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A Flow Criterion for Oriented Polyethylene in Tensile Deformation

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Tensile test specimens were cut from high density polyethylene that had been fully cold drawn. The angle between the tensile axis and the draw direction was varied from 30 to 80° and the specimens were deformed at temperatures between 0 and 120°C. Deformation beyond yield occurred without any work hardening and could be described in terms of a flow criterion. The parameters of the flow criterion were found to be slightly dependent upon the initial orientation angle, but highly temperature sensitive.

1. Introduction

Work carried out by Hinton and Rider [1] on the mode of deformation of oriented high density polyethylene (PE) at room temperature established a yield criterion of the form:

$$\sigma_S = \sigma_c - k\sigma_n , \qquad (1)$$

where σ_S is the resolved shear stress in the chain axis direction (c direction), σ_n the resolved tensile stress normal to the direction, σ_c a stress constant and k a constant. It was further suggested [1] that the stress criterion for yield (equation 1) applied equally to deformation beyond yield, which was simple shear in the c direction, indicating an absence of work hardening.* It is, therefore, considered more appropriate to refer to equation 1 as a flow criterion.

This paper describes work undertaken to investigate the validity of the flow criterion over a wider range of experimental conditions than previously reported [1].

2. Experimental

2.1. Procedure

High density PE (Rigidex type 2) was prepared in the form of compression moulded sheets 1 mm thick. The oriented material was then obtained by drawing the moulded sheets at room temperature such that a maximum draw ratio of about 8 was obtained. An orthogonal grid of ink dots 0.2 mm apart was then printed onto the drawn material with one of the principal grid directions parallel to the c direction. This grid direction was subsequently used to indicate the c direction. Dumb-bell shaped tensile test specimens, with a 10 mm long parallel region and 2.5 mm wide, were then cut out of the drawn sheets at various angles to the c direction.

The test specimens were then deformed in tension at a speed of 0.66 mm/min in a tensile testing machine (E type Tensometer). Attached to the Tensometer was an environmental chamber which enabled specimens to be tested in the temperature range of −70 to 250°C. Specimens were photographed during the test and an event marker was used to indicate on the load extension chart when a photograph was taken.

2.2 Measurements

All measurements were taken from the photographic negatives as it was found that there was a small error in taking measurements from prints owing to shrinkage. The various measurements taken are shown schematically in fig. 1. The orientation angle (λ) between the specimen edge and the c direction, and l, the distance along the edge of the specimen were measured. The initial values of λ and l were λ_0 and l_0 respectively. Errors were less than 1° for λ and 3% for l.

The value of true tensile stress (σ_T) was obtained by assuming extension at constant volume. It can be shown that if σ is the nominal tensile stress then:

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*An absence of work hardening implies that the constants in the stress criterion remain unchanged throughout the deformation.

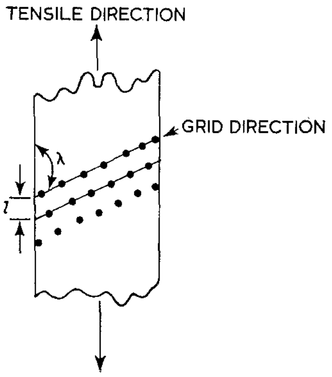

Figure 1 Diagram to illustrate the angle and length measured throughout the experiment.

$$\sigma_T = \sigma l/l_0\,, \qquad (2)$$

where l/l_0 is the extension ratio.

The values of σ_s and σ_n were obtained by resolving the tensile stress into a shear and a normal stress thus:

$$\sigma_s = \sigma_T \cos\lambda \sin\lambda \qquad (3)$$

and

$$\sigma_n = \sigma_T \sin^2\lambda\,. \qquad (4)$$

3. Results

3.1. Flow Criterion

The flow criterion (equation 1) was well obeyed for specimens tested over the temperature range 0 to 119°C, as can be seen from the linear plots in fig. 2. From these results it can be seen that the two parameters σ_c (the intercept) and k (the slope) are temperature dependent.

For specimens tested at the same temperature but with different initial orientation angle (λ_0), it was found that a series of linear plots was obtained as shown in fig. 3. Results for each specimen obey the form of the flow criterion well, but each gives a different straight line, whereas equation 1, which is independent of λ_0, gives only one straight line. However, on further inspection it can be seen that there is a range of values of λ_0, between approximately 45 and 71°, forming a central region in which there is little variation in σ_c and k. It should, therefore, be possible to superimpose data from specimens within this central region on to a master curve of tensile stress (σ_T) against orientation angle (λ). The form of curve can be obtained by combining equations 1, 3 and 4 thus:

$$\sigma_T = \sigma_c/(\cos\lambda \sin\lambda + k \sin^2\lambda)\,. \qquad (5)$$

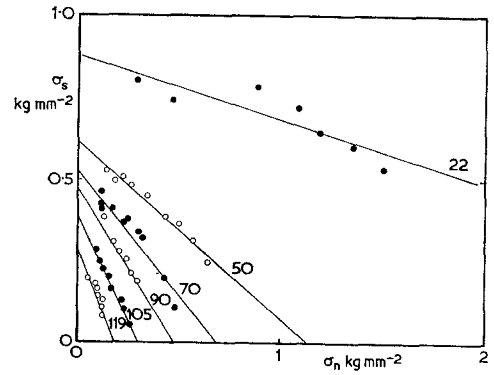

Figure 2 Variation of shear stress with normal stress for various test temperatures, which are indicated in degrees centigrade. The value of λ_0 was approximately 78° for all specimens.

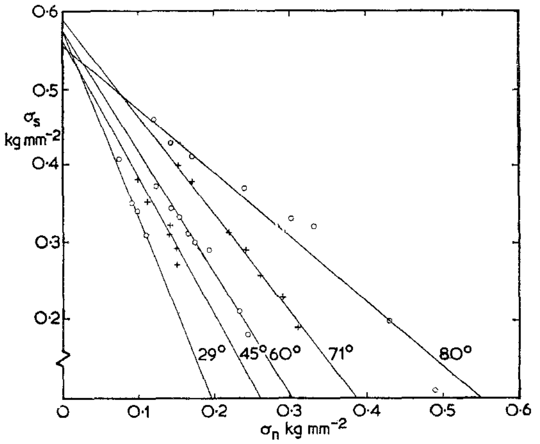

Figure 3 Variation of shear stress with normal stress for specimens of different initial orientation measured at 70°C. The values of λ_0 are indicated.

The data from the three specimens within the central region in fig. 3 are plotted in fig. 4. A master curve (equation 5) has been drawn through the data, by a least squares fitting method, and the agreement is good. In addition, on the same graph have been drawn the two curves fitted to the data for two specimens outside the central region ($\lambda_0 = 80°$ and $\lambda_0 = 29°$). The data points for these specimens have not been shown.

The generality of the flow criterion and of the master curve presentation can be seen in fig. 5 which shows data from three specimens for each of three temperatures. The initial orientation angle (λ_0) lies within the central region in all cases.

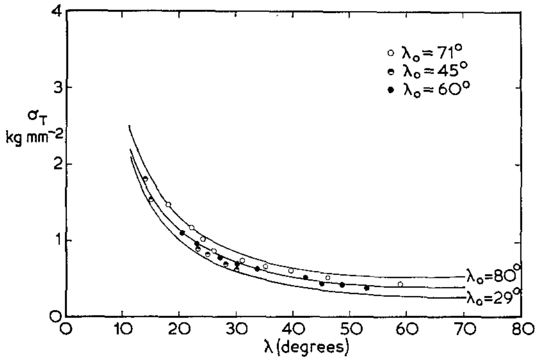

Figure 4 Variation of tensile stress with orientation angle at 70° C. The data points are from three specimens, within the central region. The centre master curve is fitted to the data points and the other curves are for specimens outside the central region.

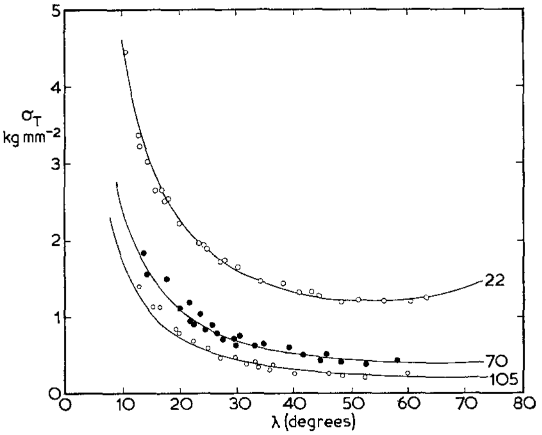

Figure 5 Three master curves for three specimens for each of three temperatures which are indicated in degrees centigrade.

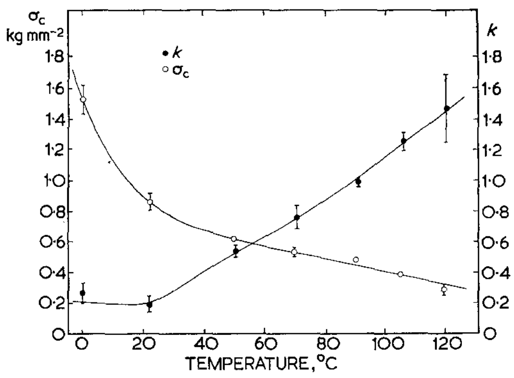

Figure 6 Variation of the parameters σ_c and k with temperature. The error for each point obtained from the least squares fitting method is shown.

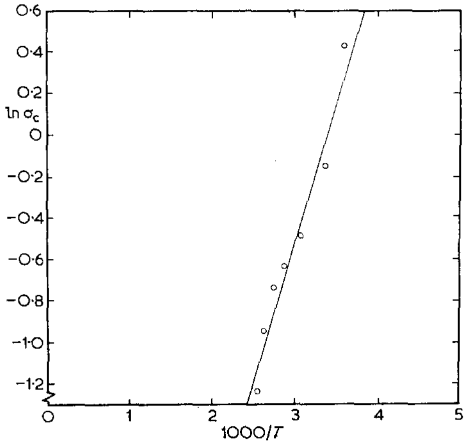

Figure 7 Logarithmic plot of σ_c against $1/T$, where T is in degrees absolute.

3.2. Temperature Dependence

The temperature dependence of σ_c and k can be seen from fig. 2 and is shown in detail in fig. 6. The constant k increases with increase in temperature, while the stress constant σ_c decreases. A further plot (fig. 7) of $\ln \sigma_c$ versus $1/T$ shows a linear relationship suggesting a temperature activated process with an activation energy of 2.7 kcal/mole.

4. Discussion

For all specimens tested at different temperatures and with different initial orientation angle λ_0, the flow-stress criterion is obeyed with results which give a linear relationship between σ_s and σ_n (equation 1), indicating an absence of work hardening. For a given temperature, results obtained from specimens with different values of λ_0 give slightly different values of the parameters σ_c and k. The reason for this dependence upon λ_0 arises most probably from the fact that the deformation prior to yield is dependent upon λ_0, owing to the elastic anisotropy of the material, and this pre-yield deformation influences the parameters in the flow criterion. The magnitude of the deformation prior to yield is indicated by the fact that the angle at yield can be as much as 15° less than λ_0. A detailed study of the deformation in this region is planned.

The effect of temperature upon the parameters of the flow criterion σ_c and k is of particular interest. It can be seen that k increases with temperature to a value greater than 1 for temperatures above about 90°C, indicating that the normal stress is the predominating component. The parameter σ_c decreases with increase of temperature in such a way (see fig. 7) as to suggest a temperature activated process with an activation energy of 2.7 kcal/mole. As σ_c is the shear stress (when $\sigma_n = 0$) for deformation in shear, σ_c can be considered as proportional to an effective viscosity for the process. Eyring [2] has analysed the dependence of flow stress upon temperature in a viscose medium in terms of the probability of the passage of a molecule over a potential barrier which is biased by an applied stress. The attempt frequency is assumed to be temperature dependent through an Arhenius activation energy Q. This model predicts a dependence of flow stress upon temperature of the form:

$$\sigma_c = \sigma_0 \exp(Q/kT) \qquad (6)$$

where σ_0 is proportional to $T^{\frac{1}{2}}$. Thus for small temperature ranges a plot of $\ln\sigma_c$ versus $1/T$ will be very nearly linear. The experimental results in fig. 7 are in agreement with this prediction. The activation energy of 2.7 kcal/mole obtained from data in fig. 7 is less than the activation energy of 5.4 kcal/mole associated with the decrease in viscosity with rise in temperature of PE in the melt [3].

The present work is to be extended to study, in detail, the geometry of the deformation processes that occur under conditions identical to those of the present study.

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