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Mode II delamination testing in uniaxially oriented PVC pipes

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The mode II fracture toughness of an oriented PVC pipe was measured using an End Notched Flexure test geometry. A relatively low value of G_{IIC} was found of 1.07 kJm^{-2}and this indicates that it is energetically more favorable for a crack to propagate in the tangential direction rather than radially through the wall of the pipe. Examination of the mechanism of crack advanced showed that although the crack was propagating globally in mode II, micro-cracks were opening ahead of the crack in mode I or in mixed mode. Growth of the crack occurred by linking up of these micro-cracks. This is similar to the mechanism found for mode II cracking in carbon fibre epoxy composites.

1. Introduction

Oriented PVC (oPVC) pipe has been used for water reticulation in the United Kingdom and Australia since the 1980's with excellent results. Uniaxial oPVC pipe is usually manufactured in a two-stage process in which a thick walled precursor pipe is extruded, cut to length and after being reheated to 10–20°C above its glass transition temperature is expanded to the desired diameter while the length is held fixed. The final diameter is increased approximately two-fold while the thickness of the pipe is reduced by approximately 50%. This imparts a molecular orientation in essentially the hoop direction. A second in-line process has also been reported [1] in which the expansion of the extruded precursor is done while the pipe is still hot from the initial extrusion process. By simultaneously drawing the hot pipe extrudate in the axial direction, biaxial orientation can be imparted to the pipe using this process. Previous work in this laboratory has characterized the molecular anisotropy in oPVC pipes [2] and quantified the strength and fracture behaviour of both uniaxially and biaxially oriented pipes [3, 4]. The molecular orientation gives significant improvements in tensile strength and modulus in the hoop direction and allows substantial materials savings for a given pressure rating.

A common feature of the fracture of oPVC is that the direction of crack growth changes from that of unoriented uPVC. Instead of propagating radially through the wall of the pipe, cracks tend to propagate circumferentially. This suggests that the fracture may be opening in mode II (shear) rather than the normal mode I (tensile opening). The work presented in this paper uses an end notch flexure (ENF) geometry to obtain the mode II strain energy release rate of uniaxial oPVC pipe. The mechanism for crack advance was also studied using this geometry.

2. The end notch flexure geometry

The end notch flexure (ENF) geometry is a three-point bend geometry developed for testing interlaminar mode II crack propagation in fibre composite materials [5–7]. Unlike testing of fibre composites where test specimens are usually flat, samples cut from oriented pipe are necessarily curved. Any attempt to flatten a section of oriented pipe would change the molecular orientation. However, provided specimens are cut from reasonably large diameter pipes, it can be assumed that the slight curvature of the sample can be ignored and the specimen will approximate a flat sample. A typical ENF sample cut from the pipe used in this study is shown in Fig. 1.

The strain energy release rate, G, can be obtained for linear elastic materials by determining the change in compliance, C, with crack length, a, using the Irwin-Kies equation:

$$G = \frac{P^2}{2B}\frac{\mathrm{d}C}{\mathrm{d}a} \quad (1)$$

where P is the load and B is the width of the sample. Russell and Street [5] presented an analytical solution based on the compliance of the ENF geometry using beam theory but neglected the effect of shear deformation on the compliance. Carlsson, Gillespie and Pipes [6] corrected this equation for the effect of shear and beam rotation giving

$$C = \frac{(2L^3 + 3a^3)}{8E_1Bh^3}\left[1 + \frac{2(1.2L + 0.9a)h^2E_1}{(2L^3 + 3a^3)G_{13}}\right] \quad (2)$$

where $2L$ is the span of the three point bend test, $2h$ is the thickness of the sample and G_{13} is the shear modulus.

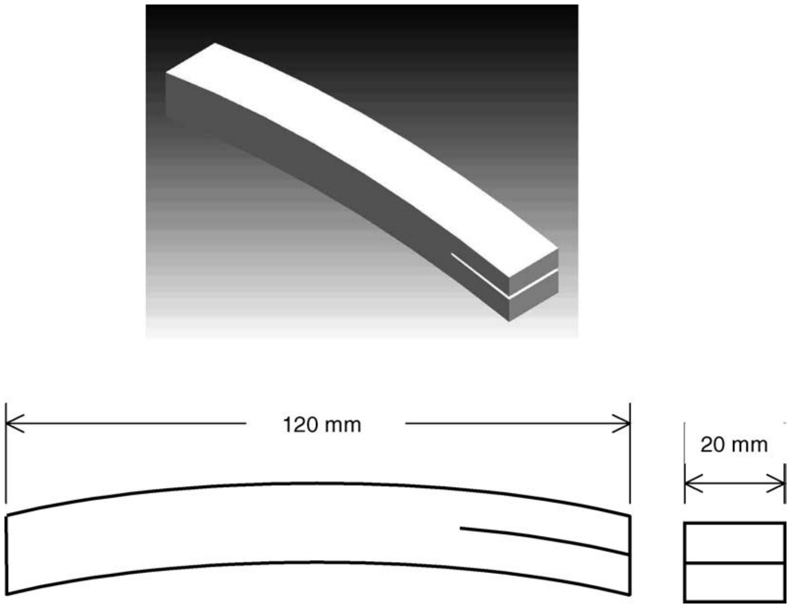

Figure 1 Shape and dimensions of the end notched flexure (ENF) test specimens used.

The mode II strain energy release rate, G_{II}, is then given by

$$G_{\text{II}} = \frac{9a^2P^2}{16E_1B^2h^3}\left[1 + 0.2\left(\frac{E_1}{G_{13}}\right)\left(\frac{h}{a}\right)^2\right] \quad (3)$$

3. Experimental methods

The oPVC used was a uniaxially oriented pipe sourced form Vinidex Pty Ltd. The diameter of the pipe was approximately 600 mm with a nominal wall thickness ranging from 14.5 to 16.5 mm. ENF specimens were cut from the pipe to the dimensions shown in Fig. 1. A slot was cut down the mid plane of the specimen from one end of the specimen to varying depths of 10 to 45 mm. For measuring the strain energy release rate, these slots were sharpened by tapping a sharp razor blade into the end of the slot. Measurements of crack length were made using a traveling microscope fitted with a vernier scale.

Flexural loads were applied using an Instron 4505 testing machine at room temperature (23°C) using a cross head speed of 1 mm/min. The span of the three point bend roller supports was set at 100 mm. In this work, the slightly curved samples were tested with convex surface uppermost.

To aid the identification of the point of crack advance, a series of parallel lines were scribed perpendicular to the sharpened notch. The deformation at the crack tip was then viewed using a stereomicroscope. With application of the shear stress, the perpendicular lines were deformed as shown in Fig. 2. With crack advance, the vertical lines became discontinuous with the strain relaxing above and below the plane of the crack.

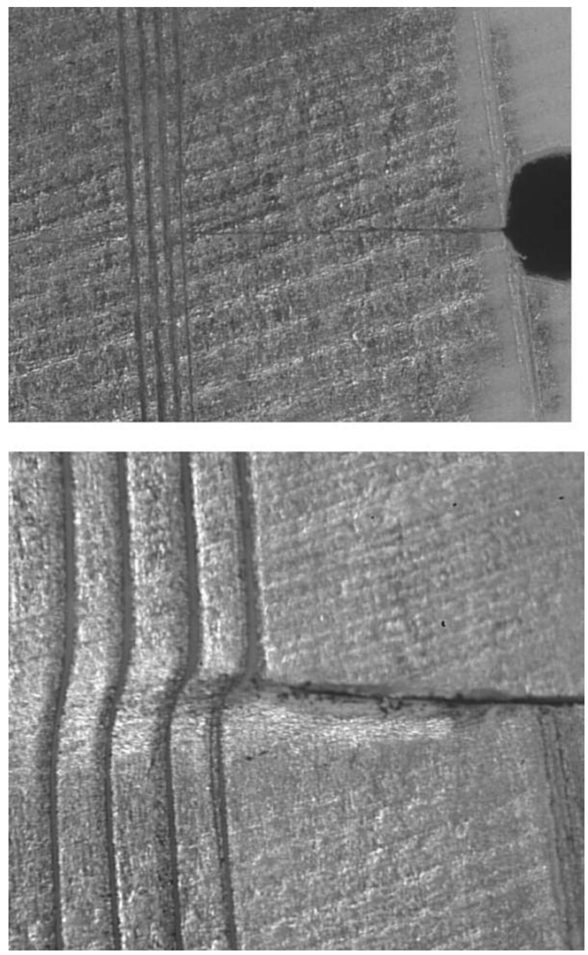

Figure 2 Scribed marks at the end of the prenotch: (a) before loading and (b) at the point of crack growth.

4. Results and discussion

4.1. Compliance

A series of ENF specimens with different notch depths were tested to measure the compliance of the samples as a function of crack depth. In this case the cracks were blunt and the loads were limited to avoid crack propagation. The stress strain curves for these samples showed a small change in the compliance when the surfaces of the prenotch came into contact. This suggests a friction effect between the crack surfaces, which is generally

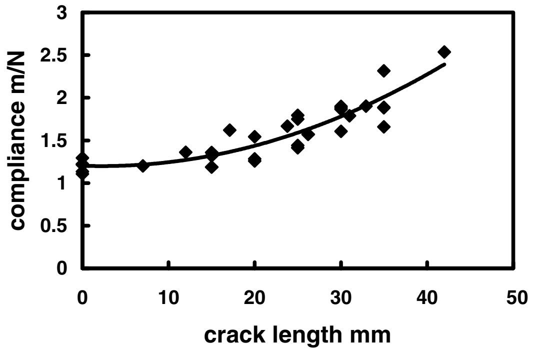

Figure 3 Compliance versus crack length for the ENF oPVC samples.

seen for this type of geometry [6]. Carlsson *et al.* [6] have analysed the friction component for the ENF test geometry and estimated that it produced errors in the order of 2–4%, which were considered insignificant in this present study. The compliance data was taken for the second higher slope. Fig. 3 shows the measured compliance as a function of crack depth for these samples. Equation 2 suggests that the compliance should vary roughly as the cube of the crack length. Significant scatter can be seen in this data. However, most of this is a direct result of the fact that the specimens were cut directly from commercial pipe samples. This means that there was significant variation in the thickness of the samples and since the compliance is dependent on the third power of thickness, this translates into substantial scatter in Fig. 3.

The solid line in Fig. 3 is the best fit of Equation 2 to the data. Equation 2 was fitted by minimizing the sum of squares of the deviations of the measured compliance from predicted values using guessed starting values of the constants. The fitting process gave values for E_1 of 2.8 GPa and G_{13} of 1.1 GPa. The Young's modulus of unoriented uPVC is ∼3 GPa. Molecular orientation in the oPVC pipes increases the elastic modulus in the hoop direction but leaves the modulus in the axial and radial directions relatively unchanged. Kwon and Truss [3] measured Young's modulus in the hoop direction for a uniaxial oPVC as 4.1 GPa at a strain rate of 10^{-3} s^{-1}. The moduli in the other directions were found to be similar to unoriented uPVC at 2.8 GPa. The value of E_1 obtained from the curve fitting of the compliance data in Fig. 3 would correspond to the Young's modulus in the hoop direction. The strain rate experienced by the ENF samples in this work was estimated to be approximately two orders of magnitude lower than those used in the tensile tests by Kwon and Truss. Considering the normal time dependence of polymer properties where the mechanical properties change by ∼10% with each decade of strain rate, then the lower value of 2.8 GPa obtained here appears to be in reasonable agreement with previously reported values for the modulus in the hoop direction for these oriented materials. The shear modulus has not been measured directly in the oPVC pipe samples. If a Poisson's ratio of 0.4 is assumed for these materials, then based on a Young's modulus of 2.8 GPa, the shear modulus would be 1.0 GPa which is also in good agreement with the fitted value.

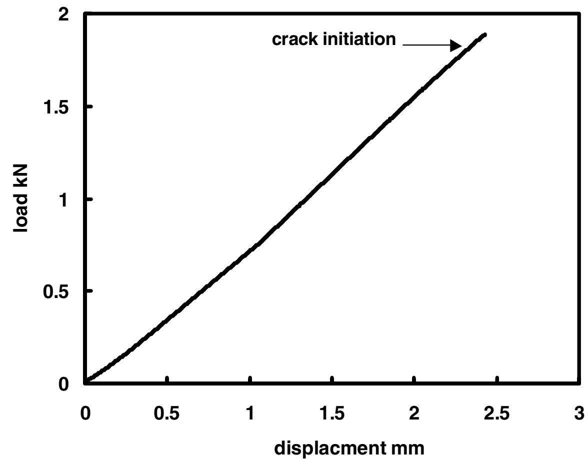

Figure 4 Typical load deflection curve for the ENF samples showing the point of crack initiation (∼16 mm notch).

Fig. 4 shows a typical load extension curve for the sharply notched ENF samples that were tested to obtain G_{IIC}. The point of crack initiation is marked on the curve and it can be seen that, after contact of the notch surfaces, which increased the slope of the load extension curve, the load rose linearly to the point of crack initiation. The point of crack initiation appeared to correspond with the onset of non-linearity in the curve. However, the change in slope was quite small and could not be used to accurately detect crack initiation. This required the point of crack initiation to be detected visually as noted in the experimental section.

Fig. 5 shows the calculated G_{IIC} values for the ENF samples of the oPVC material. The G_{IIc} values were calculated using Equation 3 and the values of Young's modulus and shear modulus of 2.8 and 1.1 GPa discussed above. Although there is some scatter in the results, there was not a systematic tend with crack length. The scatter resulted largely from the difficulty in accurately identifying visually the point of crack initiation. The average value of G_{IIC} was 1.07 kJm^{-2}. An alternative method of obtaining G_{IIC} is to fit a polynomial to the compliance data of Fig. 3 and use Equation 1 directly. This approach produced a similar average value for G_{IIC}.

Unoriented uPVC has a G_{Ic} of 3–4 kJm^{-2} and is usually measured for cracks growing in a radial direction through the wall of the pipe. An equivalent G_{IC} for mode I cracks growing through the wall of oPVC pipe

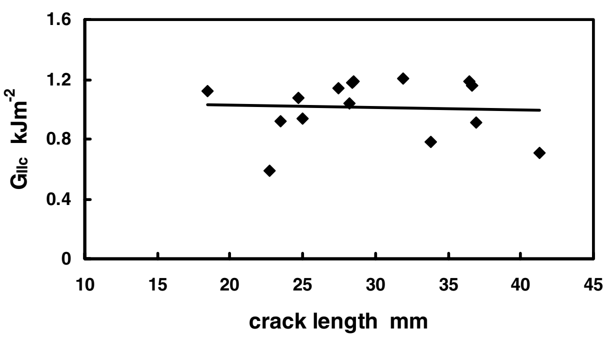

Figure 5 Measured G_{II} as a function of crack length for the oPVC ENF samples.

has not been measured since cracks with this orientation usually divert to growing circumferentially. However, G_{IC} for cracks growing in a radial direction in oPVC would be expected to be higher than that for uPVC since the crack is growing perpendicular to the molecular orientation. Cracks growing in the circumferential direction in oPVC pipes have been studied by Kwon and Truss [3, 8]. They cut specimens from an oPVC pipe containing a circumferential crack. By gripping the free ends of the cracked specimen, the crack could be peeled apart giving a nominal G_{IC} of $\sim$4 kJm^{-2}. However, these tests were conducted on a thin walled oPVC pipe and this value may not have been a plane strain value of G_{IC}. Normally, it would be expected for G_{IIC} to be higher than G_{IC} but that may be complicated by the anisotropy of these oriented materials. If the relatively low value of G_{IIC} for the oPVC pipe of $\sim$1 kJm^{-2} found here is correct, it would indeed indicate that it is energetically more favorable for the crack to propagate circumferentially rather than radially through the wall.

4.2. Crack propagation mechanisms

In order to view the features of mode II crack propagation, the loads on the specimens were raised well above the observed crack propagation load and the crack left to propagate for up to one millimetre. The cracks were then slightly opened in mode I by gently wedging apart the faces without damaging the crack tips. This opened crack features that would otherwise be difficult to detect while loading in mode II.

The specimens were viewed at their surface and also on sections cut down the centre line of the specimen. Both surface and sectioned specimens were polished using wet and dry paper with decreasing abrasive size and given a final polish with diamond paste.

Common features of the crack tip are shown in Figs 6 and 7. Fig. 6 shows that the crack tip has diverted upwards away from the plane of the crack. Fig. 7 shows a similar crack that has also diverted upwards from the plane of the crack but also shows a number of micro-cracks opening ahead of the crack tip. Note also that in both micrographs the surface of the crack back from the crack tip was reasonably rough.

The features shown here resemble those found for mode II ENF testing of fibre composites. Lee [7] has attributed the hackle patterns seen on the fracture surface of carbon fibre epoxy composites tested using the ENF geometry to micro cracks opening ahead of the crack tip as a result of the interlaminar normal stresses. These normal stresses exist on the planes of maximum principal stress.

A very similar mechanism for mode II crack propagation appears to be present in these oPVC materials. The proposed mechanism for mode II fracture of oPVC is best illustrated in Fig. 8. The oPVC pipes have a degree of orientation of the molecules in the hoop direction. In Fig. 2, the crack was propagating horizontally in the same direction as the molecular orientation and the scribed lines were perpendicular to the molecular orientation. When the load is applied, deformation occurs at the tip of the crack. This locally rotates the molecular orientation towards the vertical as seen by the distortion of the scribed lines in Fig. 2. The finer lines in the background of Fig. 8 represent the molecular orientation. The crack propagation will require least energy by following a path parallel to the molecular orientation. Consequently, the crack tip also diverts away from the plane of the crack and opens in mode I or at least in mixed mode with a strong component of mode I. The horizontal arrows in Fig. 8 indicate the remote imposed shear loads and the arrows at 45 degrees indicate the normal loads that cause the crack tip to open and grow. Continued growth of the crack at an angle to the main crack due to the normal stresses will become progressively more difficult due to the molecular orientation. Consequently it becomes energetically favorable for a

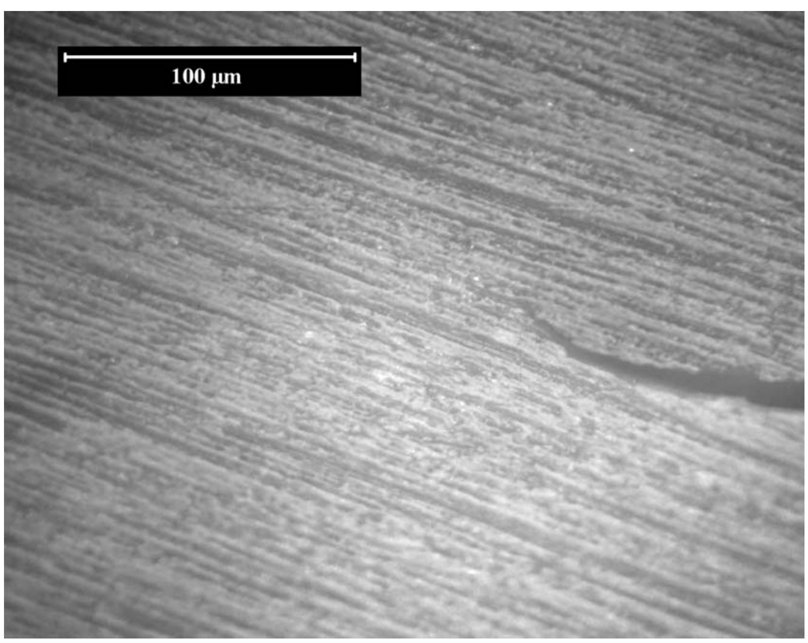

Figure 6 Micrograph of the crack tip area. Note the upward deflected crack tip.

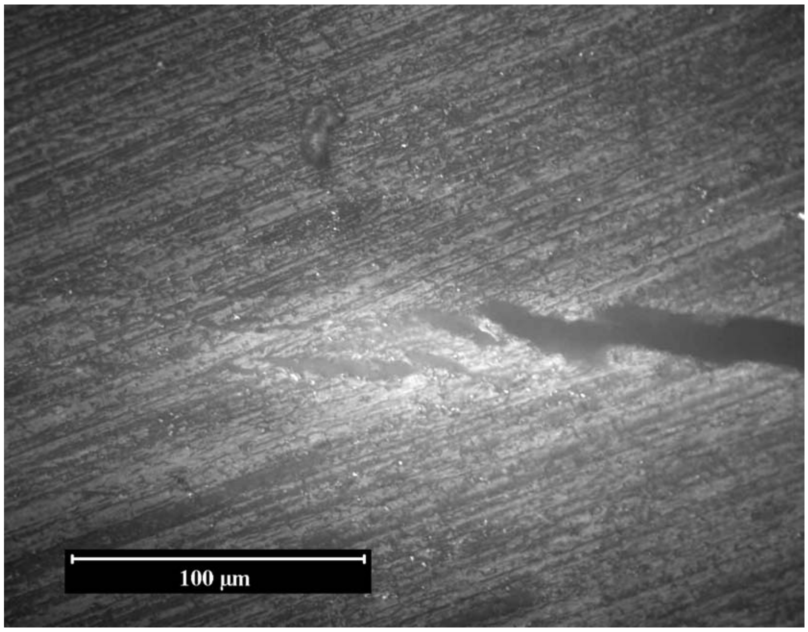

Figure 7 Micrograph of the crack tip region again with an upward deflected crack and with micro-cracks opening ahead of the main crack.

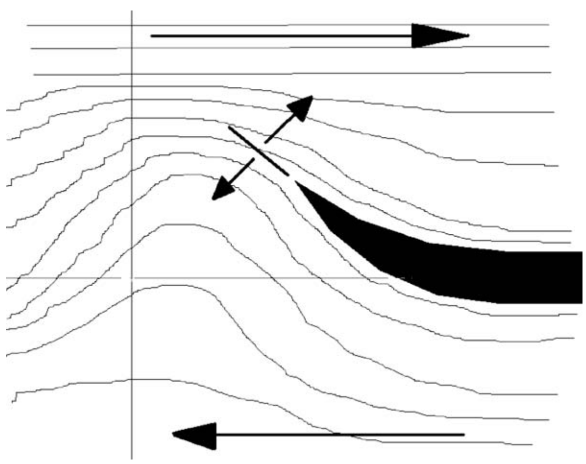

Figure 8 Schematic depicting the mechanism of mode II crack growth in these materials.

new micro-crack to form ahead of the first crack. Such micro-cracks would open between the planes of molecular orientation and again have a substantial mode I component. This is the process seen in Fig. 7. Normal uPVC pipes have sites of weakness due to the presence of particulate additives or due to low fusion between the PVC particles. These incipient flaws are thought to be aligned during the orientation process. Continued nucleation of micro-cracks at these incipient flaws in the damage zone of the crack should require relatively low energies. Continued propagation of the crack requires the linking up of the micro-cracks ahead of the main crack. Thus in the relaxed specimen, the crack appears to have propagated in a single plane. The only evidence of the micro-mechanism is a residual roughness to the fracture surface, similar to the hackle pattern on carbon fibre epoxy samples, and the presence of micro-cracks above and below the plane of the main crack.

The major difference between the failure mechanism in mode II failure of fibre composites and oPVC is that in fibre composites, the micro-cracking is confined to a small layer between the fibres. In oPVC, the micro-cracking can extend some distance from the plane of the crack. In addition, the relative stiffness of the fibres in fibre composites will restrict the degree of deformation at the crack tip to a much greater extent than the relatively modest molecular orientation in oPVC. Both of these factors would increase the relative roughness of the fracture surface in the oPVC materials and increase the energy absorbed due to intersurface friction.

5. Conclusion

The mode II strain energy release rate for OPVC pipe has been measured using an end notched flexure (ENF) geometry and has been found to be significantly lower than G_{IC} for cracks propagating radially through the wall of a uPVC pipe. The micro-mechanisms for mode II crack propagation were also studied. It was found that although the global crack was propagating in a shear mode II, the damage zone at the crack tip contained micro-cracks that were opening in tensile mode or in mixed mode. These micro-mechanisms were similar to those reported for mode II crack propagation in carbon fibre composites.

Acknowledgement

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