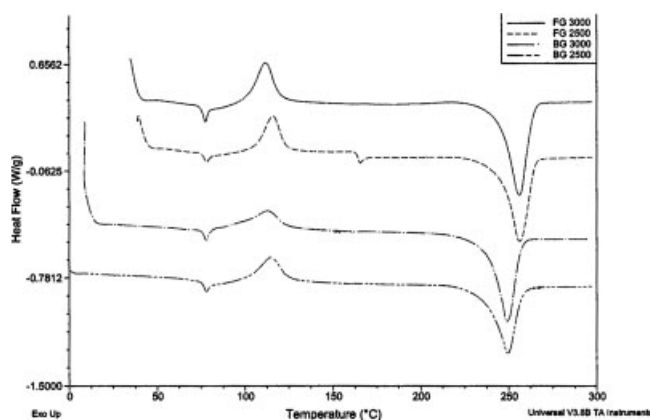


Figure 2 DSC diagrams of yarn samples.

TABLE II
Thermal Properties of Yarn Samples

Spinning speed (m/min)	Glass-transition temperature (°C)		Crystallization temperature (°C)		Melting temperature (°C)		Crystallization enthalpy (J/g)		Melting enthalpy (J/g)		Crystallinity (X_{DSC})	
	Virgin	Used	Virgin	Used	Virgin	Used	Virgin	Used	Virgin	Used	Virgin	Used
2500	75.7 (1.1)	77.0 (1.3)	100.8 (3.6)	101.6 (2.9)	245.1 (0.6)	238.1 (1.0)	20.7 (2.3)	14.3 (1.8)	49.5 (3.2)	38.5 (2.7)	10.6	14.3
3000	77.0 (0.9)	76.4 (1.5)	105.9 (4.4)	96.9 (2.7)	246.1 (0.7)	240.5 (0.8)	15.8 (1.6)	10.9 (1.1)	46.8 (4.0)	43.9 (3.3)	12.1	18.5

Note, the numbers in brackets indicate standard deviation.

TABLE III
Crystallinity Index of Yarn Samples

Spinning speed (m/min)	Crystallinity index	
	Virgin	Used
2500	0.63 (0.09)	0.69 (0.08)
3000	0.67 (0.06)	0.70 (0.11)

Note, the numbers in brackets indicate standard deviation.

TABLE IV
Intrinsic Viscosity of Yarn Samples

Spinning speed (m/min)	IV		IV loss (%)	
	Virgin	Used	Virgin	Used
Starting material	0.60 (0.03)	0.69 (0.04)	–	–
2500	0.56 (0.08)	0.61 (0.04)	6.7	11.6
3000	0.55 (0.05)	0.60 (0.02)	8.3	13.0

Note, the numbers in brackets indicate standard deviation.

from calorimetry are different from crystallinity calculated from density, trends in Tables I and II are similar.

Table III shows crystallinity index obtained from FTIR wavelengths. The results are again similar to density and calorimetry methods, i.e., higher crystallinity indexes are for used samples and for higher level of take-up speed.

To have a sign of changes in the molecular weight and possible degradation during melt spinning process, intrinsic viscosity of starting material and yarn samples were measured. As it can be seen in Table IV, although the take-up speed has a small effect on IV and IV loss, the IV loss of used samples are considerably higher than that of virgin samples. This indicates the higher degradation took place in the melt spinning process of used PET bottles.

Optical birefringence of yarn samples is presented in Table V. Increasing the take-up speed improves optical birefringence. It seems that the conditions, which prepared improved crystallinity of used samples (Tables I–III), here is also in the favor of used samples orientation.

Tensile properties and shrinkage of yarn samples can be seen in Table VI. Tenacity and breaking elongation are strongly dependent on the orientation. Higher tenacity and lower breaking elongation of used samples and yarns produced at the higher take-up speed are in accordance with the birefringence values of samples (Table V). Initial modulus is

TABLE V
Optical Birefringence of Yarn Samples

Spinning speed (m/min)	Optical birefringence (10^3)	
	Virgin	Used
2500	23.20 (0.51)	24.87 (2.06)
3000	30.50 (1.24)	34.75 (8.71)

Note, the numbers in brackets indicate standard deviation.

TABLE VI
Tensile Properties and Shrinkage of Yarn Samples

Spinning speed (m/min)	Linear density (dtex)		Tenacity (cN/tex)		Breaking elongation (%)		Initial modulus (cN/tex)		Shrinkage (%)	
	Virgin	Used	Virgin	Used	Virgin	Used	Virgin	Used	Virgin	Used
2500	121.2 (0.7)	120.1 (0.5)	15.0 (0.8)	18.2 (4.3)	211.2 (13.5)	169.8 (6.6)	74.4 (8.1)	62.8 (10.3)	52.4 (0.2)	60.0 (0.5)
3000	125.4 (0.6)	125.3 (0.8)	17.1 (1.1)	19.0 (4.1)	168.4 (13.9)	136.8 (6.7)	120.1 (8.5)	98.3 (10.6)	60.0 (0.2)	61.5 (0.4)

Note, the numbers in brackets indicate standard deviation.

usually highly related to the crystallinity, crystal size, and somewhat to the orientation. Higher initial modulus of yarns produced at the higher take-up speed for both virgin and used samples are confirmed by their crystallinity values (Tables I–III). However, lower values of initial modulus of used samples are not in accordance to their higher crystallinity values. The crystal size of used samples, which was not measured in this study, might be smaller than that of virgin samples.

Shrinkage of yarns produced at the higher level of take-up speed and from used PET shows higher values. It is difficult to find an acceptable reason, because the lower crystallinity and/or smaller crystal size and unrelaxed stress took place during orientation causes the shrinkage to be increased. However, this hypothesis cannot be perfectly applied in the result of this study.

CONCLUSIONS

Crystallinity and optical birefringence of both virgin and used samples are increased at the higher take-

up speed, and these structural properties of used samples are higher than virgin ones. Higher tenacity and lower breaking elongation of used samples and yarns produced at the higher take-up speed is in accordance to their orientation, but the initial modulus and shrinkage results are not perfectly supported by the crystallinity.

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