Plastics, Rubber and Composites Processing and Applications **17** (1992) 247–253

Charpy and dynamic fracture testing for rapid crack propagation in polyethylene pipe

P. S. Leevers, P. Yayla & M. A. Wheel

Mechanical Engineering Department, Imperial College of Science, Technology and Medicine, London, UK, SW7 2BX

(Received 15 May 1991; revised version received 30 July 1991; accepted 5 August 1991)

Abstract: Ductile pipe grade polyethylenes can, under severe conditions, fail by Rapid Crack Propagation (RCP). Critical pressures (below which RCP always arrests) of medium density and modified high density polyethylene pipes, measured using a small-scale pressure test, identify temperature and thickness mediated brittle–ductile transitions which effectively characterise their performance in full-scale tests. Instrumented Charpy tests on specimens thinner than the pipe wall reflect the transition temperatures only qualitatively. High Speed Double Torsion tests across a spectrum of crack velocities yield plane-strain dynamic crack resistance data, even at 0°C and for specimens only 6-mm thick; they therefore conceal the ductile–brittle transition, but more effectively characterise the worst case of a highly constrained crack in thicker pipe.

1 Introduction

Full-scale field tests[1] on plastic pipelines have shown that above a critical pressure, p_c, a brittle crack initiated at sufficient speed can continue to run axially at high velocity (about 100–350 ms^{-1}). The critical pressure which characterises this rapid crack propagation (RCP) failure mode falls with increasing diameter and decreasing temperature, and is strongly material-dependent. As new plastics earn acceptance for larger diameter pipe operating at higher pressures, quality assurance therefore imposes an increasing need to test as-extruded pipe for RCP resistance. Full-scale tests, however, are an extremely expensive way of doing so, and the authors have sought to develop a system for predicting p_c that can minimise the need for them.

There are four essential elements in such a system.

(1) Reference data for p_c from full-scale tests. The authors regard the standard British Gas full-scale test method,[1] using air or nitrogen for pressurisation, as definitive.

(2) A model of RCP in pipelines, which can relate p_c to material properties, pipe dimensions, and perhaps properties of the contained fluid (e.g. gas or water). The simplest model, assuming that crack propagation completely and instantaneously releases strain energy stored in the pipe wall, leads to the 'Irwin–Corten' equation:

$$p_c = \frac{t}{(D-t)}\sqrt{\frac{8EG_D}{\pi D}} \qquad (1)$$

where E and G_D are the dynamic tensile modulus and dynamic crack resistance of the pipe material and D and t are the pipe diameter and thickness (the Standard Dimensional Ratio, SDR = D/t, determines the pipe service pressure rating). More sophisticated numerical models,[2] which are outside the scope of this paper, suggest that eqn (1) seriously underestimates the critical pressure.

(3) Laboratory tests for geometry-independent material properties which the model claims to control p_c. For the model underlying eqn (1), these are E and G_D.

(4) A small-scale test for pipe, to validate the predictions of the model, whilst reflecting the effects of extrusion on residual stress and crystallinity distributions in the material. The authors have developed the 'Small Scale Steady State' (S4) pipe test[3] which broadly reflects full-scale test results.[4]

This paper focuses on the third of these elements, comparing the usefulness of Charpy and of High Speed Double Torsion tests[5] for generating material property data relevant to RCP.

2 Full-scale and small-scale pipe tests: material dependence

Medium density polyethylene (MDPE) is currently the most widely used material for gas and water distribution pipe. Most MDPE grades yield similar p_c results in full-scale tests; for MDPE-1, a typical resin, the 250-mm diameter SDR 17·6 pipe critical

Plastics, Rubber and Composites Processing and Applications 0959-8111/92/$05.00 © 1992 The Plastics and Rubber Institute, England. Printed in Great Britain

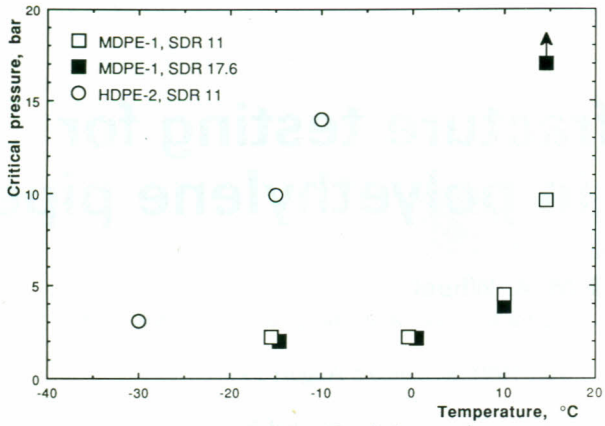

Fig. 1 Critical pressure for polyethylene pipes, measured using the S4 test.

pressure is 6·1 bar at 0°C. Recently introduced 'third-generation' modified high density polyethylene (HDPE) grades perform much better, making RCP effectively unobtainable in full-scale tests at 0°C for any pressure.

Figure 1 compares results from S4 tests on 180-mm MDPE-1 and HDPE-2 (a third-generation gas pipe grade) pipe at a range of temperatures. Each point represents a series of tests to define the characteristically sharp transition between prompt crack arrest and continuous propagation.

If the effect of diameter on critical pressure is as weak as eqn (1) suggests, it is initially surprising that the S4 test critical pressure for 180-mm diameter MDPE-1 at 0°C is so much lower than the 250-mm diameter full-scale critical pressure p_c. The explanation lies in the loss of pressure which accompanies pipe fracture. This generally takes place in two stages. Initially, gas in the uncracked pipe flows back axially towards the approaching crack front; as it accelerates, its pressure falls towards a theoretical minimum of (for air pressurisation, and for a very slow-running crack) 28% of the initial line pressure. This reduced pressure then collapses behind the crack front as gas escapes by free radial outflow. Since, in the S4 test, the initial phase — prior decompression by axial flow — is deliberately suppressed by internal baffles, the crack front sees a pressure of up to $(0{\cdot}28)^{-1}$ times that which it would see in the same pipe under a full-scale test. Although this model is simple, and although high crack speeds restrict prior decompression to less than the attainable maximum, an accumulating base of comparable S4 and full-scale data supports this contention that critical pressures *at the crack tip* are similar in both tests.

The S4 data for HDPE-2 are relatively sparse, but it is possible to infer a temperature below which p_{cS4} for each material is effectively constant. As the temperature rises further, the fracture surfaces take on ductile characteristics, and the critical pressure rises steeply; it seems fair to characterise this process as a brittle–ductile transition (BDT). The lower-shelf p_{cS4} for HDPE-2 cannot be determined from the data shown, but is clearly no more than 50% greater than that for MDPE-1. These very different materials are much more strongly distinguished by their BDT temperatures, which lie about 30°C apart, Identifying the BDT as the end-point of the lower shelf leads us to estimates of around 5°C for MDPE-1 and −25°C for HDPE-2.

3 Small-scale tests: pipe wall thickness effects

A significant feature of Fig. 1 is the weakness of thickness effects on critical pressure in MDPE-1 on the ascent from the lower shelf: SDR 11 and SDR 17·6 pipes show similar p_{cS4} values despite the 60% thickness difference. If eqn (1) holds, this experimental result implies that a thicker wall exhibits a lower dynamic toughness. For the same material, reducing the test temperature has the same effect. The equivalence of decreasing temperature and increasing thickness in their effect on the BDT is well known both for metals and for polymers. The data here are incomplete; further tests are needed to show that eqn (1) predicts the dependence of lower shelf p_{cS4} on the geometrical parameters D and SDR. Data from British Gas full-scale tests on thicker pipe suggest that it does.

Fracture surfaces created by RCP in PE pipe normally exhibit more ductility at the bore than at the outside diameter. In an attempt to suppress this ductility and study RCP in the lower-plateau plane-strain toughness state, S4 tests were carried out on 180-mm SDR11 specimens of MDPE-1 and HDPE-2 modified by a 1-mm deep axial razor cut along the entire length of the bore. This cut was expected to serve as a sidegroove (maintaining stress along a through-thickness front) without intensifying the hoop stress enough to extend radially itself. In fact, if eqn (1) holds, the hoop stress intensifying effect of even an infinitely sharp notch, h deep, along the bore would be only $\sqrt{(h/D)}$ times that of a long axial crack.

These specimens showed remarkably low critical pressures. For MDPE-1, p_{cS4} at 20°C dropped to 1·0 bar, whilst for HDPE-2, in which RCP had previously been impossible even at 0°C, p_{cS4} at 20°C was just 1·5 bar. Fracture surfaces were, as intended, glassy throughout the full thickness, showing only quasi-brittle surface features such as the 'river' markings seen in glassy polymers; there was no evidence of spurious radial crack extension from the sidegroove. For HDPE-2, p_{cS4} continued to fall at lower temperatures (0·8 bar at 0°C, 0·75 bar at −15°C), but MDPE pipes fragmented, making tests impossible.

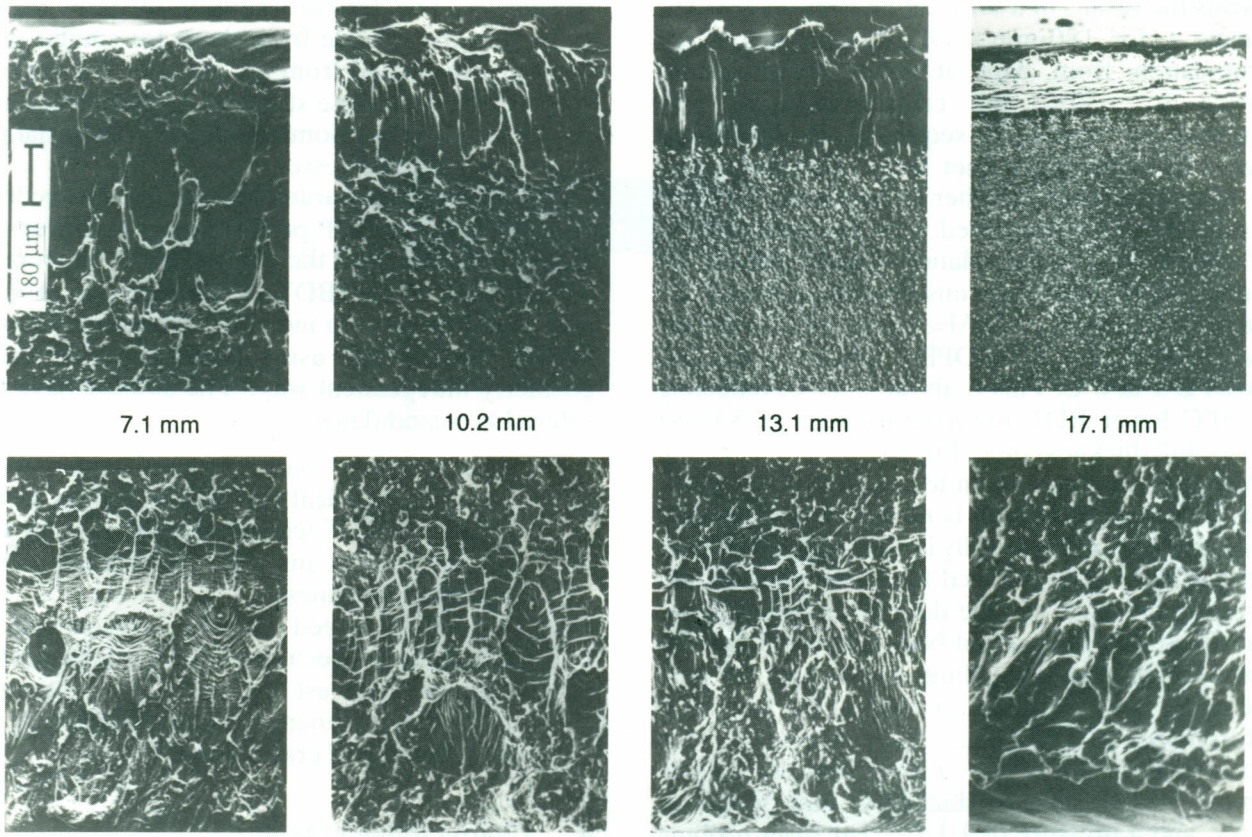

Fig. 2 Micrographs of the fracture surface from RCP at 3·5 bar in MDPE-1 180-mm pipes of decreasing wall thickness; at outer diameter (left) and bore (right).

These experiments simulated an increased — perhaps infinite — pipe thickness. The way in which *decreasing* thickness might affect the BDT was explored by reducing the wall thickness along S4 specimens, in a staircase of one-diameter long steps. A fast crack was generated in the usual way (by radial impact of a chisel-ended projectile onto an unpressurised extension of the pipe) and penetrated the pressurised section at full wall thickness. Crack propagation velocity measurements[4] showed that each subsequent reduction in thickness quickly (within $0{\cdot}2D$) decelerated the crack to a new steady velocity. Finally, the crack reached its minimum viable speed and arrested.

There seem to be two (possibly synergistic) effects at work here. At each reduction in thickness, the near tip constraint falls. Perhaps as a result of local softening, compounded by geometrical effects which reduce the limiting crack speed (i.e. the speed of circumferential contraction waves), the crack decelerates, reducing strain rates and further promoting flow. Figure 2 shows fracture surface micrographs from regions adjoining both the bore and the outside diameter. In addition to the overall increase in surface roughness, seen macroscopically as an increase in stress whitening, there is considerable broadening of the ductile zone at the outside surface

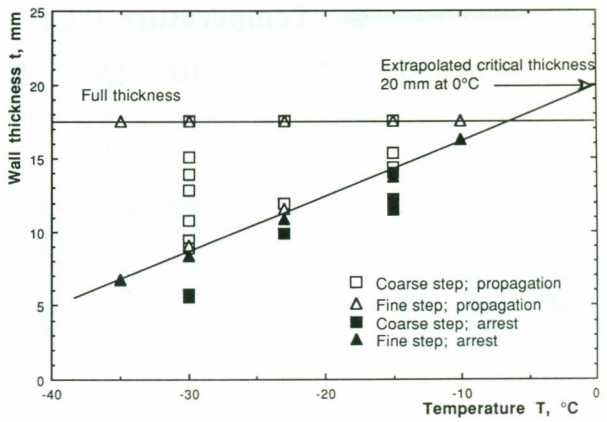

Fig. 3 Variation of critical thickness with temperature, from S4 tests on HDPE-2 pipes with step-tapered wall thickness.

(but not at the bore) as the pipe wall thickness decreases. This self-promoting increase in ductility finally precipitates crack arrest. A series of experiments has indicated that self-arrest is manifested as an effectively constant critical thickness below which RCP is not viable at any pressure.

Experiments on 180-mm pipe have shown directly that for MDPE-1 at 0°C the critical thickness, t_c, is about 6 mm, whilst for HDPE-2 it exceeds the thickness of SDR 11 pipe (17·6 mm). Figure 3

presents the results of a series of S4 tests designed to estimate t_c for 180-mm HDPE-2 pipe at 0°C by extrapolation from data at lower temperatures. Starting at −30°C, the critical thickness was measured by testing a sequence of specimens tapered in successively finer steps. This procedure was then repeated at a higher temperature, to introduce ductility in a controlled way. The results show that simple linear extrapolation should provide an adequate (and probably conservative) estimate for critical thickness: 20 mm. Also of interest is the temperature at which t_c for HDPE-2 falls to 6 mm, that of MDPE-1 at 0°C. This is about −35°C, reflecting the 30°C lower BDT temperature seen in S4 test data for full thickness pipe (Fig. 1).

Although care was taken to machine these specimens at low speeds, there is no doubt that residual stress profiles and (especially in thin section) crystallinity profiles in the reduced thickness pipes would not represent those of pipe directly extruded at the same thickness. Since it had been suspected that the slowly-cooled, high-crystallinity region near the pipe bore might be responsible for most of the high RCP performance of HDPE-2, one specimen was machined from the *bore* — rather than the outside diameter — to 12-mm thickness, and tested at −15°C and a pressure of $1{\cdot}1p_{cS4}$. Far from robbing the pipe wall of its toughness, this trans-critical thickness step arrested the crack within about 100 mm, as it had done for the externally-machined specimens. The fracture surface ductility profiles were indistinguishable from those for similar thickness pipe machined from the outside. These results suggest that transverse stress intensity profiles associated with fracture dominate those in material properties or residual stresses.

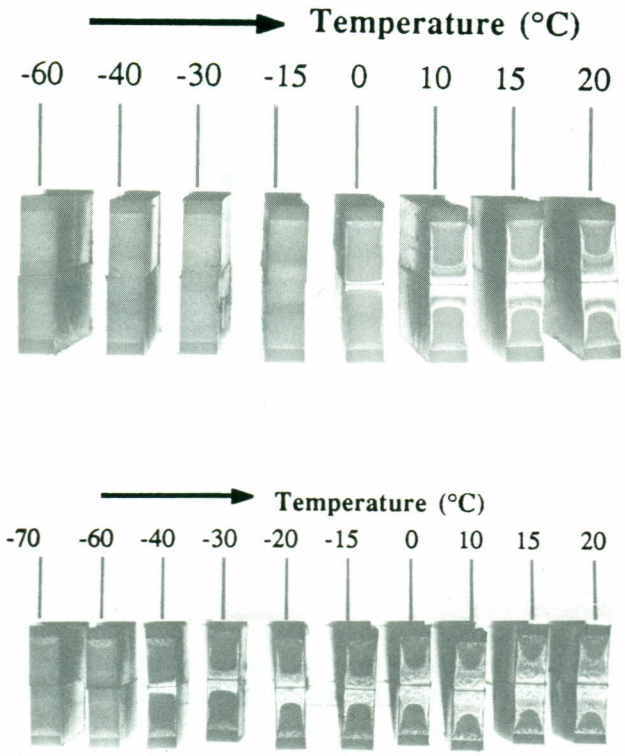

Fig. 4 Notched Charpy impact test specimens showing well-defined ductile–brittle transitions in (a) MDPE-1 and (b) HDPE-2.

In summary, two parameters seem to be needed to characterise pipe RCP performance: the lower-shelf critical pressure, and the characteristic temperature or thickness of the BDT. What material property tests could be used to index the distinction between MDPE and HDPE using these parameters in a geometry-independent way? The authors have considered two candidates:

(1) The notched Charpy 'impact' test: a widely accepted classical test which can be used to identify a BDT temperature or — using fracture mechanics analysis — to estimate a crack initiation toughness.
(2) The High Speed Double Torsion (HSDT) test. This has been developed at Imperial College over the last few years as a method for determining dynamic fracture toughness, G_D, as a function of crack speed.

4 Charpy impact tests

Notched Charpy impact tests were carried out, over a range of temperatures, using a CEAST instrumented pendulum machine. Specimens, 5 mm wide × 10 mm deep × 40 mm span, machined from the pipe wall with the initial notch in the axial/radial plane, were tested at $1{\cdot}6\ ms^{-1}$. For most temperatures the initial razor-notch depth was 2 mm in all tests. At three temperatures (−15°C, 0°C and 23°C) in each material, tests were carried out using notch depths of 2, 4 and 6 mm.

The fracture surfaces (Fig. 4), arrayed according to test temperature, manifest the BDT as a 'nil-ductility temperature': stress whitening in the least constrained areas appears above about −5°C in MDPE-1 and −55°C in HDPE-2. Figures 5 and 6 show impact energy results calculated using $BD\Phi$ analysis[5] of both peak load and total energy data. Each individual data point represents the average for three or four tests. Although application of the $BD\Phi$ analysis to tests with substantial post-peak load energy absorption is technically improper, overplotting results in this way is clearly an effective way of locating the phenomenological BDT for each material. The impact energy release rate conventionally calculated from peak load can be interpreted as an energy release rate, G_{ci}, for dynamic crack initiation. The lower shelf G_{ci} value for HDPE-2 is very well defined at $11{\cdot}5\ kJ\ m^{-2}$, but for MDPE-1 G_{ci} is still apparently falling with temperature even at −60°C, at which it is $3{\cdot}8\ kJ\ m^{-2}$. Un-

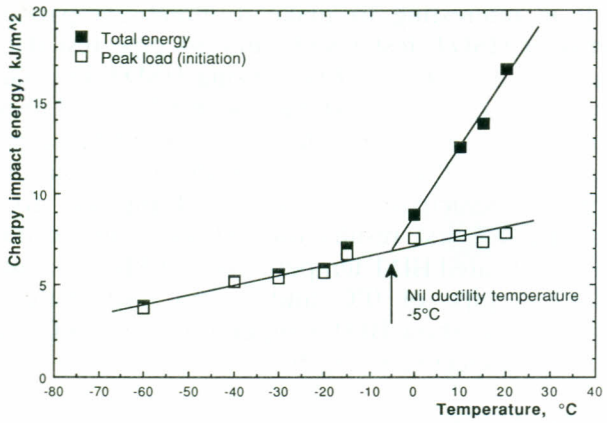

Fig. 5 Charpy impact energy versus temperature for MDPE-1.

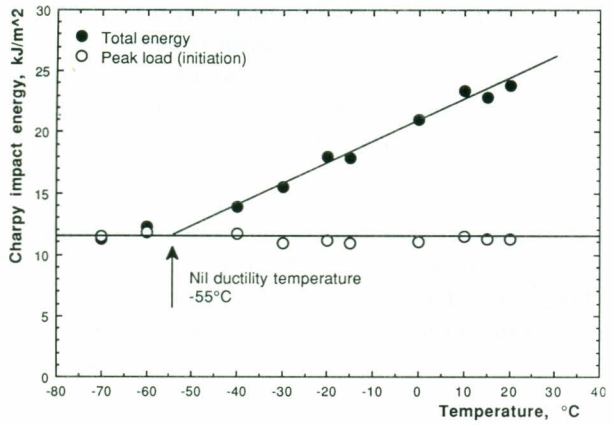

Fig. 6 Charpy impact energy versus temperature for HDPE-2.

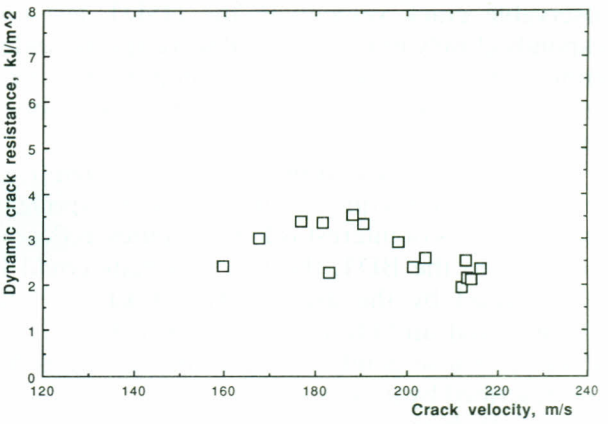

Fig. 7 Dynamic crack propagation resistance of MDPE-1 at 0°C; HSDT data.

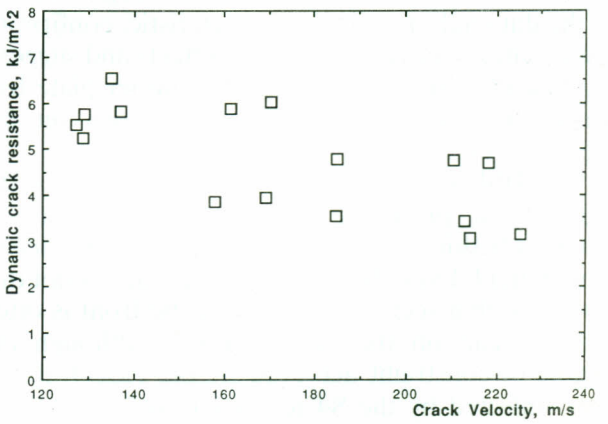

Fig. 8 Dynamic crack propagation resistance of HDPE-2 at 0°C; HSDT data.

fortunately, increased scatter with decreasing toughness is to be expected from Charpy data analysed from the $BD\Phi$ method, since G_{ci} is evaluated as a small difference between larger energy release rates subject to random and dynamic errors.

5 High Speed Double Torsion tests

Whilst the Charpy test is an 'impact' test, measuring the material's resistance to fracture initiation from a static crack under rapidly increasing loading, the HSDT test[6] is a dynamic fracture test: it generates data for resistance to steady dynamic crack *propagation*, G_D, as a function of crack velocity.

A crack is driven through a relatively large (100 mm × 200 mm) plate specimen, at a constant velocity controlled by the speed of a driving projectile, which impacts the upper surface. Although the specimen thickness is only a few millimetres (further reduced by a shallow V-shaped crack guiding groove on the lower surface) the crack front is sharply curved back from the through-plane direction to the through-thickness direction. The long crack front under high constraint corresponds to a high effective thickness. However, for polyethylenes the relatively low speed of the crack front near the upper plate surface permits increased ductility. This effect is minimised by cutting a shallow, very sharp sidegroove on this surface as well. The resulting fracture surfaces are uniformly glassy, as in the notched pipe tests.

A maximum crack velocity is imposed by the velocity of torsional wave propagation along the specimen; this is some fraction, determined by specimen thickness, of the material shear wave speed.

Figures 7 and 8 show dynamic crack propagation resistance as a function of crack velocity for MDPE-1 and HDPE-2. Although these materials are known to be very ductile, and resist low speed tearing, the data show remarkably low and velocity-independent crack resistance above some characteristic velocity. Below this velocity (about 160 ms^{-1} for MDPE-1 and 130 ms^{-1} for HDPE-2) stick–slip crack growth occurs, indicating an inverse velocity dependence G_D which may reflect the BDT. A minimum viable crack speed is also observed in pipe tests, but in both methods it is too poorly defined to serve as a characterising parameter. The maximum

observable crack velocity in the HSDT test corresponds closely to the torsional wave speed, underpinning the analysis used to compute G_D from displacement data using a one-dimensional torsional wave model.[7]

The G_D data show some scatter (less significant when it is used in eqn (1), due to its low exponent). Since the focus of interest is low velocities, reflecting proximity to the BDT, the two materials could be characterised by the average G_D (3 kJ m^{-2}) for MDPE-1 and an 'intercept' value of 6 kJ m^{-2} for HDPE-2, whose gently falling characteristic is less well described by its average.

Figure 9 shows data for another medium density polyethylene grade, in which HSDT tests were conducted on specimens at two thicknesses, and both with and without an upper razor-cut sidegroove. All of the data fall on a single characteristic, confirming the absence of intrinsic thickness effects and suggesting that the 'ductile' layer near the upper plate free surface has a relatively minor influence on the measured G_D.

The HSDT test, like the S4 test and unlike the Charpy test, produces a constant-velocity running crack embedded in an essentially quasi-static deformation field. Even the curved crack shape is not dissimilar to that seen in pipe (where the front is often seen to lead on the inner surface), although the degree of constraint achieved by the HSDT test is only reflected by the S4 test if internal notching is used.

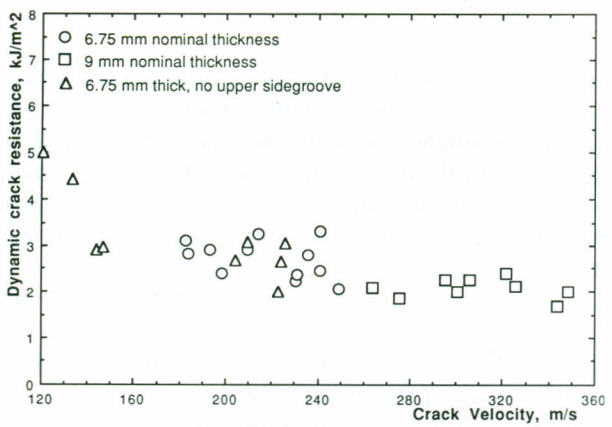

Fig. 9 Dynamic crack propagation resistance of MDPE-3 at 0°C; HSDT data.

It is interesting to make a direct comparison between HSDT test results and S4 pipe test data. Table 1 shows how $\sqrt{(EG_D)}$ (using HSDT test data for both properties) correlates with S4 critical pressure. The actual magnitude of p_{cS4} for notched pipes is only 10% of that predicted from eqn (1), but this factor is anticipated by improved pipeline RCP models.[2] S4 test results for 180-mm pipe, 6-mm thick, indicated BDT temperatures for MDPE-1 and HDPE-2 pipe of 0°C and −35°C, respectively. Charpy tests show BDT temperatures of −5°C and −55°C, respectively (Fig. 6).

7 Conclusions

S4 pipe tests on as-received pipe highlight the distinction between conventional MDPE and high performance HDPE grades, both in terms of a critical pressure at 0°C and as a transition temperature from a lower plateau. Charpy tests at varying temperatures using specimens thinner than the pipe wall reflect qualitatively, but not quantitatively, differences in the S4 test transition temperature. Lower shelf initiation crack resistance values for HDPE are three times higher than for MDPE.

High Speed Double Torsion tests show that G_D varies little with crack velocity, above a minimum velocity below which continuous RCP cannot be sustained. G_D data represent a thickness-independent lower plateau value, and are still twice as high for HDPE as for MDPE. S4 tests on pipe specimens internally notched to give maximum constraint, yield extremely low critical pressures, proportional, as expected, to $\sqrt{G_D}$ measured from the HSDT test. However, there is still a role for a dynamic crack resistance test that can reflect the influence of thickness, temperature and crack velocity. Meanwhile, practical characterisation of pipe grade polyethylenes can most usefully focus on predicting the temperature-dependent minimum thickness below which RCP is effectively impossible.

Acknowledgements

This project has been funded by a Science and Engineering Research Council grant, supported by British Gas, the Water Research Centre, BP

Table 1. Comparison of HSDT test crack resistance data with pipe performance

Material	Modulus E (GPa)	Dynamic crack resistance (kJ m^{-2})	$\sqrt{(EG_D)}$ (MPa m$^{1/2}$)	S4 test critical pressure p_{cS4} for 180-mm SDR 11 pipe (bar)		
				−15°C, Unnotched	0°C, Unnotched	20°C, Notched
MDPE-1	2·32	3·0	2·64	2·05	2·1	1·0
HDPE-2	3·19	6·0	4·37	10·0	very high	1·5

Chemicals, Stewart and Lloyds and Du Pont (UK). P. Yayla wishes to express particular appreciation for support by Du Pont (UK) and by Yıldız University, İstanbul, Turkey. The results presented in Fig. 3 were obtained by Gregory Venizelos.

References

1. GREIG, J. M., Rapid crack propagation in hydrostatically pressurised 250 mm polyethylene pipe. Paper 12, presented at 7th Intl. Conf. Plastic Pipes, Bath, UK, 19–22 September 1988.
2. LEUNG, C. P., COUQUE, H. R., GRIGORY, S. C., POPELAR, C. F., KANNINEN, M. F., O'DONOGHUE, P. E. & MAMOUN, M. M., The development and validation of a fracture mechanics methodology for rapid crack propagation in PE gas distribution pipes. Paper presented at the 12th Plastic Fuel Gas Pipe Symposium, Boston, 24–26 September 1991. American Gas Association, Arlington VA.
3. YAYLA, P. & LEEVERS, P. S., A novel technique for the study of rapid crack propagation in plastic pipes. Paper presented at the 8th European Conference on Fracture, Torino, Italy, 1–5 October 1990.
4. YAYLA, P., Rapid crack propagation in polyethylene gas pipes. PhD thesis, University of London, Imperial College, UK, 1991.
5. WILLIAMS, J. G., *Fracture Mechanics of Polymers.* Ellis Horwood, London, 1984, pp. 237–89.
6. LEEVERS, P. S. & WILLIAMS, J. G., Double torsion testing of high velocity crack resistance. *Journal of Material Science*, **22** (1987) 1097–107.
7. WHEEL, M. A. & LEEVERS, P. S., High speed double torsion testing of pipe grade polyethylenes. Paper presented at the 8th European Conference on Fracture, Torino, Italy, 1–5 October 1990.