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Simple method of determining the fracture resistance for rapidly propagating cracks in polymers

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A recently developed method has been used to obtain fracture toughness data for rapidly propagating cracks from small specimens of polymers. By varying the load on the specimen, the crack speed can be changed and this load–crack speed relationship has been used in conjunction with a mass-spring model to obtain fracture toughness, R, and the limiting crack speed in the specimen, C_L. A relationship between R and C_L is suggested and shown to describe the data.

1. Introduction

As the variety of tough polymers and their applications increase so there is a need for more precise and discriminating evaluation procedures. For polymers to be used in large, stressed, structures, important information is that relating to steady state crack propagation [1–8]. This is the situation when the crack tip has distanced itself from the impact or other initiating forces and the only strain energy available to the crack is that stored in the material by a steady applied load.

The following experimental information is needed to describe this behaviour:

(i) the threshold loading condition in the specimen to just maintain a propagating crack;

(ii) how crack velocity varies with respect to load on the specimens above the threshold;

(iii) the limiting crack speed, C_L, in the specimen;

(iv) the fracture toughness, R, for a crack propagating normal to the applied stress field generating fracture surfaces free of unwanted features such as partial arrest lines, side-lip tearing and plastic hinging.

There is often a need to obtain these data from small specimens, such as during research and development, when investigating actual failures, and also for the monitoring of full-scale material production. A method has recently been developed to meet these goals known as the frozen tongue technique [9]. The aim of this study was to validate the frozen tongue technique by using it to evaluate three grades of 6 mm thick polyethylenes of widely differing toughness. Such materials are used as pipes in the gas and water industries where there is concern with rapid crack propagation. The experimental data were analysed using a mass-spring model [10] to arrive at the fracture toughness, R, and limiting crack speed, C_L.

2. Experimental procedure

A rectangular-shaped specimen was used with a small tongue protruding from one side that extended the intended crack path [9] as shown in Fig. 1. Other shapes are possible to give a longer crack path, different strain conditions and to explore other variables. The protruding tongue of material was freeze-cooled so that a fast crack could be easily initiated and propagated into the pre-stressed main section of the specimen which was kept at room or some other evaluation temperature.

Using an Instron testing machine, the specimen was loaded normal to the crack path and then allowed to stress relax. Meanwhile the protruding tongue was freeze-cooled, using liquid nitrogen, so that a crack could be easily started with a static three-point bend of only a few degrees (see Fig. 1). The initiated crack then propagated into the pre-loaded main rectangular section of the specimen. This procedure was repeated to obtain the crack load threshold, p_0, and to determine the increase of crack velocity with load. Unlike impact methods, the propagating crack is driven only by the release of strain energy stored in the specimen prior to crack initiation. High-speed photography proved very useful for measuring crack velocity and for observing any irregularities in the propagation of the crack. An image-converter (IMACON) camera was used with back-illumination by Monolite (50 J) flash units so that the specimen appeared as a dark shadow in the photographs and the crack as a bright streak of light. Crack velocity was also measured by the breaking of metallic paint strips at the beginning and end of the crack path and from two appropriately positioned on-specimen strain gauges. For routine tests, only one method of velocity measurement would be needed.

A number of different vessels was made to hold the liquid nitrogen. These vessels had slots in one side for the tongue of the specimens to enter the vessel prior to it being filled with liquid nitrogen. The different types of nitrogen vessels provided for the specimens to be tested in the vertical or horizontal plane and for

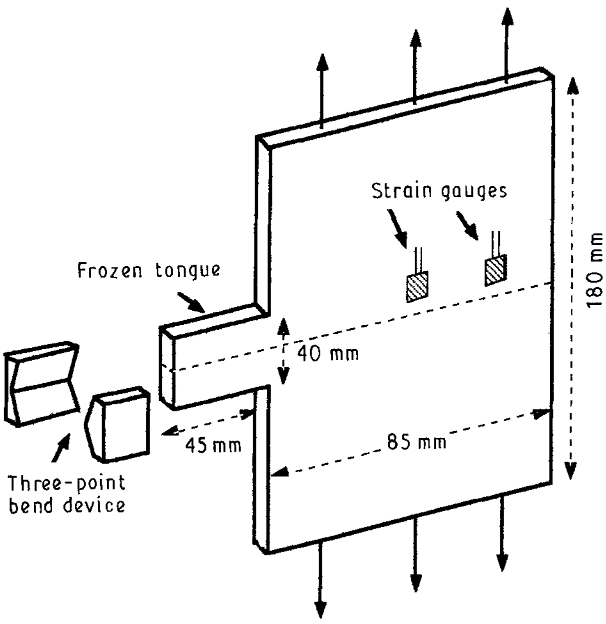

Figure 1 Schematic diagram of frozen tongue geometry with three-point bend device shown.

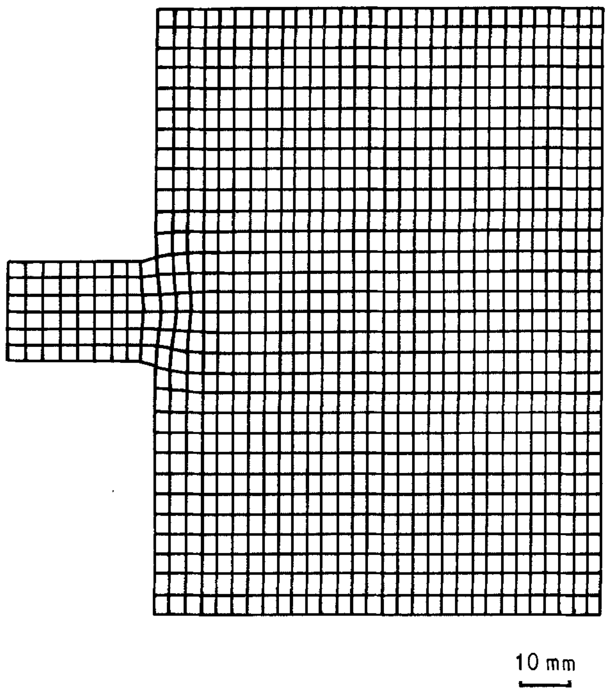

Figure 2 Strain distribution in the specimen.

different volumes of nitrogen to be held to suit different thicknesses of the specimen. The slots through which the specimen tongue entered the vessels were provided with a packing gland to make sealed joints where necessary.

The temperature of the main section of the frozen tongue specimen could be varied to study this effect but for the experiments presented in this paper, the main section of the specimen was kept at room temperature (25 °C). It was verified that the freezing of the tongue only cooled the main section of the specimen for a distance of less than 10 mm along the crack path into the main section. This was assessed by fully inserting the tongue of a polymer specimen into liquid nitrogen for the maximum freeze-time used for the experiments and then monitoring the temperature with thermocouples placed along the crack path into the main section. In the fracture experiments only the end half of the tongue was immersed in liquid nitrogen so the cooling of the main section of the specimen was less than 10 mm. The disturbance of the stress distribution in the main section of the specimen, caused by the presence of the tongue, was found to be confined also to a region 10 mm from the root of the tongue [9]. Fig. 2 shows the method devised to measure this stress distortion by a grid of squares being printed on to a specimen and the distortion of the squares at the tongue root measured. In this figure, a viscoelastic material of modulus 10 MPa has been used to emphasize the distortion which was much less in evidence in the 800 MPa polyethylene material evaluated.

The specimens were obtained from 6 mm thick sheet polyethylene. Side-grooving was not necessary to achieve specimen fracture using the frozen tongue technique but was used in this study to obtain crack paths consistently at right angles to the applied stress. The depth used for the side-grooves was 1 mm so that the plane stress shear lip effects would be minimized.

3. Theoretical model

An attraction of the mass-spring model [10] is that it can be adapted to represent different experimental conditions. For the fracture of small specimens by impact, the dynamic behaviour of the specimen, prior to and after crack initiation, can be much affected by striker and support arrangements [4]. These and the effect of different boundary constraints for other types of test can be provided for in the model.

Fig 3a shows the model in its basic form of a spring of stiffness, k_1, representing the loading system as seen from the specimen fixtures. The mass, m, and spring of stiffness, k_2, represent the effective dynamic properties of the specimen. The model can be modified in many ways to include damping and other features, but in its basic form it represents well the experimental conditions for fast crack propagation presented in this paper. The general equation of motion of the model in its basic form is

$$m(\mathrm{d}^2u/\mathrm{d}t^2) + k_2u = k_1(u_1 - u) \quad (1)$$

where u is the motion of the equivalent specimen mass and u_1 is the motion of the fixture load point. Using the mass-spring model to analyse the standard single-edge notch geometry, as shown in Fig. 3b, in the terms R is the fracture toughness, a_0 is the initial crack length, a is the length of propagating crack, σ is the stress, p is the load, E is the modulus, ρ is the density, $C = (E/\rho)^{1/2}$, H is the height of specimen between grips, D is the width, B is the thickness, the model equation of motion can then be expressed as

$$(R/G_0)(a_0/a) = 1 - (1/C_L)^2\,\mathrm{d}/\mathrm{d}t[a(\mathrm{d}a/\mathrm{d}t)] \quad (2)$$

where the initial energy release rate is

$$G_0 = (\sigma^2\pi a_0)/E$$

and the limiting crack velocity is given by

$$C_L = C(3/4\pi)^{1/2}[(D/H)^{1/2} + (k_1/BE)(H/D)^{1/2}] \quad (3)$$

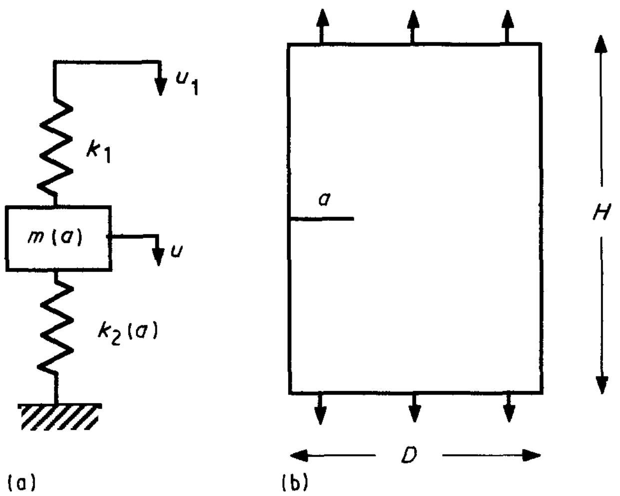

Figure 3 Dynamic mass-spring model: (a) configuration, (b) single-edge notch geometry.

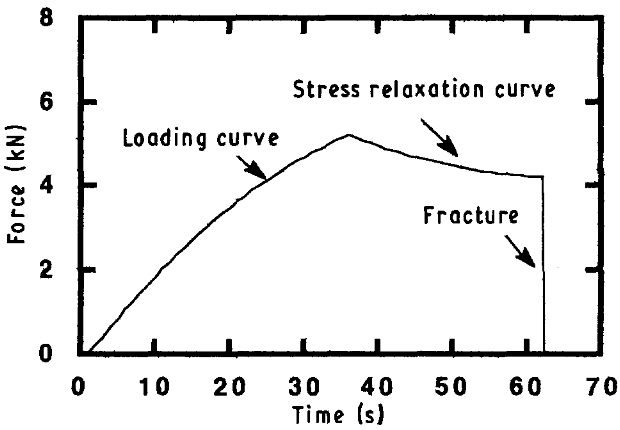

Figure 4 Load–time trace for a frozen tongue specimen (crosshead speed 5 mm min^{-1}).

Solving Equation 2 for the frozen tongue experiments when $a_0 = 0$, $(da/dt)_0 = 0$, $p = \sigma BD$ and (da/dt) is taken at $D/2$, gives

$$(1/p)^2 = (\pi/4ERB^2D)\{1 - [(da/dt)^2/C_L^2]\} \quad (4)$$

which can be rearranged putting

$$R = (\pi p_0^2)/(4EB^2D) \quad (5)$$

where p_0 is the threshold load for crack propagation to give

$$(da/dt)^2 = C_L^2[1 - (p_0^2/p^2)] \quad (6)$$

In the following results, Equations 5 and 6 are used to determine C_L and R from the experimentally determined values of p_0 and (da/dt) at $D/2$.

4. Results

Fig. 4 shows a load–time trace, using an Instron (model-1186) load-cell for a 6 mm frozen tongue specimen of medium-density polyethylene. For all these 6 mm frozen tongue specimens, a constant loading rate of 5 mm min^{-1} was used and the same degree of stress relaxation allowed after the crosshead had been stopped. This was before a crack was initiated through the centre of the specimen as guided by the 1 mm side-grooves normal to the applied stress. The materials evaluated were opaque, but in Fig. 5 a translucent specimen was used to show, by high-speed photography, a crack being launched in the frozen tongue and then propagating through the main section of the specimen passing near to the two strain gauge monitors. This was achieved by back lighting of the specimen so that the strain gauges showed up as dark

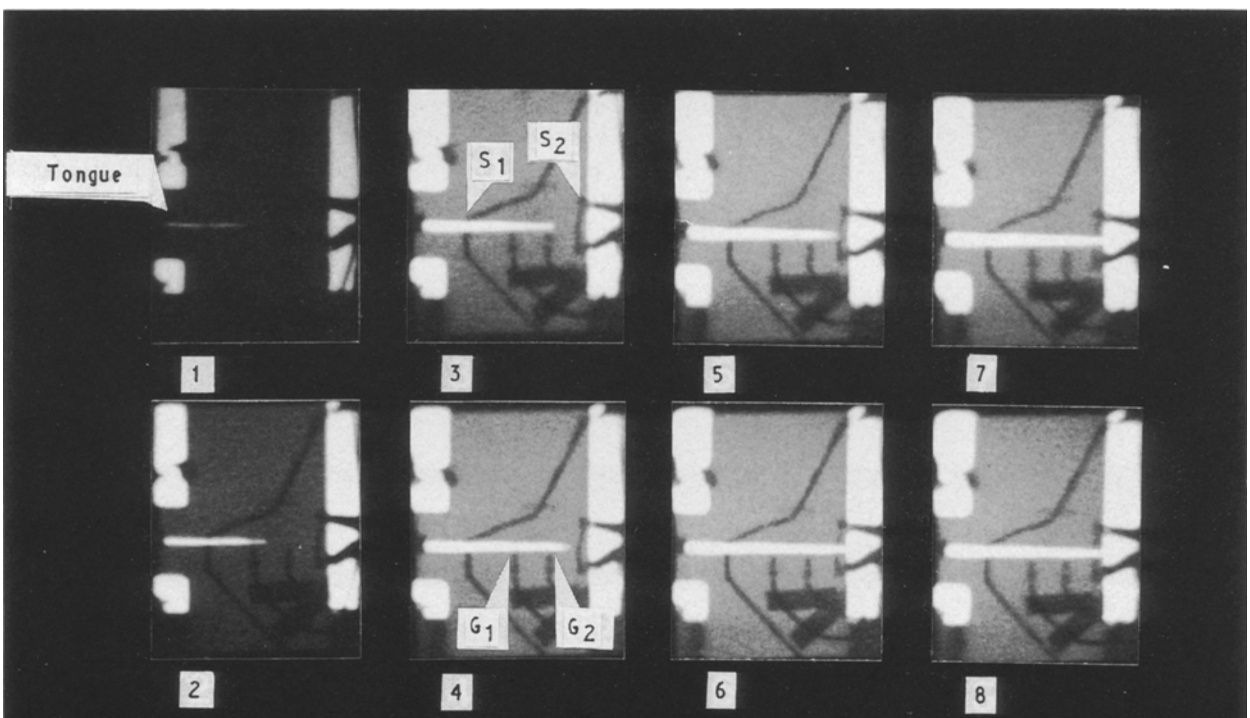

Figure 5 High-speed photographic sequence taken with IMACON image converter camera at a framing rate of 10^4 p.p.s. The first and second conducting strips are labelled S_1 and S_2, respectively. One is located on the left-hand side of the main section of the specimen and the other on the right-hand side. Likewise, the two strain gauges are located at G_1 and G_2, respectively.

shadows, as did the two painted conducting strips, one at the beginning and the other at the end of the crack path. The crack appears as a bright streak of light passing through the specimen from left to right. On-specimen instrumentation provided for several confirmatory measurements of crack velocity from the times between strain gauge sensors and conducting strips. Fig. 6 shows the recorded outputs from the strain gauges and the severing of the conducting strips. As can be seen in Fig. 7, an important advantage of the frozen tongue technique is that the crack surfaces produced are free of unwanted partial arrest lines and other features that can complicate the calculation of fracture parameters.

Fig. 8 shows the crack velocity versus stress relaxed load for 6 mm medium-density polyethylene specimens fractured by the frozen tongue method. The objective was to find the population characteristic and manufacturing variability for this medium-density polyethylene so the specimens used were samples taken from different production batches, which explains some of the scatter of results. To verify that the crack would not propagate below the p_0 value obtained from this study, several attempts were made to propagate a crack just below p_0 and this was not possible. The next step was to superimpose upon the plotted empirical data a crack velocity versus stress relaxed load curve derived from the mass-spring model (Equation 6) and this is the continuous curve shown in Fig. 8. Fitting of the mass-spring derived curve to the empirical data in a way that provided for a linear regression to be used is shown in Fig. 9. From the intercept of the regression line with the vertical axis, a value of limiting crack velocity, $C_L = 580\,\mathrm{m\,s^{-1}}$, was obtained and from its intercept with the horizontal axis a load threshold of $p_0 = 3.5$ kN. The 90% confidence limits about the regression line are shown as dotted lines. Fig. 10 compares the linear regression for medium-density polyethylene obtained, as explained above, with similar regressions for different polyethylene materials known to be of lower and higher fracture toughness. In this way a family of curves can be built up to compare the fast–fracture resistance of a variety of materials.

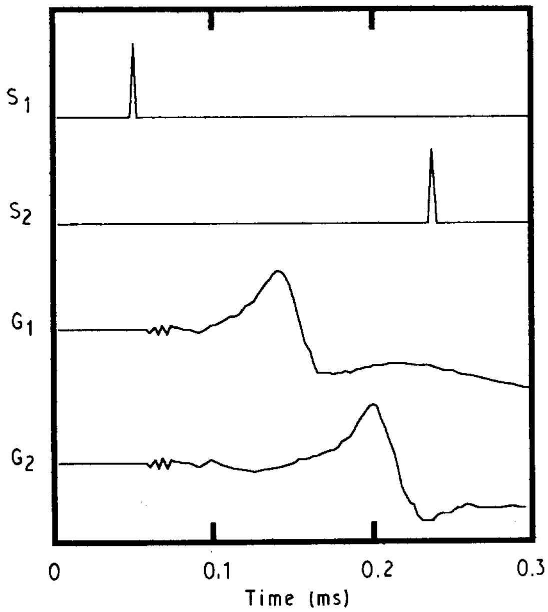

Figure 6 Instrumentation of a frozen tongue specimen. Upper two traces are outputs from first and second conducting strips (S_1 and S_2, respectively). Lower two traces are outputs from first and second strain gauges (G_1 and G_2, respectively).

Using the mass-spring model, the toughness, R, for the frozen tongue specimen can be determined from Equation 5, $R = (\pi p_0^2)/(4EBB_nD)$ which is assumed to be independent of crack velocity where B is the overall thickness of the specimen and B_n is the crack thickness after side-grooving. A frequently used value of E is that determined by speed of sound measurements and for an excitation frequency of 2 MHz the value of E, for the medium-density polyethylene samples evaluated, was found to be 1.9 GPa. This gave an R-value of $2.5\,\mathrm{kJ\,m^{-2}}$ for this medium-density polyethylene material. Using the relationship for stress intensity factor, $K = (ER)^{1/2}$, this gives $K = 2.2\,\mathrm{MPa\,m^{1/2}}$. Table I summarizes the fracture parameters for this and other grades of polyethylene used. It is interesting to observe that whilst E changes very little for each grade of material, there is a significant change of the C_L value. This supports other studies [11] that suggest that C_L relates to the local E-value about the crack tip which differs from the bulk E value of the material. Thus an appropriate relationship to

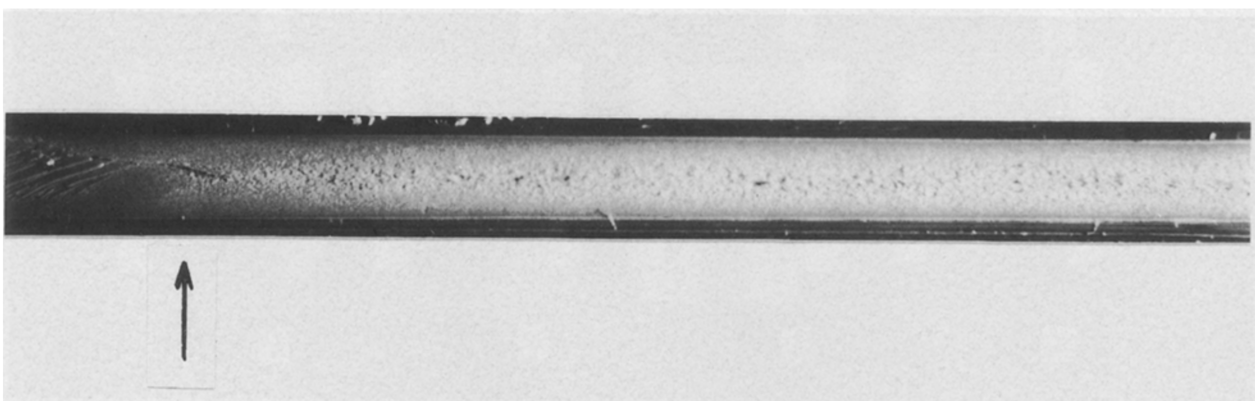

Figure 7 Optical photograph of fracture surface from frozen tongue specimen showing the transition (see arrow) from frozen tongue to the smoother main section of the specimen.

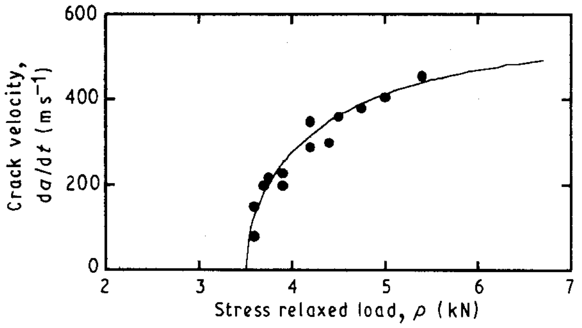

Figure 8 Crack velocity versus stress relaxed load for frozen tongue medium-density polyethylene specimens with Equation 6 fitted to data.

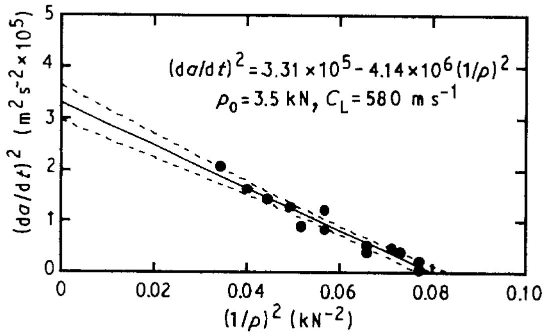

Figure 9 Linear regression of Equation 6 to experimental data with 90% confidence limits in dotted lines.

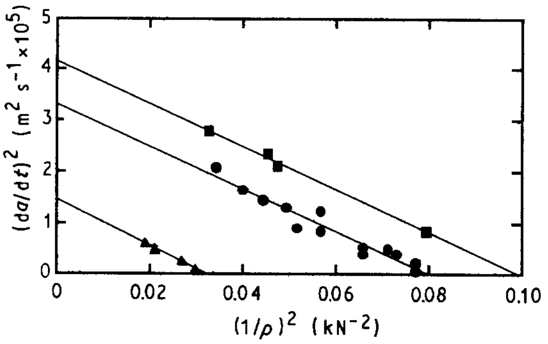

Figure 10 Comparison of linear regression for medium-density polyethylene (see Fig. 9) with similar regressions for different polyethylene materials of (■, ●) lower and (▲) higher toughness.

TABLE I Fracture parameters for polyethylene

p_0 (kN)	C_L (m s^{-1})	E (GPa)	R (kJ m^{-2})	$K(=(ER)^{1/2})$ (MPa $m^{1/2}$)
3.2	630	2.2	1.8	2.0
3.5	580	1.9	2.5	2.2
5.5	380	2.3	5.1	3.4

use is $C_L \propto (\sigma_y/\varepsilon)^{1/2}$ where σ_y is the yield stress and ε is the strain local to the crack tip. The toughness, $R \propto \sigma_y\varepsilon$, the energy dissipated at the crack tip, so that $C_L \propto (1/R)^{1/2}$. Fig. 11 shows a plot of log C_L against log R for different grades of polyethylene including those listed above which gives a slope of $-1/2$ confirming the above relationship. The C_L values will, of course, be geometry dependent but the values used here are all for the same geometry. There is scope to explore this form of relationship further.

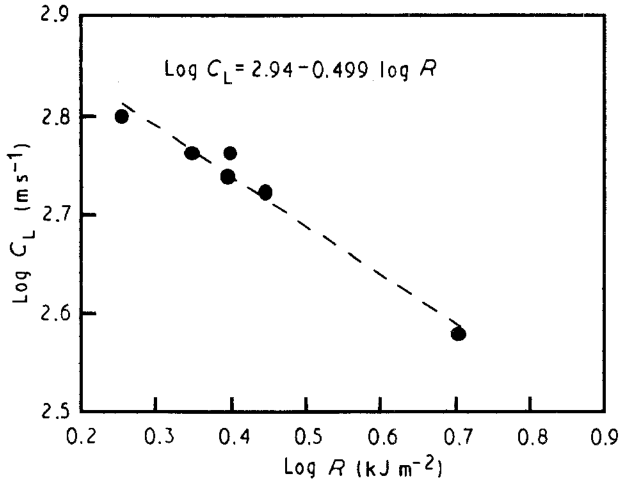

Figure 11 Plot of log C_L versus log R for different grades of polyethylene.

5. Discussion

It is convenient to be able to make measurements of fracture parameters from small specimens of material. It is particularly helpful when these data also relate well to the results of full-scale testing of pipes and other products. Charpy tests are valuable in this respect but additional data are often required, such as the threshold load to just sustain a propagating crack, and other information as listed in the measurement aims of this paper. The frozen tongue method provides these additional data and in several other ways is complementary to Charpy impact methods of fracture testing. Both are easy to perform and only require a modest expenditure on test equipment and material. Also, the time to do the experiments is short. It is thus possible to make frequent evaluations to follow trends in the changing fracture characteristics of materials through their development, manufacture and after being formed into end-products. Also, many small material samples can be taken from products that fail in service and so provide for a more detailed examination of the causes of the failure.

Some evaluation points to note are as follows.

1. These evaluations were at 25 °C, which is the working temperature for many products. However, for a fuller evaluation, then the fracture resistance of the materials at other temperatures may be needed.

2. The evaluations reported on in this paper for 6 mm specimens were near to plane-strain conditions as deep side-grooves were used. Clearly, there is scope for exploring more fully thickness and surface effects using the tongue specimen geometry.

3. The main section of the specimens can have different dimensions and shapes other than the rectangular one used for these experiments. Bonded joints and other features, as used in products, can be incorporated in the main section of the frozen tongue specimens.

6. Conclusions

It is thought the methods used in this paper provide a useful way of obtaining fracture data from small specimens of tough polymers. The advantages are that the method is easy to execute using equipment readily available in most fracture laboratories. Future aims are to evaluate a wide range of polymeric materials using the experimental and modelling concepts presented in this paper. This is to include a study of the effect of bonded joints and other features placed in the crack path. Another interest is to host the model and experimental data processing on modest-sized personal computers such as are increasingly being used to control experimental and factory test equipment.

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