Interferometric Investigation of the Optical and Structural Properties of Thermally Treated Polyethylene Fibers

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Abstract: This work throws the light on the variation of the optical and structural properties of high-density polyethylene (HDPE) fibers at different temperatures (0 °C to 50 °C). The experimental data of this work has been done using the optothermomechanical (OTM) device attached to the interference Pluta microscope. The density of HDPE fibers was determined at different temperatures. Gladstone and Dale’s equation is corrected to be valid with PE fibers. Both of the shift factor and average work per chain were presented against average refractive index of PE fiber. Two different types of polarization; the induced polarizability and the permanent dipole moment were carried out for PE fibers.

Keywords: Interferometry, HDPE fiber, Polarizability, Density, Shift factor

Introduction

Polymer fibers make up a class of products of high technological interest in many different fields, especially the high-density polyethylene (HDPE), which is a commercially important, predominantly crystalline and linear form of polyethylene. In this work, the used sample (HDPE fibers) is investigated in considerable range of temperature (0 °C to 50 °C). This temperature range is applied due to; an environmental reasons, it may covers the weather conditions of hot countries, and the different uses of HDPE fibers in many industries.

The density of the crystalline regions in the polymer fibers is usually more than that of the amorphous component. In some cases the difference between them in amount is as much as 10 %, so that the determination of density constitutes an accurate method for determining the percentage of crystallinity [1]. Crystallization occurs between the glass transition temperature (T_g) and the equilibrium melting point (T_m). The crystallization rate decreased with increasing the temperature and also decreased with the increase of the molecular weight [2]. A major feature of the behaviour of amorphous or partially crystalline polymeric materials is the glass transition. At low temperatures most plastics become hard and brittle, whereas at high temperatures they are rubbery or leathery and become great flexible and tough. The glass transition temperature (T_g) attributes to a major change in the segmental mobility of the polymer chains. Above (T_g) there is sufficient mobility, whereas below it the chains are frozen in their position [3].

In the field of polymer fibers, various attempts are considered to relate the molecular structure of a fiber to its thermal properties, which have a direct effect on the structural parameters such as refractive index, polarizability, orientation function and degree of crystallinity. Investigation of the mentioned optical properties of fibers at several different temperatures throws light on the opto-thermal behavior of the fiber under study. Recent attempts have been made by Hamza et al. to study the effect of temperature on the refractive indices and birefringence of polymer fibers [4].

Two-beam interference (Pluta) microscope [5,6] is used for measuring birefringence and refractive indices of fibers, in case of the polarized light is vibrating parallel and perpendicular to the fiber axis. These optical parameters characterize the structure of fibers, play an important role in the elucidation of the molecular arrangement within these fibers and provide useful information about the processability of the fiber [4,7].

In the present work, Pluta interference microscope attached to the opto-thermal part of the optothermomechanical (OTM) system [8] is used to evaluate the opto-thermal behavior of HDPE fibers. Effect of temperature on the refractive index, molecular polarizability, shift factor and average work per chain of PE fibers is carried out and discussed. Empirical formulae between the optical and structural properties of HDPE fibers are suggested.

Opto-thermal Part of the OTM System [8]

The schematic diagram of thermal part of the optothermomechanical (OTM) is shown in Figure 1(a),(b), which consists mainly of two stages; the first one is the cooling set-up (Figure 1(a)), in which there are: metallic base made from steel with particular dimensions to be fitted with the microscope stage. The base is coated from the bottom by thermal isolating material. In the centre of this base there is a hole that allows the light beam to pass through it. A helical pipe made from copper and an open ended to allow methyl alcohol enters from one end and emerge from the other. This pipe is enclosed between some of semi-circle bars fixed in...
the metallic base. Cooling unit consists of a cubic container filled with methyl alcohol which can be circulated into the helical pipe and a fine temperature adjustment key.

The second set-up is the heating one (Figure 1(b)), in which there are: Brass disk designed by special dimensions to be fitted suitably with the microscope stage. A hole for the passage of light punched in the centre of this disk to allow the light go through the tested fibre and then to the microscope objective, which can move up and down freely through this hole. This disk is provided with a special cavity for fitting the heater (hot finger) inside it. The bottom of the principal base of the OTM is perfectly lagged by thermal isolator to minimize the heat losses and protect the microscope from heat during the heating process. The fibre temperature can be measured and controlled via temperature controller, a sensitive thermocouple and a digital recording element of temperature ranging from 0°C to 200°C with sensitivity up to ±0.5°C. The rate of heating (0.5°C/min) of the tested fibre can be varied and controlled using AC varic of voltage ranging from 0 volt to 270 volts.

**Figure 1.** The schematic diagram of the thermal part of the OTM system, (a) cooling set-up and (b) heating set-up [8].

The refractive index of fibers is given by;

\[ n_{av} = \frac{1}{3}(n^1 + 2n^\perp) \]  

where \(n^1\) and \(n^\perp\) are the refractive indices of the fiber in case of the polarized light is vibrating parallel and perpendicular to the fiber axis. These indices can be determined from the following expression [9];

\[ n^j = n_L \pm \frac{Z\lambda}{bt} \]  

Where \(j\) denotes the state of light polarization || or \(\perp\), \(n_L\) is the refractive index of the immersion liquid, \(Z\) is the fringe shift displacement, \(\lambda\) is the wavelength of the monochromatic light used, \(b\) is interfringe spacing and \(t\) is the fiber diameter.

**Molecular Polarizability \(P_M\) of Polymeric Material**

The molecular polarizability, polarization of a collection of molecules, can arise in two ways; i) The applied field distorts the charge distributions and so produces an induced dipole moment in each molecule, ii) The applied field tends to line up the initially randomly oriented permanent dipole moments of the molecules. Therefore this molecular polarizability is given by [10];

\[ P_M = p_i + \frac{p_d^2}{3K_B T} \]  

where \(p_i\) is the induced (electronic and ionic) polarizability, \(p_d^2\) is the square value of the permanent dipole moment, \(K_B\) is the Boltzmann’s constant and \(T\) is the temperature. In terms of the refractive indices, the molecular polarizability \(P_M\) can be given as follows [11];

\[ P_M' = \frac{3}{4\pi} \left( \frac{n_j^2 - 1}{n_j^2 + 2} \right) \]  

The graphical representation of equation (3) is a straight line between 1/\(T\) and \(P_M\), from this relation the induced polarizability \(p_i\) can be calculated from the intercept of the line with the \(P_M\) axis and the square value of permanent dipole moment \(p_d^2\) can be calculated from the slope of the line.

**Density (\(\rho\)) of Fibers**

The density of a fiber is related to its \(n_{av}\) via the following Lorentz-Lorenz expression [c.f. 12];

\[ \frac{n_{av}^2 - 1}{n_{av}^2 + 2} = k\rho \]  

where \(k\) is a constant depending on the type of fiber, its value for PE fibers is 327.5 m²/kg [13]. Since the refractive index of a material is determined by an appropriate summation of the polarizabilities of the bond present in each of its molecules, it is to be expected that the refractive index will increase as the number of molecules present increases, that