HIGH SPEED DOUBLE TORSION TESTING OF PIPE GRADE POLYETHYLENES

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The High Speed Double Torsion Test has been developed to measure the dynamic fracture resistance of pipe grade polyethylenes under stable, high speed, steady state conditions. Modulus values appropriate to the fracture test have been obtained, using a technique based on the test itself, and the use of these values has led to a dramatic reduction in scatter seen in the calculated resistance data.

INTRODUCTION

Both the gas and water supply industries throughout Europe are using large quantities of polyethylene (PE) pipe to augment and replace their existing distribution systems. One potentially catastrophic mode of failure that has been identified is rapid crack propagation (RCP). Field tests performed by British Gas [1] have shown that under the extreme experimental conditions of impact loading and initiation zone cooling a high speed crack can be introduced into a section of pipe. One feature evident from these tests is a well defined critical pressure, p_c, below which the crack arrests shortly after initiation, and above which it will propagate at 100-300m/s for a considerable distance. A simple steady state analysis of the problem allows p_c to be determined if the dynamic fracture resistance, G_D, of the material is known. While the accuracy of this analysis is, as yet, uncertain, it does suggest that improving the G_D values of candidate PE pipe grades will give increased p_c values. The material manufacturer is, therefore, interested in establishing G_D values so that comparisons can be made between development grades. To be compatible with the failures observed in pipe tests, a technique to measure G_D should produce steady and sustained RCP over the same crack velocity regime. The conventional Charpy test is suspect because the crack velocity is undefined and crack growth is unsteady, being dominated by the initiation event.

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In order to generate steady RCP in PE samples it has been necessary to develop an impact version of the conventional double torsion (DT) test. Static loading techniques fail to initiate brittle fractures in PE specimens because extensive flow occurs at the notch tip upon loading, and gross yielding follows even if the notch tip is embrittled prior to testing [2].

THE HIGH SPEED DOUBLE TORSION TEST

The high speed double torsion (HSDT) test, shown in Fig.1, uses a projectile to load the sample and in the current test rig configuration impact velocities in the range of 5-35m/s are produced. The sample is usually cut from 6mm or 9mm thick compression moulded plates and measures 100x200mm overall. A 90° "V" groove is machined along the longer axis of the specimen, which serves to guide the crack, whilst a 1mm deep razor blade slit is scribed along the same axis on the opposite face to the groove, to produce a more uniform fracture surface. A 40mm long prenotch at the start of the groove helps to separate the striker impact and fracture initiation events in time. The sample rests on four supports with the groove facing downwards. The striker impacts the sample on the upper surface at the notched end creating a torsional disturbance in each half of the specimen that loads the notch tip then initiates a fast fracture and drives the crack. A gauge, consisting of a series of graphite resistive and silver conductive tracks, painted onto the underside of the sample, is used to measure the crack length history, from which the crack velocity, $\dot{a}$, may be found. Piezoelectric load cells on the impact plane supports record the load history. The time of flight of the striker between two infra red detectors is recorded just prior to impact, allowing the striker velocity to be computed.

EXPERIMENTS ON PIPE GRADE POLYETHYLENES

Five pipe grade PEs have now been tested using the HSDT test. Most of the experiments have been performed at 0°C by pre-cooling the specimens. Tests on 6mm thick samples produced steady crack velocities of 125-240m/s for striker speeds in the range of 15-30m/s. At impact speeds below 15m/s the cracks tended to grow in a stick / slip manner and arrest lines were seen on the fracture surface. Typical load histories suggested that the load level remained constant throughout the crack propagation phase of the experiment, confirming that a steady state is established within the sample during the test. A limited number of tests have also been performed on 9mm thick specimens. The same range of striker impact speeds produced crack velocities in the range of 250-350m/s.

THE STEADY STATE DYNAMIC ANALYSIS

The key to adopting the global energy balance approach for computing G_D is to be able to calculate accurately the strain energy and kinetic energy in the sample together with the external work that is being done on the specimen. In order to be able to do this the sample deformation must be correctly established. The steady state analysis assumes that the rotation of the torsion beam sections decreases linearly between the loading plane and the crack tip plane as in the earlier quasi-static analysis of the dynamic test [3]. Beyond the crack tip a torsion beam on rotational elastic foundation model predicts that the rotation decays exponentially, with a decay constant of 1/sH, falling to zero rotation at an infinite distance ahead of the crack tip, as depicted in Fig 2. H here is the sample half width. The steady state analysis then invokes the idea of self similarity by assuming that this exponentially decaying rotation profile translates at the crack speed without any change in shape. The analysis also accounts for the effective stiffening of the torsion beams caused by the suppression of cross section warping in the crack tip region. High speed photographic work has shown that this assumed deformation is correct.

A simple analysis allows G_D to be determined by considering the flow of energy into and the associated changes of strain energy and kinetic energy that occur within a fixed control volume, extending from the crack tip through the elastic foundation region to the end of the sample, during an infinitesimal extension of the crack. G_D is then given in terms of the end rotation of the beam arms, θ, and the crack length, a, by :-

$$G_D = GK\left(\frac{\theta}{a}\right)^2 \left\{1 - \left(\frac{\mathring{a}}{C_T}\right)^2 + f(s)\right\} \qquad (1)$$

where GK is the torsional rigidity of the beam cross section and C_T is the torsional wave speed. Alternative expressions that allow G_D to be determined from a knowledge of either the end moment, M, applied by the striker to the sample or the end rotation rate, θ, and crack velocity can be found by noting that :-

$$\frac{M^2}{GK} = GK\left(\frac{\theta}{\mathring{a}}\right)^2 = GK\left(\frac{\theta}{a}\right)^2 \qquad (2)$$

RESULTS FOR POLYETHYLENES OBTAINED USING LINEAR ELASTIC MATERIAL PROPERTIES

Data for medium density (A) and high density (B) pipe grade polyethylene materials is shown in Fig. 3. Each data point corresponds to an G_D value calculated from a separate test using equation (1) at an instant when the crack has propagated a distance of 80mm from the load plane. Similar G_D values are obtained if each experiment is re-analysed after the crack has propagated 120mm showing that G_D is independent of crack length.

Grade B performs much better than A in small scale tests on pipe sections [4]. Fig. 3 does reflects some difference in the mean G_D values. However, there is some systematic scatter in G_D values obtained for a particular material at a given crack velocity; higher values are yielded by tests performed at higher striker speeds.

The results depicted in Fig. 3 were calculated using Young's modulus values of 2.06GPa and 2.85GPa for materials A and B respectively. These modulus figures were obtained using ultrasonic immersion techniques [5] which produce high strain rate, low strain test conditions.When G_D values are computed using the measured end moment, via equation (2) instead, they do not agree with those shown in Fig. 3; they are, on average, much lower. This suggests that the use of high strain rate, low strain modulus values may be inappropriate to the HSDT test.

A TECHNIQUE TO MEASURE SHEAR MODULUS VALUES APPROPRIATE TO THE HSDT TEST

An alternative modulus measurement technique makes use of the HSDT sample geometry and test rig described already. A fractured HSDT sample is locally reconnected at the opposite end to the load plane using a simple clip. The sample may thus be regarded as two independent torsion beams. Once again the sample is precooled, loaded into the rig and impacted at a measured speed by the striker, sending a torsional wave down both beams. The load appears to remain fairly constant during the test and it's mean value is used to compute the applied moment.

The analysis assumes that at any given time the rotation falls linearly from the load plane to the front of the disturbance, that is, the rotation gradient in the disturbed region of the beams is constant. This rotation gradient is related linearly to the shear strain in each beam arm and the magnitude of the gradient is governed by the wavefront speed and the load plane rotation rate. Thus different rotation gradients and hence shear strains can be imposed simply by varying the striker speed. The imposed gradient can be related to the measured end moment, as in the static case, allowing the shear modulus to be calculated. Some typical data that shows how the shear modulus varies with applied shear strain is depicted in Fig. 4. The shear modulus falls as the shear strain is increased implying that the stress-strain relationship for this material is non linear. It is, of course, well known that such non linear relationships are also produced when static tests are performed on these materials over similar ranges of applied strain.

RESULTS OBTAINED FOR POLYETHYLENES USING NON LINEAR ELASTIC MATERIAL PROPERTIES

The results presented in Fig. 3 have been re-analysed using a modulus-strain relationships shown in Fig. 4. Imposing these relationships upon the analysis means that the choice of modulus is no longer independent of the test conditions; the modulus now depends on the shear strain which is governed by the gradient imposed in the free beams by the striker. Effectively the modulus is striker speed dependent. The modified results are presented in Fig. 5, which now shows a clear difference between the two materials. The scatter in the range of G_D values seen at a given crack velocity has also been significantly reduced.

References

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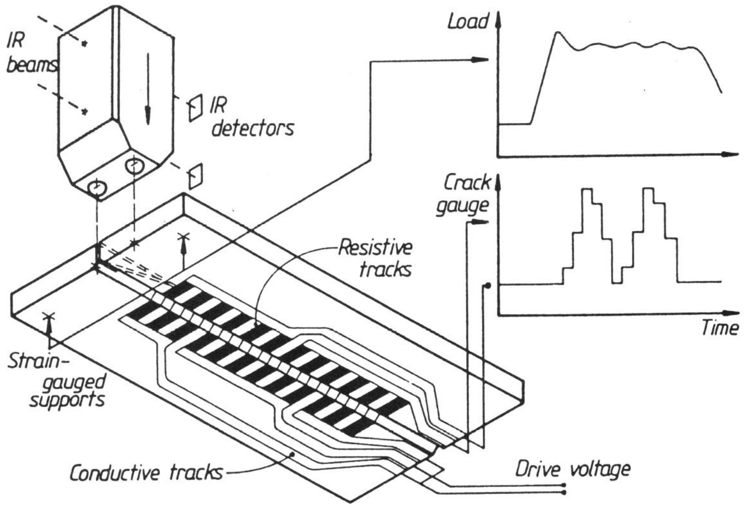

Fig. 1 The High Speed Double Torsion Test

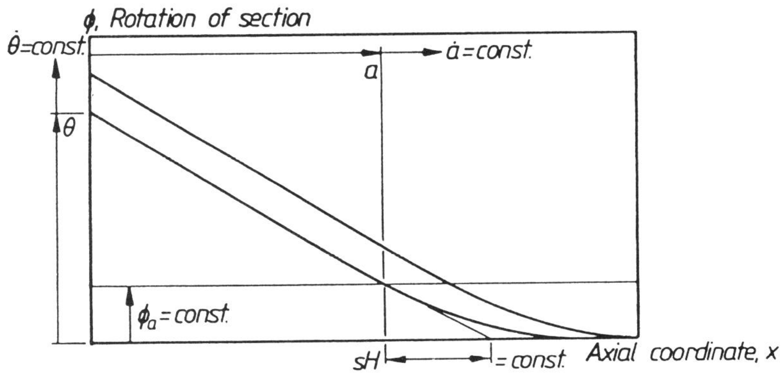

Fig. 2 Sample Deformation Assumed By The Steady State Analysis

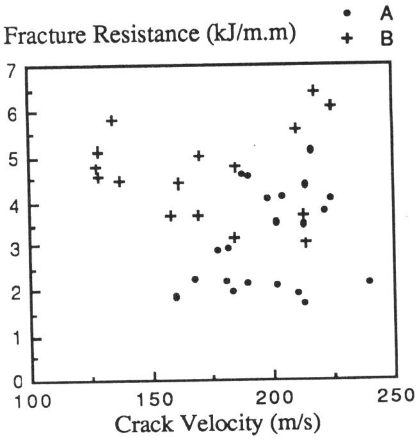

Fig. 3 Resistance vs. crack speed (linear elastic modulus values)

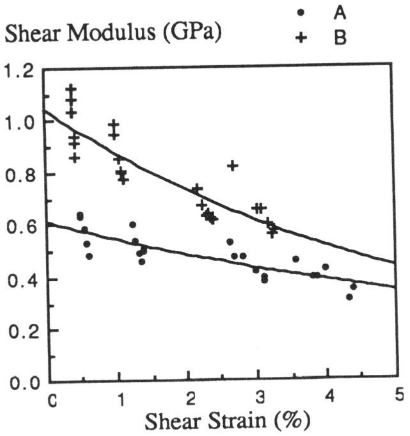

Fig.4 Variation of shear modulus with applied shear strain

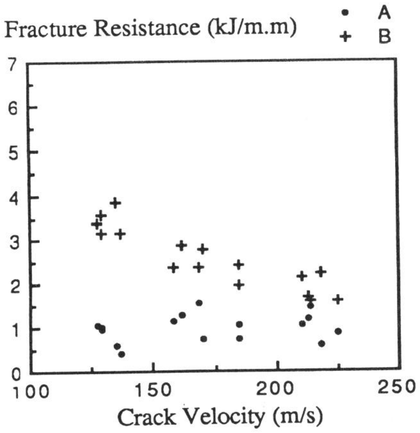

Fig.5 Resistance vs. crack speed (non-linear elastic modulus values)