Birefringence of aramid fibres

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Values of refractive indices and birefringence of aramid fibres measured by different authors are commented on and a modified approach to the spectrophotometric method is proposed.

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It has come to my attention that Roche et al. stated at the end of one of their papers that 'Hamza and Sikorski', a few years ago, and Pluta, most recently, have measured values of the Kevlar® nil index that are greatly in error because they assumed that the apparent achromatic fringe represented the true optical path difference (OPD). This statement is without foundation. Notwithstanding that researchers using interferometric techniques should know that, in general, such an assumption cannot be made, the statement displays a misunderstanding of my paper on the variable wavelength microinterferometry of textile fibres.

This new interferometric method, referred to as the VAWI method, does not require the position of the zero-order interference fringe and the achromatic fringe to be identified among the fringes displaced by an object under study. The VAWI method (or the VAWI-1 version described in ref. 3) employs monochromatic light of continuously variable wavelength. It functions especially well when the true OPDs are relatively large, and thus objects such as polymer fibres do not require an immersion liquid to be used for reducing the OPD if the mean refractive indices are measured at the centre of a cylindrical fibre.

Moreover, a single poly(p-phenylene terephthalamide) (PPT) fibre I measured was more than 10 years old. As can readily be seen, its birefringence for $\lambda = 600$ nm is coincident with the results reported by Yang et al. in 1982 (Figure 1). However, a very high spectral dispersion of birefringence reported by Hartshorne and Laing is doubtful.

A small criticism can also be made against the assumption of Roche et al. that the Cauchy expression applies to the spectral dispersion of birefringence of aramid fibres in a way similar to that used for the refractive indices of immersion oils.

At any rate, the discrepancies between the results of different authors (Figures 1 and 2) are very large, and thus it is useful to explain such a situation. In particular, it would be of interest to measure the same sample of aramid fibres using Roche et al.'s equipment and my VAWI-1 technique using a double-refracting microinterferometer Biolar PI (known as Pluta's polarizing interference microscope).

In my earlier paper, it is important to note that the refractive index $n_2$ and its spectral dispersion (Figure 2) are determined very accurately due to the fact that a specific situation, referred to as the object-adapted interferometry in the interfringe domain, occurred. On the other hand, the values of $n_3$ can suffer from an error, but $\Delta n_1$ is not greater than 0.05 because the initial interference order $m_1 = 27$ was also possible (in the place of $m_1 = 28$ as shown in Table 5 of ref. 3). Consequently, the broken line in Figure 2 can also be considered as the true dispersion curve for $n_3$. Similarly, $m_1 = 13$ is also possible in the place of $m_1 = 14$ for the PPT fibre birefringence B (see Table 4 in ref. 3), and thus the broken curve in Figure 1 may be lowered by $\Delta B = \sim 0.05$.

As far as the spectrophotometric method is concerned, the order of interference deduced from the slope of a plot of $m$ as a function of $1/\lambda$ can certainly suffer from inaccuracy similar to that shown by Roche et al. However, I propose to use another approach. In principle, the equation $\text{OPD} = m_2 = d \Delta n$, given by Roche et al., should be written as

$$\delta_1 = m_2 \lambda_1 = B_1d$$

$$\delta_2 = m_2 \lambda_2 = B_2d$$

$$\delta_3 = m_3 \lambda_3 = B_3d$$

... ...

where $\delta_1$, $\delta_2$, $\delta_3$, ... are the OPDs corresponding to wavelengths $\lambda_1$, $\lambda_2$, $\lambda_3$, ... for which the minima of light intensity are measured by the spectrophotometer, $d$ is the fibre thickness (or diameter) and $B_1$, $B_2$, $B_3$, ... are the fibre birefringences ($\Delta n$), respectively. Equations (1b), (1c), ... may be written as

$$\delta_s = m_s \lambda_s = (m_1 + q_s) \lambda_s = B_sd$$

where $s = 2, 3, ...$ and $q_s = 1, 2, ...$ (for $s = 1$, $q_s = 0$ and equation (1a) holds). The parameter $q_s$ is referred to as the increment of the current interference order $m_s$ with respect to the initial interference order $m_1$ when the light wavelength decreases from $\lambda_1$ to $\lambda_2$, $\lambda_3$, ... Consequently, $m_s = m_1 + q_s$. It is recommended that the initial wavelength $\lambda_1$ (for which $m_1 = m_1$, $q_s = 0$ and $B_s = B_1$) should be selected as large as possible in the longwave (red) region.

From equations (1a) and (2) we obtain

$$m_1 = d \frac{\lambda_1}{B_1 \lambda_1 - \lambda_s}$$

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where $B_{\lambda} = B_{s}/B_{1}$. As can be seen, equation (3) is identical to equation (6) derived for the VAWI-1 technique.

In the red spectral region the relationship between $B$ and $\lambda$ is more linear, so we can therefore assume $B_{\lambda} \approx 1$ and calculate the initial interference order $m_1$ from the relation

$$m_1 = q_1 \frac{\lambda_s}{\lambda_1 - \lambda_s}$$

(4)

In general, the approximate value for $m_1$ calculated from equation (4) will be slightly greater than the true value following from equation (3) if the spectral dispersion $B(\lambda)$ is normal and the dispersion coefficient $B_{\lambda}$ is known a priori. For instance, if equation (4) gives $m_1 = 23.2$ in the red and/or orange region, the true initial interference order $m_1$ may be, at most, equal to 23.

The main goal of the above approach is to determine the birefringence of the fibre (or fibres) under study. We can distinguish two steps. The first is to read (or measure) the wavelengths $\lambda_1, \lambda_2, \lambda_3, \ldots$ for consecutive minima of light intensity, to which the current interference orders $m_1 = m_1, m_1 + 1, m_1 + 2, \ldots$ correspond, and then calculate the initial interference order $m_1$ from equation (4) and take for $m_1$ the integer which is the nearest to but not greater than the value following from equation (4) applied to $\lambda_1$ and $\lambda_s$ from the longwave region (see above). The second step is to calculate the optical path differences

$$\delta_1 = m_1 \lambda_1, \delta_2 = (m_1 + 1) \lambda_2, \delta_3 = (m_1 + 2) \lambda_3, \ldots$$

and determine the birefringences $B_1 = \delta_1/d, B_2 = \delta_2/d, B_3 = \delta_3/d, \ldots$ if the fibre thickness (diameter) $d$ is known or can be measured accurately. If there are any doubts, the initial order $m_1$ can also be verified by analysing the coefficient

$$B_{FC} = B_{F}/B_{C} = \frac{\delta_F}{\delta_C}$$

(5)

where the subscripts $F$ and $C$ denote the spectral lines of wavelengths $\lambda_F = 486.1$ nm and $\lambda_C = 656.3$ nm. The relation $B_{FC} = \delta_F/\delta_C$ follows directly from equations (1a) and (2) if the subscripts 1 and $s$ are replaced by $C$ and $F$, respectively. An inaccurate initial interference order $m_1$, differing from its true value by at least unity ($+1$ or $-1$), leads to a value of the coefficient $B_{FC}$ differing greatly from that characterizing known textile fibres which produce the optical path differences $\delta$ not greater than, say, 10 $\mu$m and their birefringence $B$ is low or moderate. Otherwise, if $\delta > 10$ $\mu$m or $B$ and $B(\lambda)$ are high, as in the case of aramid fibres, the value of $B_{FC}$ becomes improbable when $m_1$ differs from its true value by $\pm 2$ or more. This defect is reduced if the VAWI-1 technique is used, due to the fact that $m_1$ can also be calculated from a formula which is similar to (4), but $\lambda_1$ and $\lambda_s$ are replaced by the interference spacings. It is also important to note that the wavelengths $\lambda_1$ and $\lambda_s$ must be known or measured as accurately as possible, say, with an error of $\leq \pm 0.1$ nm.

The above approach to the spectrophotometric method appears to be more accurate than the procedure used to date based on the derivation of the interference orders from the slope of a plot of $m$ as a function of $1/\lambda$. Moreover, it is worth noting that the fibre thickness (or
diameter $d$ if the fibre is cylindrical) must be measured more accurately than the optical path difference $\delta$ to achieve the same inaccuracies of $\Delta B$, due to $\Delta d$ and $\Delta \delta$, in determining the fibre birefringence $B$. This problem is discussed at length in references 7 or 8.

References


2 Hamza, A. A. and Sikorski, J. J. Microsc. 1978, 113, 15
3 Pluta, M. J. Microsc. 1988, 149, 97
5 Hartshorne, A. W. and Laing, D. K. Microscope 1984, 32, 11
6 Barakat, N. and Hamza, A. A. 'Interferometry of Fibrous Materials', Adam Hilger, Bristol, 1990, pp. 35–43
7 Dorau, K. and Pluta, M. Przeglqd Wfirkiennicy 1983, 37, 7 (in Polish)