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The Design and Development of a Multiaxial Test Machine for Polymeric Materials

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ABSTRACT The development of a new machine for the multiaxial testing of plastic materials is described. Since the design is based on a family of machines developed previously and described in other publications, this paper concentrates on features that differ significantly, from previous designs especially in relation to the testing of plastic pipe materials.

Validation tests are discussed, principally to indicate the considerable versatility of the machine.

Introduction

Multiaxial test facilities are inherently expensive and can only be justified if they offer considerable advantages over conventional machines. However, in many cases, uniaxial test methods are so totally unrepresentative of the stress regime imposed on a component in service that such tests would be meaningless, whereas carefully structured multiaxial tests would be an acceptable alternative to full scale testing. Justification for a multiaxial facility can be provided where the full extent of future test programmes is unknown, where the engineering applications of the material are under active development, and where the applications are complex and varied. Some materials are so anisotropic (e.g., fibre reinforced composites, extruded bar, injection moulded and cast metals) that to test in the uniaxial mode would be misleading. Polymer based pipe systems have all of the above features to some degree, depending upon the application, the characteristics of the base polymer, and the manner by which the pipe is formulated and produced. It was the need to have a better understanding of some of the loading factors found in commercial pipe and pipe installations that led to the development of the machine described here, although the machine is constructed in such a way that its use is not confined to tubular specimens.

A classical method of inducing a triaxial stress regime is to pressurize a thick walled tube (1). Commercial plastic gas pipes would be considered as comparatively 'thin walled' tubes that distend viscoelastically and, if tested in a way that will induce short term failure, distend so grossly and unpredictably that analysis

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is virtually impossible. However, the introduction of a notch will constrain the point of failure and can promote crack propagation and brittle fracture. This effect is noticed also where there is a rapid change of section, such as at a butt fusion joint or socket fusion joint to pipe interface, which then behaves as a quasi-notch. Exploratory tests, within the laboratory, had shown that socket welds used to join straight sections of polyethylene (PE) gas pipe and fusion butt welds in other grades of PE pipe, failed in a brittle type fracture. As indicated above, the expense of a multiaxial machine can only be justified against a clearly defined need, and for this reason the evaluation programme had to test the machine, and at the same time add to the general understanding of the behaviour of plastic pipe systems.

A natural choice for the initial test sample for the evaluation programme was a fusion butt weld since very little is known about the behaviour of this type of weld under complex load. A number of tests were conducted in both uniaxial and multiaxial modes, but the only failures were ductile and in the parent pipe remote from the joint. This outcome was reassuring to the gas engineer, but was not an effective vehicle for the evaluation programme.

Another area of interest to the gas engineer was the morphology of the fracture. Environmental stress cracking (ESC) is particularly undesirable in pipe systems. There is much debate over what constitutes true ESC, but in general as the surface becomes less featureless or more 'brittle' in appearance, the longer the fracture takes to propagate through the wall of the sample. Ductile fracture surfaces associated with a very long time to failure are indicative of an ideal pipe material for long term pipe installations.

A second set of test samples were made from plain pipe, with a circumferential notch. Whilst this provided a sample that would be particularly prone to brittle failure, it was not ideal since commercial pipes cannot be made perfectly round. Under these circumstances it was not possible to make circumferential notches of constant depth. Therefore, although these samples were acceptable for the test programme, it is unlikely that samples notched in this way could ever be used for routine quality control (QC) testing.

Specification and design of the apparatus

This machine is the fifth in a family of machines and has the following specification.

Axial load	±56 kN with a ±75 mm stroke
Torsion load	5.6 kNm with a ±30 degree stroke
Internal pressurisation	0 to 34 bar (3.4 MN/m^2) for a 2.6 l charge with choice of pressurising fluid plus compensation for inherent axial load for samples up to 100 mm internal diameter
Maximum separation between plattens	1650 mm

Dead head adjustment	±75 mm with a 75 mm step positioning
Control function	Manual, function generated, or computer
Sensor: force	Strain gauge based
displacement	Linear variable displacement transformers (LVDTs) on all axes. (Velocity transducer on internal pressurisation mode.)
Frequency/waveform	Square, ramp, sinusoidal, or random; frequency limited by waveform and stiffness of system, but for a material such as polyethylene, from 0 to 5 Hz

An access and mounting facility is provided to allow bending moments to be applied on either side of the sample and machine.

Machine concept and design

The basic design philosophy remained the same as for earlier machines, i.e., the machine should be exceptionally rigid. This was achieved by making all the load bearing sections 'over designed' by conventional standards. This technique ensures that the stress–strain loads are transmitted along the machines loading axes. The principal reason for this approach is the need to avoid interaction between the stress modes within the framework of the machine. The only serious limitation is inertial effects of the heavy moving sections. Whilst very extensive and successful programmes have been conducted on all the earlier machines (**2**)(**3**), there is always the possibility of improvement. A series of novel improvements have been incorporated in the present machine and, in order to avoid repetition, only these elements will be discussed in depth. Figure 1 shows a photograph of the new machine and Fig. 2 is a line diagram, annotated to indicate the operational elements referred to in the discussion below.

Torsion stiffness in the earlier machines was achieved by either a massive subframe or heavy space frame, but these limited the access behind the specimen. The new machine has a torsion cage (a) that is comparatively light. It consists of two concentric semi-circular shells that have the portion beyond the specimen removed. The resulting aperture was stiffened with a skirt and flange (b) which also had a large second moment of area to prevent any bending that may arise through off-axis loading, such as an actuator to induce bending. The flange also provided a mounting surface for experiments that might have required additional devices (such as extensometry or cameras) or asymmetric specimens, i.e., 'T' joints. A base was designed to couple with this cage and act as a support when the machine was operated in the horizontal mode. The torsion cage was made detachable so that the machine could be used in the conventional tensile test machine mode. If the machine should be used in this way for extended periods then the base extension (c) was removable which would then permit uninterrupted access to the machine. In either the vertical or horizontal mode the machine was very stable due to the eccentric displace-

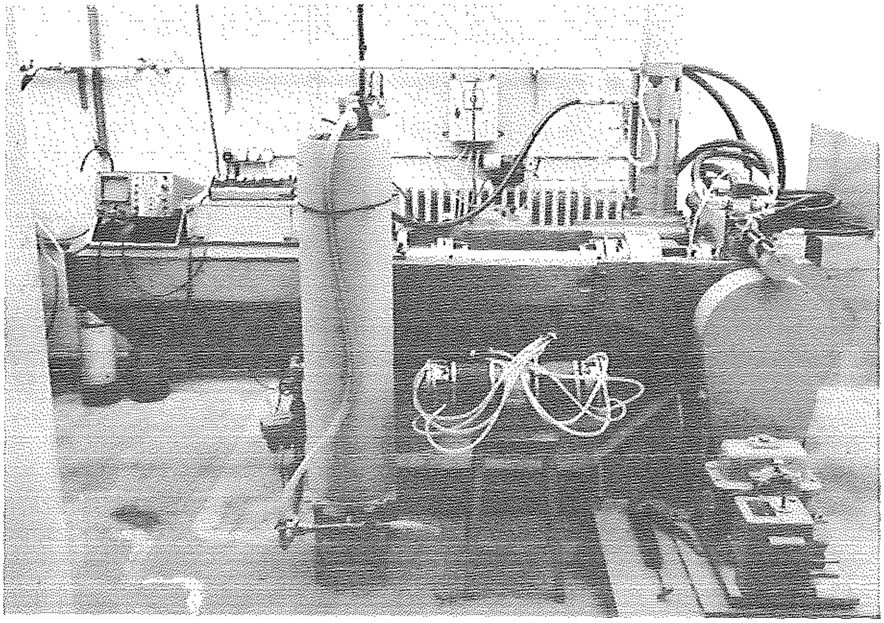

Fig 1 Photograph of the machine in the installed position, but without ancillary equipment such as control units, heating bath, transducers, etc.

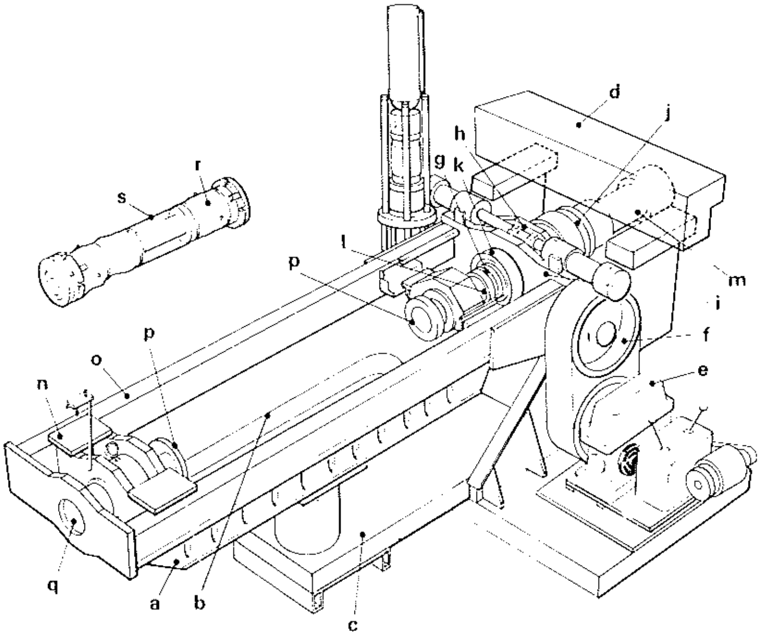

Fig 2 Line drawing of the machine indicating the salient features described in the text

ment of the counter balance weight (d). The position of the centre of gravity of the main counter balance-weight (one tonne) provided a moment for vertical retention. The null balance point was at 70 degrees to the horizontal, but any intermediate angle was possible. The machine positioning was power assisted with final adjustment by a hand wheel. In practice the machine was stable in any attitude. The power input was via a double reduction gear box (e) and a heavy chain drive (f).

In previous designs the technique employed to maintain specimen concentricity required considerable finesse in acquiring linear alignment of the bearings, and to assist in this respect the live torsion head was designed to be opposite the push–pull system. A heavy duty roller spline bearing (g) enabled the whole mechanism to be housed in the one unit which was supported on three locations. This provided ideal kinematic balance as well as other advantages. As a direct result of this bearing configuration a static fixing of the torque drive (h) and anchorage system was possible, and consequently the dynamic mass was reduced. The re-positioning of the torque drive (i) had a further advantage in that it allowed the design of the static end of the machine (dead-head) to be simplified. The whole dead-head assembly was made to be adjustable within the main frame.

The same technique of compensating for the axial load that results from internal pressurisation, as reported in earlier machines **(2)(3)(4)**, was incorporated into this machine in order to give pure hoop stress. However, the rotation of the shaft extension about the axial loading system (j) complicated the design. The auxiliary piston was arrested on a crossbar as before, but the resultant load on the bar was transmitted to the frame via horseshoe shaped rings mounted on a large angular contact ball bearing (k), thereby allowing sympathetic rotation of the shaft extension with any torque loading. As in the previous design this allowed the operator the choice of compensation or zero compensation. The piston housing liner was made detachable and, consequently, by inserting an appropriate liner, compensation for any diameter of specimen could be arranged up to a maximum specimen size of 110 mm internal diameter. For the present programme of work the internal pressurizing medium was to be water and, therefore, all the components of the pressurizing system were made water-compatible including the compensation system. Quasi-compensation for this induced loading was possible by applying a complementary compressive stress along the axis of the sample (typically half the hoop stress) in-phase with the internal pressurization, being ideally actuated from the output transducer of the internal pressurisation system. This was possible because of the comparatively slow response characteristic (high damping) of plastic pipes under internal pressurization. Similarly, the internal pressurization can be made to simulate a free-standing pipe by calling for zero stress on the tensile axis. This method has an error of the order of 2 per cent. If a completely free end is required the push–pull piston (m) can be decoupled.

A particularly useful innovation was the dead-head or static head (n). This whole assembly could be positioned at specific intervals (75 mm) along the main frame (o). This enabled the chuck mounting flanges (p) to be kept common and the shaft of the dead-head to be hollow for the central supply of pressurising fluid. A problem associated with multiaxial loading is to provide an adequate chucking method for the complicated loads that are possible, whilst at the same time allowing easy loading and alignment of the specimen. The uncomplicated design of the dead-head allowed for the central, hollow shaft to be manipulated with full rotation, together with plus and minus 75 mm axial movement, when loading and unloading the sample, but which could then be locked hydraulically during a test. The hollow shaft enabled a fully assembled and air purged sample to be loaded in the horizontal mode. The hydraulic clamp unit was supplied by Amtec Hydraclamp.

The waveform used for calibration tests was squarewave (within the experimental constrains) and, since it was clearly an advantage that data from earlier tests could be correlated with the present evaluation tests, it was essential that some tests be done at 80°C. Consequently, the chucking system was designed to have a water jacket, as in the earlier work (4), but with much more flexibility. The violent distension of the specimen with squarewave loading sends shock waves into the surrounding water jacket and pipe system, inducing a slight compressive resistance on the outside of the specimen. This was reduced greatly by using neoprene rubber (r) in the wall of the water jacket having a centre portion of glass (s). With this design the jacket was able to accommodate the changing load. An interesting aspect of this design was a special purpose rubber moulding, obtained at low cost. The refinement of tangential inlets and outlets, which gave swirl to the circulating water, was an additional benefit, and the thermal losses were less than those in the aluminium jacket used in the previous design.

Evaluation programme

The machine was commissioned to supplement a comprehensive programme of work and to establish an acceptable short term test (a quality control test of 50 hours or less duration) for commercial grades of medium density polyethylene (MDPE) gas pipe. The requirement for these pipes was a maximum service life of 50 to 60 years. The difficulties of testing due to the difference in time scales is exaggerated further by the safety consciousness of the British Gas Corporation, whose specification for pipes, together with their codes of practice for installation, include large factors of safety.

Early work on the programme (5) placed an emphasis on notched pipes, not simply because of the reduced test times, but because the resulting fractures were brittle in nature, and this type of fracture is a design limitation in its own right.

An essential requirement for any routine test that may be derived from this programme was a need for the test system to be easily transferable to the production floor. Initial testing was based upon simple internal pressurization; a method closely associated with the static test methods currently in use. Notching, however, localises the fracture and may mask a potential fault elsewhere in the body of the pipe. Since faults are likely to occur along the extrusion flow lines, various notching methods have, therefore, been tried or suggested (**6**). Spiral or circumferential notches have also been tried, but these were not ideal for internal pressurization tests since the longitudinal stress was only half that of the loop stress. This stress ratio is not true of the other test modes, but in principle the circumferential notch had the advantage of simplicity. However, because there were certain production difficulties in producing circumferential notches (owing to irregular wall thickness) it was decided to use fusion welded butt and socket joints, which have a rapid change in section and, as such, would simulate sharp notches. Test samples made in this way were much more consistent than the machined notches, but their inherent tenacity (see Figs 3(a) and 3(b)) necessitated a reversion to the less favourable machined groove.

The new machine was built to meet a number of test conditions not possible on existing equipment: e.g., the facility for larger diameters and gauge lengths to study size effects, the ability to test joint configuration such as 'T's and 'elbows', and the need to increase the data gathering capability of the research unit. However, the over-riding priority was to establish a quality control standard for industry without undue delay. This, coupled with the extremely good predictability of the earlier internal pressurization tests, which had established, already, a probable quality control procedure, restricted the time that could be justified for a wide range of evaluation tests. A major switch in

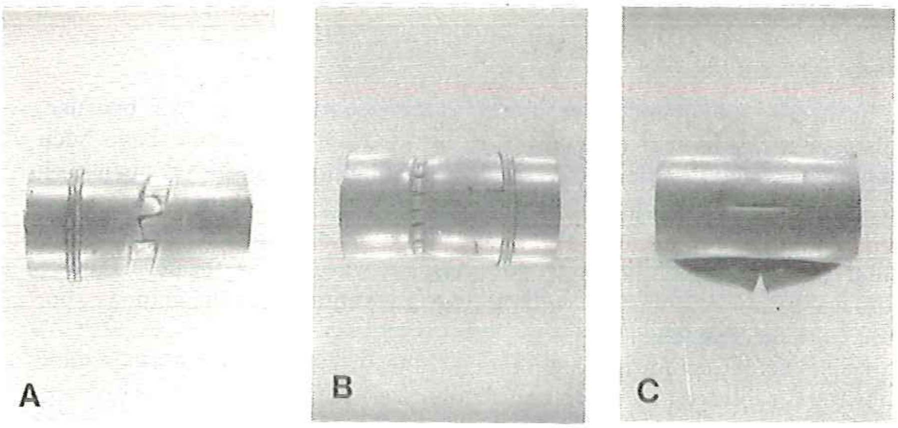

Fig 3 Samples of butt welded joints used in the initial programme: (a) sample subjected to pure tension; (b) sample subjected to pure torsion; (c) classical 'bird beak' failure due to internal pressurisation

industrial quality control test procedures requires extensive verification before adoption, so every hour of test time was vital. Consequently, only a limited amount of time was allocated for machine evaluation in the various modes that were possible. Despite the limitation cited earlier, the test samples were eventually machined with circumferential notches.

The standard industrial quality control (QC), tests rarely produce a ductile failure in less than 2000 hours, and, whilst these tests would give an indication of poor pipe quality, they would not indicate the level of resistance of the pipe to brittle-type failure or permit any measure of its absolute quality. A notch or rapid change of section will reduce the time to failure by approximately forty times or more. Of course, the time to failure is of considerable importance, but there is also a great deal to be gained from examining the fracture surface and from deducing the mechanisms by which the crack proceeds throughout the failure process. The new QC tests were expected to yield several pieces of information; an indication of the components suitability for purpose, a means of determining the comparative quality (based on the time taken to total rupture, by random samples taken from each production batch), and an indication of the resistance of the material to brittle type failure.

The quality of the notching process has been shown (7) to have a marked effect on the fracture surface, particularly initial crack formation. The pipes are extruded and the history of the extrusion process is retained in the final product, in both the structural orientation of the material and variation in wall thickness. This latter aspect affects the machining of the notch in terms of retained wall thickness. However, for the purposes of this test series, it has been assumed that the characteristic behaviour of the samples was consistent, since all the samples were produced on the same machine and from the same batch of pipe. The fractures were, therefore, related directly to the mode of testing and the nature of the load.

The test programme

The tests were all conducted at a given loading condition. This was because, whilst the measurement of primary strain at the chucks would have been comparatively simple, the precise strain determination would have been both extremely difficult and meaningless because of the inaccessibility of the notch tip. However, since the monitoring signals from the load transducers were similar (i.e., analogue voltages, frequencies, and waveforms), the performance of the machine was evaluated, with the added advantage that the findings were germane to the project.

Since much of the time allocated for machine evaluation had been expended on testing the jointed pipe samples, the time for multiaxial testing was severely constrained. Nevertheless, examination of fracture surfaces was important and, therefore, the programme was arranged to study the type of fracture as well as the time to failure of a commercial grade of notched gas pipe under multiaxial loading conditions. Most tests were conducted in the crack opening mode, i.e., internal pressure plus torsion, tension plus torsion, internal pressure plus tension, and tension–tension. The reason for this was that any mechanism which closed the crack would tend to damage the newly cracked surface. The paradox is that the crack progresses with a more 'refined' flat fracture surface when the notch is closed (effectively resharpened) at each cycle. The term 'refined' is used to imply a featureless surface without gross yielding when viewed normally. This avoids the academic argument of whether it constitutes true ESC, but which is none the less typical of most catastrophic service failures. Indeed, within the range of tests that do not result in rapid creep failure, it is observed that the greater the static load, the greater is the degree of notch blunting and the longer the time to failure. Some of the earlier materials tested, and high density polyethylenes, do not exhibit this characteristic. However, surfaces resulting from this notch blunting type behaviour have fracture surfaces with a high proportion of ductile yielding.

Because of the association of ESC with catastrophic failures seen in actual pipe systems an essential feature of any material evaluation test is to establish the material's propensity to brittle type fracture. Thus, an ideal test should induce a high percentage of ESC type fracture, especially since the last portion of the fracture plane is always ductile because of unrestricted creep in the extremely weak ligament that remains. Ideally, this flat fracture zone should extend over 50 per cent of the wall thickness, but only if the failure can be induced in realistic times, e.g., 20–40 hours. Another important aspect is the effect of the notch itself. In samples with axial notches, cracks tend to propagate from the ends of the notch, or if the notch was machined along the entire length of the pipe, the fracture would be adjacent to the chuck constraints. Thus the resulting fractures are influenced by material properties and geometry. It would also be of interest to observe the influence of loading patterns on the fracture surface.

The test sample

It had been found experimentally that whole pipe samples could be failed by fatigue in very short times (say 10 hours), but the resultant fractures were always of the classical 'bird beak' ductile mode (see Fig. 3(c)). For this reason, and the unexpected tenacity of the welded joints, the final test samples were made with circular 'V' (60 degree) notches nominally 1.5 mm deep. The pipe was gas grade 90 mm outside diameter with a 9 mm wall thickness.

Test objectives

The primary aim was to ensure that the machine would perform to specification and the second objective was to derive an insight into gas pipe behaviour under complex loading. The process of achieving the second objective would of necessity cover most of the first; however, it is helpful to consider the importance of the fracture mode on pipe evaluation.

As has already been stated, data from ductile failures is of limited use to the gas engineer, since almost every case of catastrophic failures of pipe systems in service is associated with ESC. Many studies have been made of fractures induced by uniaxial loading and, in general, the time to failure of pipes is closely associated with the progressive refinement of the ESC fracture surface for a specific loading arrangement. Since little was known about crack growth through polyethylene pipe under fatigue loading, other than those observed in pressurised systems, it was decided to make an exploratory study of fracture surfaces under complex cyclic loading.

Factors affecting the test programme

The mechanism of ESC fracture in MDPE pipe is complex, but can be divided into three basic regions, crack formation, 'flat' crack growth, and a final tearing rupture. The basic terminology used here is illustrated in Fig. 4.

Formation of a crack is not fully understood, but it is dependent on the quality and form of the preparation of the notch and hence the method of manufacture (6). In general, the more crude the method of notching, the earlier the crack is established, the greater the number of fracture sites, and the greater the ductile tearing zone immediately behind the notch root. This may be seen in electron micrographs (6) and the photographs of fractures at the notch-to-material interface which are shown in Fig. 5. The obvious, but salient, factor being that the larger the tearing zone, the less remains for the important ESC growth.

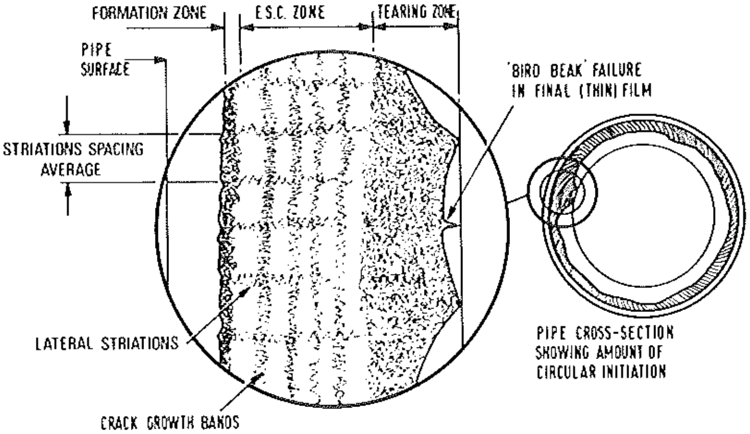

Fig 4 Schematic of the features seen on a typical fatigue surface for an external circumferentially-notched pipe

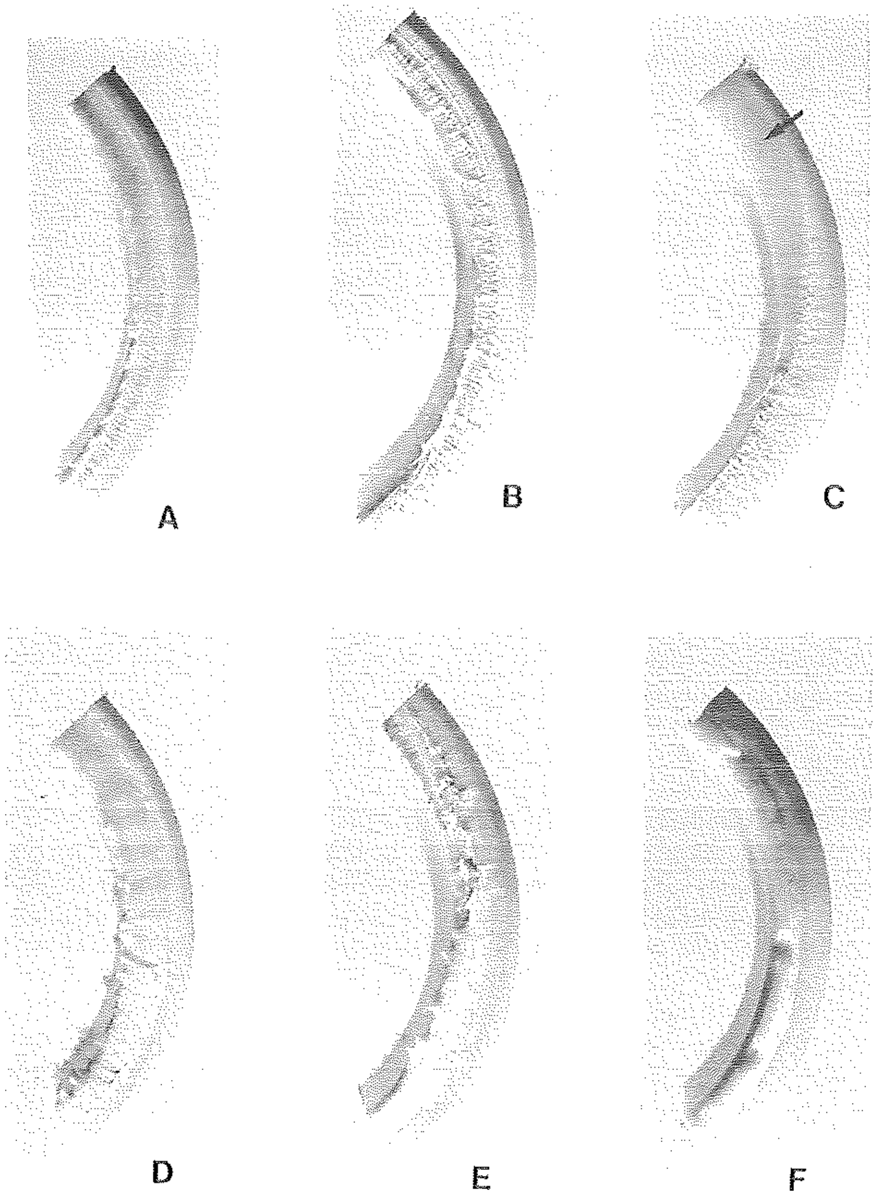

Fig 5 Fracture surface due to various cyclic loading modes: (a) torsion–tension, 9.7 hours; (b) internal pressure, 97.8 hours; (c) torsion–pressure, 50.0 hours; (d) no load–tension, 46.1 hours; (e) compression–tension, 170.2 hours; (f) torsion–pressure, 200.1 hours. Mean wall thickness of sample, 8.7 mm. Depth of surface notch, 1.5 mm (nominal)

The crack propagation phase was dependent on many factors, such as static load, frequency, ratio of time at high and low stress levels, upper and lower load levels, and temperature. For this reason, wherever possible one or more test parameters were kept constant, i.e., wall stress, frequency, temperature, etc. The usual pattern of crack growth behaviour comprising of fast and slow bands can be seen in Fig. 5(b). It was expected that the topography of the surface could be dependent on many factors; however, for the purposes of these tests it was assumed that the more refined the surface the nearer the failure approaches the ESC seen in service. A feature that appears to inhibit the crack growth is seen at locations where fracture planes, formed at differing sites, intersect. This characteristic was dominant when the applied stress was inclined to the plane of the notch (mixed mode), a situation endemic to most practical applications, but certain to be present in tests where there is a torsional element to the load regime.

Final catastrophic tearing was inevitable when there was insufficient material ahead of the crack tip to withstand the applied stress; this zone was completely ductile. In the case of internal pressurization, there is a miniature 'bird-beak' fracture formed by the thin (0.2 mm) membrane drawn out at the very base of the notch just prior to failure. This final failure took only a few cycles and involved a similar process to that which gave rise to the drawn-out fibres seen in the ductile fracture surface. Stress and temperature were very important, and if either of these were excessive, then, again, the tearing would be extensive, and diminish the ESC zone. Stresses that were not normal to the fracture plane also have an effect on the tearing zone. Residual stresses are possible because the samples were cut from commercial pipe. There is also the inherent axial stress associated with internal pressurization. Table 1 lists the various tests undertaken in the evaluation programme. It can be seen from Table 1 that there are insufficient data to make any conclusive findings. However, it does indicate the scope of the machine and the different results that arise from multiaxial loading.

Figure 5(a) is a photograph of the tension–torsion test failure. This test indicated that the light torsional load of 0.25 kNm did not influence the fracture behaviour greatly until the crack had propagated to a depth of 2.5 mm. This is consistent with the increasing influence of the torsion as the remaining ligament area decreases. It can be seen in this and the other photographs in Fig. 5 that the fracture does not propagate uniformly around the sample. This is a characteristic of pipe material and is most pronounced for the triaxial stress states at discontinuities such as notch ends, socket welds, and chuck clamps. In these samples the noted failure behaviour could also result from inconsistent machining, changes of wall thickness, or asymmetric deformation. Once the fracture mode has been established, for whatever reason, the non-uniformity merely adds to the other asymmetric factors causing failure.

Figure 5(b) shows that in the initial stage of fracture there is a similar characteristic to that seen in Fig. 5(a). This is because, although the relative

Table 1 Test results on 90 mm commercial grade PE gas pipe, wall thickness 8.7 mm, with a 1.5 mm (nominal) circumferential notch tested at 23°C

Pressure (MPa) high/low and (Frequency)	*Axial load (Kn) high/low and (Frequency)*	*Torsion load (kNm) and (Frequency)*	*Time to failure (Hours)*
0	−2/0 (1 Hz)	+0.25/−0.25 (0.5 Hz)	9.7
0.69/0.069 (1 Hz)	0	+0.28/−0.28 (0.5 Hz)	200
2.07/0 (1 Hz)	0	+0.1/−0.1 (0.5 Hz)	50
0	−8/0 (0.5 Hz)	0	46
0	−6/6 (0.5 Hz)	0	170
0	−2/0 (1 Hz)	+0.28/−0.28 (0.5 Hz)	35.2
0	−3/1 (1 Hz)	+0.28/−0.28 (0.5 Hz)	21
0	−5/1 (1 Hz)	+0.15/−0.15 (0.5 Hz)	6.6
0	−5/1 (1 Hz)	+0.1/−0.1 (0.5 Hz)	10.2
0	−1/−1 zero	+0.3/−0.3 (0.5 Hz)	83.8
0	−2/−1 (1 Hz)	+0.3/−0.3 (0.5 Hz)	56.6
0	−3/−1 (1 Hz)	+0.3/−0.3 (0.5 Hz)	14.9
0	−4/−1 (1 Hz)	+0.3/−0.3 (0.5 Hz)	6

Note. There was a rise in temperature of up to 10°C as the test progressed, depending upon the cyclic energy rate applied to samples

stress to strain ratio changes significantly during the course of failure, at the commencement of the test, the ratio of hoop to axial stress is approximately 2:1. However, as the fracture proceeds into the sample the hoop strain remains constrained by the parent pipe either side of the notch, whereas the axial strain is not so restricted.

It is not surprising, therefore, that there is a progressive change from Mode I dominated to Mode III dominated fracture. It would require a detailed study, with tests on samples of different wall thickness and various loading patterns, to be more certain of the mechanism of failure. This uncertainty exists because the material is quite unlike metals in that strain does not follow stress in any Hookean way, but is complex. Time dependency is important since the frequencies used in these tests were far faster than those required for the dynamic stability suggested by Turner (7). The tests were also at ambient temperature, but with no control over localised heating, especially at the root of the notch.

Figure 5(c) shows an example of where there has been localised failure. It is shown because it is a typical example of a surface where the initial stages of the fracture surface are such that it would be universally accepted at ESC. The smooth area indicated by an arrow is where the sample was 'snapped' open for examination and is a good example of a high speed (impact) fracture surface.

It is a characteristic of these materials that under certain loading conditions, if an excessive overload is given to a notched sample, there is gross ductile yielding at the root of the notch, thereby effectively 'blunting' the notch. It then requires an extended period before the fracture will propagate through the highly modified material. This process is evidenced by the highly refined surface immediately adjacent to the notch root. Since the loads in this test were comparatively high the grossly yielded surface seen prior to failure is typical of a creep dominated ductile failure. This part of the fracture process would have involved only a few (typically 10) cycles to failure.

A typical surface resulting from a tension–compression test is shown in Fig. 5(e) and has a polished appearance. This is almost certainly due to attrition between the surface asperities during the compression half of the cycle. Again the crack has taken an appreciable number of cycles to become mobile. Time lapse photographic studies of the notch during tests on internally pressurised fatigue samples, as well as analysis of electronmicrographs, have shown that there are zones at the crack front which consist of high density fibrils. These fibrils would have to fold and displace under the heavy compressive load. There were small amounts of debris extruded from the crack, which also supports this model of folding with attrition.

It is clear that the latter stages of fracture are similar to those seen in Fig. 5(d). The tensile load effect could have been enhanced by the compressive load, since it is a characteristic of plastics and rubbers under compressive stress to have within the vicinity of the notch zones a high residual tensile stress on the unloading half of the cycle, and for fatigue failure to proceed under, what is, outwardly, a compressively loaded regime.

The sample shown in Fig. 5(f) has a complex fracture emanating from an initial fracture surface that has all the characteristics of a Mode 1 fracture. The bright portion is the inclined 45 degree surface where the crack has bifurcated around the whole sample. At places around the sample the crack undergoes a further change of direction and has begun to travel down the axis of the pipe. This occurred half way across the sample wall. A small section of that crack may be seen at the bottom of the photograph. The ultimate failure mechanism occurred when the pipe began to 'shrink' into a smaller section, in a similar way to that seen in the reduced sections shown in Fig. 3. The reduced membrane had to be cut through so that a photograph of the surface could be taken.

All of the surfaces show striations at right angles to the notch. These are due to the coalescence of cracks that are running at slightly different levels from the root of the notch. Their size and frequency are a function of the sharpness and method of cutting the notch.

These striations are quite different from the type that may be seen in the later stages of crack propagation which are somewhat larger and more regular ('factory roof' 45 degrees), typical of samples subjected to a proportion of shear loading; see Fig. 5(b).

Conclusions

(1) A comprehensive multiaxial test facility for testing plastic pipe has been commissioned for under £50 000.
(2) Brittle type fatigue fractures can occur in MDPE commercial grade pipe, in comparatively short times (e.g., 30 hours) for various loading modes.
(3) Each loading mode produces a distinctive fracture surface, implying a totally different fracture mechanism. This shows that there is a need to study the fracture processes in this material arising from loading modes other than the sample pressurisation method used in most test procedures.
(4) No load regime could be found in which a fusion butt weld in the MPDE gas pipe would fail in preference to a zone in the parent pipe.

Acknowledgements

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