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On Young's modulus profile across anisotropic nonhomogeneous polymeric fibre using automatic transverse interferometric method

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ABSTRACT

This paper provides the Young's modulus profile across anisotropic nonhomogeneous polymeric fibre using an accurate transverse interferometric method. A mathematical model based on optical and tensile concepts is presented to calculate the mechanical parameter profiles of fibres. The proposed model with the aid of Mach–Zehnder interferometer combined with an automated drawing device are used to determine the Young's modulus profiles for three drawn polypropylene (PP) fibres (virgin, recycled and virgin recycled 50/50). The obtained microinterferograms are analyzed automatically using fringe processor programme to determine the phase distribution.
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1. Introduction

Synthetic fibres become one of the most interesting materials due to their great importance in all fields of industry and technology. Polymer fibres are the most important materials for society today. Synthetic fibres are based on synthetic chemicals (often from petrochemical sources such as PP) [1]. The polymeric material is a system formed by an assembly of macromolecules obtained by the covalent linking of a large number of constitutional repeat units called monomeric units. So the monomeric units represent the most important foundation for synthetic fibres. They are employed in nearly every device. For example, they are used in making interior of automobiles, also used for body parts and for under-the-hood applications. Actually, the current perception is: "There are no bad polymers but only bad applications" [2].

Due to these reasons, the physical properties, such as optical, thermal, mechanical and structural properties of polymers in their several forms must be studied carefully. Investigation of the mechanical properties of polymers is very interesting. The mechanical properties of polymeric materials give deep physical meanings about the nature and the structural properties of such materials. Many authors [3–11] studied the optical, mechanical and structural properties of polymeric fibres using different techniques. A lot of models and theories were introduced to describe what happens due to mechanical effects on polymeric materials [11–15] and even for optical fibres [16,17].

Undrawn synthetic fibres are often isotropic in their physical properties. They have low tenacity, low modulus of elasticity, high plastic deformability, etc. If they are drawn, one can get improved fibres with high birefringence and high anisotropy. These drawn fibres are valid as textiles and for different industrial applications [3,18]. The drawing process can be characterized by an important curve, called the stress–strain curve. For a stretched polymeric fibre, the stress–strain curve gives a lot of information about the elasticity, plasticity, strength, rupture, elastic moduli as Young's modulus and other tensile properties of these materials.

The mean value of Young's modulus was determined for many polymeric forms as fibres, blends and films [1,19]. In 2004, Mirone et al. [11] introduced a model for determining the Young's modulus profile in the cross sections of drying alkyd coating films. This model was based on trends which are observed by confocal Raman micro spectroscopy. It exhibits the profile of the consumption of double bonds and thus can be used to monitor the development of cross-link density as a function of depth from the film surface. This model was applied for films with high thicknesses compared with polymeric fibres. By the year 2006, the mechanical properties of a PVC foam core, especially the Young modulus profile along a commercial 50 mm beam thickness, were determined by Ferreira et al. [20]. The in-plane strain fields of one cube face under loading in both directions (vertical and horizontal) are achieved using the speckle interferometry. A numerical model is built using finite elements code CAST3M. This method was applied to a cube with a very high thickness

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compared with polymeric fibres. This non-transverse interferometric method gives a plane profile. So, these methods do not suit the polymeric fibres which are introduced in this work.

In addition, interferometry is one of the most highly accurate techniques for studying opto-mechanical properties of polymeric materials [4,8–10]. These researchers succeed to determine the mechanical parameters based on optical measurements using both two and multiple beams interferometry. They used the simple definition of the Young's modulus as the ratio between the longitudinal stress and its corresponding strain. They determined the mean values of the Young's modulus for their samples and they do not introduce profiles using the interferometric methods.

In this paper, Young's modulus profiles across anisotropic nonhomogeneous polymeric fibres (polypropylene fibres) are presented. The work was done using the Mach–Zehnder interferometer and with the aid of an automated drawing device. The problem was how to get the Young's modulus profile across the fibre i.e., getting the value of the Young's modulus for each point along the diameter of the fibre accurately. So, the interferometric method was supposed for this work which is an accurate, simple and not expensive method.

The obtained microinterferograms are analyzed automatically using fringe processing program developed by BIAS (Bremer Institut fur Angewandte Strahltechnik, Germany), which based on the Fast Fourier Transform (FFT) to calculate the interference phase maps.

A mathematical model is presented to calculate the optical and mechanical parameters for the used samples, where the optical and tensile concepts are considered. This model as well as the extracted interference phase differences across the samples are used to calculate the Young's modulus profiles for three samples.

2. Theoretical considerations

2.1. The Young's modulus profile of a fibre having a circular cross-sectional shape

In the elastic region of the stress–strain curve of a stretched polymer, the Young's modulus E can be described by the following equation [19];

$$E=\sigma/\varepsilon, \tag{1}$$

where σ is the longitudinal stress and ε is the corresponding strain. The calculated value of E is the mean value for homogeneous materials (fibres, blends, films or bulks). For nonhomogeneous materials there is a problem to calculate the value of E, since these materials (as graded index fibres) do not have a constant structure for every point through the cross section. The physical properties for these materials as, E, vary along the diameter. Here, we will prefer here a model to calculate Young's modulus profile for nonhomogeneous fibres. This model can be applied for the homogeneous or nonhomogeneous anisotropic axially-symmetric fibres. In this model, the fibre is assumed to be consisting of a large number of coaxial cylinders. Each one has the same shape as the outer one and has a constant value of E. Each cylinder has a circular cross section in shape and is considered to have the value of E_j, where the cylinders are numbered by $j=1,\ldots,Q$, starting from the inner layer.

For a constant external force (stretching force) F, the stress σ_j acting on a cross section A_j is given by

$$\sigma_j=\frac{F}{A_j}, \tag{2}$$

where

$$A_j=\pi(r_j^2-r_{j-1}^2), \tag{3}$$

For an initially isotropic fibre, the birefringence Δn and the applied stress σ are related to each other by the following equation [20,21];

$$\Delta n=C_s\sigma, \tag{4}$$

where C_s is the stress-optical coefficient and it is given by the following equation [22];

$$C_s=\frac{2\pi}{45K_BT}\frac{(\overline{n}^2+2)^2}{\overline{n}}(\alpha^{\parallel}-\alpha^{\perp}), \tag{5}$$

where

$$\overline{n}=\frac{n^{\parallel}+2n^{\perp}}{3},\ \alpha^{\parallel}=\frac{3\varepsilon_0 m}{N_A\rho}\frac{(n^{\parallel})^2-1}{(n^{\parallel})^2+2}\quad\text{and}\quad\alpha^{\perp}=\frac{3\varepsilon_0 m}{N_A\rho}\frac{(n^{\perp})^2-1}{(n^{\perp})^2+2} \tag{6}$$

where $\overline{n}$ is the isotropic refractive index of the fibre, $\alpha^{\parallel}$ and $\alpha^{\perp}$ are the polarizabilities of the fibre when the monochromatic light propagates parallel and perpendicular to the fibre's axis, respectively. ε_0 is the dielectric permittivity of the free space. N_A is the Avogadro's number, m is the molecular weight and its value is 1.419×10^5 kg/mol, 1.19×10^5 kg/mol and 1.3×10^5 kg/mol for VPP, RPP and VRPP, respectively [23]. ρ being the density and is given for polypropylene by the following equation [15];

$$\rho=\frac{\overline{n}-0.9374}{0.6273}, \tag{7}$$

For an initially anisotropic fibre, the relation between the birefringence Δn and the applied stress σ can be represented by the following equation;

$$\Delta n=C_s\sigma+\Delta n_0, \tag{8}$$

where Δn_0 is the fibre's birefringence if there is no applied stress.

The refractive index profile of the fibre is measured by using Hamza et al. model [24]. According to this model the recurrence relation, which predicts the optical path difference of the refracted beam due to an optical path through Q zones of the fibre is given by;

$$n_Q=\frac{\lambda Z_Q}{hL_Q}-\frac{1}{L_Q}\left[\sum_{j=1}^{Q-1}n_jL_j-n_0L_0\right], \tag{9}$$

where, Z_Q, h, and λ are the fringe shift in layer Q, inter fringe spacing and the wavelength of the monochromatic light used, respectively. n_0 is the refractive index of the immersion liquid and L_0 is the path length if there is no fibre. L_q and L_j are given by the following equations;

$$L_Q=\sqrt{(a_{Q+1}-a_Q)^2+(b_{Q+1}-b_Q)^2}, \tag{10}$$

$$L_j=\sqrt{(a_{j+1}-a_j)^2+(b_{j+1}-b_j)^2}+\sqrt{(a_{2Q-j+1}-a_{2Q-j})^2+(b_{2Q-j+1}-b_{2Q-j})^2}, \tag{11}$$

where, $j=1,\ 2\ldots\ Q-1$.

From the ray and cross-sectional equations ($f_Q(x,y)=0$), we can obtain the values of the intersection points (a_j, b_j) between the light ray and the different layers of the fibre. These values are used to calculate the path length L_j and L_Q of the light ray at any position inside the fibre.

The birefringence Δn is given by the following relation;

$$\Delta n=n^{\parallel}-n^{\perp}, \tag{12}$$

where, $n^{\parallel}$ and $n^{\perp}$ are the fibre's refractive indices when the linearly polarized light propagates parallel and perpendicular to its axis, respectively. Based on Eq. (9), the birefringence profile

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