The long-term behaviour of an aluminium-reinforced polyethylene pressure pipe

J. BOWMAN*
Brunel University, Uxbridge, Middlesex UB8 3PH, UK

The long-term behaviour of an aluminium-reinforced polyethylene pressure pipe has been explored by undertaking stress rupture tests at 60 and 80 °C. The results of the tests showed these macrocomposite pipes have a time-dependent strength, such that with an increasing time under load the strength declined. In addition the pipes were weaker at 80 °C when compared to the 60 °C strength. The analysis of the influence of time and temperature on strength showed these multilayer pipes can be considered to behave as do conventional homogeneously structured plastic pipes, and that to describe the influence of time on the pipe strength, the accepted procedures developed for conventional plastics pipes can be applied. In addition the mode of failure of the pipes was examined. Pipe failure initiates by the strain-controlled failure of the reinforcing aluminium layer. The polyethylene layers then fail almost instantaneously in a ductile mode. This analysis of the mode of failure was supported by freeze–thaw cycling tests to − 25 °C and the 60 and 80 °C stress rupture tests.

1. Introduction

The majority of pressure-rated plastic pipes are manufactured from either polyvinyl chloride or polyethylene, and so processed that these pipes are essentially uniform in structure from the bore to the outer wall. Such pipes exhibit good performance characteristics for low temperature (50 °C and below) or low pressure (16 bar gauge or less) applications. But there is a need for higher pressure- and temperature-rated pipes. This paper reports on the time-dependent performance of a novel plastics-based pipe, capable of meeting the more exacting demands of the higher-temperature and pressure pipe markets. The novel pipe is of a macrocomposite arrangement consisting of five layers, four of which are made from polyethylene-based resins. The fifth layer is formed from an aluminium foil, welded to form a tube that sits near the middle of the wall of these continuously extruded pipes. The correct juxtapositioning and proportioning of the five layers gives properties that cannot be attained in homogeneously structured plastic or metal pipes.

The paper first describes the arrangement of the layers within, and the sizes of, these macrocomposite pipes. Data are then given on the time-dependent mechanical properties, together with selected results on the response of pipes to freeze cycling to − 25 °C. This is followed by a discussion of the probable failure mechanism of the plastic and metal phases of the pipe. The paper then considers how time influences the strength of these macrocomposite pipes, concluding with an estimation of their relative long-term strength. All the data and analysis relate to pipes failing in short (less than 2 years) test times and characterized by the ductile rupture of the plastic component. Separate consideration will be required for any brittle failure of the plastic component.

2. KiTEC macrocomposite pipes

2.1. Basic structure

The macrocomposite pipe considered here was developed in France in the 1970s, patented and now marketed under the name of KiTEC [1]. For variation and brevity the term “macrocomposite pipe” is used interchangeably with the name KiTEC. Two types of KiTEC pipe are currently available, one based on thermoplastic polyethylene (TP-PE), the other on crosslinked polyethylene (XLPE).

Fig. 1 schematically illustrates the basic structure of these macrocomposite pipes. On the bore and outer wall are layers of polyethylene (TP-PE or XLPE), with the greatest thickness on the bore. Near the middle of the pipe wall is aluminium metal in the form of an ultrasonically welded foil. The aluminium weld line lies parallel with the pipe axis (see Fig. 1). This aluminium tube is bonded to the inner and outer layers of polymer by two thin layers of melt adhesive on either side of the aluminium. The use of a melt adhesive gives the pipe structural integrity and avoids delamination.

* *Present address*: Fusion Group Plc, Smeckly Wood Close, Chesterfield, Derbyshire S41 9PZ, UK.

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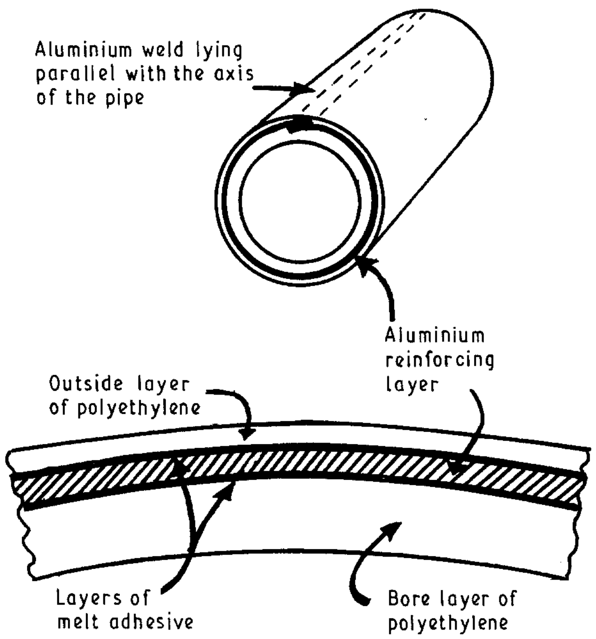

Figure 1 Schematic representation of the structure of the wall and the weld for KiTEC macrocomposite pipes.

2.2. Materials and pipe dimensions

Different temperature capabilities for KiTEC pipes are arrived at by the appropriate selection of the main polymer. For low service temperatures high stress-crack resistant pipe-grade TP-PE resins, capable of producing pipes with a smooth bore and outer wall, are used. For higher service temperatures XLPE is used for the bore layer and outer wall. Cross-linking can be introduced by electron beam processing, or a silane-grafted pipe grade polyethylene can be extruded to give the pipe, this layer subsequently cross-linking. For both the TP-PE and the XLPE the resin must be correctly stabilized with the appropriate anti-oxidant package [2].

The aluminium foil is a low alloy content metal subjected to a heat treatment-procedure designed to both maximize its ductility and preserve that ductility after ultrasonic welding. The aluminium is bonded to either the XLPE or the TP-PE by a thin (about 0.1 mm) layer of melt adhesive. The melt adhesive is based on an extrusion-grade polyethylene that has acrylic acid side-chains grafted on to the main chain [1]. The pipe is produced by an extrusion process where the melt adhesive and the TP-PE or XLPE first contact one another in the melt phase. This melt-to-melt contact encourages molecular diffusion at the interfaces to give good bonding between these two polyethylenes.

The materials identified above are formed into pipes, the sizes of which are annotated in Table I and in ASTM specifications [3, 4]. For both the TP-PE and XLPE based pipes the dimensions of the five layers are the same for a given diameter, but differ between diameters. The concept of a dimension ratio, the ratio of the mean outside diameter to the specified minimum wall thickness, cannot be correctly applied to help identify the pressure rating of these pipes. With each pipe size the temperature and fine pressure capabilities are defined by the diameter and form of polyethylene used for the bore and outer wall layers.

2.3. Some general properties of KiTEC pipes

KiTEC pipes exhibit three properties not found in conventional, homogeneously structured plastic pipes. First, these pipes can be bent to a shape that they retain. In bending, the proof stress of the aluminium is exceeded and the metal plastically deformed. On removal of the bending force the aluminium will exhibit a very small amount of elastic recovery; the expected recovery of the plastic component is not possible as the force it generates is insufficient to overcome the resistance offered by the aluminium. Hence the pipe retains the bent form, and without kinking on the pipe bore.

Second, it is well known that the polyolefins allow gases, such as oxygen, to diffuse through. This can lead to the corrosion of metallic components incorporated within a polyolefin pipe system. These multilayer plastics-based pipes possess a zero diffusion rate for oxygen [1], an unusual and valuable feature for a polyolefin-based pipe.

Third, the aluminium layer strengthens the pipe, both in respect of ramp burst strength and the long-term hydrostatic strength. For conventional plastic pipes the aspect of long-term strength is critical to designing pressure-rated pipes [2, 5, 6]. Reported here, in depth, is the time-dependent strength response of KiTEC pipes, together with comments on the probable failure mechanism.

TABLE I Dimensions of the three smallest sizes of KiTEC multilayer pipes (for both TP-PE- and XLPE-based pipes)

	Pipe nomenclature		
	0912	1014	1216
Minimum outside diameter (and tolerance) (mm)	12.00 (+0.30)	14.00 (+0.30)	16.00 (+0.30)
Minimum total wall thickness (and tolerance) (mm)	1.60 (+0.40)	1.60 (+0.40)	1.65 (+0.40)
Minimum aluminium thickness (and tolerance) (mm)	0.20 (+0.02)	0.20 (+0.02)	0.20 (+0.02)
Outer TP-PE/XLPE thickness (and tolerance) (mm)[a]	0.40 (+0.20)	0.40 (+0.20)	0.40 (+0.20)

[a] Excludes the TP-PE or XLPE overlaying the weld.

3. Experimental procedure

3.1. Pipe samples and materials

All the data reported here are for pipes having a nominal outside diameter of 16 mm; these pipes are referred to as 1216 pipes (see Table I). Two forms of 1216 pipe have been assessed, one based on a thermoplastic medium-density polyethylene (MDPE), the other on a thermoplastic high-density polyethylene (HDPE) material. Pipes were extruded at the premises of KiTechnology (UK) Ltd of London, England, using a special production line.

Aspects of the characteristics of the pipe-grade MDPE and HDPE resins used are recorded in Table II together with an identification of the two polymers supplied by BP Chemicals Ltd of Grangemouth, Scotland. The methods for characterizing the physical properties of the two resins were the standard routine techniques. These two TP-PE resins are both typical of high stress-crack resistant pipe-grade resins, and both gave pipes with a smooth inner and outer wall without any voiding or deleterious blemishes.

3.2. Constant-pressure tests

Elevated-temperature, constant-pressure lifetime tests (stress rupture tests) were undertaken on straight lengths of pipe. The pipe wall thickness and diameter were measured at several points prior to testing. The sample length was ten times the outside diameter when measured between the end fittings. Samples were filled with hot tap-water and all free air excluded, sealed and then immersed in a temperature-controlled hot water bath. All tests were unconstrained to allow the development of axial stresses. The procedures, pressures and the water-bath temperatures were held within the limits described in ASTM D1598.

Failure of the samples was detected by a pressure drop technique. At failure samples were isolated from the pressure source, depressurized and removed from the test tank. The pipe diameter after failure and at room temperature was measured using a Pi tape immediately adjacent to, but not at, the failure site. The location of the failure in the aluminium layer with respect to the ultrasonic weld was noted.

3.3. Oxidative stability

Pipe-grade polyethylene resins contain a thermal stabilization package, the presence of which is particularly important for pipes designed to operate at the higher temperatures (see section 5.1). The presence of the stabilization package can be inferred from measurement of the oxidation induction temperature [7, 8]. The oxidation induction temperature (OIT) of selected samples was determined in air at a scanning rate of 10 K min^{-1} using a Mettler differential scanning calorimeter.

Samples were taken from selected MDPE-based 1216 pipes that covered a range of test times for pipes subjected to pressure testing at 80 °C. The OIT samples were taken from the TP-PE layer on the bore of the pipes using the 0.5 mm lying closest to the bore. The sample weights all lay within the range 5 to 10×10^{-3} g.

3.4. Freeze–thaw tests

Freeze–thaw cycling tests were undertaken on 1/2 in. (13 mm) half-hardened copper pipes and 1216 KiTEC pipes. One-metre long lengths of pipe had their diameter and wall thickness measured, and were formed to give a U-bend shape with the radius equal to five times the pipe outside diameter. Samples were filled with cold tap-water, pressurized to 1.0 MPa gauge pressure and cooled to $-25(\pm 1)$ °C for 18 h with the fluid pressure maintained by sealing both ends. Test samples were subsequently de-pressurised and brought back to ambient (20 °C) temperature, and then re-pressurized to 1.0 MPa to check for any leaks. The freeze–thaw cycling was repeated till sample failure or 10 cycles, whichever occurred first. The location of any failure was noted together with the pipe diameter adjacent to the failure point.

4. Results

4.1. Elevated-temperature lifetime studies

The lifetimes of the various macrocomposite pipes tested to failure have been correlated with σ_n, the nominal pipe hoop stress. σ_n is calculated from the applied internal pressure P, the measured minimum total pipe wall thickness t and the mean pipe outside diameter d using the equation

$$\sigma_n = \frac{P(d-t)}{2t} \quad (1)$$

This equation gives only the nominal pipe hoop stress; it takes no account of the different Young's moduli of

TABLE II Characteristics of thermoplastic polyethylene resins

	MDPE resin	HDPE resin
BP Chemicals grade	Rigidex PC002-50 R968	Rigidex PC001-55 R102
Colour	Blue	Black
Measured MFR (g per 10 min)[a]	0.227	0.144
Density (kg m^{-3})[b]		
From pipe bore layer	940.2	949.5
From MFR extrudate	942.1	954.1
Oxidation induction temp. of bore layer (°C)	246.1	> 250[c]

[a] At 190 °C and 2.16 kg load.
[b] Measured using a density gradient column.
[c] Data from BP Chemicals Ltd.

the different layers which will distribute the stresses in a significantly non-uniform way.

Straight lengths of pipe manufactured from the MDPE resins were tested to failure at 60 °C at pressures between 2.8 to 3.5 MPa gauge, and at pressures between 2.0 and 2.9 MPa gauge at 80 °C. For valid pipe failures (failures at least one diameter away from the end fitting), Fig. 2 for the MDPE-based pipe plots pipe lifetime against σ_n on double-logarithmic axes. In Fig. 3 data for pipe produced with the HDPE resin are presented in the same format. For the HDPE-based pipes the internal pressure was within the range 2.7 to 4.0 MPa gauge for the 60 °C data and between 2.0 and 2.9 MPa gauge for the 80 °C tests.

4.2. Failure characteristics of pipes tested at elevated temperatures

For lifetime tests on the HDPE- and MDPE-based pipes tested at 60 and 80 °C the failures of the aluminium foil were either immediately adjacent to or at the ultrasonically-made weld. Fig. 4 shows that the failures were either offset to one side of the weld or at the weld.

For all the pipes tested to date at 60 and 80 °C the TP-PE layers failed in a ductile mode. There was no evidence of the slit type of failure sometimes seen with conventional polyethylene pipes tested at elevated

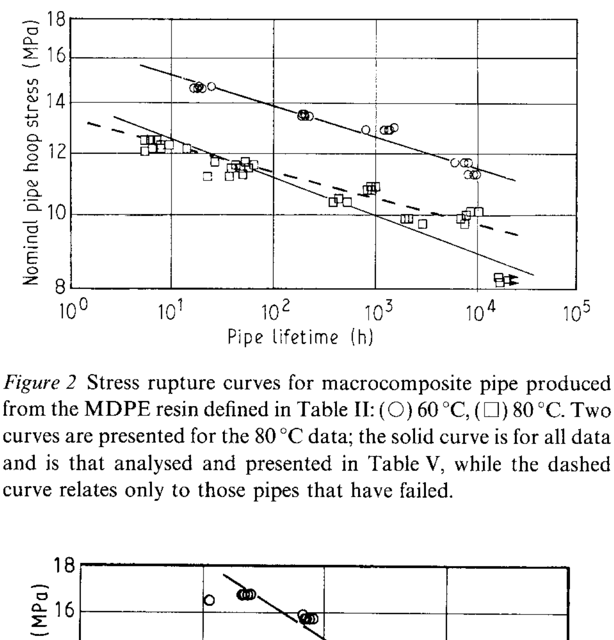

Figure 2 Stress rupture curves for macrocomposite pipe produced from the MDPE resin defined in Table II: (○) 60 °C, (□) 80 °C. Two curves are presented for the 80 °C data; the solid curve is for all data and is that analysed and presented in Table V, while the dashed curve relates only to those pipes that have failed.

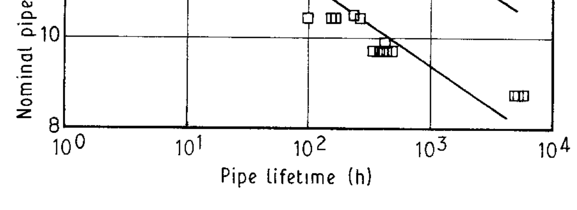

Figure 3 Stress rupture data for macrocomposite pipes tested to failure at (○) 60 and (□) 80 °C for pipes extruded from the HDPE resin defined in Table I.

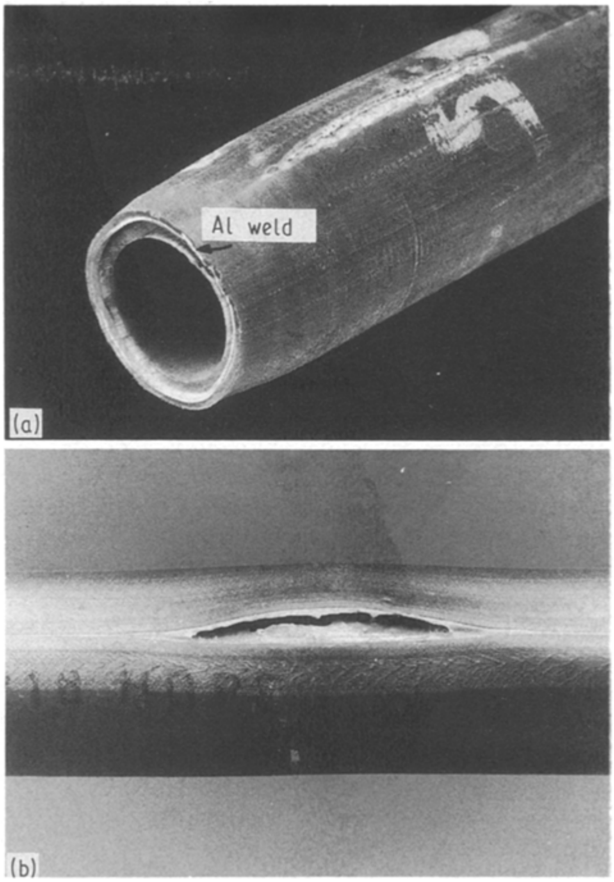

Figure 4 Photographs of failed stress rupture tested macrocomposite pipes: (a) failure adjacent to the ultrasonically made weld in the aluminium foil, (b) failure along the weld interface.

temperatures and low stresses [5]. A close examination of the pipe bore and outer wall of failed pipes did not reveal any nascent slit-like cracks, either remote from or adjacent to the aluminium weld.

Data on the measured OIT are given in Table III. It can be seen that there was an initial fall-off in the OIT, but after that there was only a marginal drop in OIT for test times up to and in excess of 17 000 h (2 years). This infers that using the OIT test as an indicator of the stabilization package there is no significant and continuing loss of stabilizer for the tests run to date.

4.3. Hoop strains in stress rupture-failed pipes

The most substantial series of tests undertaken on these macrocomposite pipes were the constant-pressure lifetime tests. For a selected number of failed samples the pipe diameter adjacent to the failure site was measured when the pipe had cooled to ambient

TABLE III Oxidation induction temperature as a function of ageing for pressure-tested MDPE-based KiTEC pipe

Ageing time (h)	Oxidation induction temperature (°C)
0	246.1
982	245.5
2878	241.7
7637	241.1
17257	239.9

TABLE IV Failure strains in KiTEC pipes

	Hoop failure strain (%)	
	MDPE-based KiTEC pipe	HDPE-based KiTEC pipe
80 °C pressure tests	5.7 to 11.3	3.1 to 13.8
60 °C pressure tests	5.6 to 12.6	3.1 to 10.6
Freeze–thaw cycling	6.5	5.5

temperatures. Knowing the initial diameter, a hoop strain at failure was calculated. For the MDPE- and HDPE-based pipes Table IV records that the observed range of hoop strains at failure for both the 60 and 80 °C stress rupture tests were within the range 3.1 to 13.8% for both materials at both temperatures.

4.4. Freeze–thaw testing

Freeze–thaw cycling tests were conducted on conventional copper pipes and on macrocomposite pipes made from the MDPE and HDPE resins. The half-hardened copper pipes failed in the first freeze cycle by longitudinal cracking, presumably because the expansion of the water on freezing exhausted the strain capacity of the copper pipes. This result confirms a sound experimental procedure. KiTEC pipes were multiple-freeze resistant, so that 15 of 18 samples tested were able to sustain 10 freeze–thaw cycles without failure. For the three samples that did fail, the failures were after five or more freeze–thaw cycles, indicating that KiTEC pipes have capacity to withstand freeze–thaw cycling.

For the failures seen from freeze–thaw cycling the hoop strain adjacent to the failure site was 6.5% for the MDPE-based pipe, while that for the HDPE-based pipe was 5.5% (see Table IV). These values fall within the range recorded for elevated-temperature pressure testing. For the limited number of failures seen during freeze–thaw cycling the failure mode was similar to that for the failures from elevated-temperature pressure testing. Local bulging was seen together with a longitudinal rupture of the aluminium layer. The failure of the polyethylene layers was ductile.

Data have now been presented on the stress rupture lifetimes, freeze–thaw cycling response and failure modes of these macrocomposite pipes. Discussions will now take place on the factors that determine the failure of these macrocomposite pipes and on their long-term strength. These detailed discussions will be preceded by a brief résumé on the long-term strength of conventional polyethylene pipes.

5. Discussion

5.1. The long-term strength of conventional MDPE and HDPE pipes at elevated temperatures

For conventional homogeneously structured MDPE and HDPE pipes, extensive constant-pressure, elevated-temperature (60 °C and above) lifetime testing has identified three distinct failure modes [2, 8, 9]. At short failure times and relatively high hoop stresses ductile failures are observed. Ductile failures are characterized by excessive local deformation and are associated with a yield process [10]. At intermediate failure times and hoop stresses slit-type failures are seen [8, 10], the fracture appearing brittle despite the local microductility on the fracture surface [11]. These brittle or slit-type failures often initiate from adventitious flaws [12], with the crack propagating in a slow, stable mode [10]. Finally, at very very long test times the antioxidant package within the pipe-grade polyethylene is exhausted, and then the polymer begins to break down chemically resulting in a loss in molecular weight [13]. For failure by this chemical breakdown process it is common to observe many brittle cracks on the pipe bore. This failure process is not significantly influenced by the level of stress applied to the pipe [8] but is associated with the environment in and around the pipe and the time spent at elevated temperatures [2, 8, 13].

For a polyethylene pipe exhibiting only ductile failures, relationships between the applied hoop stress σ_n and the time to failure f_t have been proposed [14, 15]. For the data on the macrocomposite pipes, it is proposed to utilize the two-coefficient model:

$$\ln f_t = A + B \ln \sigma_n \quad (2)$$

The two-coefficient equation is specified in a number of plastic pipe standards, including ASTM D2837 [16] and BS 6572 [17]. Its use is for a single failure mode only, with the constants A and B being determined from the experimental data.

5.2. Failure mode of the polyethylene component in KiTEC pipes

The TP-PE component in KiTEC pipes may fail by a chemical breakdown process, by slow crack growth or by ductile rupture. For all the pipes tested to failure at 60 and 80 °C the evidence is that the TP-PE component failed in a ductile mode, with extensive local deformation of the inner and outer layers (see Fig. 4). No slit-type brittle failures were seen on the bore or outer wall layers of TP-PE either at or remote from the ultrasonically welded aluminium foil. Measurement of the OIT of the TP-PE from the bore of pipes tested for almost two years at 80 °C (see Table III) revealed an OIT close to the minimum recommended value [7]. There was no evidence of chemical breakdown of the bore layer of polyethylene; the layer of aluminium acted as an effective barrier to oxygen to preserve the polymer's oxidative stability.

It can therefore be concluded that for the pipes tested to date the TP-PE component failed by the single failure mode of ductile rupture. This evidence for a single failure process for the TP-PE layers supports the use of the two-coefficient model (Equation 2) to describe the influence of the nominal pipe hoop stress on the pipe lifetime.

5.3. Failure mode of the aluminium layer in KiTEC pipe

For the 60 and 80 °C lifetime tests conducted to date on these MDPE- and HDPE-based pipes, the evidence is that the aluminium layer failed either by splitting parallel with the pipe axis or by failure of the aluminium weld. Measurement of the hoop strain at failure revealed that for pipes tested at both 60 and 80 °C and a range of hoop stresses, the failure strains were below 14% (see Table IV). And, most importantly, freeze–thaw cycling tests to − 25 °C revealed similar failure strains in samples that were induced to fail, as annotated in Table IV. It is thus concluded that the failure of the aluminium layer was precipitated by the pipe expanding and attaining a critical strain.

The failures in the aluminium layer were either immediately adjacent to or at the ultrasonic weld, thus confirming that a strong and good weld of the aluminium was effected during production. The probable cause of the failure close to the weld is ascribed to the following effects. To create the ultrasonic weld, mechanical energy imparted from the horn plastically deformed the metal immediately around the weld (Fig. 5). This deformation lowered the failure strain of the aluminium around the weld compared to metal remote from the weld. But another part of the mechanical energy from the horn was converted into heat energy to both assist in creating the observed good weld and to anneal the plastically deformed aluminium. The metal that was annealed was that closest to the horn, while more distant areas received heat but not sufficient to effect annealing (see Fig. 5).

The combined effects of the mechanical deformation and the local annealing created at the weld region a thick zone of annealed metal; when subjected to load the stress was low and the metal had significant reserves of ductility. Adjacent to the weld the aluminium was only plastically deformed, was marginally thinner and was of a lower ductility. As the pipe expanded, either because of the internal pressure at elevated temperature or because of the repeated freeze–thaw cycling, the strain in the pipe exhausted the residual ductility of the metal in the area adjacent to the ultrasonic weld. Hence failures were observed adjacent to but not at the ultrasonic weld. Once the aluminium failed the polyethylene component had insufficient strength at these high internal pressures, and thus failed almost instantaneously in a ductile mode.

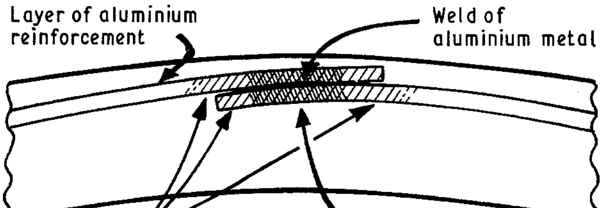

Figure 5 Schematic illustration of a proposed structure of the aluminium metal at the weld due to the combined influence of the mechanical and heat inputs from the ultrasonic welding process.

In the above two sections the failure mode of the TP-PE layers and the aluminium layer has been examined. The TP-PE failed by a ductile mechanism only, this supporting the use of the two-coefficient model to describe the influence of pipe hoop stress on pipe lifetime. The next few sections examine the time-dependent strength of KiTEC pipes, and compares this strength with that of conventional MDPE-based pipes.

5.4. Describing how time influenced pipe strength

The data in Figs 2 and 3 have been analysed by linear regression analysis, assuming that Equation 2 describes the influence of nominal hoop stress on pipe lifetime. The calculated values for the intercept (A) and slope (B) of Equation 2, together with the correlation coefficients, are contained in Table V for the MDPE and HDPE forms of the multilayer pipe for both the 60 and 80 °C pressure tests. Also in Table V are values for A and B for ductile failures of conventional pipe tested at 60 and 80 °C. Note that the calculations of A and B for KiTEC MDPE-based pipe at 80 °C include the intact pipes, i.e. those that did not fail.

The correlation coefficients for the MDPE- and HDPE-based macrocomposite pipes lie in the range − 0.985 to − 0.924. These values are similar to those supplied (on a confidential basis) by various pipe-grade resin manufacturers for conventional polyethylene pipes failing in a ductile mode. Furthermore it is seen from Figs 2 and 3 that there were no unexpected short or long pipe lifetimes for a given pipe hoop stress for both the 60 and 80 °C data. All the test results on these 1216 pipes produced from the resins cited in Table II are recorded in Figs 2 and 3. Thus it is concluded from the data in Figs 2 and 3 and from the correlation coefficients in Table V that:

(a) the strength of the pipes has a time-dependent dimension, pipe strength declining with increasing time under load;

(b) a double-logarithmic plot of nominal hoop stress against lifetime gives a reasonable straight-line plot, confirming the use of the two-coefficient model [14, 16];

(c) the correlation coefficients are typical of those for conventional polyethylene pipes failing in a ductile mode;

(d) the observations (a) to (c) hold for two forms of 1216 KiTEC pipe, one MDPE-based and the other HDPE-based, and hold for tests at both 60 and 80 °C.

The above suggests that the time-dependent strength of these multilayer pipes can be described using procedures developed for conventional plastic pipes. However, the conclusions are for the polyethylene component of the multilayer pipe failing in the ductile mode only. Separate analysis will be required if brittle failure of the TP-PE layer is encountered in the continuing tests. It should also be noted that further work can be undertaken on the statistics of pipe lifetimes (see for instance Palermo and De Blieu [14]). The

TABLE V Calculated values for the intercept (A) and slope (B) for Equation 2

Pipe type	Values for Equation 2			
	Temp. (°C)	A	B	Correlation coefficient
KiTEC pipe, MDPE-Based	80	52.93	− 20.01	− 0.924
	60	69.59	− 24.71	− 0.978
KiTEC pipe, HDPE-Based	80	31.85	− 11.17	− 0.931
	60	36.58	− 11.81	− 0.984
Conventional pipe, PC 002-50 R968	80	86.19	− 47.31	N/A[a]
	60	86.67	− 41.47	N/A

[a] N/A = not available.

objective here has been to provide an overview on the time-dependent strength and failure mode of KiTEC pipes. Further data, particularly at temperatures other than 80 and 60 °C, will help identify the correctness of using the two-coefficient model.

5.5. Comparing the time-dependent strengths of conventional and multilayer pipes

In this final section the extrapolated strength of KiTEC pipe is compared to the extrapolated strength of conventional pipe at lifetimes up to 100 years for the following conditions:

(a) temperatures of 60 and 80 °C;

(b) assuming that both forms of pipe fail in a ductile mode at lifetimes up to 100 years (extrapolation of the ductile curve);

(c) assuming that the extrapolation for these multilayer pipes, from relatively short test times of two years to 100 years, is valid and is based on Equation 2 and the values for A and B as annotated in Table V.

For lifetimes up to 100 years, Fig. 6 shows how the relative strength of the multilayer pipe, made from Rigidex PC002-50 R968, varies in relation to the strength of conventional pipe made from the same polymer. At 1 year, at both 60 and 80 °C, the multilayer pipe is at least 76% stronger than conventional

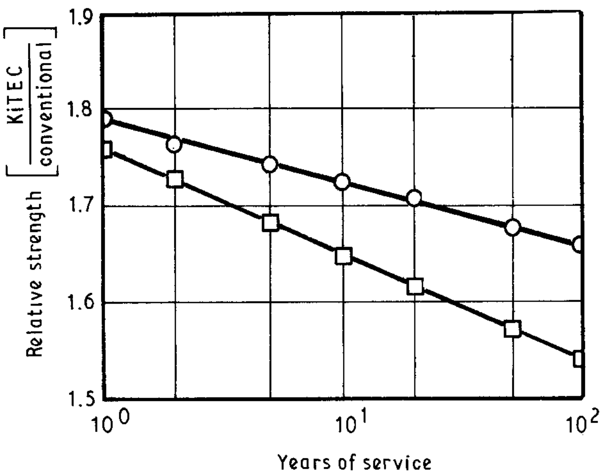

Figure 6 Comparison of the extrapolated strengths of macrocomposite KiTEC pipes compared to conventionally extruded pipes, when both are extruded from the same resin, Rigidex PC002 50 R968: (○) 60 °C, (□) 80 °C.

pipe. With time under load this improvement in strength declines to 54% at 80 °C and to 66% at 60 °C. This small loss in relative strength with time under load assumes that both pipes fail in a ductile mode. This is known to be unlikely for conventional MDPE and HDPE pipes, where brittle slow crack growth failure is likely at long test times and at these elevated temperatures [8, 13]. At present we see no signs of such a failure in KiTEC pipe, and if brittle failures are absent in the polyethylene layers of the multilayer pipes at long test times they will become significantly stronger relative to conventional pipes as the lifetime increases.

Fig. 6 shows the strength of KiTEC pipe to be typically 60% stronger than conventional pipe, this increase in strength arising from the incorporation of a 200 μm thick layer of aluminium. This benefit of increased long-term strength is in addition to the other benefits that multilayer pipes possess (see section 2.3).

In respect of the time-dependent strength further work should be undertaken in the following areas:

(a) at temperatures below 60 °C;

(b) to longer times at 80 °C to assess if slow crack growth failures [8, 10, 11] or depolymerization [2, 7, 13] might cause the polyethylene layer to fail first;

(c) with other pipe-grade resins, particularly the newer high density polyethylenes, and

(d) with multilayer pipes of other sizes.

Some of this work is ongoing, with the encouraging aspect that known and trusted procedures developed for conventional plastics pipes [6, 9, 14–18] can be applied to describe the influence of time on the strength of these multilayer pipes. Furthermore, the current work showed the pipes were produced to a consistently high quality, with the aluminium weld not acting to initiate slit-like cracks as might be expected [12]. These observations lend support to the proposal that this multilayer pipe can, in respect of its time-dependent strength, be considered to behave as a conventional homogeneously structured plastic pipe.

6. Conclusions

Tests have been undertaken on a novel multilayer pressure pipe of a single diameter and a single total wall thickness, made substantially from either MDPE or HDPE pipe-grade resin. Short-term freeze–thaw cycling tests were undertaken together with an extensive series of pressure-lifetime tests at both 60 and 80 °C. The failure mechanisms of the key layers of the pipe were explored. The influence of time on the strength of these 1216 KiTEC pipes has been examined using the methods commonly used for conventional plastic pipes. The conclusions arising from these studies are divided into two main groups.

6.1. The mechanism for ductile pipe failure

(a) For the 60 and 80 °C tests undertaken on pipes made from high stress-crack resistant pipe-grade polyethylene resins only ductile failures have been observed. No slit-like brittle cracks were seen.

(b) The OIT of the bore layer of polyethylene appeared to stabilize at acceptable values. Failure by depolymerization at long times therefore appears to be delayed in these multilayer pipes.

(c) The ultrasonically made aluminium weld did not act to initiate any brittle-type cracks of either the inner or outer layers of polyethylene.

(d) The aluminium layer failed at a total pipe strain of between 3 and 14% for both the elevated-temperature and the freeze–thaw cycling tests. The aluminium layer failed either close to the ultrasonic weld or at the weld.

(e) The failure close to the ultrasonic weld was associated with the cold work imparted to the metal by the process of welding.

(f) Pipe failure starts with the failure of the aluminium layer, which appears to be strain-controlled. After the metal layer fails the remaining ligament of polyethylene is not sufficiently strong to sustain the stresses arising from the high internal pressures, and fails almost instantaneously in a ductile mode.

6.2. The influence of time on pipe strength

(a) For both the MDPE- and HDPE-based multilayer pipes, at both 60 and 80 °C, the pipes had a time-dependent strength; the stress to cause pipe rupture declined as the time under load increased. In addition, for both the MDPE- and HDPE-based pipes, increases in the temperature of testing from 60 to 80 °C reduced pipe strength for a given failure time.

(b) At both 60 and 80 °C, and for both the MDPE- and HDPE-based pipes, the procedures used for describing the influence of time on the strength of conventional plastic pipes can be used on these KiTEC pipes.

(c) The two-coefficient model for describing the long-term strength of plastic pipe (as specified in ASTM D2837) aptly described the influence of time on pipe strength. The stress in these multilayer pipes, used in the two-coefficient model, was the nominal, which simplifies the application of this model.

(d) These multilayer pipes can therefore be considered to behave as do conventional, homogeneously structured, plastic pipes in respect of their time-dependent strength.

(e) The incorporation of a layer of aluminium 200 μm thick raised the short- and long-term strength of the macrocomposite pipes when compared to comparable conventional plastic pipes. At 60 °C the MDPE-based multilayer pipe was at least 60% stronger than the equivalent conventional pipe at both short and long times, the latter by extrapolation.

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