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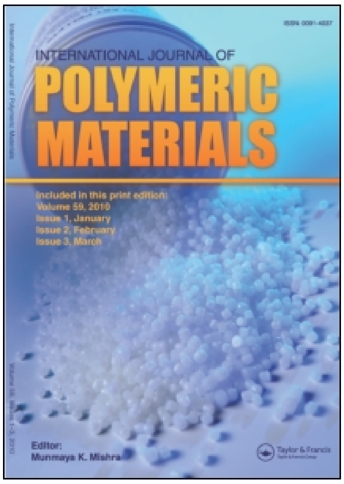

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Interferometric Determination of Optical Properties of Bicomponent Fibers

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Interferometric Determination of Optical Properties of Bicomponent Fibers

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Both double-beam and multiple-beam interferometry were applied for the determination of refractive indices and birefringence of nylon 6 sheath, nylon 66 core bicomponent fibers. Double-beam technique was applied to determine the mean refractive indices for plane polarized light vibrating parallel and perpendicular to the fiber axis and the mean birefringence. Multiple-beam Fizeau fringes in transmission and in reflection were used to determine these optical parameters for each component of these fibers.

INTRODUCTION

A large number of parameters determine the optical characteristics and physical properties of fibers. The most important parameters are fiber diameter, surface conditions, mechanical strength, Young's modulus, thermal characteristics, spectral transmission, light scattering, inhomogenities and birefringence.

Bicomponent fibers usually exhibit different shrinkage levels, different thermal behaviour and different optical properties for each component. These differences enable yarn and fabric producers to introduce greater bulk, retained sheerness and attractive appearance into the end use product.

In the present work a sheath/core type bicomponent fiber including sheath nylon 6 and core nylon 66 has been studied.

From the totally duplicated images of the fiber, using the Pluta[1-3] polarizing interference microscope, the mean refractive index of the fiber n_a can be calculated from the following formula:

$$n_a = n_L + \frac{dz}{\Delta z}\frac{\lambda}{t} \tag{1}$$

where, n_L = the refractive index of the immersion liquid, λ = the wavelength of light, and $dz/\Delta z$ = the ratio of the amount of fringe shift inside the fiber to the interfringe spacing in the liquid region. The mean birefringence of the fiber Δn_a can be determined either from the values of refractive indices for plane polarized light vibrating parallel and perpendicular to the fiber axis, or directly from the non-duplicated image of the fiber using the Pluta microscope. In the last case, the birefringence Δn_a can be calculated from the formula

$$\Delta n_a = \frac{dz_N}{\Delta z} \cdot \frac{\lambda}{t} \tag{2}$$

where dz_N is the amount of the fringe shift inside the fiber using the non-duplicated image of the fiber.

For the application of multiple-beam Fizeau fringes to bicomponent fibers, we will consider each fiber consists of a cylindrical fiber having a core surrounded by a double skin.

Papers dealing with interferometric measurements of the optical properties of fibers are not numerous, amongst which those mentioned in Refs 2–5. Interferometric methods enables one to determine the refractive indices and birefringence on a single fiber and by one technique. This is of current interest to fiber producers today.

By using the mathematical formulation of multiple-beam Fizeau fringes, crossing a core surrounded by multiple-skin,[5] the principal refractive indices of bicomponent fiber (nylon 6 sheath, nylon 66 core) were calculated. In this case it is assumed that the core is surrounded by a double skin. Using the following formula:[5]

$$\frac{dz}{\Delta z} = 4/\lambda \sum_{k=0}^{n} A_k \tag{3}$$

where, $dz/\Delta z$ is the ratio of the amount of fringe shift inside the fiber to the interfringe spacing in the liquid region at the same point from the centre of the fiber. λ is the wavelength of monochromatic light used, and

$$A_k = (n_k - n_{k+1})(r_k^2 - x^2)^{1/2}$$

where n_k = the refractive index of the layer k of the fiber, n_{k+1} = the refractive index of the medium in which the fiber is immersed (immersion liquid of refractive index n_L), r_k = the radius of the skin of the order k from the core, and x = the distance measured from the centre of the fringe shift and at which the fringe shift tends to zero. Hence,

$$n_L = n_{k+1}, \qquad n_0 = n_c, \qquad r_m = r_f \quad \text{and} \quad r_0 = r_c.$$

where n_0 is the refractive index of the core, r_f is the radius of the fiber, and r_m and r_0 are the radii of the layers m and the central layer (core).

The amount of the fringe shift inside the fiber varies from one layer to another due to the effect of different inequalities in the refractive indices of the fiber layers and the immersion liquid.

EXPERIMENTAL RESULTS AND DISCUSSIONS:

Figure 1 shows the transverse-sectional view of bicomponent fibers (nylon 6 sheath, nylon 66 core).

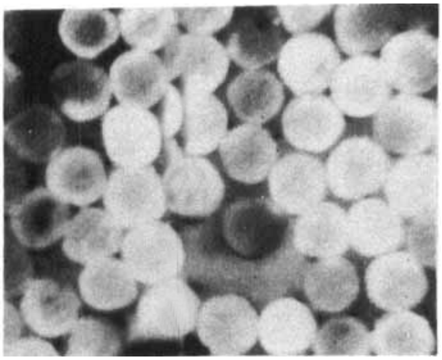

FIGURE 1 Transverse-sectional view of bicomponent fibers (nylon 6 sheath, nylon 66 core).

FIGURE 2 Totally duplicated image of the fiber using white light vibrating parallel to the fiber axis.

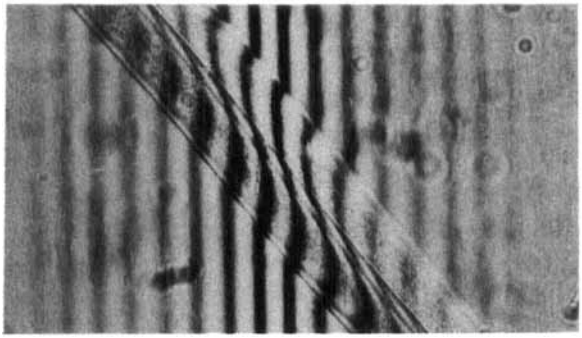

FIGURE 3 Totally duplicated image of the fiber using white light vibrating perpendicular to the fiber axis.

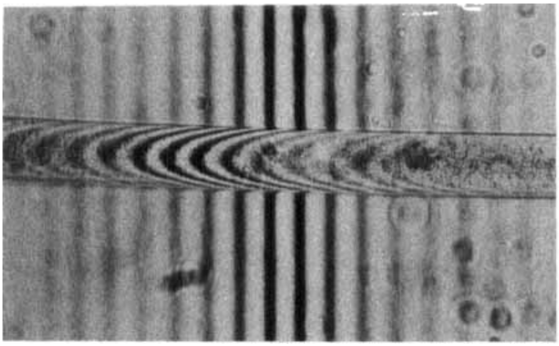

FIGURE 4 Differentially sheared (non-duplicated) image of the fiber using Pluta microscope.

Figure 2 is a microinterferogram for the duplicated image of the bicomponent fiber using the Pluta microscope.[1,2] White light vibrating parallel to the fiber axis was used. The refractive index of the immersion liquid $n_L = 1.515$ at 24°C. Using plane polarized light vibrating perpendicular to the fiber axis, Figure 3 was produced. To determine the mean birefringence of the fiber directly the differentially sheared (non-duplicated) image of the fiber was used. Figure 4 is an interferogram of the differentially sheared image of a bicomponent fiber.

The results of the mean refractive indices $n_a^{\parallel}$ and $n_a^{\perp}$ for plane polarized light vibrating parallel and perpendicular to the fiber axis, respectively, are given in Table I. The mean birefringence Δn_a of these fibers are also given in this table.

Another two-beam interference technique "Interference Microscope Interphako" have been used for the measurement of refractive indices and hence birefringence of bicomponent fibers. Figures 5a, b are two microinterferograms for a nylon 6 sheath, nylon 66 core bicomponent fiber using the Interphako, White light vibrating parallel and perpendicular to the fiber axis, respectively, was used. Figure 6 is a microinterferogram using monochromatic light of wavelength 589.3 nm vibrating perpendicular to the fiber axis. The results of measurements using the Interphako are also given in Table I.

It is clear from Table I that the mean refractive indices and birefringence measured using the Interference Microscope Interphako are in agreement with those measured using the Pluta microscope.

TABLE I

The measured values of the mean refractive indices and birefringence of nylon 6 sheath, nylon 66 core bicomponent fibers. The refractive index of the immersion liquid $n_L = 1.515$ at 24°C

Instrument	Wavelength[a] nm	$n_a^{\parallel}$	$n_a^{\perp}$	$\Delta n_a = n_a^{\parallel} - n_a^{\perp}$	Δn_a from differentially sheared image
Pluta microscope	550	1.573	1.521	0.052	0·051
Interphako	550	1.575	1.520	0.055	—

[a] Taken as an 'average' for white light.

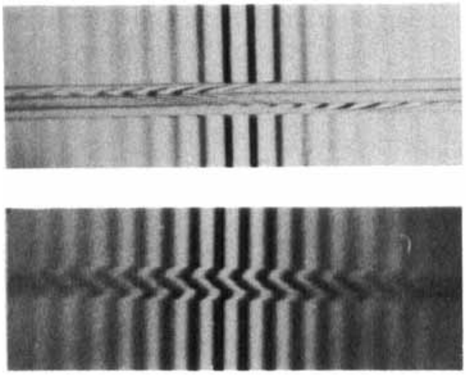

FIGURE 5a, b Microinterferograms of the fiber using the interference microscope Interphako Plane polarized light vibrating parallel and perpendicular to the fiber axis, respectively, was used.

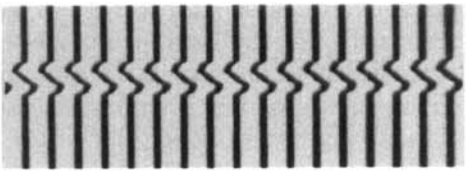

FIGURE 6 Microinterferogram of the fiber using monochromatic light of wavelength = 589.3 nm vibrating perpendicular to the fiber axis.

Multiple-beam interferometric determination of the principal refractive indices and the birefringence of each layer of nylon 6 *sheath, nylon* 66 *core bicomponent fibers:*

The set-up for producing multiple-beam Fizeau fringes are discussed by Barakat and El-Hennawi.[4] They determined the mean refractive index n_a of a fiber from the relation

$$\frac{dz}{\Delta z}\frac{\lambda}{2} = (n_a - n_L)t_f \tag{4}$$

where $dz/\Delta z$, λ, n_L are defined as before and t_f is the fiber thickness.

The values of the refractive indices of the outer layer of nylon 6 sheath, nylon 66 core bicomponent fibers ($n_s^{\parallel}$ and $n_s^{\perp}$) and its

TABLE II

Principal refractive indices ($n_s^{\|}$, $n_s^{\perp}$) and birefringence Δn_s for nylon 6 sheath, nylon 66 core bicomponent fibers.[a] The wavelength of light being 546.1 nm

Temperature pC	$n_s^{\|}$	$n_s^{\perp}$	Δn_s
22	1.5811	1.5330	0.0481
25	1.5810	1.5310	0.0500
30	1.5780	1.5263	0.0517

[a] The Becke-line method is repeated with known liquids until the nearest approximation to the refractive index is obtained.

birefringence Δn_s measured by the Becke-line[6] method are given in Table II.

By this method, values can be measured with an accuracy of ± 0.0005.[6]

The refractive indices of nylon 6 sheath, nylon 66 core bicomponent fibers were determined interferometrically. Figure 7 shows multiple-beam Fizeau fringes in transmission for plane polarized light vibrating parallel to the fiber axis using monochromatic light of wavelength $\lambda = 546.1$ nm $n_L = 1.5745 \pm 2 \times 10^{-4}$ at 22°C. Figure 8 is a microinterferogram for the same direction of light vibration. The experiment was performed at a temperature of 17°C; n_L being $1.5780 \pm 2 \times 10^{-4}$.

It is clear from the microinterferograms shown in Figures 7 and 8 that the sheath of the fiber consists of two layers. The inner layer is denoted by the first skin s_1 and the outer layer of the sheath is

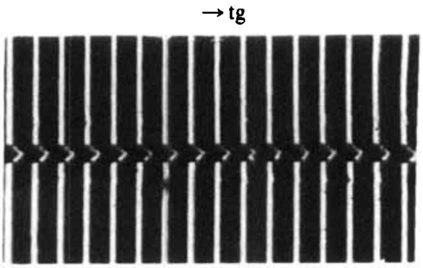

FIGURE 7 Multiple-beam Fizeau fringes in transmission for light of wavelength $\lambda = 546.1$ nm vibrating parallel to the fiber axis $n_L = 1.5745$.

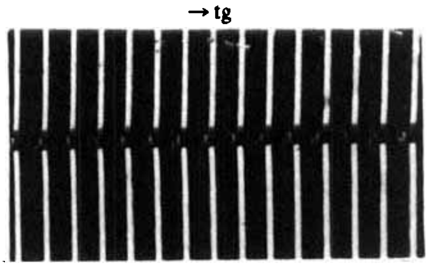

FIGURE 8 Multiple-beam Fizeau fringes in transmission for light of wavelength $\lambda = 546.1$ nm vibrating perpendicular to the fiber axis. $n_L = 1.5780$.

denoted the second skin s_2. In Figures 7 and 8 it is noticed that the fringe shift for light passing through the second skin and the core is towards smaller interferometric gap thickness (t_g), i.e. towards the apex of the interferometer. The shift in the first skin is towards greater (t_g), i.e.:

$$n^{\|}_{s_2} > n_L, \qquad n^{\|}_{s_1} < n^{\|}_{s_2} \quad \text{and} \quad n^{\|}_c > n^{\|}_{s_1}$$

Table III represents data obtained from Figures 7 and 8 using Eq. (3).

Figures 9a, b, c show transmission multiple-beam Fizeau fringes for three samples of nylon 6 sheath, nylon 66 core bicomponent fiber. Each figure corresponds to the light vibrating at perpendicular to the fiber axis. A monochromatic light of wavelength $\lambda = 546.1$ nm was used. It is noticed that in the second skin and in the core the

TABLE III

Refractive indices $n^{\|}_c$, $n^{\|}_{s_1}$, $n^{\|}_{s_2}$ for nylon 6 sheath, nylon 66 core bicomponent fibers

Figure	Layer	Temp. °C	n_L[a]	Radius[b] micron	$\frac{dz^{\|}}{\Delta z}$	$n^{\|}$[c]
7	Core	22	1.5745	8.3	0.483	1.5735
	First skin	22	1.5745	16.6	0.680	1.5768
	Second skin	22	1.5745	25.69	0.871	1.5806
8	Core	17	1.5780	7.12	0.417	1.5810
	First skin	17	1.5780	19.37	0.256	1.5776
	Second skin	17	1.5780	28.26	0.687	1.5825

[a] The absolute error for the accuracy of the Abbe-refractometer is $\pm 2 \times 10^{-4}$.
[b] The absolute error for the accuracy of the Abbe-comparator is $\pm 0.25\ \mu$m.
[c] The absolute error for the values obtained was ± 0.0006.

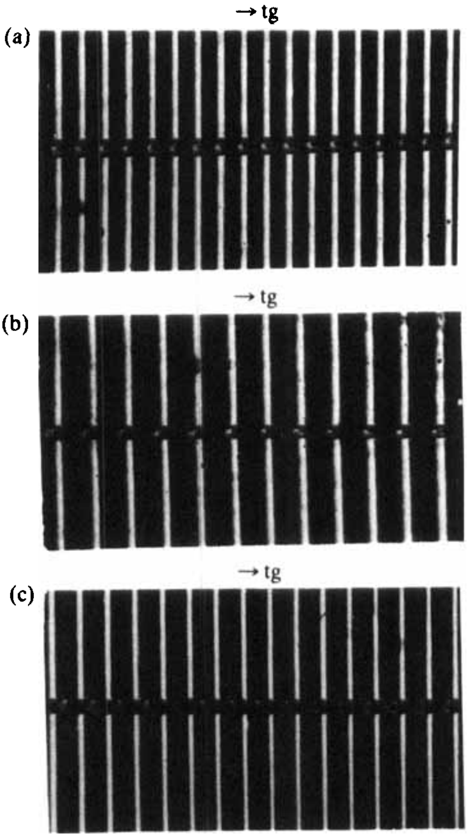

FIGURE 9a, b, c Multiple-beam Fizeau fringes in transmission crossing three samples of bicomponent fibers (nylon 6 sheath, nylon 66 core).

fringes shifts were towards greater (t_g); while for the first skin the shifts were towards smaller (t_g). Hence;

$$n_{s_2}^{\perp} < n_L, \qquad n_{s_1}^{\perp} > n_{s_2}^{\perp} \quad \text{and} \quad n_c^{\perp} < n_{s_1}^{\perp}$$

Figure 10 shows multiple-beam Fizeau fringes in reflection for light vibrating perpendicular to the fiber axis using monochromatic light of wavelength $\lambda = 546.1$ nm.

It is noticed that the shift for the light passing through the second skin, the first skin and the core is towards smaller (t_g); i.e.

$$n_L < n_{s_2}^{\perp}, \qquad n_{s_2}^{\perp} < n_{s_1}^{\perp} \quad \text{and} \quad n_{s_2}^{\perp} < n_c^{\perp}$$

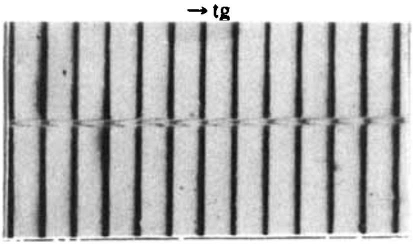

FIGURE 10 Multiple-beam Fizeau fringes at reflection crossing a bicomponent fiber.

Figure 11 shows a schematic diagram for the fringes present in Figure 10. Table IV gives the results obtained from Figures 9a, b, c and 10.

Figure 12a shows multiple-beam Fizeau fringes in transmission for light vibrating parallel to fiber axis using monochromatic light of wavelength $\lambda = 546.1$ nm. The temperature of the experiment was 17°C, $n_L = 1.5370 \pm 2 \times 10^{-4}$. It is noticed that the shift for the light passing through the second skin, the first skin and the core is towards smaller t_g, i.e.

$$n_L < n_s^{\|}, \qquad n_{s_2}^{\|} < n_{s_1}^{\|} \quad \text{and} \quad n_{s_1}^{\|} < n_c^{\|}$$

Figure 12b is for the same fiber but for the light vibrating perpendicular to the fiber axis. The shift for the light passing through the second skin is towards greater (t_g), as well as for the

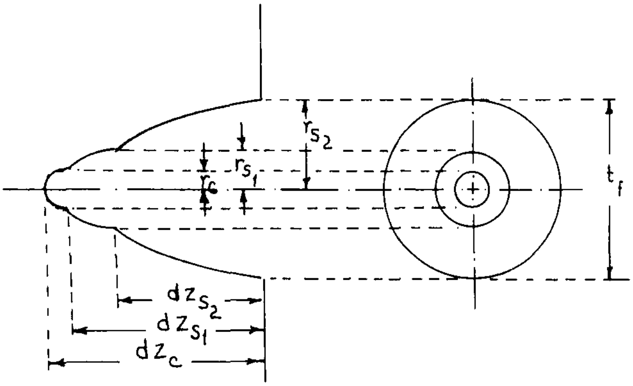

FIGURE 11 Schematic diagram for the fringes present in Figure 10.

TABLE IV

Principal refractive indices $n_c^\perp$, $n_{s_1}^\perp$ and $n_{s_2}^\perp$ for (nylon 6 sheath, nylon 66 core) bicomponent fiber[a]

Figure	Layer	Temperature °C	n_L	Radius micron	$\frac{dz^\perp}{\Delta z}$	$n^\perp$
9a	Core	20	1.5360	5.93	0.168	1.5373
	First skin	20	1.5360	16.6	0.108	1.5395
	Second skin	20	1.5360	25.69	0.814	1.5313
9b	Core	21	1.5390	5.93	0.077	1.5393
	First skin	21	1.5390	16.6	0.153	1.5413
	Second skin	21	1.5390	25.29	0.854	1.5329
9c	Core	22	1.5345	7.1	0.421	1.5377
	First skin	22	1.5345	13.04	0.616	1.5327
	Second skin	22	1.5345	21.74	0.900	1.5272
10	Core	31	1.5255	8.3	1.13	1.5337
	First skin	31	1.5255	15.81	1.05	1.5332
	Second skin	31	1.5255	25.69	0.97	1.5320

[a] The error in $n_c^\perp$, $n_{s_1}^\perp$ and $n_{s_2}^\perp$ due to Eq. (3) and according to the absolute error in $n_L = (\pm 2 \times 10^{-4})$, and r_c, r_{s_1}, $r_{s_2} = \pm 0.25\,\mu\text{m}$ is $\pm 6 \times 10^{-4}$.

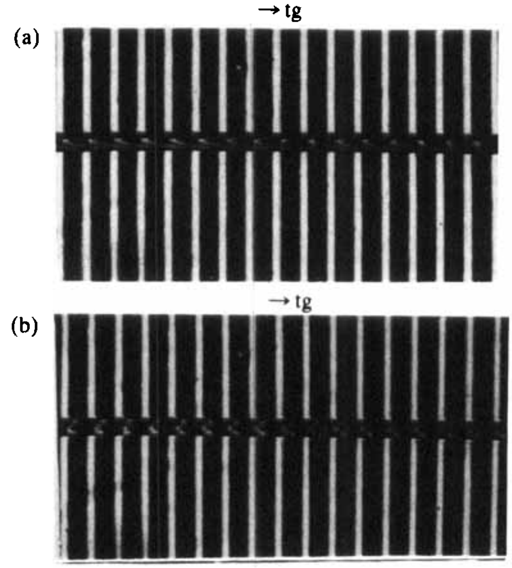

FIGURE 12a, b Multiple-beam Fizeau fringes in transmission crossing a fiber using monochromatic light of $\lambda = 546.1$ nm vibrating parallel and perpendicular to the fiber axis, respectively.

TABLE V

The principal refractive indices and the birefringence for nylon 6 sheath, nylon 66 core bicomponent fibers

Layer	Radius micron	$\frac{dz^{\parallel}}{\Delta z}$	$\frac{dz^{\perp}}{\Delta z}$	$n^{\parallel}$ [a]	$n^{\perp}$ [a]	Δn
Core	7.91	4.770	0.736	1.5849	1.5320	0.0529
First skin	17.4	4.648	0.503	1.5823	1.5365	0.0458
Second skin	25.3	4.545	0.951	1.5708	1.5300	0.0408

[a] The absolute error for the values obtained was $\pm 6 \times 10^{-4}$.

light passing through the core; while for the first skin, the shift is towards smaller (t_g), i.e.

$$n_L > n_{s_2}^{\perp}, \qquad n_{s_2}^{\perp} < n_{s_1}^{\perp} \quad \text{and} \quad n_{s_1}^{\perp} < n_c^{\perp}$$

Table V gives the data obtained from Figures 12a, b for the principal refractive indices and the birefringence of nylon 6 sheath, nylon 66 core bicomponent fibers.

Experiments using multiple-beam Fizeau fringes in transmission

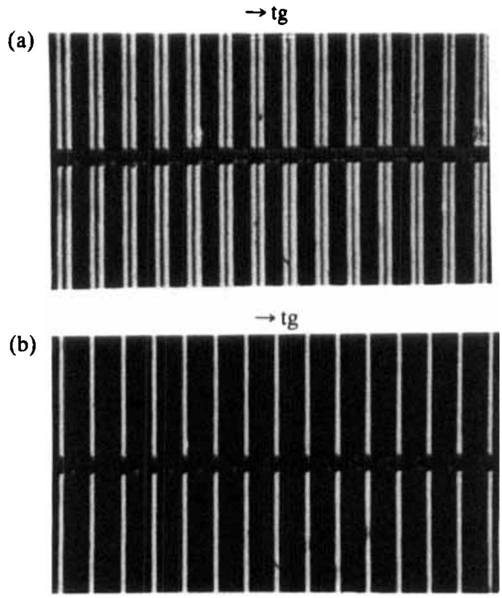

FIGURE 13a, b Microinterferograms of bicomponent fiber using monochromatic light of wavelengths 578.0 and 546.1 nm, respectively.

for perpendicular direction of light vibrations were performed to measure $dn^{\perp}/dt$ for each layer of nylon 6 sheath, nylon 66 core bicomponent fibers following the same method previously, explained.

The experimental results gave:

$$dn_c^{\perp}/dt = -11.2 \times 10^{-4}\ (°\mathrm{C})^{-1}$$
$$dn_{s_1}^{\perp}/dt = -7.8 \times 10^{-4}\ (°\mathrm{C})^{-1}$$
$$dn_{s_2}^{\perp}/dt = -9.8 \times 10^{-4}\ (°\mathrm{C})^{-1}$$

To show that the sheath is indeed due to nylon 6, the birefringence or the interference pattern between 210°C and 290°C can be

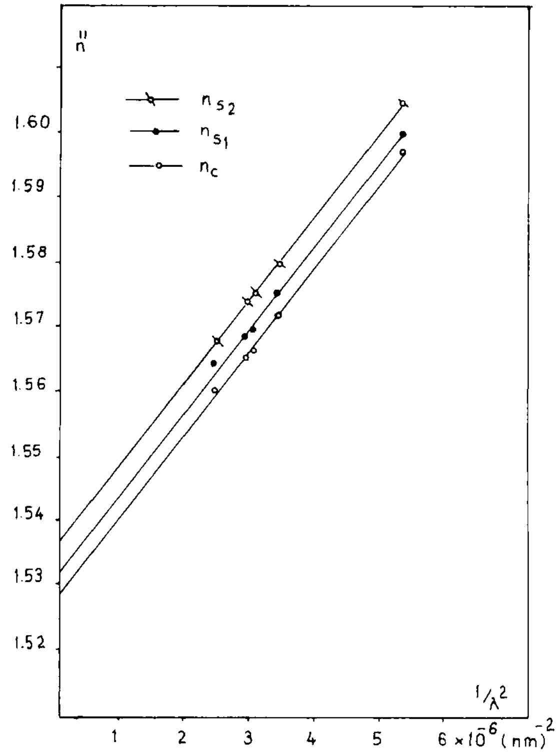

FIGURE 14 Variation of refractive indices $n_{s_2}^{\parallel}$, $n_{s_1}^{\parallel}$, $n_c^{\parallel}$ of the bicomponent fiber with $1/\lambda^2$.

observed and the disappearance of nylon 6 (sheath) component is detected. An alternative optical method was used as follows:

The birefringence of the sheath Δn_{st} was calculated from the refractive indices of the first skin n_{s_1} and of the second skin n_{s_2} for light vibrating parallel and perpendicular to the fiber axis. The refractive index of the sheath n_{st} is given by

$$n_{st} = \frac{n_{s_1} \cdot t_{s_1} + n_{s_2} \cdot t_{s_2}}{t_{s_1} + t_{s_2}}$$

where t_{s_1} and t_{s_2} are the thickness of the first and second skins, respectively.

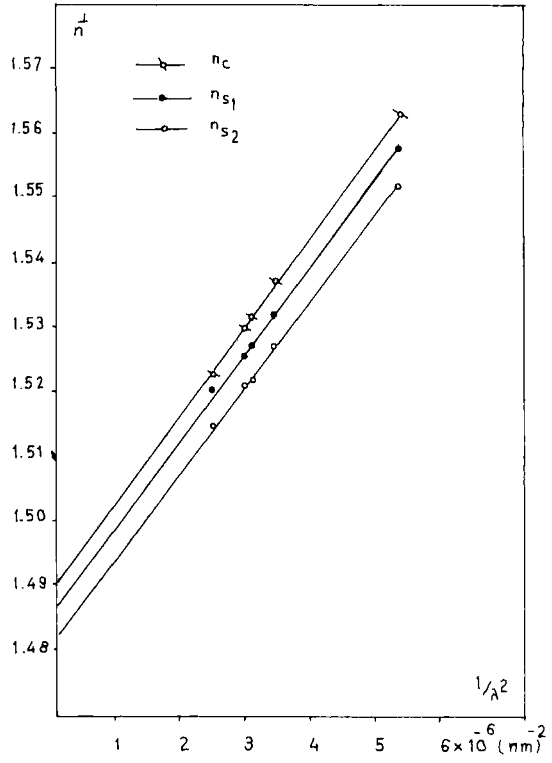

FIGURE 15 Variation of refractive indices $n_{s_2}^{\perp}$, $n_{s_1}^{\perp}$, $n_c^{\perp}$ of the bicomponent fiber with $1/\lambda^2$.

TABLE VI

Values of Cauchy's dispersion formula constants for nylon 6 sheath, nylon 66 core bicomponent fibers

	Constant A		Constant B	
Layer	$A^{\parallel}$	$A^{\perp}$	$B^{\parallel}$ (nm)^2	$B^{\perp}$ (nm)^2
Core	1.5270	1.4910	12.39×10^3	13.29×10^3
First skin	1.5310	1.4870	13.07×10^3	13.35×10^3
Second skin	1.5370	1.4820	13.18×10^3	13.27×10^3

The mean values of our measurements are: $\Delta n_{st} = 0.044$ and $\Delta n_c = 0.053$. From these results it is clear that the sheath of the studied bicomponent fiber acquire lower values of birefringence than those of the core. These findings show clearly that the sheath is indeed nylon 6 and the core is nylon 66. The obtained values of birefringence of sheath and core are in accordance with those values given by Hartshorne and Stuart[7] for nylon 6 ($\Delta n = 0.056$) and nylon 66 ($\Delta n = 0.056$), respectively.

Applications of multiple-beam Fizeau fringes for calculating the constants of Cauchy's dispersion formula for nylon 6 *sheath, nylon* 66 *core bicomponent fibers:*

Figures 13a, b show multiple-beam Fizeau fringes in transmission for light vibrating perpendicular to the fiber axis using monochromatic light having wavelengths 578.0 and 546.1 nm, respectively.

Figure 14 shows the relation between ($n^{\parallel}_{s_2}$, $n^{\parallel}_{s_1}$, $n^{\parallel}_c$ and $1/\lambda^2$); while Figure 15 shows the relation between $n^{\perp}_{s_2}$, $n^{\perp}_{s_1}$, $n^{\perp}_c$ and $1/\lambda^2$). From these relations the constants A and B of the well known Cauchy's formula:

$$n_\lambda = A + B/\lambda^2 \tag{4}$$

were calculated and are shown in Table VI.

Discussion

Extruding two filaments of different composition produces bicomponent fibers. There are three basic methods for making bicomponent fibers: (a) two compatible filaments spun side by side (s/s) so that they seal together; (b) one component used to make a filament core that is surrounded by the second component that forms a sheath (c/c or s/c); and (c) two mutually incompatible polymers spun together as a matrix with fibriles (M/F). In this work sheath/core type including sheath nylon 6 and core nylon 66 has been studied.

Double-beam interference technique was used to determine the mean refractive index and the mean birefringence of these fibers. Multiple-beam interferometric methods were applied for the determination of the refractive index of the inner layer of the bicomponent fiber for plane polarized light vibrating parallel and perpendicular to the fiber axis.

Equations (1) and (2) were applied for the determination of the mean refractive indices and birefringence of the bicomponent fibers using a two-beam interference microscope. It is possible to determine many optical parameters by one technique using Eq. (3). Application of these interferometric techniques provide accurate methods for the determination of the optical properties of these fibers. The slight variations in the obtained results with respect to the published data have been due to the drawing and spinning process.

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