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The determination of Poisson's ratio and extensional modulus for polyethylene terephthalate sheets by an optical technique

I. WILSON*, N. H. LADIZESKY†, I. M. WARD
Department of Physics, University of Leeds, Leeds, UK

The extensional compliance parallel to the draw direction, and the Poisson's ratio in the plane of the sheet, have been determined for one-way drawn polyethylene terephthalate sheet. The technique was to photograph an electron microscope grid printed on the surface of the sheets and thus measure changes in dimension under load. The results show good internal consistency and those for the extensional compliance agree well with other determinations.

1. Introduction

The present paper is one of a series which describes the measurement of the mechanical anisotropy of one-way drawn polyethylene terephthalate (PET) sheet. This sheet has orthorhombic symmetry [1, 2] and its mechanical behaviour at low strains shows very small time-dependency at room temperature [2]. It is, therefore, comparatively straightforward to combine measurements from different techniques to obtain a comprehensive picture of the mechanical anisotropy.

For an anisotropic elastic solid, the low strain mechanical behaviour can be described by the generalized Hooke's law relating strains ϵ_p to stresses σ_q, with

$$\epsilon_p = S_{pq}\sigma_q \text{ and } \sigma_q = C_{qp}\epsilon_p$$

where S_{pq} and C_{qp} are the compliance and stiffness constants respectively and p, q take values $1, 2, \ldots, 6$.

We choose the 1, 2, 3 axes as the principal axes of symmetry with 3 parallel to the initial draw direction and 1 in the plane of the sheet perpendicular to 3. As the experiments involve measuring the strains in the sample subsequent to the application of stress, it is convenient to work in terms of the compliance constants S_{pq}, accepting that these will be time-dependent.

This paper is concerned with the measurement of the Poisson's ratio compliance S_{13}, which describes the contraction in the 1 direction for loading in the 3 direction. The extensional compliance S_{33} is also determined, giving the Poisson's ratio $\nu_{13} = -S_{13}/S_{33}$. The method is to determine by direct observation the changes in dimensions under load of electron microscope grids printed on the surfaces of the sheets. Similar measurements on cold-drawn low density polyethylene sheets have been described previously [3]. Because oriented PET is very much stiffer than oriented low-density polyethylene, it has been necessary to design and construct more sophisticated apparatus to stretch the samples. A brief discussion of the experimental method will therefore be presented, together with the results for the PET sheet.

2. Experimental

2.1. Preparation of samples

As an identical procedure was adopted for the preparation of the samples to that described in the previous publication [3], only a brief summary will be given here. A grid of perpendicular lines was printed on the surface of the sample with one set of lines parallel to the draw direction. The procedure was to accurately align an electron microscope grid of 0.305 cm diameter and 200 lines/in. on the surface of the sheet by viewing the sheet

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*Present address: Toll Bar Comprehensive School, Grimsby, UK.

†Present address: Department of Electrical Engineering, University of Glasgow, UK.

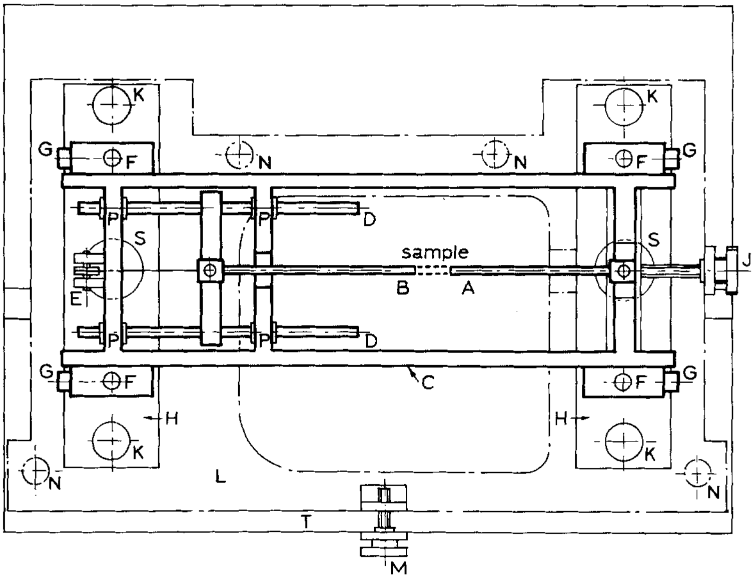

Figure 1 Overhead projection of Poisson's ratio apparatus.

between crossed polars in a polarizing microscope. A thin coat of aluminium was then deposited by placing the sheet in a vacuum coating unit. It was particularly important to cut the sample parallel to one set of lines of the grid, and this was done using a special cutting device which is described in the previous paper [3].

2.2. Extension of the sample

As already mentioned the comparatively high stiffness of the PET samples necessitated the construction of a robust but friction-free extensometer. A plan view of this is shown in Fig. 1. The sample is held between two clamps, one of which A, is fixed to the frame C, whilst the other B is attached to the sliding rods D, which can move through four linear bearings P, which are also supported by the frame C. The sample is loaded by suspending weights from a wire which passes over the pulley E and is attached to the back of the moveable clamp which holds B.

The main frame C, holding the extensometer, can be raised or lowered about the four vertical supports F, by adjusting screws S, fixed by screws G. These four supports are incorporated in two end base-plates H. These base-plates can be moved horizontally (parallel to AB) by means of the screw J and fixed by screws K to a further base-plate L. This further base-plate L can then be moved horizontally in the perpendicular direction (i.e. perpendicular to AB) by the screw M and fixed by the screws N to the base-plate P.

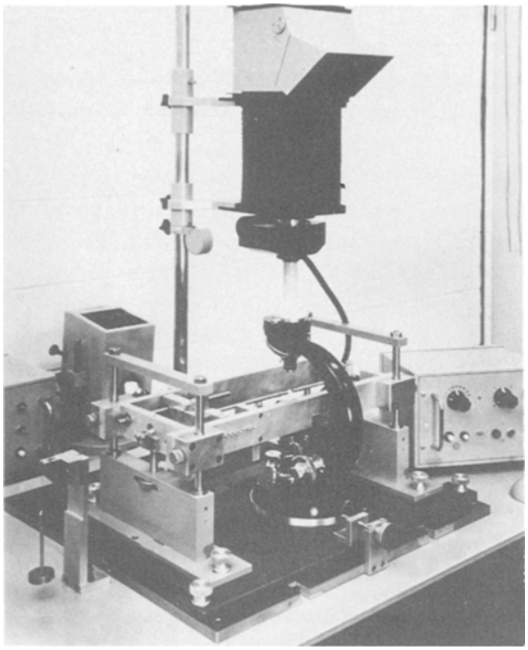

Figure 2 Photograph of Poisson's ratio apparatus.

A photograph of the apparatus is shown in Fig. 2. A microscope is held in a framework attached to the main base-plate and the sample is in the position normally occupied by the microscope stage. An extension camera, on a moveable support, is positioned vertically above the microscope. It can be seen that the rather elaborate system of screws G, J, M and S enable the sample to be very accurately positioned in a plane perpen-

TABLE I

Sample dimensions (cm)	Load (kg)	Extension (%)	Contraction (%)	ν_{13}	S_{33} $(10^{-10}\ m^2\ N^{-1})$	$-S_{13}$ $(10^{-10}\ m^2\ N^{-1})$
0.305 ± 0.004 × 0.0252 ± 0.0003	5	0.57 ± 0.01	0.17 ± 0.01	0.29 ± 0.02	0.88 ± 0.02	0.25 ± 0.01$_5$
	10	1.29 ± 0.01	0.44 ± 0.02	0.34 ± 0.02	1.01 ± 0.02	0.34 ± 0.01$_5$
	15	2.23 ± 0.05	0.83 ± 0.02	0.37 ± 0.02	1.16 ± 0.04	0.43 ± 0.01
0.300 ± 0.006 × 0.030 ± 0.001	15	1.91 ± 0.03	0.63 ± 0.04	0.33 ± 0.03	1.17 ± 0.05	0.39 ± 0.03

dicular to the axis of the microscope, and the image of the grid to be accurately brought into focus.

A load of 2 kg was applied to remove any curvature present in the sample. Measurements were then made for additional applied loads of 5, 10 and 15 kg, regarding the 2 kg load as a "zero-load".

2.3. Photographic and optical measurements

A photograph of the electron microscope grid is taken under the "zero-load" of 2 kg. A second photograph is taken by opening the camera shutter 10 sec after the application of the applied load of 5, 10 or 15 kg. The deformation which occurred is estimated by measuring up the photographs with a travelling microscope.

For the photographs, 9 × 12 cm ortho half-tone plates were found to be suitable. For example, to determine a Poisson's ratio of 0.5 at 1% extension, requires the measurements on the photographic plate to be ±0.001 cm if 10% accuracy is to be attained. With careful procedure this can be achieved. As the measurements are made by comparing different plates, all photographic variables had to be carefully controlled, including automatic exposure. The use of glass as the base of the emulsion was essential to achieve dimensional stability. The photographs were taken in transmitted light, with a green filter, because as the plates are green sensitive, this gives better use of the emulsion without unduly increasing the exposure time.

For each level of applied load, at least five plates were obtained. In each case, measurements were made along four lines, two in the direction of extension and two in the direction of contraction, these lines forming a small rectangle in the centre of the grid. The final results were obtained by taking a weighted average, weighting the average result for each plate inversely as its own variance.

3. Results and discussion

Measurements were undertaken on a sample of PET sheet at three different loads. Fig. 3 shows a plot of relative extension and contraction against the axial load. From the results the Poisson's ratio ν_{13} can be obtained immediately as a function of axial load. The values are shown in Table I, together with calculated values for S_{13} and S_{33}, for which the cross-sectional area of the sample was also required. Table I also contains a set of results for a second sample of PET sheet taken from the same roll of material. This result gives an indication of the overall reproducibility of the data, which is seen to be good.

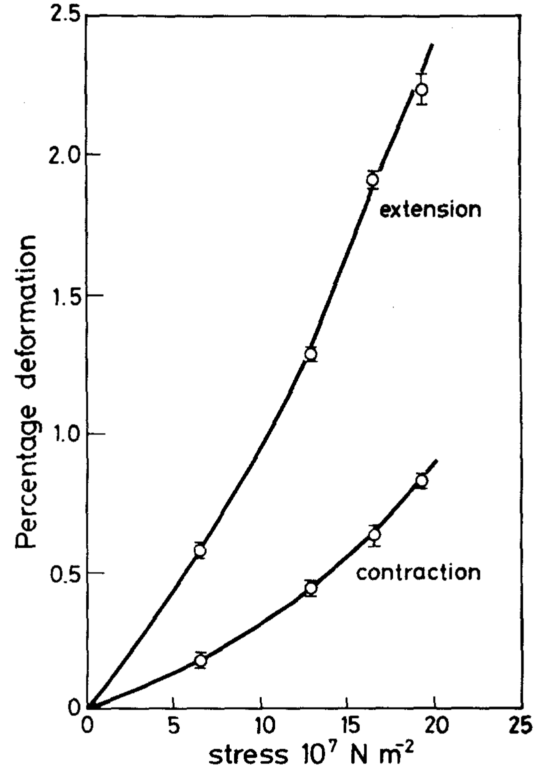

Figure 3 Extensional and contractional strains as a function of applied stress.

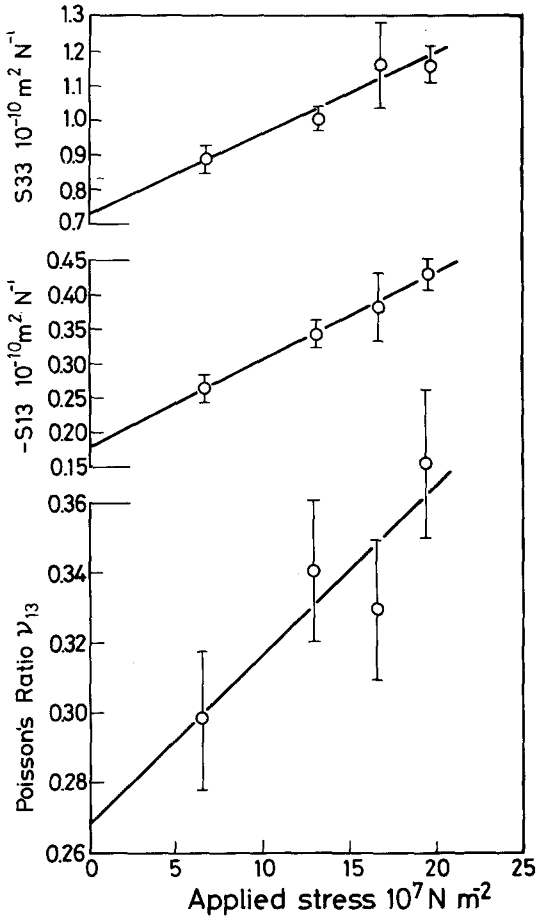

Figure 4 Compliances and Poisson's ratio as a function of applied stress.

It can be appreciated from Table I that the measurements of ν_{13}, S_{13} and S_{33} are being made at quite large strains. This is necessitated by the comparative inaccuracy of the photographic technique. In most of our other work on anisotropic mechanical behaviour, the compliance constants were obtained for strains ~ 0.1%, whereas here the extensional strains are as high as 2%. In addition, it proved necessary to use a fairly substantial "zero-load" to provide a steady plane surface for photography. It is, therefore, not surprising that the values of ν_{13} and the compliance constants are strain-dependent. Plots of Poisson's ratio ν_{13} and the compliances S_{13} and S_{33} against applied stress are shown in Fig. 4. The intercepts at zero applied stress give values of 0.27 ± 0.03 for ν_{13} and -0.18 and 0.74×10^{-10} m^2 N^{-1} for S_{13} and S_{33} respectively. From Table I it can be inferred that zero applied stress corresponds to an extensional strain of about 0.2%.

This value for S_{33} compares very well with the value of 0.76×10^{-10} m^2 N^{-1} determined for 0.1% extension using a dead-loading creep equipment. The values for S_{13} of -0.18×10^{-10} m^2 N^{-1} and $\nu_{13} = 0.27$ can be compared with values of $S_{13} = -0.3 \times 10^{-10}$ m^2 N^{-1} and $\nu_{13} = 0.44$ for oriented fibres [4]. A more detailed discussion of these results is made in a related publication [5], where values for S_{21} and S_{23} for these sheets are reported.

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