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RESISTANCE OF PIPE GRADE POLYETHYLENES TO HIGH SPEED CRACK PROPAGATION

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Résumé - Les polyéthylènes (PE) de moyenne à forte densité pour tubes pressurisés sont caractérisés par une grande ductilité et une haute résistance aux faibles vitesses de propagation des fissures, mais les tubes extrudés de PE testés sous pression de gaz peuvent supporter la propagation à haute vitesse (100-300 ms^{-1}) des fissures axiales fragiles. La méthode du test de Double Torsion à Haute Vitesse (HSDT) a été dévelopée pour mesurer la résistance aux fissures aux conditions d'état stationnaire à haute vitesse stable. Comme l'indique le test des tubes, la résistance aux fissures à grande vitesse dans les polyéthylènes est même plus faible que celle suggérée par les tests conventionnels des impacts de Charpy.

Abstract - Medium to high-density polyethylenes (PE) for pressure pipe service are characterised by high ductility and high resistance to low speed crack growth, but extruded PE pipelines tested under gas pressurisation can sustain axial "brittle" crack propagation at high speeds (100-300 ms^{-1}). The High Speed Double Torsion test method has been developed to measure crack resistance under stable, high speed, steady state conditions. As the pipe tests indicate, resistance to a high speed crack in PE is even lower than conventional Charpy impact tests would suggest.

1 - INTRODUCTION

Medium or High Density Polyethylene (MDPE and HDPE) extruded pressure pipe is now widely used throughout Europe for gas and water distribution, and this use is set to increase towards larger diameters. PE is not intrinsically a very "strong" material. In short-term tests it yields at stresses much lower than those required to cause fracture; pressure pipes of standard outside-diameter to thickness ratio 11 (17.6) bursting by yield at around 24 bar (15 bar) in 1 hour. Regression of the yield stress with time reduces this to a minimum of about 16 bar (10 bar) for a 50-year lifetime, a value which is further safety-factored to arrive at a service rating.

Candidate materials are currently assessed and compared mainly on their resistance to slow crack growth, the usual cause of local failures in service; this resistance is usually very good. There has been concern, however, that local impact damage in service could initiate a much more destructive failure mode: fast-running axial rapid crack propagation (RCP). Field tests by British Gas and others have shown that this can indeed occur, and at pressures well above those applied in service (*e.g.* 6 bar for 250mm diameter /1/), *but less than that predicted to ensure a 50 year lifetime.*

In these experiments, a running crack is initiated in a long pipe, usually by a splitting impact on a locally supercooled region, and the length for which it subsequently propagates is measured. At some critical pressure p_c, a transition occurs from prompt crack arrest to sustained RCP through most of the remaining pipe length. This pressure p_c is material dependent.

A simple steady-state energy balance analysis leads to an expression for the crack driving force, and hence to the relationship:

$$p_c = \frac{B}{D} \sqrt{\frac{8ER}{\pi D}},$$ (1)

in which D and B are the pipe diameter and wall thickness, E is the tensile modulus and R the crack resistance (the work needed to drive a crack front through unit area of material, broadly equivalent to the "critical energy release rate", G_c) of its material. Thus for a given material and stress rating (B/D ratio), a move to larger diameters must be expected to reduce p_c.

To be compatible with this model and with the observed failure mode, R should correspond to sustained, steady crack velocities of 100-300 m/s. Data from Charpy impact bend tests, in which the crack velocity is undefined and unsteady, measure crack *initiation* resistance. Conventional dynamic crack *propagation* tests such as that based on the statically-loaded Double Cantilever Beam specimen, on the other hand, were tried but failed because plastic crack blunting prevents initiation. What seemed to be needed was a test in which a fast crack could be initiated by impact, but then settle rapidly to a steady state in which it was driven at constant velocity.

2 - THE HIGH SPEED DOUBLE TORSION TEST

The Double Torsion (DT) test is commonly used for measuring R at low crack velocities in rate-sensitive materials. A rectangular plate, grooved axially along its underside for crack guidance, is subjected to four-point loading at one end (usually at a constant displacement rate), splitting the plate apart along its central axis by subjecting its two halves to opposing torsion. The test usually settles quickly to a steady state during which the end moments M and the crack velocity remain virtually constant, and R can be calculated directly from load or from current crack length a and end rotation θ:

$$RB_c = \frac{M^2}{\mu K},$$ (2a)

or

$$RB_c = \mu K \left(\frac{\theta}{a_e}\right)^2,$$ (2b)

where B_c is the crack path width, μK is the torsional rigidity of the specimen half-section, and a_e is an *effective* crack length, increased to account for the compliance of the specimen ahead of the tip.

This steady state, and even the translated curved crack front shape in the DT test, seems to offer an appropriate representation of the pipe failure mode, but the velocities are much lower. The slow DT test is of little use for PE anyway: gross elastic and plastic deformation precedes crack propagation.

To achieve more appropriate crack velocities, crosshead speeds of 10-50 m/s would be needed. The High Speed Double Torsion (HSDT) test already described elsewhere (Leevers and Williams /1/) uses a 1.3 kg projectile, fired by a gas gun, which passes through an infra-red beam timing device to measure its speed immediately prior to impact. Speeds exceeding 4 m/s always initiate a brittle crack (even without an initial notch), and continue to drive it through the length of a 200 mm specimen at a fairly constant velocity. The crack length is monitored in 10mm increments during the test, using a pattern of conductive and resistive strips painted onto the specimen (Figure 1). This crack length gauge output signal, and the reaction load on the strain-gauged supports, are recorded using a digital oscilloscope.

3 - EXPERIMENTS on PIPE GRADE POLYETHYLENES

Compression-moulded 6mm plate specimens of several PE grades have been tested, in a programme coordinated with the full-scale pipe tests by British Gas. Two are of special interest. Material A is a gas pipe grade of UK manufacture, showing excellent slow crack growth resistance and a satisfactory

critical pressure for RCP. Material B does not out-perform A in conventional pipe or Charpy tests, but RCP could not be sustained at *any* pressure. HSDT tests were carried out at 0°C and 23°C (since pipe tests had shown a marked temperature sensitivity) and at impact velocities from 4.5 to 25 m/s. All tests maintained steady crack propagation at an effectively constant velocity, but the materials differed somewhat even from direct observation: for a given impact speed, material B sustained a significantly lower crack velocity.
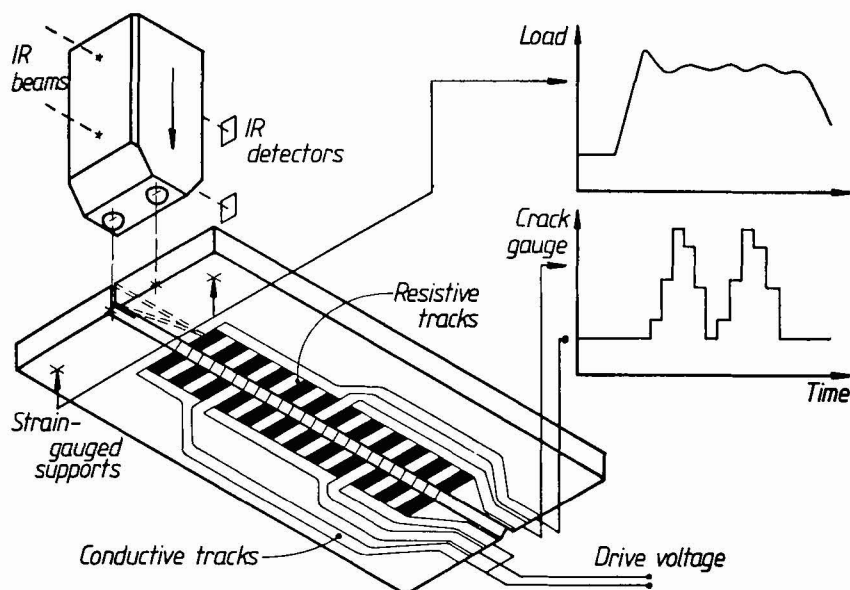

Fig. 1 - The High Speed Double Torsion Test

4 - STEADY-STATE DYNAMIC ANALYSIS

The DT test has a further and almost unique advantage for dynamic work: the deformation mode which is conventionally assumed for its low-rate analysis remains admissable at high velocities (*i.e.* no inertial forces are induced), offering a simple starting point for dynamic analysis.

Each half of the specimen is treated as a rectangular beam in simple torsion. Thus any cross-section at x simply rotates by an angle ϕ (and warps proportionally to the twist $d\phi/dx$ only), and the axial rotation profile $\phi(x)$ at any instant completely describes the deformation of the whole specimen (Fig. 2a). In static tests torsion is uniform along the seperated beams. The crack extends at constant velocity $\dot{a}$ when driven by a steady end rotation rate, and R can be computed by Equations (2). *If the ratio of crack length to velocity remains equal to that of imposed end rotation to rotation rate*, the torsion remains constant everywhere, there are no angular accelerations, and the end moment remains at its static value. Accounting for the kinetic energy gained as the seperated beams extend leads to expressions:

$$R = \text{(statically computed value)} \times \left[1 - \left(\frac{\dot{a}}{c_t} \right)^2 \right] . \tag{3}$$

where c_t is the torsional wave speed (geometry-dependent, and typically 20-25% of the shear wave speed), which clearly limits the attainable crack velocity.

For HDPE, c_t for our specimen dimensions (100mm × 200mm × 6mm thick) is only about 200m/s, apparently limiting the usefulness of the test. HSDT tests on epoxies, however, have exhibited crack velocities exceeding c_t by up to 40%; to explain this, a more realistic "beam on elastic foundation" analysis of the beam root region was developed (Fig. 2b). Accounting for inertial moments and local stiffening of the torsion beam due to non-uniform torsion (which tends to suppress warping) predicts an exponential decay of rotation ahead of the crack tip, with a velocity-dependent decay constant s. The extra energy which can be transmitted through the stiffened beam accounts satisfactorily for crack velocities exceeding c_t.
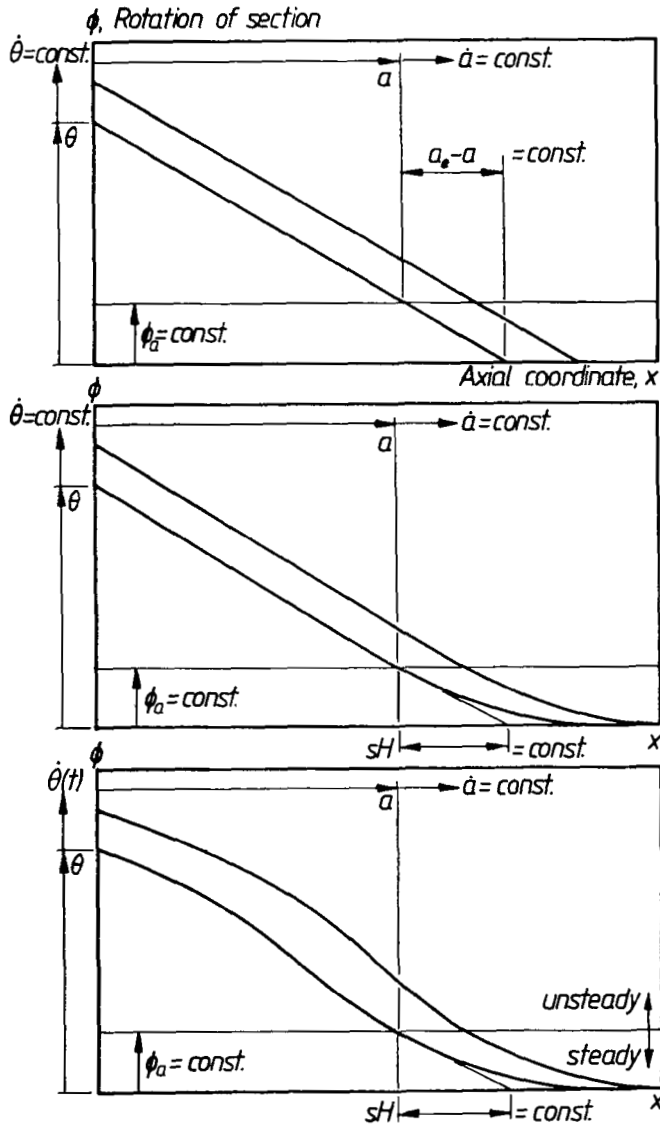

Fig. 2 - (a) Quasi-static, (b) Steady-state and (c) Dynamic models of the HSDT test

5 - RESULTS for PIPE GRADE POLYETHYLENES

Data for standard (A) and RCP-resistant (B) materials using this analysis are shown in Fig. 3. Whilst the data clearly show the expected fall-off in R as crack velocity rises, and seem to reflect the better service performance of Material B more accurately than does the Charpy data also shown, there is considerable scatter. Much of the scatter is systematic: for a particular crack velocity, a higher apparent R value is yielded by testing at a higher impact velocity.

Along with the observation that load/time traces for fast tests are not flat-topped as for slow ones, this tends to indicate that the steady-state displacement model may be inadequate: a truly dynamic analysis is needed. Due to the rather low torsional wave velocity, crack propagation in fast tests is initiated by the torsional shock wave from impact and only later settles to a velocity appropriate to that of the projectile. A torsion-waveguide dynamic model of the DT specimen, on the lines of that previously developed for the DCB type by Kanninen *et al* /2/ is under development. This models the crack's "bow-wave" as a steady-state constant velocity region, but allows torsional vibrations within the seperated beams (Fig. 2c).

There are also crack shape effects, arising from the range of true crack speeds along the curved DT crack front travelling at a constant axial velocity. It has previously been demonstrated that crack shape variations from specimen to specimen (due to geometry differences) are additional source of scatter in materials whose $R(a)$ characteristic has a marked slope /4/, as the PE's clearly have.
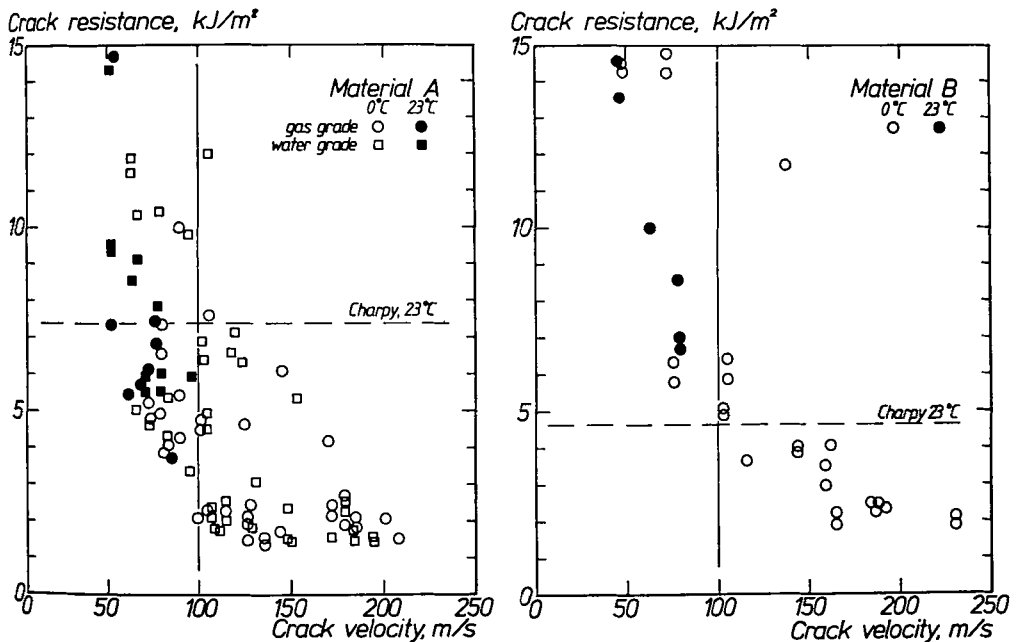
Fig. 3 - The variation of crack resistance with crack velocity for two pipe grade polyethylenes

REFERENCES

/1/ Greig, J.M., "Fracture Arrest Conditions in Polyethylene Gas Pipes", *Plastics Pipes VI*, Proc. 6th
      Intl. Conf. Plastics Pipes, York, UK (1985); PRI, London.

/2/ Leevers P.S. and Williams J.G., *J Materials Sci.* **22** (1987) 1097.

/3/ Kanninen M.F., Popelar C. and Gehlen P.C., "Dynamic Analysis of Crack Propagation and
      Arrest in the Double-Cantilever-Beam Specimen", *Fast Fracture and Crack Arrest*, G T Hahn
      and M F Kanninen (eds.), ASTM STP 627, American Society for Testing and Materials,
      Philadelphia, (1977) 19-38.

/4/ Leevers, P. S. and Williams, J.G., *J Materials Sci.* **20** (1985) 77.