JOURNAL OF MATERIALS SCIENCE **37** (2002) 1115– 1119

The essential work of fracture through the wall of a uPVC pipe

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The specific essential work of fracture, w_e, has been measured for a relatively thick walled uPVC pipe as a function of position through the wall of the pipe. w_e was highest at the surface of the pipe and decreased significantly at the centre of the pipe wall. The variation in w_e through the wall of the pipe correlated with the processing level of the uPVC material as measured by the critical temperature, T_c. The variability in the measured values of w_e was substantially higher in the centre of the pipe where the processing levels were lower. This was likely to be a result of the variability in the microstructure of the material where poor processing had introduced regions of poor fusion of primary PVC particles.

1. Introduction

Measurement of the fracture toughness of unplasticised polyvinyl chloride (uPVC) pipe poses difficulties for a number of reasons. Firstly the size requirement for plane strain conditions implies that valid plane strain fracture toughness values can only be obtained in thick walled pipes of large diameter. Lowering the temperature or increasing the strain rate can decrease the wall thicknesses for which valid plane strain fracture toughness can be obtained but this approach is limited and often takes the pipe thickness outside the normal range of operating conditions. The second difficulty is that the fracture toughness varies with the level of processing in uPVC pipe and this can vary through the wall for thick walled pipes. One measure of processing is the temperature reached by the melt during the extrusion process. This can be measured by DSC as the critical temperature, T_c, between the two melting endotherms [1]. A number of workers have shown that T_c varies through the wall of a uPVC pipe [2, 3]. Consequently, it would be expected that the measured fracture toughness of a pipe would also vary depending on the position of the pre-notch in the specimens cut from the pipe. This has been recognised in some quality standards that attempt to locate the region of poorest quality before placing a notch for fracture toughness testing.

Recently the essential work of fracture approach, as suggested by Broberg [4], has been applied to polymers by Mai and Cotterell [5]. This approach partitions the specific total work of fracture, w_f into two parts. The first is the specific essential work of fracture, w_e, which is a material constant, and the second is the specific non-essential work of fracture, w_p, which is related to work done on the specimen outside the fracture process zone and is therefore geometry dependent. For notched specimens, these quantities are related by

$$w_f = w_e + \beta w_p L \tag{1}$$

where L is the remaining ligament depth for a specimen of width W and notch depth a and β is a plastic zone shape factor. When w_f is plotted against L, a linear relationship should result. If this straight line is extrapolated to a zero ligament length, then w_e can be obtained from the intercept with the w_f axis.

This approach measures a plane stress work of fracture and a number of restrictions on specimen size have been suggested to establish the stress state and appropriate yielding conditions in the ligament [6–8]. The restrictions usually applied are for

$$W/3,\, 2r_p \geq L \geq 3B \text{ to } 5B \tag{2}$$

where B is the thickness of the sample and r_p is the plastic zone size.

This technique has been applied to uPVC films by Arkhireyeva *et al.* [9] and has recently been shown to be useful in characterising the fracture toughness of oriented uPVC pipes [10, 11]. This paper describes work where the essential work of fracture has been measured through the wall of a uPVC pipe. It was undertaken to assess the suitability of the technique to characterise fracture toughness of uPVC pipes and to establish the resolution of the technique in differentiating between pipes having different thermo-mechanical processing histories.

2. Experimental

A nominal 150 mm class 18 extruded uPVC pipe (AS1477 : 1996) made to series 2–cast iron outside dimensions [12] was studied in this work. The pipe had an outside diameter of ∼177.4 mm and a wall thickness of

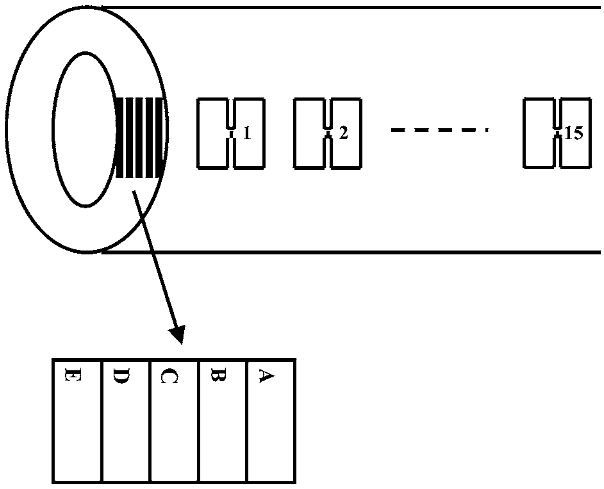

Figure 1 Position of samples cut from the uPVC pipe.

~14.5 mm. 75 double-edge notched tension specimens were machined from the pipe. 15 specimens were machined along the length of the pipe at 5 different depths through the pipe wall as shown in Fig. 1. Position A was near the outer surface of the pipe and position E was near the inner bore of the pipe.

The DENT specimens were machined to a thickness of ~0.75 mm thick, a width of 25 mm and a height of 35 mm. The side notches were machined to a nominal depth and sharpened with a new sharp razor blade. Actual remaining ligament lengths were measured by a travelling microscope after testing of the samples. Remaining ligament lengths ranged from ~2 to 8 mm. The DENT specimens were tested on an Instron tensile testing machine at a crosshead speed of 1 mm min^{-1} at room temperature, $22 \pm 2°C$.

The processing level through the wall thickness was assessed with Differential Scanning Calorimetry. A Perkin Elmer DSC7 system was used over a temperature range 30 to 230°C and a heating rate of 20°C min^{-1}. Specimens ~12 mg in size were cut for thermal analysis from Positions A to E at one diameter of the pipe. A second DSC series was conducted using samples cut at the same depth through the wall but at different positions along the axis of the pipe to check the consistency of the processing along the length of the pipe. An empty reference pan was also tested to correct the baseline.

3. Results

Fig. 2 shows typical load displacement curves for the DENT specimens with a range of ligament lengths. The energy for fracture was measured as the area under the load displacement curves and the results are plotted as the specific work of fracture against ligament length for five different positions through the wall of the pipe in Fig. 3. Each plot is linear and can be extrapolated to zero ligament to give the specific essential work of fracture. The slope gives βW_p. The specific essential work of fracture, w_e, and the slope, βw_p, for each position under consideration are listed in Table I. w_e is also plotted against specimen position in Fig. 5. The measured value of w_e was ~11 kJm^{-2} near the outside wall, ~3 kJm^{-2} at the centre of the pipe and ~8 kJm^{-2} near the inside wall. The error bars in Fig. 5 are 95% confidence intervals. It should be noted that because flat samples were machined from curved sections, the value of w_e could not be obtained right at the surface but was always ~1 mm from the surface. No significant trend in βw_p was observed through the wall thickness.

TABLE I

Position	w_e kJm^{-2}	95% confidence interval	βw_p kJm^{-1}
A Outer wall	11.4	1.8	2.7
B	7.2	2.3	4.1
C Centre	3.0	3.0	3.5
D	6.6	2.8	4.0
E Inner wall	8.1	1.2	2.5

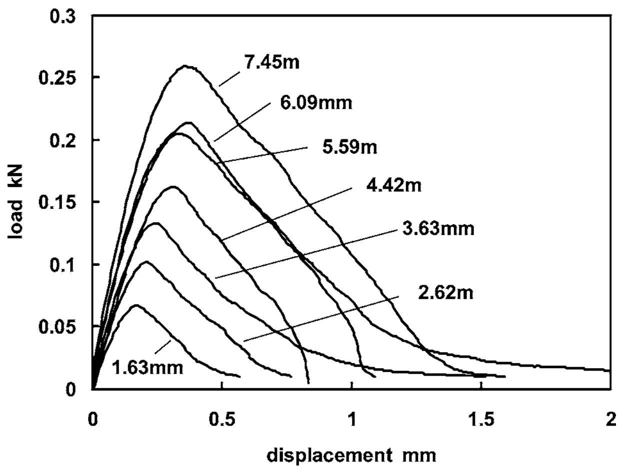

Figure 2 Load displacement curves for the DENT specimens cut from position A in the pipe with a range of ligament lengths.

Fig. 4 shows a DSC trace for position A, which is near the outside wall of the pipe. Other positions through the wall gave similar curves with only the position of T_c and the magnitude of the endotherms on either side of T_c changing with position. The traces were typical of extruded uPVC pipe [1, 2] and showed higher T_c values at the surfaces of the pipe than at the centre of the wall. T_c is plotted in Fig. 5 against pipe wall position. Since very small specimens are required for DSC, extra samples were taken very close to the outer and inner surface of the pipe and these are also included in Fig. 5. DSC traces down the axis of the pipe at a constant wall depth did not show any significant differences.

4. Discussion

The results plotted in Fig. 5 suggest a correlation between the specific essential work of fracture and the critical temperature, T_c. The error bars in Fig. 5 were based on the 95% confidence limit and for clarity these limits are also listed in Table I. These values indicate that there was a significant difference between the specific essential work of fracture measured near the surface of the pipe and at the centre of the pipe wall. In fact these results suggest a reasonably strong dependence of w_e on T_c since there was only a few degrees difference in the value of T_c across the region of the pipe wall from which the specimens were cut.

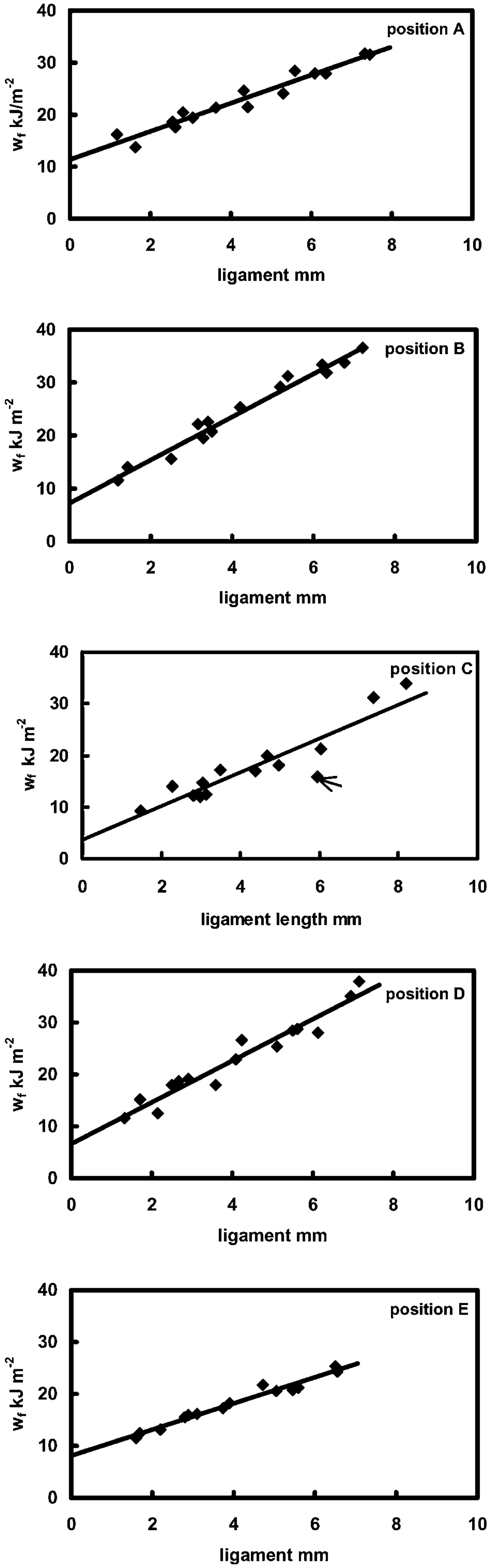

Figure 3 Specific work of fracture versus ligament length for five different positions through the wall of the pipe.

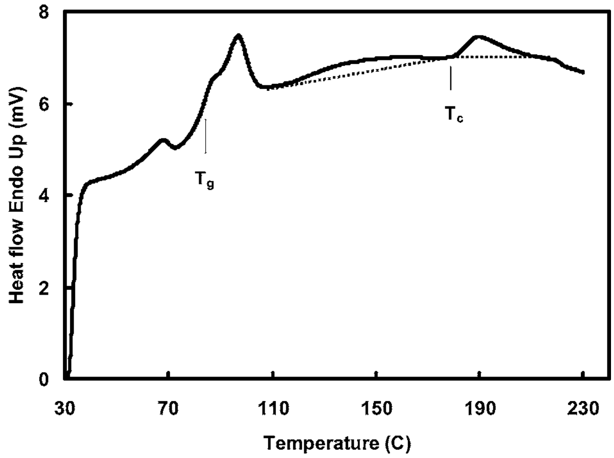

Figure 4 Typical DSC trace for uPVC samples showing T_c (position A, near the outside wall of the pipe).

It should be noted that the essential work of fracture for the pipe tested in this work has been tested previously and was reported as 2–3 kJm^{-2} [10, 11]. The samples used to obtain that value were cut from the centre of the pipe and are therefore consistent with the values obtained in this work. Arkhireyeva *et al.* [9] measured the essential work of fracture for an unplasticised PVC film and obtained a value of ~35 kJm^{-2} which is significantly higher than those obtained here. uPVC film is likely to be well processed and if extruded may also contain some orientation which may explain the high result of Arkhireyeva *et al.* [9].

Mai and Cotterell [5] have argued that for the DENT specimen, the state of stress changes with the ligament length. At small ligament lengths, the constraint imposes a state of plane strain while at larger remaining ligament sizes, the stress state is one of plane stress. The conditions for plane stress were given above in Equation 2. For a circular zone shape, linear elastic fracture mechanics gives the zone size as

$$r_p = 1/2\pi(K_c/\sigma_y)^2 = 1/2\pi\left(Ew_e/\sigma_y^2\right) \qquad (3)$$

if w_e is equated to G_c. K_c is the fracture toughness and σ_y is the yield stress. Hashemi has argued that rather than the yield stress, the flow stress, σ_f [13], or some combination of the flow stress and the yield stress [9] should be used to determine the zone size. The flow stress for uPVC is ~40 MPa while the modulus is ~3 GPa. This gives $2r_p$ at the centre of the pipe as 1.8 mm and at the outside of the pipe as 6.6 mm. For a line zone, r_p is defined as

$$r_p = \pi/8\,(K_c/\sigma_y)^2 = \pi/8\left(Ew_e/\sigma_y^2\right) \qquad (4)$$

and $2r_p$ would be ~4.4 mm at the centre of the pipe and ~16.2 mm at the outside wall. The ligament length used was from ~2–8 mm and consequently the conditions for plane stress may have been violated at least for samples cut from the centre of the pipe wall. An alternative method for assessing the stress state in the ligament is to compare the net section stress, σ_n, to the yield stress or the flow stress. Due to the notch constraint in the DENT specimen, full ligament yielding occurs when

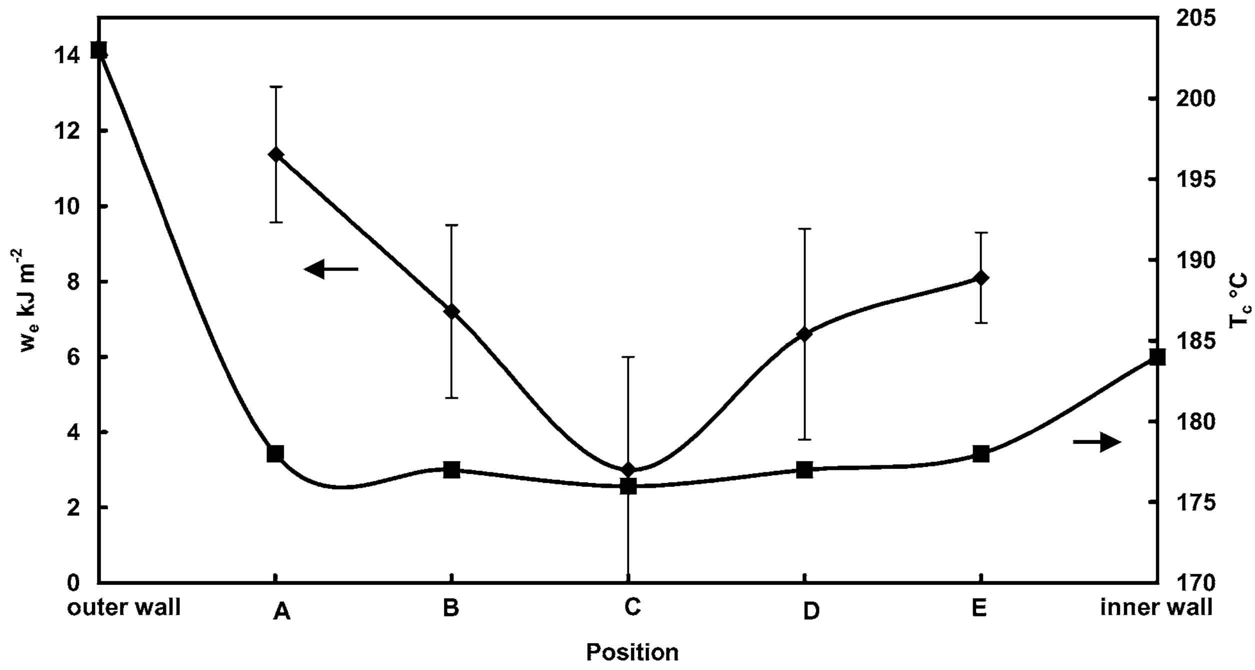

Figure 5 The essential work of fracture and the critical temperature T_c found from DSC as function of position through the wall of the pipe.

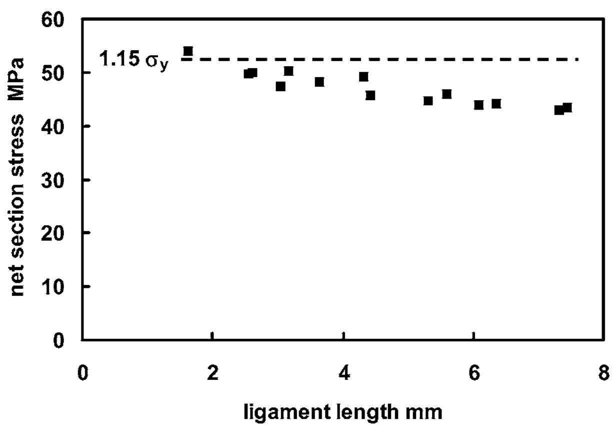

Figure 6 Net section stress as a function of ligament length of samples cut from position A in the pipes.

$\sigma_n = 1.15\ \sigma_y$. Fig. 6 is a plot of the net section stress as a function of ligament length, L, for specimens cut from position A in the pipe. σ_n decreased slightly with L but except for values of $L < \sim 2$ mm, $\sigma_n < 1.15\ \sigma_y$. This result is similar to that obtained by Kwon and Truss [11] previously for this pipe.

The value of the work of fracture under plane strain conditions is expected to be slightly lower than if plane stress conditions applied. The yield stress of uPVC shows only a slight dependence on the level of processing. Consequently, the zone size is smaller when the toughness is low and mixed mode or plane strain conditions would be more likely when the toughness is low. This may accentuate the difference in the measured essential work of fracture for samples cut from the centre of the pipe compared to those cut from near the surface. It should be noted however that several workers [9, 13, 14] have suggested that the requirements specified by Equation 2 are somewhat more restrictive than those required for plane stress and consequently the strong dependence of w_e on T_c may in fact be real.

Another important observation on the results shown in Fig. 4 and Table I is that the 95% confidence limits for samples cut from the centre of the wall (where w_e was low) was substantially higher than for those from near the surface (where w_e was higher). This would be expected since a characteristic of lower levels of processing in uPVC is a greater variability in the microstructure of the material. When a poorly processed pipe is subjected to a solvent immersion test, the damage is rarely uniform and varies around and down the pipe. Equally, when such a pipe is subjected to a 180°C oven test, delamination is often observed in bands through the pipe. The presence of unfused primary particles has been reported on the surface of the delamination [15]. Poor fusion of the primary particles would be expected to produce poor toughness in the material. Since the essential work technique uses small and thin specimens, such variability would be detected between specimens. Thus at least some of the scatter for samples taken from the centre of the pipe is likely to have resulted from real material variability and not from the testing methodology. Better processing, as reflected by higher T_c, is expected to eliminate regions of poor fusion therefore producing more consistent levels of toughness throughout the material and less scatter in the measured values of w_e.

No clear trend in the value of βw_p with position emerged from this work. The shape of the plastic zone was difficult to determine but SEM suggested a similar shaped elliptical zone for all samples, which would suggest little dependence of w_p on position or processing level.

5. Conclusions

A strong dependence of the measured specific essential work of fracture, w_e, on T_c has been found for a relatively thick walled uPVC pipe and that the value of w_e at the centre of the pipe was significantly lower than at the wall of the pipe. No significant trend was found in the value of βw_p as a function of position through the wall of the pipe. The variability in the measured values of w_e was substantially higher in the centre of the pipe where the processing levels were lower. This is likely to be a result of the variability in the microstructure of the material where poor processing has introduced regions of poor fusion of primary PVC particles.

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Received 9 April
and accepted 22 October 2001