Opto-Thermal Properties of Fibers. XV. A Study of the Drawing Behavior of Quenched Poly(ethyleneterephthalates) Fibers

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ABSTRACT: Studies of the mechanical and optical properties of undrawn uniaxially stretched polyester PET (Egyptian manufacture) fibers by annealing and cold drawing were performed. The optical properties and strain produced in PET fibers at different conditions were measured interferometrically at room temperature. A two-beam interferometric technique was used to determine refractive indices and birefringence of the investigated PET samples with strain produced by different stresses. Using a microstrain device attached to a microscope stage and through the application of the appropriate mathematical equations, the refractive indices and the birefringence values were determined as a function of the draw ratios. The resulting data were utilized to calculate the polarizability per unit volume, the number of molecules per unit volume, Poisson's ratio, the strain optical coefficient, and several other parameters and constants. Also, some structural parameters are determined, such as form birefringence, the virtual refractive index, the harmonic mean polarizability of the dielectric, the harmonic mean specific refractivity, and the isotropic refractive index. The generalized Lorentz–Lorenz equation given by de Vries is used to determine PET fiber structure parameters. Comparison between the results have been compared with Hermans' optical orientation function. Relationships between the various optical parameters and the draw ratios are plotted, and the effect of draw ratio on the refractive index profile is studied. Microinterferograms are given for illustration. © 1999 John Wiley & Sons, Inc. J Appl Polym Sci 72: 1869–1880, 1999

Key words: drawing; PET; optical parameters; crystallinity; orientation; birefringence; polarizability

INTRODUCTION

The refractive index and the birefringence values of fibers provide parameters that characterize the structure of polymers on a molecular level. The birefringence depends on the molecular orientation in the polymer fiber, as it contains contributions from the polarizabilities of all the molecular units in the sample.[1]

In recent years, interferometric methods have been used in studying the thermal, mechanical, and chemical properties of natural and synthetic fibers.[5–8] The most readily available techniques for changing the polymeric structure are annealing and quenching.[9–14]

In the study of mechanical properties of a textile fiber, the authors' aim is to establish a connection between the molecular structure and these properties and suggest beneficial modifications in the preparation or processing of the fiber. The mechanical properties are particularly important because they are more quantitative than

any others, such as feel, bestir, or other elusive properties that are dependent on sense perception.

In the case of a synthetic fiber, it is always the concern of the chemist and physicist to understand the effect of the processes on the end product because their tasks are often to produce a certain type of fiber for a specific purpose.[15]

In previous investigations, the drawing behavior of PET fiber was studied by several authors.[16–25]

Molecular orientation is commonly used to improve the properties of polymeric materials. Thus, there is a great deal of interest in knowledge at the molecular level of the phenomena occurring during stretching or annealing or any forming process.

Several techniques have been proposed to measure orientation (including X-ray scattering and Raman spectroscopy).[26] Among all these techniques, interferometry represents a very valuable technique to get an insight into the processes occurring at the molecular level.[27,28]

The present work deals with the influence of experimental conditions of stretching (quenching, cold drawing) on orientation and mechanical parameters in uniaxially stretched polyester (PET), using a two-beam Pluta polarizing interference microscope. In addition, different opto-mechanical parameters effected by thermal treatment are evaluated.

THEORETICAL CONSIDERATIONS

Using the Pluta interference microscope in the case of a totally duplicated image of the fiber to measure the mean refractive indices in parallel and perpendicular directions of PET was discussed in detail elsewhere.[29,30] Also, by applying the equations used by Hermans[31] and Ward,[32,33] we can obtain the optical orientation parameters, as discussed previously in extensive works.

MEAN POLARIZABILITY OF MONOMER UNIT

The polarizability of a monomer unit like the polarizability of a simple organic molecule usually differs in different directions. As the refractive index of a polymer depends on the total polarizability of the molecules, this leads to the Lorentz–Lorenz equation by the following equations[34]:

$$\frac{n_{\parallel}^2 - 1}{n_{\parallel}^2 + 2} = \frac{N_{(1)}\alpha^{\parallel}}{3\Psi} \tag{1a}$$

An analogous formula used for $n_a^{\perp}$, where $n_a^{\parallel}$ and $n_a^{\perp}$ are the mean refractive indices of the fiber for light vibrating parallel and perpendicular to the fiber axis.

$$\frac{\bar{n}^2 - 1}{\bar{n}^2 + 2} = \frac{N_{(1)}\bar{\alpha}}{3\Psi} \tag{1b}$$

where $\bar{n}$ is the average refractive index (isotropic refractive index), $\bar{\alpha}$ is the mean polarizability of a monomer unit, and Ψ is the permitivity of free space equal to $8.85 \times 10^{-12} \ \mathrm{Fm^{-1}}$.

For a bulk polymer of density ρ and monomer unit molecular weight M, the number of monomer units per unit volume $N_{(1)} = \dfrac{N_A\rho}{M}$, where N_A is Avogadro's number 6.02×10^{23}, and M for PET $= 192$.[35] Also, N is the number of carriers of the dipole moment.

de Vries[35] gave a theory on the basis of internal filled with the aid of classical electromagnetic theory, in which he generalized the Lorentz–Lorenz equation; so for monochromatic light, the well-known Lorentz–Lorenz becomes

$$\frac{n^2 - 1}{n^2 + 2} = \frac{N_{(1)}\alpha}{3\Psi} \tag{2}$$

The right-hand member of eq. (2) is proportional to the density ρ (Kg m^3) of the medium and may also be written as

$$\frac{n^2 - 1}{n^2 + 2} = \varepsilon\rho \tag{3}$$

where ε (m^3 Kg) is called the specific refractivity of the isotropic dielectric. Writing this equation for fibers in parallel and transverse components, the generalized Lorentz–Lorenz equations is

$$\frac{n_{\parallel}^2 - 1}{n_{\parallel}^2 + 2} = \frac{N_{(1)}\alpha^{\parallel}}{3\Psi} = \varepsilon_{\parallel}\rho \tag{4}$$

An analogous formula is used for $n_a^{\perp}$.

Also, de Vries defined the invariant refractive index, which he call the "Virtual refractive index" n_V by

Table I Values of the Parameters Characterizing the Deformation Process Relating the Cross-sectional Area

Annealing Temperature (°C)	β	$\gamma \times 10^{-4}$	$\alpha \times 10^3$
120	0.250	−1.728	5.729
140	0.987	−2.870	6.87
160	0.159	−1.987	14.69

$$n_V = \sqrt{1 + \frac{3[n_\parallel^2 - 1][n_\perp^2 - 1]}{[n_\perp^2 - 1] + 2[n_\parallel^2 - 1]}} \quad (5)$$

where the virtual refractive index n_V replaces the isotropic refractive index equation,

$$n_{iso(1)} = \frac{(n_a^\parallel + 2n_a^\perp)}{3} \quad (6)$$

This equation [eq. (5)] leads to the harmonic mean polarizability of the dielectric α_V by the following equation:

$$\alpha_V = \frac{3\Psi}{N_{(1)}} \cdot \frac{n_V^2 - 1}{n_V^2 + 2} \quad (7)$$

Likewise, for the harmonic mean specific refractivity, we have

$$\varepsilon_V = \rho^{-1} \cdot \frac{n_V^2 - 1}{n_V^2 + 2} \quad (8)$$

Hermans[28] defined the optical orientation function as $\dfrac{\Delta n_a}{\Delta n_{max}}$ where Δn_a is the measured birefringence, and Δn_{max} is the maximum birefringence for the fully oriented fiber. The value of Δn_{max} has been previously determined to be[36] (0.24).

The optical orientation function and orientation angle can be calculated using the Hermans' equations[31]:

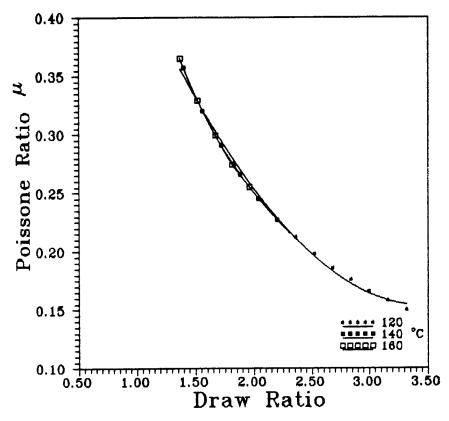$$F_\Delta = \frac{\Delta n_a}{\Delta n_{max}} \quad (9)$$

Figure 1   Relation between Poisson's ratio (μ) of PET fibers, with different draw ratios R at different annealing conditions: annealing temperature, 120, 140, and 160°C; constant annealing time, 4 h.

Table II   Poisson's Ratio and Strain Optical Coefficient

Draw Ratio	Poisson's (μ)	Strain Coefficient (C_e)
1.00 : 1.40	0.357	0.03618
1.40 : 1.56	0.320	0.12443
1.56 : 1.72	0.291	0.08860
1.72 : 1.88	0.266	0.07770
1.88 : 2.04	0.245	0.06950
2.04 : 2.20	0.227	0.06411
2.20 : 2.36	0.212	0.06013
2.36 : 2.52	0.198	0.05999
2.52 : 2.68	0.186	0.05710
2.68 : 2.84	0.176	0.05483
2.84 : 3.00	0.166	0.05247
3.00 : 3.16	0.158	0.05100
3.16 : 3.32	0.150	0.04815
1.00 : 1.40	0.357	0.1239
1.40 : 1.56	0.320	0.1020
1.56 : 1.72	0.291	0.0879
1.72 : 1.88	0.266	0.0743
1.88 : 2.04	0.245	0.0705
2.04 : 2.20	0.227	0.0649
1.00 : 1.37	0.365	0.1524
1.37 : 1.52	0.329	0.1057
1.52 : 1.67	0.299	0.1030
1.67 : 1.82	0.274	0.0847
1.82 : 1.96	0.255	0.0799
1.96 : 2.04	0.245	0.0766

The average value of the optical orientation function $\langle P_2(\theta) \rangle$, due to Ward,[32,33] is given by

$$\langle P_2(\theta) \rangle = \frac{\Delta n_a}{\Delta n_{\max}} \qquad (10)$$

which is the same function named by Hermans.[28] $\langle P_2(\theta) \rangle$ is related to the polarizability, as follows:

$$\frac{\Phi^\| - \Phi^\perp}{\Phi^\| + 2\Phi^\perp} = P_2(\theta_m)\langle P_2(\theta) \rangle \qquad (11)$$

where $\Phi^\|$ and $\Phi^\perp$ are the polarizability parallel and perpendicular to the fiber axis, respectively, where

$$P_2(\theta)_m = \tfrac{1}{2}(3 \cos^2 \theta_m - 1) = \text{const} \qquad (12)$$

Also, eq. (11) can be written in the following form:

$$\frac{\Phi^\| - \Phi^\perp}{\Phi^\| + 2\Phi^\perp} = \left(\frac{\Delta\alpha}{3\alpha_0}\right) \langle P_2(\theta) \rangle \qquad (13)$$

where $\Delta\alpha = \alpha^\| - \alpha^\perp$, the difference between the electric polarizabilities of one molecule when using monochromatic light vibrating parallel and perpendicular to the fiber, respectively.

$\alpha_0 = \tfrac{1}{3}(\alpha^\| + 2\alpha^\perp)$ is the isotropic polarizability, and the quantity $\left(\dfrac{\Delta\alpha}{3\alpha_0}\right)$ depends on the molecular structure and is nearly constant for a given polymer.[35] The values of $\Phi^\|$ and $\Phi^\perp$ can be determined from the following equation, $\Phi^\| = \dfrac{n_\|^2 - 1}{n_\|^2 + 2}$ and the analogous equation for the perpendicular direction $\Phi^\perp$.

In a recent approach to the continuum theory of birefringence of oriented polymer,[27] it was found that the value of F_θ is equal to the following:

$$F_\theta = \left[\frac{n_1^2 \, n_2^2}{n_\|^2 \, n_\perp^2}\right] \cdot \left[\frac{n_\| + n_\perp}{n_1 + n_2}\right] \cdot \frac{\Delta n_a}{\Delta n_{\max}} \qquad (14)$$

which is slightly different from the original simple expression for the degree of orientation used by Hermans.[31] Hermans' optical orientation function F_Δ ($F_\Delta = \langle P_2(\theta) \rangle$) has been corrected by de Vries to be F_θ in the range $0 < \Delta n < 0.8$ as

$$F_\theta = (1 + a)\, F_\Delta - a\, F_\Delta^2$$

where

$$(1 + a) = \frac{2n_1^2 \, n_2^2}{n_V^3 \, (n_1 + n_2)} \qquad (15)$$

n_1, n_2, and n_V are given from de Vries,[35] and $n_V \cong n_{\text{iso}}$, evaluated from eq. (15); so the constant (a) was calculated and found to be (0.8).

DENSITY MEASUREMENT

For PET, de Vries and coworkers found a linear relation between the density and the following parameters[37] by the following relation:

Table III   Values of the Parameters Characterizing the Deformation Process Relating the Birefringence

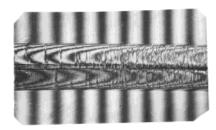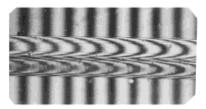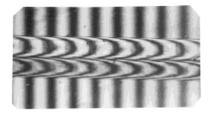| Annealing Temperature (°C)	m	b	C
120	0.1088	-0.1174	9.248
140	0.2752	-1.7096	5.663
160	0.3056	-1.8177	5.052

Plate (1-a)

Plate (1-d)
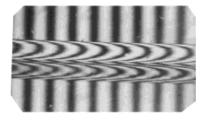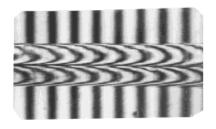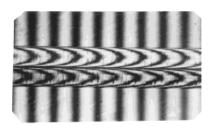

Plate (1-b)

Plate (1-e)

Plate (1-c)

Plate (1-f)

Plate 1 Microinterferograms (a–f) of a totally duplicated image of PET fiber at different draw ratios (1.4 and 1.8), annealed at different annealing temperatures (120, 140, and 160°C) and a constant time (4 h) of λ = 546 nm.

$$\rho = 4.047 \frac{(\bar{n}^2 - 1)}{(\bar{n}^2 + 2)} \qquad (16)$$

where $\bar{n}$ is calculated as the isotropic refractive index from eq. (6).

CRYSTALLINITY EQUATION

The degree of crystallinity χ was determined by the relation.[38]

$$\chi = \frac{\rho - \rho_a}{\rho_c - \rho_a} \qquad (17)$$

where ρ_c are ρ_a the densities of the crystalline and noncrystalline regions, with $\rho_c = 1.457 \times 10^3$ kg m^3 and $\rho_a = 1.336 \times 10^3$ kg m^3.

Volume fraction of amorphous material was determined by the relation:

$$1 - \chi = 1 - \left[\frac{\rho - \rho_a}{\rho_c - \rho_a} \right] \qquad (18)$$
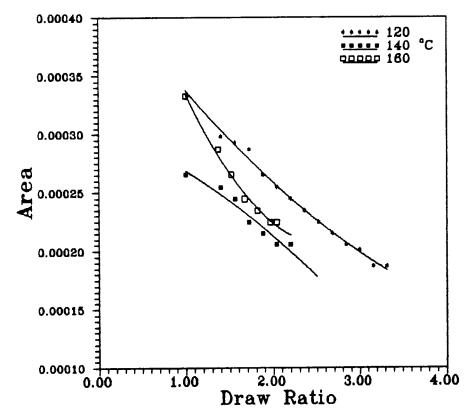
Figure 2 Relation between the cross-sectional area A of PET fibers with different draw ratios R at different annealing conditions: (annealing temperature, 120, 140, and 160°C; constant annealing time, 4 h.

where χ is the volume fraction of crystalline material.

CALCULATION OF THE ISOTROPIC REFRACTIVE INDEX

The specific volume is given by the following equation:

$$(n_{\text{iso}} - 1)V = \text{constant} \tag{19}$$

Also, the Lorentz–Lorenz equation is used to relate polarizabilities and refractive index. We have[39]

$$\frac{n_{\text{iso(2)}}^2 - 1}{n_{\text{iso(2)}}^2 + 2} = \frac{\rho_i}{3\rho}\left[\frac{n_{\parallel}^2 - 1}{n_{\parallel}^2 + 2} + 2\frac{n_{\perp}^2 - 1}{n_{\perp}^2 + 2}\right] \tag{20}$$

where ρ and ρ_i are the density of measured and of the isotropic tested polymer, respectively. Obtained values for $n_a^{\parallel}$, $n_a^{\perp}$, and ρ are used with eq. (20) to determine the isotropic refractive index

values for quenched PET fibers ($\rho_i = \rho_a = 1.336 \times 10^3$ kg m^3).

EXPERIMENTAL RESULTS AND DISCUSSION

Annealing of Samples

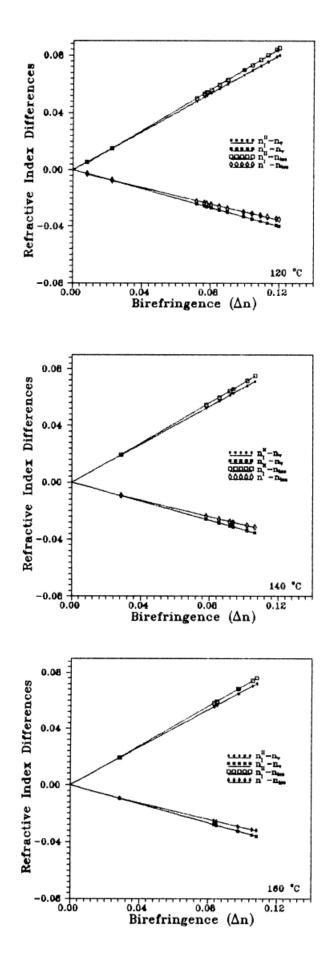For the annealing conditions used, the procedures were outlined in our previous publications,[30,40] and then quenched in ice.

Results

The results show that the cross section of the PET fiber seen by high-power optical microscopy was a perfectly circular shape.[40]

APPLICATION OF TWO-BEAM INTERFEROMETRY

The totally duplicated image of the fiber obtained with a Pluta polarizing interference microscope

with a fiber was used as a manipulation device to calculate the mean refractive indices $n_a^{\parallel}$ and $n_a^{\perp}$ of PET fibers.[41,42]

On straining, the fiber becomes thinner, and both the radius (r) and the cross-sectional area (A) of the fiber decreased with an increase in the draw ratio (R), according to the following empirical formula[43]:

$$A = \frac{\alpha}{\beta}R^{-\beta} + \frac{\gamma}{\beta} \tag{21}$$

where α, β, and γ are parameters that characterize the deformation process.

Using the differential form of eq. (21),

$$\frac{dA}{d \ln R} = \gamma - \beta A \tag{22}$$

The values of the parameters: α, β, and γ are given in Table I. In addition to these parameters, the change in radius (r) can be related to the change in length (ℓ) via the logarithmic Poisson's ratio μ,[43] as defined by

$$\frac{dr}{r} = -\mu\frac{d\ell}{\ell} \tag{23}$$

The average values of μ over different strain ranges are plotted against the birefringence Δn, as in Figure 1.

One of the important coefficients, called the strain optical coefficient C_e, defined as

$$C_e = \frac{d(\Delta n)}{(de)} \tag{24}$$

where e is the strain, was measured in all the strain ranges. The results are given in Table II for both samples.

The birefringence was found to vary with the draw ratio according to the following formula[44]:

$$\frac{d(\Delta n)}{d(\ln R)} = m + b\Delta n \tag{25}$$

Figure 3 Relations between the birefringence Δn and the refractive indices differences ($n^{\parallel} - n_V$, $n^{\perp} - n_V$, $n^{\parallel} - n_{\text{iso}}$ and $n^{\perp} - n_{\text{iso}}$) of fiber at different draw ratios at different annealing conditions: annealing temperature, 120, 140, and 160°C; constant annealing time, 4 h.

Table IV   Refractive Indices $n_a^\#$, and $n_a^\perp$, Isotropic Refractive Indices $n_{iso_{(1)}}$, $n_{iso_{(2)}}$ and Vertical Refractive Index n_V and Orientation Angles θ, θ^* and $N_{(1)}$ the number of Monomer Units per Unit Volume

Draw Ratio	$n_a^\#$	$n_a^\perp$	$n_{iso_{(2)}}$	$n_{iso_{(1)}}$	n_V	θ	θ^*	$N_{(1)} \times 10^2$
Undrawn	1.584	1.575	1.578	1.5743	1.578	53.07	53.37	42.11
1.40	1.605	1.582	1.590	1.5743	1.590	50.29	50.99	42.81
1.56	1.685	1.607	1.633	1.5738	1.631	41.12	42.16	45.31
1.72	1.683	1.611	1.635	1.5739	1.633	42.18	43.10	45.43
1.88	1.685	1.609	1.634	1.5739	1.632	41.37	42.36	45.37
2.04	1.687	1.606	1.633	1.5738	1.631	40.69	41.74	45.32
2.20	1.688	1.603	1.631	1.5737	1.629	39.84	40.99	45.21
2.36	1.690	1.600	1.630	1.5736	1.627	38.98	40.21	45.16
2.52	1.696	1.596	1.629	1.5735	1.626	37.34	38.69	45.12
2.68	1.699	1.595	1.630	1.5734	1.626	36.51	37.91	45.13
2.84	1.701	1.592	1.629	1.5734	1.624	35.60	37.10	45.06
3.00	1.703	1.590	1.628	1.5733	1.623	34.86	36.42	45.02
3.16	1.706	1.588	1.627	1.5732	1.622	33.89	35.55	44.98
3.32	1.707	1.587	1.627	1.5732	1.622	33.59	35.29	44.95
Undrawn	1.607	1.579	1.5	1.5742	1.588	49.14	50.03	42.72
1.40	1.687	1.609	1.635	1.573	1.632	41.12	42.11	45.41
1.56	1.691	1.605	1.634	1.573	1.631	39.81	40.90	45.35
1.72	1.693	1.601	1.632	1.573	1.629	38.70	39.90	45.26
1.88	1.693	1.599	1.630	1.573	1.627	38.29	39.57	45.15
2.04	1.697	1.595	1.629	1.573	1.626	36.89	38.27	45.11
2.20	1.701	1.595	1.630	1.573	1.626	36.13	37.53	45.16
Undrawn	1.610	1.581	1.591	1.5742	1.591	49.17	50.03	42.88
1.37	1.692	1.607	1.635	1.5738	1.633	39.97	41.01	45.44
1.52	1.691	1.607	1.635	1.537	1.633	40.24	41.27	45.44
1.67	1.696	1.599	1.631	1.5737	1.628	37.77	39.03	45.23
1.82	1.697	1.599	1.632	1.5736	1.628	37.71	38.98	45.24
1.96	1.702	1.596	1.632	1.5735	1.628	36.33	37.67	45.24
2.04	1.703	1.595	1.631	1.5734	1.627	35.88	37.26	45.22

which becomes, by integration,

$$\Delta n = \frac{c}{b}R^b - \frac{m}{b} \qquad (26)$$

where c, m, and b are parameters that characterize the deformation process. These parameters are determined, and they are given in Table III for PET sample.

Plate 1(a)–(f) are microinterferograms of the totally duplicated images of PET fibers samples with different draw ratios (1.4 and 1.8) at different annealing conditions (annealing temperature: 120, 140, and 160 ± 1°C; constant annealing time, 4 h). Monochromatic light of 546-nm a wavelength was used. The refractive index of the immersion liquid was selected to allow the fringe shift to be small. Using these interferograms, the mean refractive index of the parallel and perpendicular directions at different draw ratios were

calculated. Plate 1 also shows that the fringes shifts changed as the draw ratio increases and the diameter decreased.

Figure 2 shows the mean cross-sectional area of PET fibers, with different draw ratios. From this figure, the fiber becomes thinner, and the cross-sectional area A of the fiber decreases with increasing draw ratio R.

Figure 3 shows the relation between the birefringence Δn and the refractive indices differences ($n^\| - n_V$, $n^\perp - n_V$, $n^\| - n_{iso}$ and $n^\perp - n_{iso}$). In Figure 3, n_V and Δn_{max} are used to predict the values of refractive indices n_1 and n_2 for fully oriented fibers. These values are found to be 1.80 and 1.56, respectively, at 28°C, which are in agreement with the published values.[24]

Table IV gives some experimental results for annealed PET fibers, refractive indices, the calculated values of the number of monomer units per
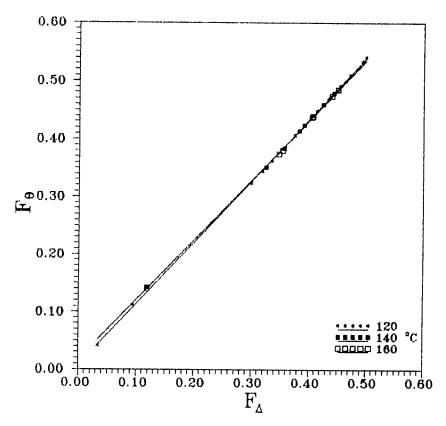
Figure 4   Relation between F_Δ and F_θ of PET fiber due to the change of draw ratios at different annealing conditions: annealing temperature, 120, 140, and 160°C; constant annealing time, 4 h.

unit volume ($N_{(1)}$), the calculated values of virtual refractive index (n_V), and the isotropic refractive index, which was calculated using eqs. (6) and (20), respectively.

Figure 4 shows the relation between corrected values of optical orientation function F_θ and the Hermans' function F_Δ for different draw ratios with annealing fibers at three annealing temperatures, from which F_θ/F_Δ is found to be 1.13 for 120, 140, and 160°C. The calculated values of the orientation angle θ from F_θ and θ' from F_Δ and at different draw ratios are given in Table IV.

In Table V, the calculated values of $\alpha^\parallel$, $\alpha^\perp$, and $\bar{\alpha}$ and the specific refractivity of the isotropic dielectric of parallel and perpendicular and its mean value ($\varepsilon^\parallel$, $\varepsilon^\perp$, and $\bar{\varepsilon}$) at different draw ratios are given for annealing PET fibers.

Figure 5 shows the variation of $\dfrac{\Phi^\parallel - \Phi^\perp}{\Phi^\parallel + 2\Phi^\perp}$ with $P_2(\theta)$ due to changing of draw ratios.

DISCUSSION

Synthetic polymer fibers play an important role in the textile industry, where most textiles now are mixed with synthetic yarns. So, investigation of the characteristics properties of these fibers aid in the main end use.

Thermal processing and drawing of polymer films and fibers are a processes that aim to improve the strength and modulus and other physical and mechanical properties of these materials. It produces an orientation that seeks to gain greater insight at the microstructure level. The degree of orientation, crystallinity, and other structural parameters are correlated to the final fiber end use. So the degree of orientation could vary significantly from one fiber to another, depending on the fiber history during manufacture and subsequent processing operations. The effect of drawing on the refractive index, birefringence, and other optical parameters were investigated in this article. As expected, the values of the refractive index when the light vibrates parallel to the fiber refractive index and to the fiber axis are increased with increasing the draw ratio. This is because the drawing process aligns the molecules in adirection that allows the transmission of much light intensity.

Table V   The Polarizability of a Monomer Unit $\alpha^{\parallel}$, $\alpha^{\perp}$, and $\bar{\alpha}$, the Specific Refractivity of the Isotropic Dielectric $\varepsilon^{\parallel}$, $\varepsilon^{\perp}$, $\bar{\varepsilon}$, $\bar{\varepsilon}_V$

Draw Ratio	$\alpha^{\parallel} \times 10^{-33}$	$\alpha^{\perp} \times 10^{-33}$	$\bar{\alpha} \times 10^{-33}$	$\alpha_V \times 10^{-33}$	$\varepsilon^{\parallel}$	$\varepsilon^{\perp}$	$\bar{\varepsilon}$	ε_V
Undrawn	2.108	2.084	2.096	2.092	0.2490	0.2461	0.2476	0.2471
1.40	2.136	2.071	2.103	2.092	0.2522	0.2445	0.2484	0.2470
1.56	2.226	2.023	2.125	2.087	0.2629	0.2389	0.2509	0.2464
1.72	2.216	2.029	2.122	2.088	0.2617	0.2396	0.256	0.2465
1.88	2.224	2.025	2.124	2.087	0.2626	0.2391	0.2509	0.2465
2.04	2.231	2.021	2.126	2.086	0.2634	0.2387	0.2511	0.2464
2.20	2.239	2.016	2.128	2.086	0.2644	0.2381	0.2513	0.2463
2.36	2.248	2.012	2.130	2.085	0.2654	0.2376	0.2515	0.2462
2.52	2.264	2.003	2.133	2.083	0.2673	0.2366	0.2520	0.2460
2.68	2.272	1.999	2.135	2.082	0.2682	0.2361	0.2522	0.2459
2.84	2.280	1.994	2.137	2.081	0.2693	0.2355	0.2524	0.2458
3.00	2.287	1.990	2.139	2.080	0.2701	0.2351	0.2526	0.2457
3.16	2.296	1.985	2.141	2.079	0.2712	0.2345	0.2528	0.2456
3.32	2.299	1.984	2.142	2.079	0.2715	0.2343	0.2529	0.2455
Undrawn	2.147	2.065	2.106	2.091	0.2536	0.2438	0.2487	0.2470
1.40	2.226	2.023	2.125	2.087	0.2629	0.2389	0.2509	0.2464
1.56	2.239	2.016	2.128	2.086	0.2645	0.2381	0.2513	0.2463
1.72	2.250	2.010	2.130	2.086	0.2657	0.2374	0.2516	0.2462
1.88	2.254	2.008	2.131	2.084	0.2662	0.2372	0.2517	0.2461
2.04	2.268	2.001	2.134	2.083	0.2678	0.2363	0.2511	0.2460
2.20	2.275	1.997	2.136	2.082	0.2687	0.2358	0.2523	0.2459
Undrawn	2.147	2.065	2.106	2.091	0.2535	0.2438	0.2487	0.2470
1.37	2.238	2.017	2.127	2.086	0.2643	0.2382	0.2512	0.2463
1.52	2.235	2.019	2.127	2.086	0.2640	0.2384	0.2512	0.2463
1.68	2.259	2.006	2.133	2.084	0.2668	0.2368	0.2518	0.2461
1.82	2.260	2.005	2.133	2.084	0.2669	0.2368	0.2519	0.2461
1.96	2.273	1.998	2.136	2.082	0.2685	0.2360	0.2522	0.2459
2.04	2.278	1.996	2.137	2.082	0.2690	0.2357	0.2523	0.2458

As birefringence yields information about the crystallinity and orientation of polymer molecular chains, the isotropic refractive index of medium also gives information about not only the molecular package but also specification of the unit cell of the crystalline part. All oriented polymers have a common property: namely, their strength and modulus of elasticity in stretching in the direction of orientation are much higher than in a nonoriented polymer, while the strength and modulus in deformation are lower than in the initial nonoriented polymer.

It is clear that birefringence Δn of PET fiber increased with draw ratio R, according to the empirical relation in eqs. (25 and 26), in which m, b, and c are parameters that characterize the deformation process, where m indicates the initial slope of the birefringence natural extension curve if the drawing would start from the isotropic state. m can assume positive or negative values according to the sign of the birefringence in the fiber. The different values of b express the difference in interaction between the chain element accordingly as they become progressively better oriented with respect to the fiber axis. For instance, assuming $b = 0$ to represent the neutral case, for negative values of b, we would have to explain that the polarizability of the chain elements would be diminished by their orientation, and so the increase in birefringence would be impeded; in the opposite case, positive b, it would be enhanced by the interaction. c is the constant that appears to be due to the integration process for eq. (25).[37,40] It is now well accepted that the tensile strength of polymeric fibers is strongly dependent on their length and diameter,[46] and are also parameters that are given to understand the fiber size and length changes due to stress–strain effects, which are of great importance for materials design and manufacturing.

When a polymeric fiber is quenched and drawn, its structural behavior is changed due to accumu-
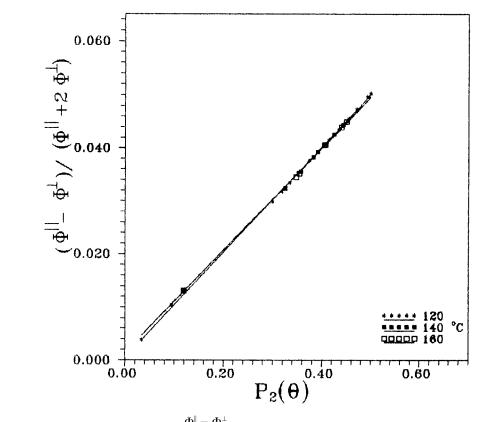
Figure 5   Relation between $\dfrac{\Phi^{\parallel} - \Phi^{\perp}}{\Phi^{\parallel} + 2\Phi^{\perp}}$ and $\langle P_2(\theta) \rangle$ of PET fiber, due to the changing of draw ratios at different annealing conditions: annealing temperature, 120, 140, and 160°C; constant annealing time, 4 h.

lation of several structural processes that are responses for both annealing and drawing conditions.

CONCLUSION

It is clear that the two-beam and acoustic methods are useful and quick techniques to clarify the mechanism of the optical and density parameters of PET fibers with different thermal and drawing conditions. From the measurements relating the changes of optical properties, density, and crystallinity parameters to thermal and drawing effects in PET fibers, the following conclusions may be drawn.

1. The density and crystallinity depends greatly on the thermal energy of the intermolecular interaction, which affects the molecular motion in PET fibers and is also indicative of the effect of a structural transformation change on the opto-thermal

and mechanical parameters of PET fibers, as seen in Table IV.

2. Calculating the degree of crystallinity and the total birefringence leads to calculating the form birefringence (Table IV), which must not be neglected to explain the structural phases in some fibers.

3. Comparison between $n_{\mathrm{iso}_{(1)}}$, $n_{\mathrm{iso}_{(2)}}$, and n_V (Table IV) shows that every equation has its own merit. In case the density of the material under investigation is known, $n_{\mathrm{iso}_{(2)}}$ is more accurate, where ρ is indicative for mass redistribution due to any physical changes.

4. It is clear that $a = 0.8$ is constant, whatever the fiber thermal and mechanical treatment processes (quenched in ice).

5. Calculated refractive indices for fully oriented fibers were found $[n^{\parallel} - n^{\perp} = \Delta n]$, which confirm the previous published results.

6. Changes in orientation are accompanied by a change of crystallinity due to the thermal

and drawing processes. This indicates mass redistribution within the fiber chains. Also, this indicates the change in density.

From the above results and considerations, we concluded that the practical importance of these measurements provides acceptable results for the opto-thermal and mechanical parameters changes for PET fibers.

REFERENCES

1. Samules, J. R. Structural Polymer Properties, Vol. 20; John Wiley & Sons: New York, 1974, p. 51.
2. Barakat, N.; Hamza, A. A. Interferometry of Fibrous Materials; Hilger: Bristol, 1990, Chap. 4, p. 94.
3. Hamza, A. A.; Fouda, I. M.; Sokkar, T. Z. N.; Shahin, M. M.; Seisa, E. A. Polym Test 1992, 11, 297.
4. Fouda, I. M.; El-Tonsy, M. M. J Mater Sci 1990, 25, 121.
5. Fouda, I. M.; El-Tonsy, M. M.; Hosny, H. M. Polym Degrad Stab 1994, 46, 287.
6. Hamza, A. A.; Fouda, I. M.; Sokkar, T. Z. N.; El-Bakary, M. A. Polym Int 1996, 39, 129.
7. Hamza, A. A.; Fouda, I. M.; Kabeel, M. A.; Shabana, H. M. Polym Test 1996, 15, 391.
8. Fouda, I. M.; Kabeel, M. A.; El-Sharkawy, F. M. J Polym Compos 1997, 5, 203.
9. Fouda, I. M.; Seisa, E. A.; El-Farahaty, K. A. Polym Test 1996, 15, 3.
10. Fouda, I. M.; Seisa, E. A. J Polym Compos Vol 4, No. 4, 1996, 247.
11. Staton, W. O. S. J Polym Sci, Part A: Polym Chem 1992, 210, 1587.
12. Decondia, F.; Vittoria, V. J Polym Sci, Polym Phys Ed 1985, 23, 1217.
13. Murthy, S. M.; Miror, H.; Latif, A. J Macromol Sci, Phys B 1987, 26, 427.
14. Fouda, I. M.; El-Nicklawy, M. M.; Naser, E. M.; El-Agamy, R. M. J Appl Polym Sci 1996, 60, 1247.
15. Robins, H. A. in High Polymer Physics; Remsen Press: Brooklyn, NY, 1948, p. 61.
16. Perena, I. M.; Duckett, A. A.; Ward, I. M. J Appl Polym Sci 1980, 25, 1381.
17. Pinnock, P. R.; Ward, I. M. Br J Appl Phys 1954, 15, 1559.
18. Rietsch, F.; Duckett, R. A.; Ward, I. M. Polymer 1979, 20, 1133.
19. Nobbs, J. H.; Bower, D. I.; Ward, I. M.; Patterson, D. Polymer 1974, 13, 287.
20. Ficher, E. W.; Fakirov, S. J Mat Sci 1976, 11, 1041.
21. Ward, I. M. Polymer 1974, 15, 379.
22. Yazdanian, M.; Ward, I. M.; Brody, H. Polymer 1985, 26, 1779.
23. Wilson, I.; Cunningham, A.; Ward, I. M. J Mater Sci 1976, 11, 1976.
24. Padibjo, S. R.; Ward, I. M. Polymer 1983, 24, 1103.
25. Neill, M. A. O.; Duckett, R. A.; Ward, I. M. Polymer 1988, 29, 54.
26. Lefebrre, D.; Jasse, B.; Monnerie, L. Polymer 1983, 24, 1240.
27. Fouda, I. M.; El-Sherif, M.; Bayoumi, O. A. J Polym Compos 1997, Vol. 5, No. 4, 281.
28. Fouda, I. M.; El-Tonsy, M. M.; Metawe, F. M.; Hosny, H. M.; El-Easawi, K. H. J Appl Polym Sci 1997, 65, 7, 1293.
29. Hamza, A. A.; Fouda, I. M.; El-Tonsy, M. M.; El-Sharkawy, F. M. J Appl Polym Sci 1995, 56, 1355.
30. Hamza, A. A.; Fouda, I. M.; Kabeel, M. A.; Seisa, E. A.; El-Sharkawy, F. M. J Appl Polym Sci 1997, 65, 2031.
31. Hermans, P. H. Contributions to the Physics of Cellulose Fibers; North Holland: Amsterdam, The Netherlands, 1946.
32. Ward, I. M. Proc Phys Soc London 1962, 80, 1176.
33. Ward, I. M. J Polym Sci, Polym Symp 1977, 53, 9.
34. Mills, N. J. in A Materials Science Handbook, Vol. 1; Jenkins, A. D., Ed.; North Holland: Amsterdam, The Netherlands, 1972; Chap. 7, p. 492.
35. de Vries, H. Z Colloid Polym Sci 1979, 257, 226.
36. Morgan, H. M. Text Res J 1962, 32, 866.
37. de Vries, A. J.; Bonnebat, C.; Beatutemps J Polym Sci, Polym Symp 1977, 58, 109.
38. Bourvelles, G. L.; Beautemps, J. J Appl Polym Sci 1990, 39, 329.
39. Cunningham, A.; Ward, I. M.; Willis, H. A.; Zichy, V. Polymer 1974, 15, 749.
40. Happy, F. Applied Fiber Science, Vol. 1; Academic Press: London, UK, 1983; p. 130.
41. Hamza, A. A.; Fouda, I. M.; Kabeel, M. A.; Seisa, E. A.; El-Sharkawy, F. M. Polym Test to appear.
42. Pluta, M. J Opt Acta 1971, 18, 661.
43. Pluta, M. J Microsc 1972, 96, 309.
44. Angad Gaur, H.; de Vries, H. J Polym Sci 1975, 13, 835.
45. de Vries, H. J Polym Sci 1959, 34, 761.
46. Termonia, Y. J Polym Sci, Part B: Polym Phys 1995, 33, 147.