Determining the Optical and Geometrical Properties of Irregular Fibers During the Dynamic Cold Drawing Process

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ABSTRACT: A dynamic method was suggested to determine the variation of both refractive index and transverse sectional area of regular and/or irregular fibers during the dynamic cold drawing process. The suggested method depends on the physical principle of constant volume of the filament during the cold drawing process. The mathematical analysis of the method was given. The optical and geometrical properties of acrylic fibers with denier 2 and polypropylene fibers were determined. One dimension optical Fourier transform was used for automatic analysis of microinterferograms. J Appl Polym Sci 112: 1909–1915, 2009

Key words: irregular fibers; drawing; refractive index; transverse section; dynamic

INTRODUCTION

Determination of the optical and geometrical parameters of fibers is important for textile and dying industries. Interferometric techniques were developed for studying the optical and geometrical properties of fibers.[1–6] Many authors[7–12] used the principle of optical diffraction, laser scattering, optical and scanning electron microscopy to determine the geometrical dimensions of fibrous material. Hamza et al.[13] modified a manipulation device[14] to rotate the fiber around its longitudinal axis. They used this device to study the optical and geometrical properties of fibers having regular and/or irregular transverse sections. Recently, Hamza et al.[15] modified the mechanical-rotating device to detect the variation of the optical and geometrical properties of fibers during the cold drawing process. The video opto-mechanical device (VOM)[16] was designed to study the effect of the drawing speed on the optical and structural properties of fibers during dynamic drawing process. Also an empirical formula correlating the birefringence with the speed of drawing and the draw ratio was suggested.

The observation of cross sections of fibers leads to important conclusions related with the crystalline structure. The cross sections of synthetic polymers show remarkable differences depending on polymer parameters (structure and molecular weight) and on crystallization and orientation conditions, which control the size and number of spherulites in the section.[17]

The mechanical properties of fibers formed from polymeric materials represent the primary properties for which these fibers are applied in practice.[18] When fibers are mechanically distorted, distortion on the macroscopic level produces changes in the molecular level. The bonds and interactions between components of the macromolecules forming the fiber become stressed. These stresses are distributed throughout the structure of the fiber and depend on the state of organization of the molecular chains within the fiber.[19]

One of the most characteristic features of fiber structure is its optical anisotropy. The anisotropy is related to the fiber structural properties. These properties can vary due to complicated factors acting during different processes.[20] Optical anisotropy in a given polymer, due to the fact that the properties along the molecular axis are different from those across the molecular axis, determines the behavior of the material, especially its mechanical behavior.[21,22] Many authors[21,23,24] studied the molecular orientation for different mechanisms that occur during drawing of the fibers.

In this article, a method is suggested to determine dynamically by interferometry the variation of the optical and geometrical properties of fibers during dynamic cold drawing process. This method

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depends on the physical principle of constant volume of the filament during the cold drawing process. The mathematical analysis of the method is given and applied for determining the geometrical and optical properties of fibers during cold drawing processing. Acrylic fibers as a case for irregular fibers and polypropylene fibers as a case for regular fiber will be used in this study.

THEORY OF THE METHOD

A homogenous fiber is immersed in a liquid with refractive index n_L. Using multiple-beam Fizeau fringes, the refractive index of the fiber is given by the formula[2]:

$$n = n_L + \frac{F\lambda}{2bA} \tag{1}$$

The above equation can be used for light vibrating parallel and perpendicular to the fiber axis for determining the refractive indices $n^{\parallel}$ and $n^{\perp}$. F is the enclosed area under the fringe shift, λ is the wavelength of the monochromatic light used, A is the transverse sectional area, and b is the interfringe spacing.

When a fiber is stretched by an axial cold drawing, in addition to a change in length, a change in the cross sectional area is produced. Experiments show that Poisson ratio is a constant[25] during the elastic deformation. The decrease of the transverse sectional area of the fiber is compensating the increase in the fiber length to keep the volume of the fiber constant, so

$$V = AL \tag{2}$$

where V is the volume of the fiber and L is the fiber length. Thus using eq. (2) in eq. (1), the refractive index of the undrawn fiber is given by the following equation,

$$n = n_L + \frac{F\lambda L}{2bV} \tag{3}$$

for a drawn fiber with draw ratio DR_1,

$$A_1 = V/L_1 \tag{4}$$

so that,

$$n_1 = n_L + \frac{F_1\lambda L_1}{2bV} \tag{5}$$

for another draw ratio DR_2:

$$A_2 = V/L_2 \tag{6}$$

so that

$$n_2 = n_L + \frac{F_2\lambda L_2}{2bV} \tag{7}$$

Equation (7) can be rewritten in its recurrence form as follows,

$$n_s = n_L + \frac{F_s\lambda L_s}{2bV} \tag{8}$$

where $s = 0, 1, 2, 3\ldots$ is the draw ratios.

The main problem here is how to measure the volume of the filament. To overcome this problem, the matching process during cold drawing the fiber is used. A certain immersion liquid of refractive index n_{L_2} is selected to give a matching case at certain draw ratio during the cold drawing process. Thus, the refractive index of the fiber at this draw ratio equals n_{L_2}. Another immersion liquid of refractive index n_{L_1} is used for a new filament. This filament is drawing up to the same draw ratio which give the matching case when we use n_{L_2} is reached. Using the obtained values of n_{L_1}, L, b, F, λ, fiber refractive index ($n_f = n_{L_2}$) in eq. (8), the fiber volume can be calculated. The above process is carried out for light vibrating parallel and perpendicular to the fiber axis to determine the average value of the volume. Using the obtained value of the volume, the fiber length L and b, F, λ from the microinterferograms obtained when using n_{L_2} for different draw ratios, the variation of the refractive index is measured during the dynamic drawing process.

EXPERIMENTAL TECHNIQUE

The multiple-beam Fizeau fringe system in transmission[1] was modified by adding a CCD camera and a frame grabber digitizer to transfer the image into an image analysis screen; to be automatically analyzed by using optical Fourier transform method.[26] The resulting fringes give qualitative and quantitative information about the optical and structural properties of the fibers under investigation. The VOM setup used in this work consists of three basic units [see Fig. 1].

Interferometric unit

Fizeau system in transmission [cf. Ref. 4]; This system consists of a mercury lamp (1), condenser (2), iris diaphragm (3), collimating lens (4), polarizer (5), monochromatic filter (6), reflector (7), and wedge interferometer (14).

Mechanical unit

The system consists of a DC battery (9), stepper motor interface (10), stepper motor (11), the bidirectional driving axis (12), and two gear boxes (13).

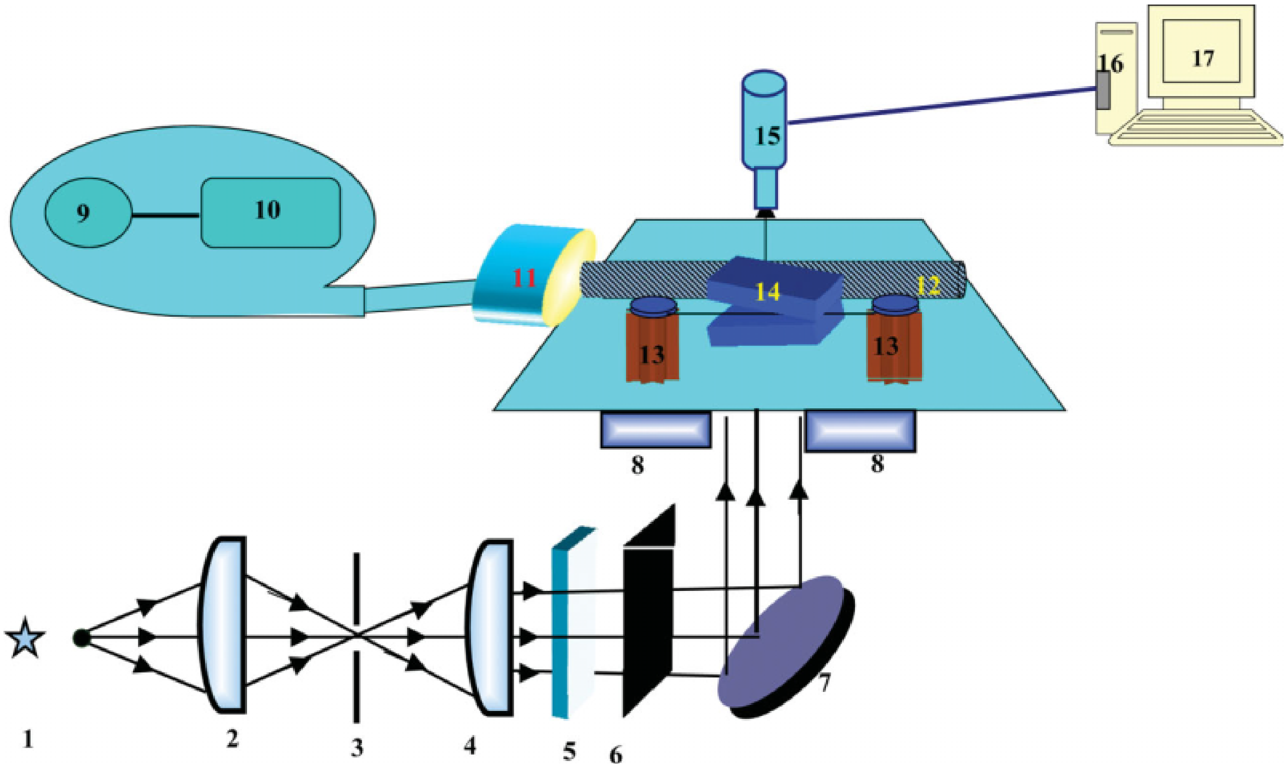

Figure 1 A schematic diagram of the optical and the mechanical setup of VOM, in which; (1) Spectrum lamp, (2) Condenser lens, (3) Iris diaphragm, (4) Collimating lens, (5) Polarizer, (6) Monochromatic filter, (7) Reflector, (8) Microscope stage, (9) DC battery, (10) Steppermotor interface, (11) Stepper motor, (12) Bidirectional driving axis, (13) Two gear boxes, (14) Silvered liquid wedge interferometer, (15) CCD micro camera, (16) Computer, and (17) Digital monitor. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Computerized unit

This unit consists of a Panasonic CCD micro camera (15), computer (16), and digital monitor (17).

The above experimental setup is used to determine the variation of the transverse sectional area and optical properties of acrylic and polypropylene fibers during the dynamic cold drawing process. On the lower optical flat of the liquid wedge interferometer, a fiber of a certain length was fixed from its ends with the two gear boxes (13). The immersion liquid of refractive index n_{L_1} was used. The (VOM) drawing system was transferred into the optical interference system. Using this (VOM) drawing system, the fiber was drawn from its two ends. A parallel beam of polarized monochromatic light was used to illuminate the interferometer, which is adjusted in such a way that the fiber axis was perpendicular to the interference fringes in the liquid region. The speed of drawing was adjusted using the software program of the (VOM) system installed in the computer. The obtained fiber image was captured using CCD camera with frame rate 25 frame/s. The capture images were digitized directly via the frame grabber digitizer. The digitized image was recorded on the computer storage media. The fiber image was recorded when the illuminating light vibrates parallel and perpendicular to the fiber axis. The draw ratio at any time was calculated using eq. (16):

$$\mathrm{DR} = \frac{2M}{L} ft + 1 \tag{9}$$

where DR is the draw ratio, f is the frequency of rotation (step/s), M is machine constant and equals to 0.0149 cm/step, and L is the initial length of the fiber.

The main issue here is how to measure the fiber volume V. To solve this problem according to the theory of the suggested method, an immersion liquid of refractive index n_{L_2} was selected to reach a matching case for a certain draw ratio during the drawing process. The recorded microinterferogram of matching case is selected. In this case, the refractive index of the fiber is equal to the refractive index of the immersion liquid n_{L_2}. In this case, the draw ratio is calculated using eq. (9). The microinterferograms of recorded image in case of using immersion liquid of refractive index n_{L_1} is selected for the same draw ratio used in matching case. Using the refractive index of the fiber $n_\mathrm{f} = n_{L_2}$, $n_\mathrm{L} = n_{L_1}$, L, b, F, λ in eq. (5), the volume of the used fiber of length L can be calculated. Using eq. (2), the cross section area of the fiber can be determined; also using eq. (8), we can determine the refractive index of irregular/regular fiber at the desired draw ratio.

RESULTS AND DISCUSSIONS

Measuring the variation of the transverse sectional area and refractive indices during the dynamic drawing process

The (VOM) drawing device attached with multiple-beam interferometric system allows the online determination of the optical and geometrical properties during the cold drawing process using the suggested method.

For irregular fiber

A filament of an acrylic fiber as a case of irregular fiber was fixed between the two gear boxes on the lower flat of the liquid wedge interferometer. The fiber was immersed in a drop of an immersion liquid with $n_{L_2} = 1.5116$, at temperature 30°C. The wedge angle was adjusted to obtain sharp fringes inside the fiber. The speed of drawing is selected to be $v = 0.0596$ cm/s to avoid the necking deformation.[16] The obtained video film of the cold drawing process is recorded using the CCD camera. Then

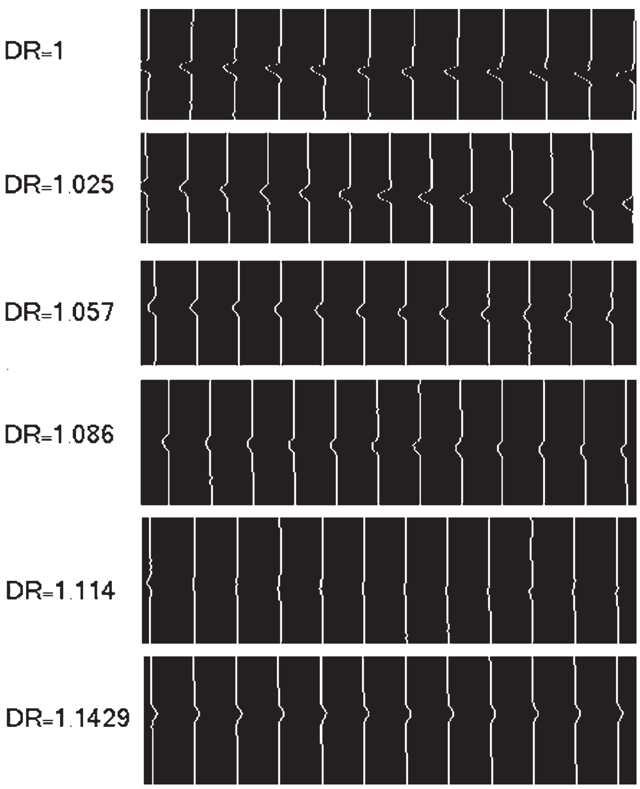

Figure 2 Some of microinterferograms containing the contour line of an acrylic fiber for light vibrating parallel to the fiber axis at different draw ratios.

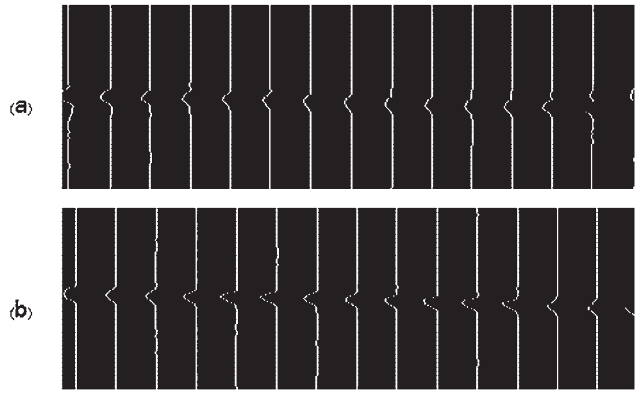

Figure 3 (a) The microinterferogram with its automatic contour lines for light vibrating parallel to the fiber axis when $n_{L_1} = 1.5114$ at DR = 1.1143, (b) the microinterferogram with its automatic contour lines for light vibrating perpendicular to the fiber axis using $n_{L_1} = 1.5114$ at DR = 1.1429.

this video film is cut into separate frames, each frame corresponding to a certain draw ratio. The draw ratio was calculated using eq. (9). During the cold drawing process the matching case occurred at DR = 1.1143, and the fiber refractive index was $n_f = 1.5116$. Figure 2 shows the obtained microinterferograms with their automatic contour lines of an acrylic fiber for light vibrating parallel to the fiber axis at different draw ratios. The illuminating light used has a wavelength of 546.1 nm.

Another immersion liquid of refractive index $n_{L_1} = 1.5114$ was used. Figure 3(a) shows the obtained microinterferogram with its automatic contour line for light vibrating parallel to the fiber axis when $n_{L_1} = 1.5114$. Using the value of the fiber refractive index $n_f = n_{L_2} = 1.5116$ at DR = 1.1143, the obtained image at the same draw ratio using $n_{L_1} = 1.5114$, and the values of b, F, and L and using eq. (8) the volume of the filament when light vibrating parallel to the fiber axis was calculated ($V = 370 \times 10^5$ μm^3).

For light vibrating perpendicular another immersion liquid with refractive index $n_{L_3} = 1.5133$ was used. During the drawing process the matching case occurred at DR = 1.1429, and the fiber refractive index was $n_f = 1.5133$. Figure 3(b) shows the obtained microinterferogram with its automatic contour line for light vibrating perpendicular to the fiber axis using $n_{L_1} = 1.5114$. Figure 4 gives the microinterferograms with its automatic contour line when light vibrates perpendicular to the fiber axis at different draw ratios ($n_L = 1.5134$). Using the value of the fiber refractive index, the obtained image at the same draw ratio using $n_{L_1} = 1.5114$, b, F, L and eq. (8), the volume when light vibrating perpendicular to the fiber axis equals 363×10^5 μm^3. So that the average value of the volume of the used fiber for a certain length is equals (366.5×10^5 μm^3) using the

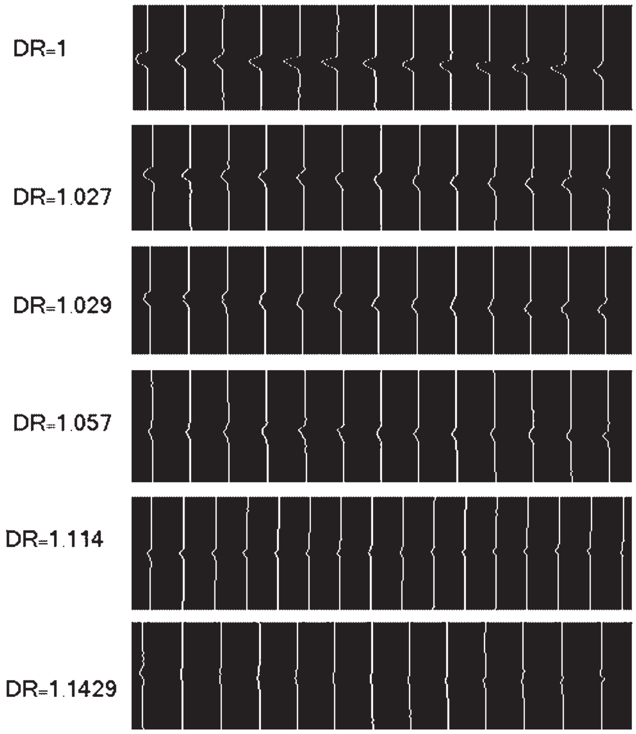

Figure 4 The microinterferograms containing the contour lines for light vibrating perpendicular to the fiber axis at different draw ratios for acrylic fibers (n_L = 1.5134).

values of V, L, and F, b from the recorded microinterferograms during dynamic cold drawing process in case of using immersion liquid $n_L = 1.5116$ in eq. (8) we can determine the parallel refractive index of acrylic fiber at different draw ratios. The same method is used to determine the perpendicular refractive index of acrylic fiber. Figure 5 shows the variation of the refractive indices of acrylic fibers with the draw ratio for light vibrating parallel and perpendicular to the fiber axis. It is clear that the refractive index decreases with increasing the draw ratio. For each draw ratio it is noticed that $n^{\perp} > n^{\parallel}$. Thus the birefringence ($n^{\parallel} - n^{\perp}$) has always a negative sign and increases with the draw ratio. Using eq. (2), we can calculate the cross sectional area of the acrylic fiber at different draw ratio. Figure 6 shows the variation of the cross sectional area with the draw ratio of acrylic fiber.

For regular fiber

A filament of polypropylene fiber as a case of regular fiber was fixed on the two gear boxes. The fiber was immersed in a drop of immersion liquid with refractive index $n_L = 1.5077$, at temperature 30°C. The speed of drawing is adjusted to be $v = 0.0596$ cm/s to avoid necking deformation. A matching case was obtained at DR = 1.389. In this case the refractive index of the fiber was $n_f = 1.5077$. Figure 7 shows some of the obtained microinterferograms with its automatic contour line of multiple-beam Fizeau fringes for polypropylene fibers when light vibrating parallel to the fiber axis and $n_L = 1.5077$ at different draw ratios.

Another immersion liquid of refractive index $n_L = 1.5114$ is used. Figure 8(a) shows the obtained microinterferogram with its automatic contour line of polypropylene fibers when light vibrates parallel to the fiber axis at draw ratio, DR = 1.389 and using immersion liquid of refractive index $n_L = 1.5114$. Using the value of the fiber refractive index, the

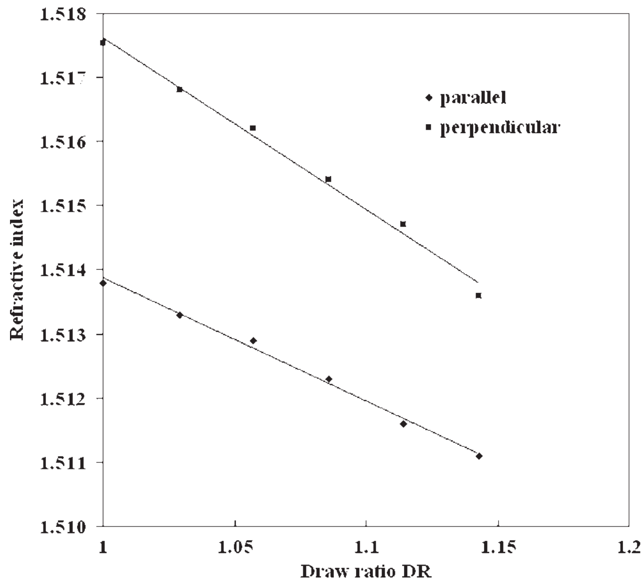

Figure 5 The variation of the refractive indices of acrylic fibers with the draw ratio for light vibrating parallel and perpendicular to the fiber axis.

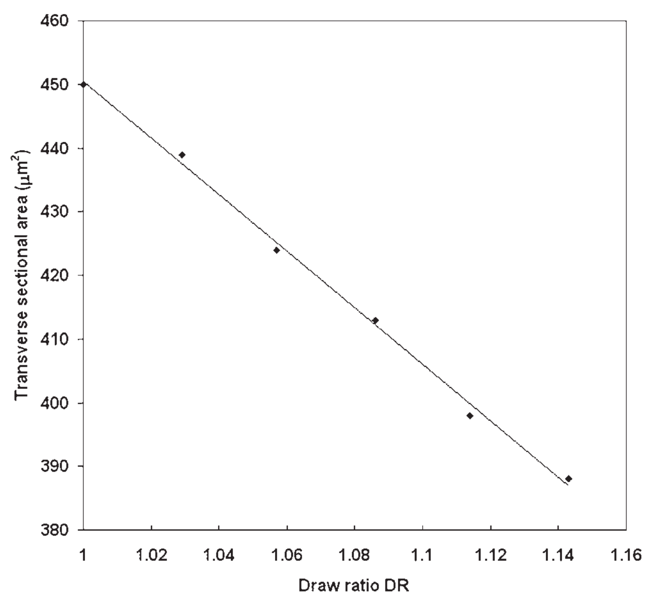

Figure 6 The variation of the cross sectional area with the draw ratio of acrylic fiber.

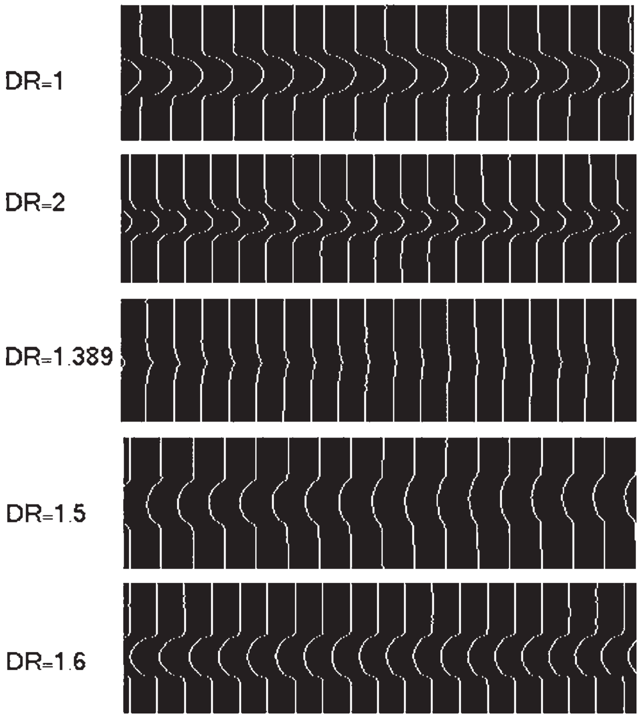

Figure 7 The microinterferograms containing the contour line of polypropylene fibers for light vibrating parallel to the fiber axis when $n_L = 1.5077$ at different draw ratios.

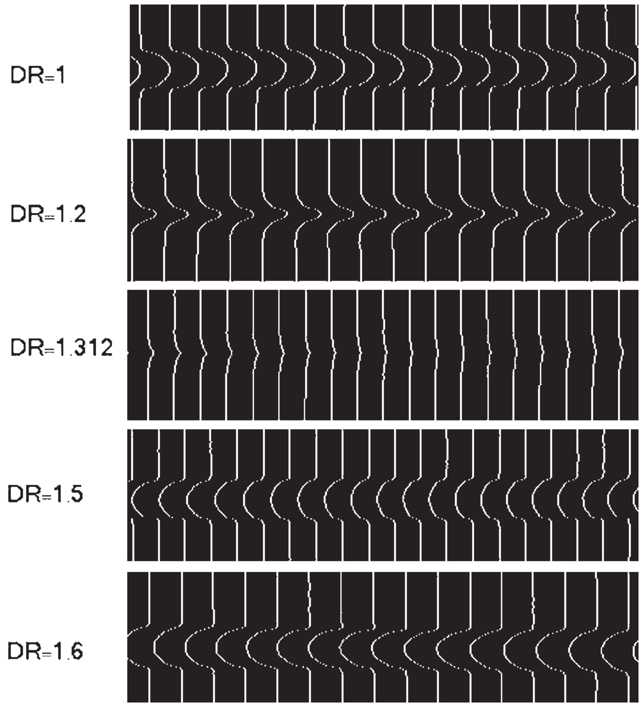

Figure 9 Microinterferograms containing the contour lines of multiple-beam Fizeau fringes for polypropylene fibers when the incident light vibrates perpendicular ($n_L = 1.5022$) to the fiber axis, at different draw ratios.

obtained image at the same draw ratio using $n_{L_1} = 1.5114$, b, F, L and using eq. (8), the volume when light vibrating parallel to the fiber axis can be calculated ($V = 1116 \times 10^6$ μm^3).

To determine the perpendicular refractive index another immersion liquid of refractive index $n_L = 1.5022$ is used. The matching case was occurred at DR = 1.312. Thus the refractive index was $n_f = 1.5022$ for perpendicular direction. Figure 9 shows some of the obtained microinterferograms with its automatic contour lines of multiple-beam Fizeau fringes for polypropylene fibers for light vibrating perpendicular to the fiber axis when $n_L = 1.5022$ at

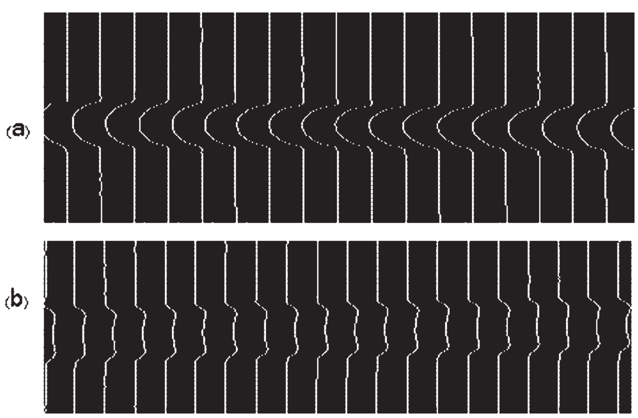

Figure 8 The microinterferograms with its automatic contour line of polypropylene fibers (a) when light vibrating parallel to the fiber axis at draw ratio DR = 1.389, (b) when light vibrating perpendicular to the fiber axis at draw ratio DR = 1.312.

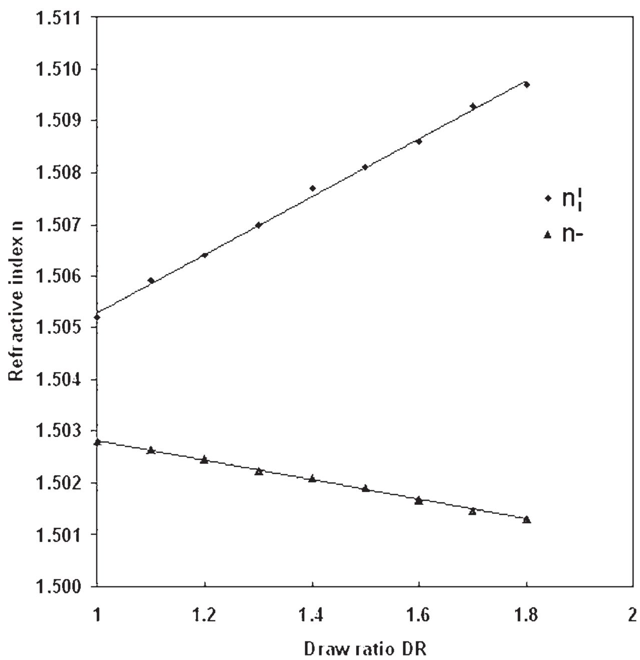

Figure 10 Variation of the refractive indices of polypropylene fibers with the draw ratio.

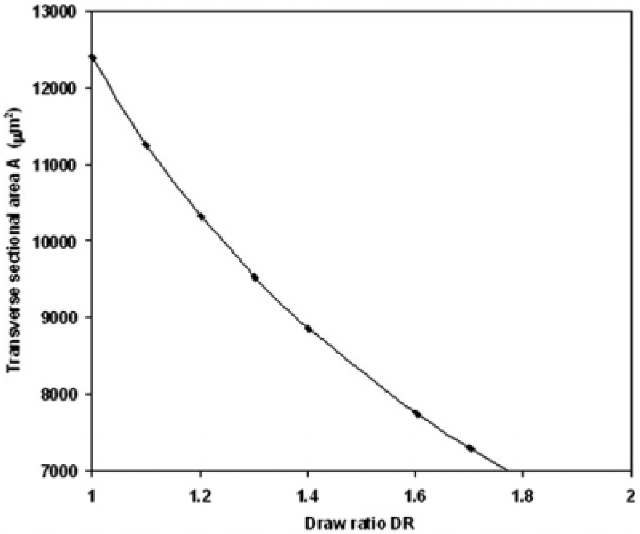

Figure 11 Variation of the cross sectional area of polypropylene fiber with the draw ratio.

different draw ratios. Figure 8(b) shows the obtained microinterferogram when using $n_L = 1.5114$ for light vibrating perpendicular to the fiber axis. The volume for polypropylene fibers was 1105×10^6 μm^3, so that the average value of the volume of polypropylene fiber for a certain length is equals ($V = 1110.5 \times 10^6$ μm^3). Figure 10 shows the variation of the refractive indices of polypropylene fibers with variation of the draw ratio whereas Figure 11 shows the variation of the cross sectional area with the variation of draw ratio.

It is clear from Figures 6 and 11 that, the transverse sectional area decreases gradually with increasing the draw ratio. The decrease of the transverse sections of the fiber results from stretching of the fibers and so their lengths increase. In the conventional methods for studying the opto-mechanical and geometrical properties of fibers due to cold drawing process, we need two techniques for measuring the transverse sectional area of the fibers under study during the cold drawing process besides the interferometric technique. The advantage of the described method is that the determination of the refractive indices, birefringence and transverse sectional area of fibers can be carried out simultaneously using one technique. Consequently, the accuracy of the measurements depends on the accuracy of the measurements using multiple-beam Fizeau fringes technique.[4]

The accuracy in measuring the fringe shift that is produced by multiple-beam techniques and automatically fringe pattern analysis are remarkably high because the interference fringes produced from these techniques are extremely sharp and the fringe displacement is proportional to twice the phase difference introduced by the fiber.[27] The error in the refractive indices measurements is ± 0.0007.[28]

CONCLUSION

A new method is suggested to determine the variation of the optical and geometrical properties of regular and/or irregular fibers during dynamic cold drawing process. This method uses the constant volume concept during the cold drawing process of the sample. The mathematical representation of this method was given and analyzed. The suggested method and the (VOM) device attached with the multiple Fizeau fringes interference system are promised for studying the optical and geometrical properties of irregular fibers at the desired draw ratio without using another technique.

References

1. Barakat, N. Text Res J 1971, 41, 167.
2. Hamza, A. A. J Microsc 1986, 142, 35.
3. Pluta, M. J Microsc 1972, 96, 309.
4. Bakarat, N.; Hamza, A. A. Interferometry of Fibrous Materials; Adam Hilger: Bristol, 1990.
5. Ramadan, W. A. J Opt A: Pure Appl Opt 2000, 2, 234.
6. Abdulhalim, I. Meas Sci Technol 2001, 12, 1996.
7. Buchner, H.-J.; Stiebig, H.; Mandryka, V.; Bunte, E.; Jager, G. Meas Sci Technol 2003, 14, 311.
8. Curry, S. M.; Schawlow, A. L. Am J Phys 1974, 42, 12.
9. Hamza, A. A.; Fouda, I. M.; Sokkar, T. Z. N.; El-Bakary, M. A. J Opt A: Pure Appl Opt 1999, 1, 359.
10. Sokkar, T. Z. N.; El-Bakary, M. A. J Phys D: Appl Phys 2001, 1, 359.
11. Hamza, A. A.; Fouda, I. M.; Sokkar, T. Z. N.; El-Bakary, M. A. J Appl Polym Sci 1998, 69, 1495.
12. Hamza, A. A.; El-Dessouki, T. Text Res J 1987, 57, 508.
13. Hamza, A. A.; Sokkar, T. Z. N.; El-Bakary, M. A.; Ali, A. M. Meas Sci Technol 2002, 13, 1931.
14. Hamza, A. A.; El-Farahaty, K. A.; Helaly, S. A. Opt Appl XVIII 1988, 2, 133.
15. Hamza, A. A.; Sokkar, T. Z. N.; El-Bakary, M. A. Meas Sci Technol 2004, 15, 831.
16. Sokkar, T. Z. N.; El-Tonsy, M. M.; El-Bakary, M. A.; El-Morsy, M. A.; Ali., A. M. Opt Las Technol, 2009, 41, 310.
17. Fatou, J. G. In Applied Fibre Science; Happy, F. H., Ed.; Academic: London, 1978; Vol. 1, p 69.
18. Feughhelman, M. J Text Inst 1954, 45, 630.
19. Feughhelman, M.; Robinson, M. S. Text Res J 1971, 41, 469.
20. El-Bakary, M. A. Polym Int 2004, 53, 48.
21. Mabrouk, M. A. Polym Test 2002, 21, 897.
22. Malinaric, S.; Kluvanec, D.; Jambrich, M. J Phys D: Appl Phys 1998, 31, 2104.
23. Ng, M. W.; Smith, G. B.; Dligatch, S. J Phys D: Appl Phys 1995, 28, 2578.
24. Djendli, S.; Sahsah, H.; Monin, J. J Opt A: Pure Appl Opt 1999, 1, 386.
25. Sprackling, M. T. The Mechanical Properties of Matter; W & J Mackay & Co Ltd.: Chatham, 1970; Chapter 1.
26. Hamza, A. A.; Yatagai, T.; Sokkar, T. Z. N.; Mabrouk, M. A.; El-Morsy, M. A. J Appl Polym Sci 2002, 85, 475.
27. Hamza, A. A.; Sokkar, T. Z. N.; Kabeel, M. A. J Phys D: Appl Phys 1985, 18, 1773.
28. Hamza, A. A.; Kabeel, M. A. J Phys D: Appl Phys 1986, 19, 175.