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The use of tensile tests to determine the optimum conditions for butt welding polyethylene pipes of different melt flow index

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The butt fusion welding of four different grades of polyethylene pipe has been studied and the feasibility of producing good welds between pipes of different melt flow index has been examined. Weld quality has been assessed on the basis of tensile tests and microstructural studies. The factors influencing the microstructure are discussed; in particular, the flow of molten polymer within the welds.

1. Introduction

In recent years the use of polyethylene pipes has become increasingly widespread in gas distribution systems. Polyethylene has several advantages over the traditional materials, for example corrosion resistance, lightness and lower cost. A number of different grades of polyethylene have been used as pipe materials and even if standardization is achieved and only one type of pipe laid throughout the U.K., it is inevitable that joints between dissimilar polyethylene pipes will occasionally be required to repair or extend existing systems. Thus it is essential to know whether these joints can be made successfully using existing techniques.

There are two approaches to testing welds in polyethylene gas pipes. One can attempt to predict the long-term behaviour of the jointed pipe under service conditions on the basis of stress rupture tests [1–4], or the strength of the joint in the short term can be measured and compared with that of the unwelded material [5, 6]. In this paper the second approach has been adopted and tensile tests carried out to observe the effects of variations in the welding conditions on weld strength. It has been shown [6] that the sensitivity of this technique is greatly increased if the welding bead is removed prior to testing. If the welding bead is not removed, fracture is always initiated by the notch between the welding bead and the gauge length. (In practice the welding bead will, of course, always remain.) The quality of a weld is assessed using two parameters obtained from the tensile test results: the percentage elongation to failure, which should be similar to the value obtained for the unwelded material, and a welding factor f defined by Menges and Zöhren [5] as

$$f = \frac{\text{yield strength of welded material}}{\text{yield strength of unwelded material}}$$

should be equal to or greater than unity. For a weld to be deemed satisfactory, tensile specimens cut longitudinally down the pipe and across the weld should show a large percentage elongation to failure and a welding factor close to unity.

2. Experimental

2.1. Materials

The following types of polyethylene pipe have been studied: (i) Muntz HDPE of outer diameter 60 mm and wall thickness 5.8 mm (supplied by Yorkshire Imperial Plastics, Leeds, U.K.), (ii) Muntz LDPE of outer diameter 60.2 mm and wall thickness 8.3 mm (supplied by Yorkshire Imperial Plastics), (iii) Rigidex PE of outer diameter 63 mm and wall thickness 6.0 mm (supplied by Yorkshire Imperial Plastics), (iv) Aldyl 'A' PE pipes of outer

TABLE I Properties of materials used

Property	Muntz HDPE	Rigidex PE	Aldyl 'A' PE	Muntz LDPE
Density (kg m^{-3})	0.96	0.945	0.94	0.93
Yield stress (MPa)	25.5	23	21	14.5
Elongation (%)	720	640	970	590
Melt flow index*	0.05	0.2	1.5	0.7

*Values stated by suppliers.

diameters 60.2 and 63 mm, and wall thickness 6.0 mm (supplied by the Dupont Co UK Ltd., Derbyshire, U.K.). Some properties of the materials are given in Table I.

2.2. Techniques

2.2.1. Welding

A Bielomatik welding machine (Model HV493) supplied by Bielomatik Lenze Co., West Germany, was used. The surface temperature of the heating plate was determined accurately using a thermocouple. The welding pressure was calculated from the welding force, which was shown on the machine, and the area of the pipe end. Prior to welding, the pipe ends were turned until they were smooth and square and then degreased using an acetone swab.

Butt welds were made using the procedure outlined previously [6]. The pipe ends were heated by contact with the heating plate under slight pressure until a small uniform bead had formed and then for a further period with zero pressure. The heating plate was removed and the pipe ends pushed together until a welding bead of the correct size formed. The pressure was maintained during cooling to prevent the formation of shrinkage cavities.

2.2.2. Tensile testing

Tensile test specimens were cut from the welded pipes using a high speed, air driven router. The router was also used to remove the welding beads from the specimens. After machining, the gauge length was polished with fine emery paper. Tensile tests were carried out on an Instron testing machine at room temperature. The crosshead speed was 0.83 mm sec^{-1} and for a 25.4 mm gauge length this corresponds to a strain rate of 3.28×10^{-2} sec^{-1}.

2.2.3. Etching

Specimens to be etched were cut from across the weld and a smooth surface produced using an M.S.E. Base Sledge Microtome. The etchant [7] was a saturated solution of chromic oxide (CrO_3) in water at 340 K. The solution with the sub-

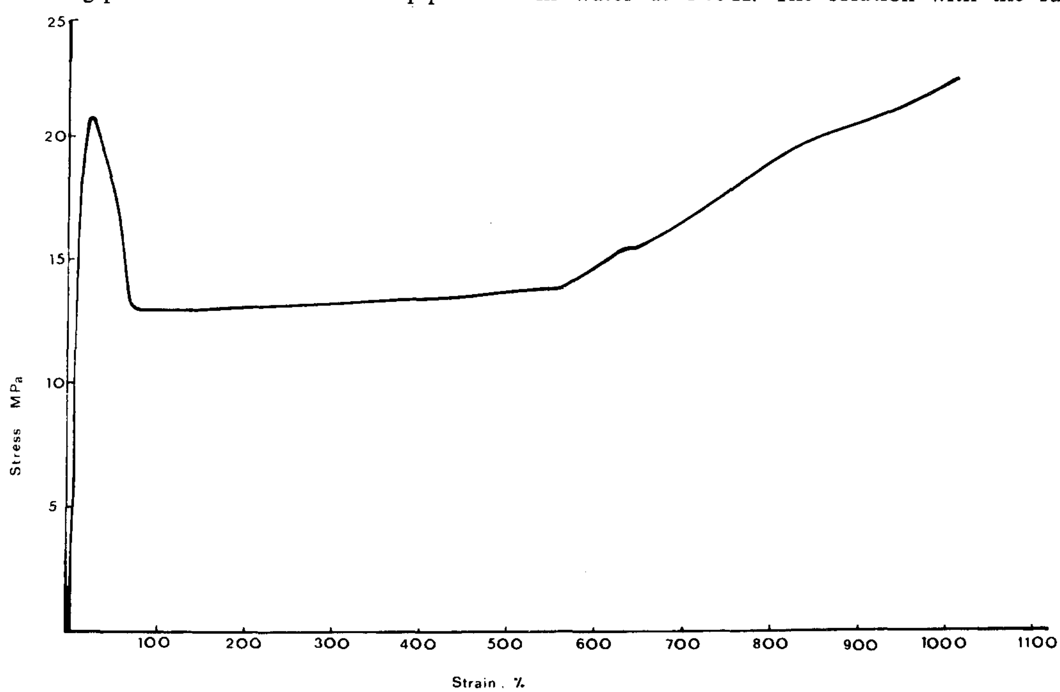

Figure 1 Typical stress–strain curve for Aldyl 'A'.

merged specimens was contained in "Quickfit" test tubes maintained at 340 K in an oil bath. An etching time of 10 to 12 h was used.

2.2.4. Transmission optical microscopy

Sections of thickness 15 μm were cut from across the weld using the sledge microtome. The sections were transferred to microscope slides and cover slips positioned on top. A few drops of xylene were introduced between the slides and the cover slips. The specimens were then viewed using a Vickers M55 optical microscope with crossed polars.

3. Results

3.1. Results of tensile tests on welds between pipes of the same material

All four types of polyethylene were studied in the same way. Tensile tests were first carried out on unwelded specimens and typical values of yield stress and percentage elongation at fracture obtained for each material. A typical stress–strain curve is illustrated in Fig. 1. A series of welds was then made for each material over a range of welding temperatures and pressures but always using the same initial heating time of 60 sec. Six tensile specimens were cut longitudinally across each weld and from four of these the welding beads were removed. The assessment of weld quality was made using the results from these four specimens as it has been shown previously [6, 7], and confirmed here, that the removal of the bead gives greater sensitivity to the effects of variations in the welding parameters. The weld quality was assessed in terms of the welding factor and the percentage elongation at fracture. In addition the fracture surfaces were examined in the scanning electron microscope and, where possible, studies made of the microstructures produced in the welds.

3.1.1. Aldyl 'A' welds

Figs. 2 and 3 show the average values of welding factor and percentage elongation plotted against welding temperature and welding pressure. It can be seen that a high welding factor and percentage elongation can be achieved over a fairly wide temperature range, 453 to 518 K, but that the

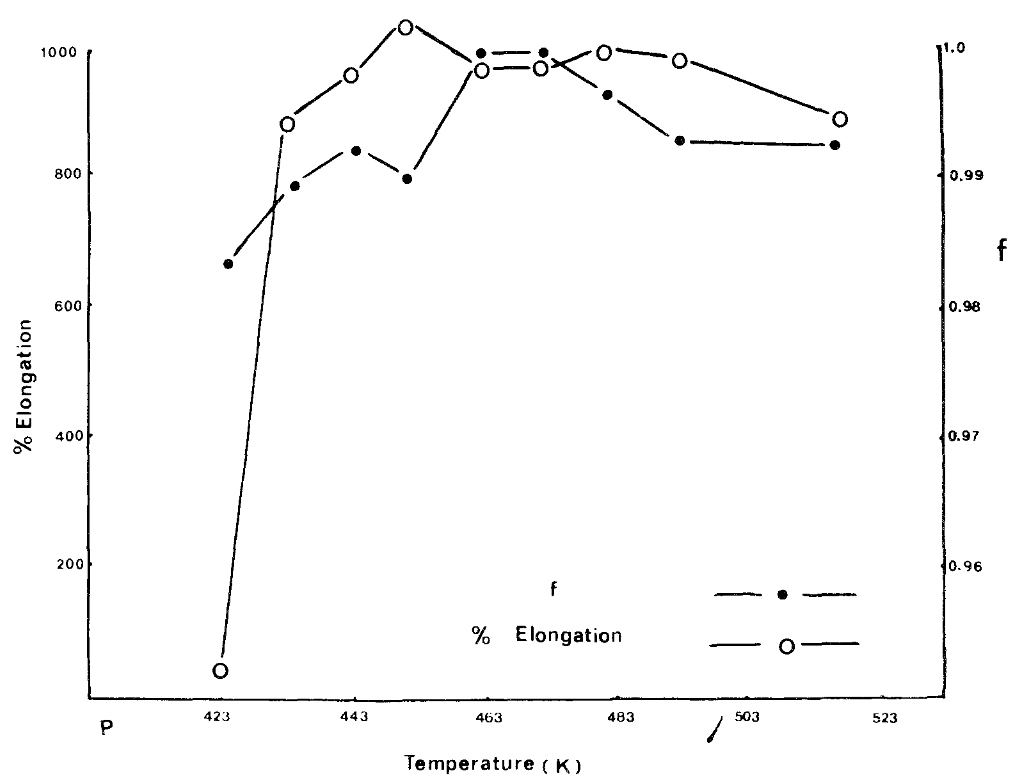

Figure 2 Graph of welding factor and percentage elongation versus welding temperature for Aldyl 'A' welds; welding pressure constant at 0.1 MPa.

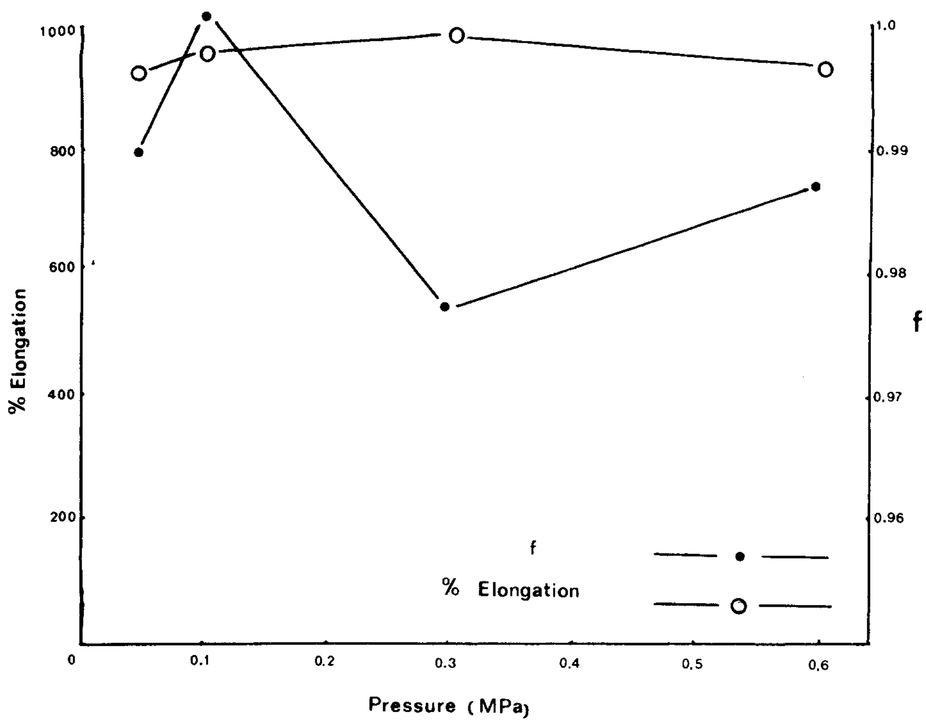

Figure 3 Graph of welding factor and percentage elongation versus welding pressure for Aldyl 'A' welds; welding temperature constant at 463 K.

welding factor reaches a maximum at about 463 K. Below 433 K, the elongation falls to a very low value although the welding factor decreases only little. This emphasizes the importance of considering both welding factor and percentage elongation in determining the weld quality. Up to a welding temperature of 518 K no adverse effects are noticed except that the bead is somewhat larger than desirable. Presumably, if still higher welding temperatures had been used, thermal degradation would have caused a drop in both welding factor and percentage elongation. Welding pressures in the range 0.05 to 0.6 MPa are acceptable, the optimum pressure being 0.1 MPa.

Most specimens gave elongations in excess of 800%. A neck formed and ran through the weld until fracture occurred at the shoulder at one end of the gauge length. When the welding bead was left on, however, fracture was initiated by the notch between the bead and the gauge length and the nature of the fracture surface gave an indication of the quality of the weld. Fig. 4 shows the fracture surface of a good weld, Fig. 5 shows the fibrillation which characterizes a poor weld and which may be ascribed to lack of adhesion. The amount of fibrillation increases as the welding conditions deviate from the optimum. The lack of adhesion in poor welds is also indicated by etching in chromic acid. At welding temperatures below 463 K the weld interface is attacked preferentially and this has been stated [6] to be due to incomplete adhesion.

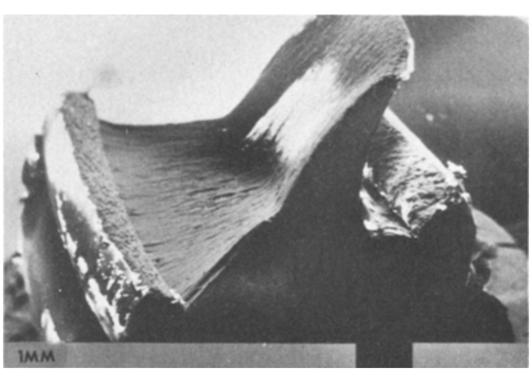

Figure 4 For specimens welded under near optimum conditions no fibrillation was observed when specimens were tested with the welding bead left on (scanning electron micrograph). Bar = 1 mm.

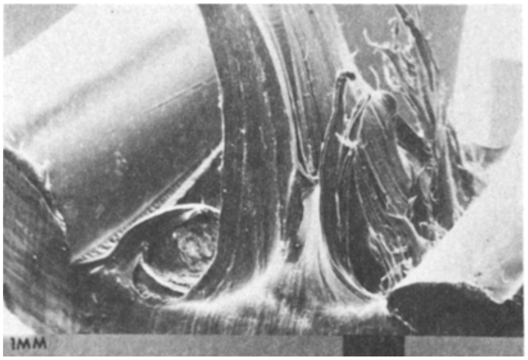

Figure 5 As welding conditions deviate from the optimum the amount of fibrillation visible on fracture surfaces increases (scanning electron micrograph). Bar = 1 mm.

The specimens which necked through the weld gave stress–strain curves of the type shown in Fig. 6. A small drop in the drawing load was observed as the neck passed through the weld. In this region the true stress was around 105 MPa compared with 94 MPa for the rest of the gauge length.

3.1.2. Muntz LDPE welds

Initially, the effect on the quality of the welds of varying the welding temperature whilst keeping the welding pressure constant at 0.1 MPa was examined. Temperatures in the range 463 to 518 K were examined and in all cases the welding factors and elongations were very low. Then the effect of varying the welding pressure at a constant welding temperature of 473 K was studied. Fig. 7 shows that a pressure in the region of 0.25 MPa is near the optimum. Consequently, the variation in weld quality with temperature was examined at a constant welding pressure of 0.25 MPa. These results are presented in Fig. 8. It can be seen that the optimum welding conditions are a welding temperature of 473 K with a welding pressure of 0.25 MPa and that even small deviations from these values produce large decreases in weld quality.

The stress–strain curves were similar to those for Aldyl 'A', but most Muntz LDPE specimens failed at the weld after drawing various amounts. The fracture surfaces always showed some fibrillation even when the weld was produced under optimum conditions. When the welding pressures were low, contraction cavities could be seen in the fracture surfaces and the welds were etched preferentially in chromic acid.

It is apparent that satisfactory welds cannot be produced in this material. The highest average welding factor obtained was 0.955 and only welds with welding factors between 0.99 and 1.0 are considered satisfactory. In addition there were considerable variations in welding factor and

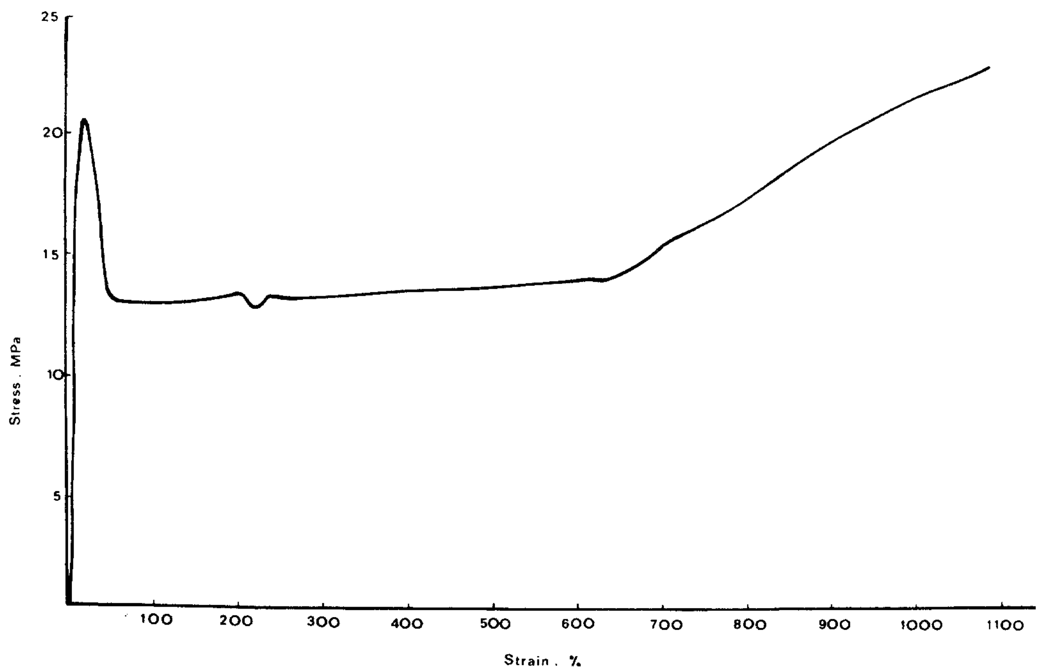

Figure 6 Typical stress–strain curve for a welded Aldyl 'A' specimen that has failed away from the weld.

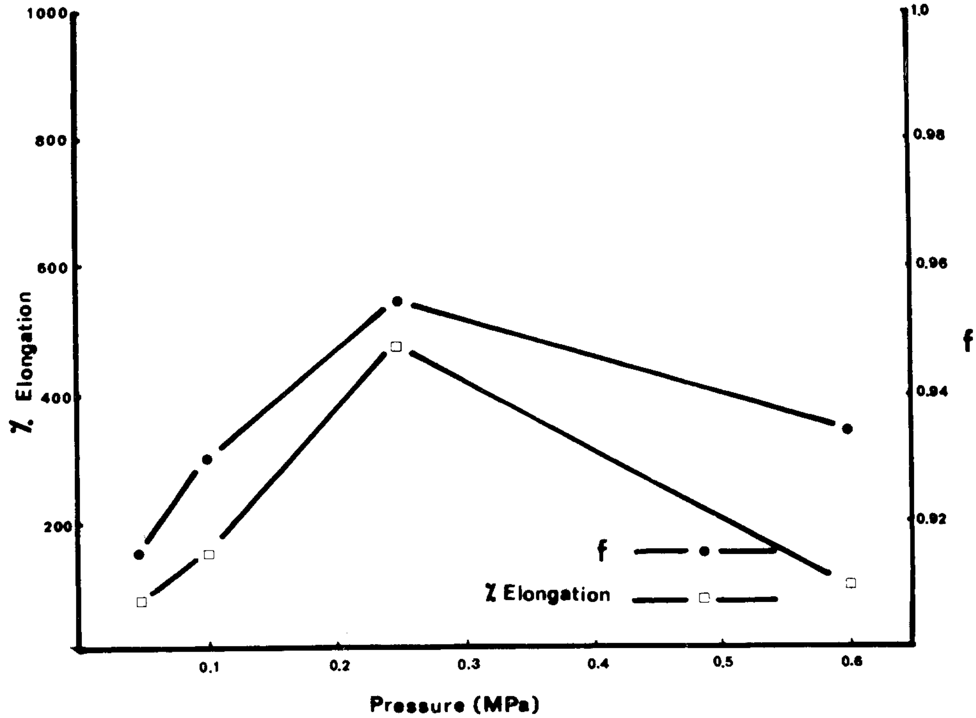

Figure 7 Graph of welding factor and percentage elongation versus welding pressure for Muntz LDPE welds; welding temperature constant at 473 K.

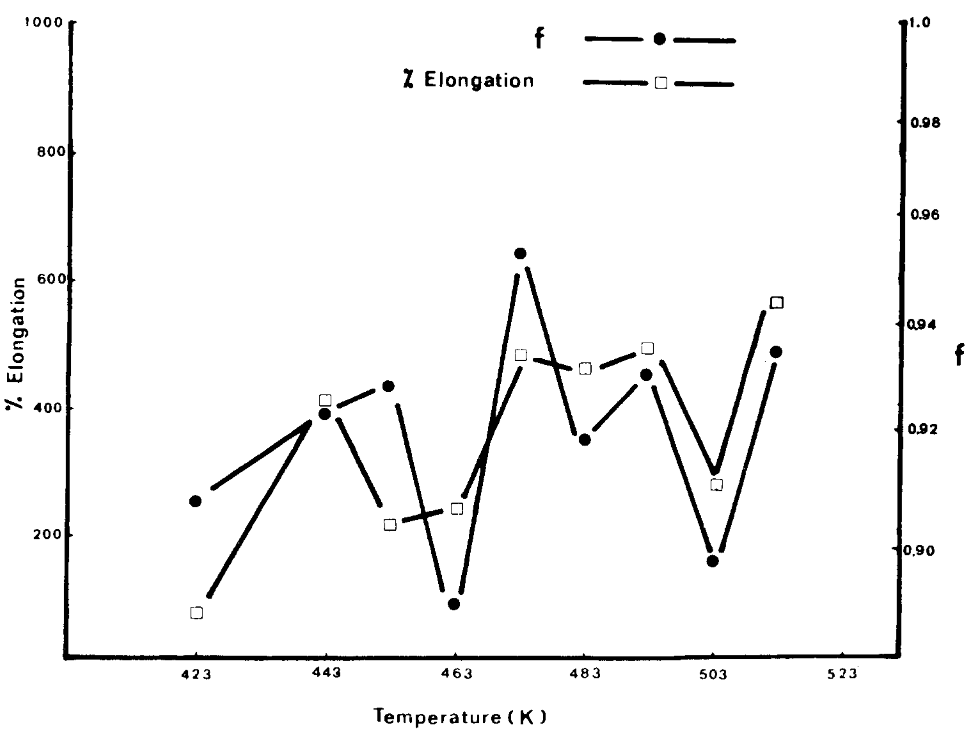

Figure 8 Graph of welding factor and percentage elongation versus welding temperature for Muntz LDPE welds; welding pressure constant at 0.25 MPa.

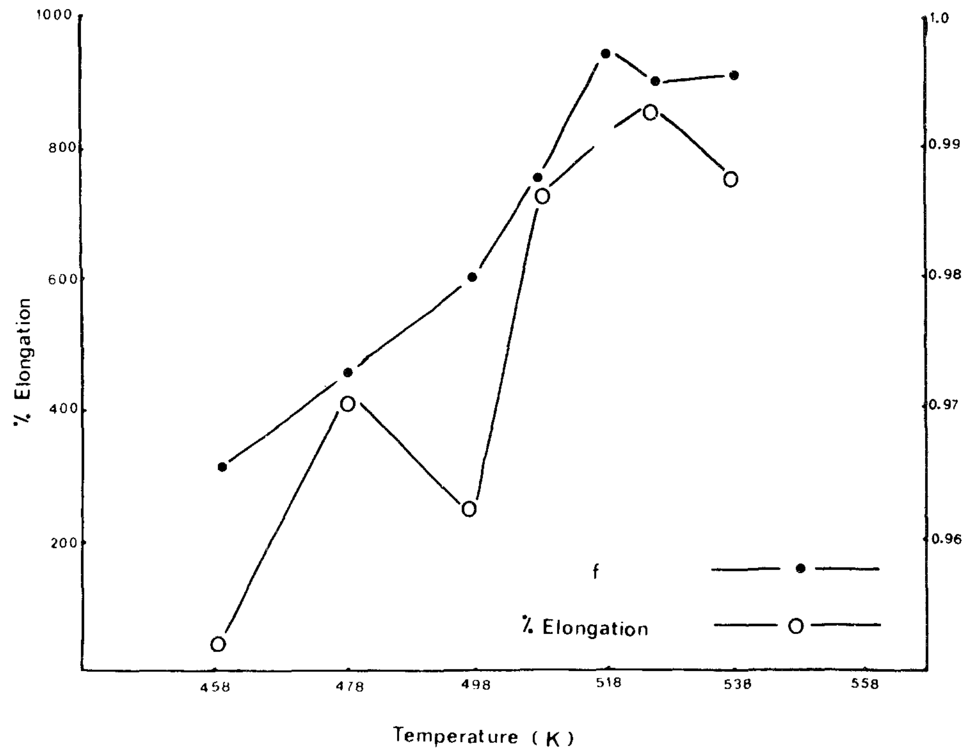

Figure 9 Graph of welding factor and percentage elongation versus welding temperature for Muntz HDPE; welding pressure constant at 0.1 MPa.

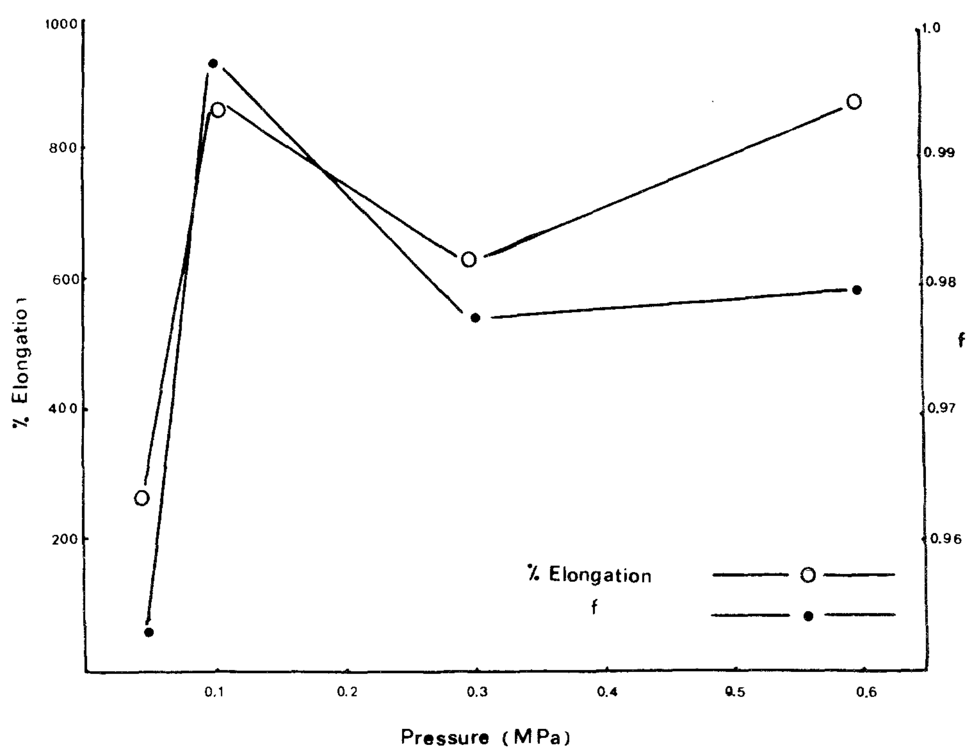

Figure 10 Graph of welding factor and percentage elongation versus welding pressure for Muntz HDPE; welding temperature constant at 518 K.

elongation between the four specimens from a good weld, indicating a variation in quality around the circumference. In view of these observations, no welds were made between this material and any others.

3.1.3. Muntz HDPE welds

Welds were again made over a range of temperatures and pressures and the results are presented in Figs. 9 and 10.

If the welding pressure is kept constant at 0.1 MPa, the quality of the welds improves with increasing welding temperature until a temperature of 518 K is reached. If the welding temperature is higher than 528 K, the quality is reduced. The effect of variations in welding pressure using a welding temperature of 518 K is shown in Fig. 10. The optimum welding pressure is 0.1 MPa and there is a sharp drop in weld quality at lower welding pressures when the welds become brittle. An increase in welding pressure up to 0.6 MPa has little effect.

The optimum welding conditions are, therefore, a welding temperature of 518 K and a welding pressure of 0.1 MPa. The fall in quality at low pressures is probably due to the very low melt flow index of Muntz HDPE. The viscosity of the molten polymer will be much higher than, for example, Aldyl 'A' PE and hence higher welding pressures will be required to obtain the complete contact necessary for good adhesion.

When the welding bead was machined off, the following types of fracture were observed. At low temperatures or pressures the fracture surfaces were flat and smooth and their appearance suggested very limited adhesion. At low welding pressures contraction cavities could be seen at the interface. For welds made under satisfactory conditions, fracture occurred at the end of the gauge length at elongations greater than 600%. The ductile fracture was typical of the unwelded material. The stress–strain curves from specimens with good welds showed the usual drop in load as the neck passed through the weld. The drop was larger than that found for Aldyl 'A' and was again accompanied by a slight decrease in cross-sectional area. But unlike Aldyl 'A', the true stress in this region fell slightly, from 89 to 86 MPa. We believe that this is due to frozen-in stresses present in Muntz HDPE welds. These stresses are relatively large due to the low melt flow index. This will be discussed further in another publication [8].

Specimens tested with the welding bead left on failed in the usual way, the fracture being initiated

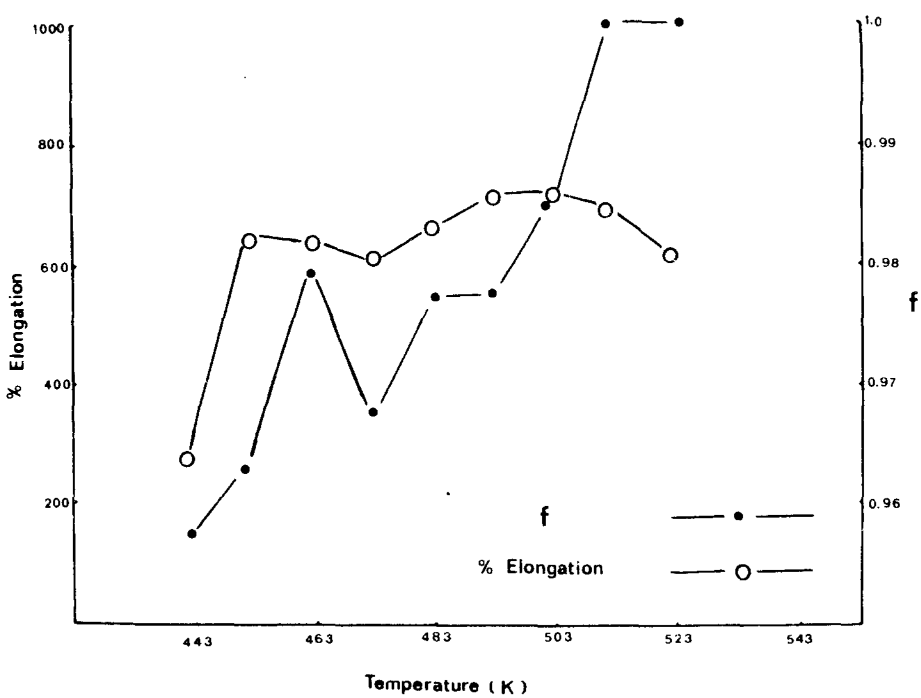

Figure 11 Graph of welding factor and percentage elongation versus welding temperature for Rigidex welds; welding pressure constant at 0.1 MPa.

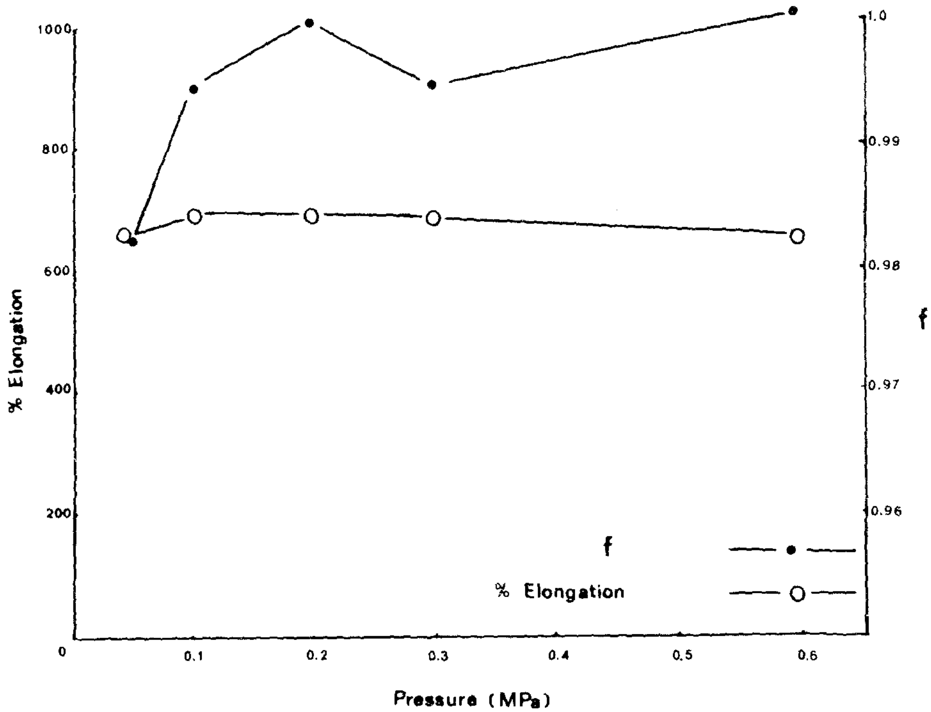

Figure 12 Graph of welding factor and percentage elongation versus welding pressure for Rigidex welds; welding temperature constant at 493 K.

by the notch between the bead and the gauge length. Once again, as the welding conditions deviated from the optimum the extent of fibrillation increased.

3.1.4. Rigidex PE welds

Welds were made over a range of temperatures and pressures as for the other materials. First, the variation of weld quality with welding temperature was observed using a constant welding pressure of 0.1 MPa. The results are presented graphically in Fig. 11 and show that acceptable welds may be produced in the temperature range 493 to 523 K, with the optimum welding temperature being about 503 K. Variations in welding pressure were then studied at a constant welding temperature of 493 K. Fig. 12 shows that good results are achieved over the pressure range 0.05 to 0.6 MPa but that the optimum welding pressure is probably in the range 0.1 to 0.3 MPa.

The stress–strain curves for specimens which necked through the welds showed the usual trough in the drawing load at the weld. In this region the true stress was calculated to be 80 MPa compared with 83 MPa elsewhere. This difference is much less than that for the Muntz material, probably because the residual frozen-in stresses are lower in Rigidex welds as this material has a higher melt flow index. The fact that less preferential etching is observed in Rigidex welds supports this view. The fracture behaviour was similar to that seen in Muntz HDPE. If the welding beads were removed, fracture occurred away from the welds. If the welding beads remained, fracture occurred at the welds and the amount of fibrillation increased as the welding conditions deviated from the optimum.

3.1.5. General comments

If the results for Aldyl 'A' PE, Muntz HDPE and Rigidex PE are compared, the influence of the melt flow index on the welding characteristics can be seen. As the value of the index decreases, the lower limit of the welding temperature and the optimum welding temperature are raised. Hence the available temperature range is narrower for materials of low MFI (melt flow index) such as Muntz HDPE. The welding pressure range is also reduced. Muntz HDPE welds deteriorate appreciably at low welding pressures and, to a lesser extent, if high pressures are used. Materials of higher MFI require less precise welding conditions and thus good welds are easier to produce. If the MFI is too high, however, this could have a deleterious effect on the long term stability and strength of the pipe.

The results for Muntz LDPE indicate how difficult it is to produce even moderate welds with this material. The welds could not be classified as satisfactory. Butt fusion welding cannot therefore be considered as a possible joining technique.

3.2. Results of tensile tests on welds between dissimilar materials

3.2.1. Welds between Muntz HDPE and Aldyl 'A' PE

A series of welds was made over a range of temperatures and pressures. The temperature range of 473 to 518 K was chosen because the optimum welding temperature for Aldyl 'A' was 473 K and that for the Muntz material 518 K. The pressure range chosen was 0.05 MPa to 0.6 MPa, even though the optimum welding pressure for both materials had previously been determined as 0.1 MPa, as it was felt important to observe the effect of variations in the welding pressure. The heating times in contact with the hot plate were also varied in an attempt to reduce the effects of heating one pipe above and the other below their optimum welding temperatures. Thus the Aldyl 'A' PE heating time was reduced from the normal value of 60 sec, whilst the heating time for Muntz HDPE was increased to more than 60 sec.

Six tensile specimens were cut longitudinally across each weld and the welding beads removed from four of these. Tensile tests were then carried out in the usual way. For those specimens from which the beads had been removed, yielding always occurred in the Aldyl 'A' half of the specimen. This was expected as the yield stress for Aldyl 'A' PE is 21 MPa compared with 25.5 MPa for the Muntz material. It means that the welding factor can no longer be used as a criterion of weld quality between materials of different yield stress. The welding factor is found to be constant and equal to 1.0 if based on the yield stress of Aldyl 'A'. It does indicate, however, that the strength of the weld is at least equal to the strength of the weaker component. The percentage elongation can still be used as a measure of weld quality, particularly when taken in conjunction with microstructural studies of the welds.

Fig. 13 shows that, if the welding pressure remains constant at 0.1 MPa, successful welds can be made in the temperature range 488 to 518 K, but at temperatures below 488 K the percentage elongation decreases fairly rapidly. Fig. 14 shows the effect of increasing the welding pressure at a welding temperature of 518 K. The percentage elongation reaches a maximum at a pressure of 0.1 MPa but only falls slightly even when the pressure reaches 0.6 MPa. However, if the pressure falls below 0.1 MPa there is a sharp drop in the percentage elongation. The same effect was observed for Muntz/Muntz welds but not for welds in Aldyl 'A'.

A further series of welds was made in which the heating time for one of the pipe materials was varied from the normal time of 60 sec. The

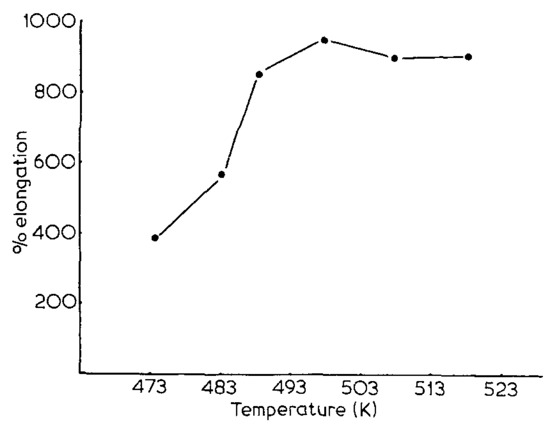

Figure 13 Graph of percentage elongation versus welding temperature for welds between Muntz HDPE and Aldyl 'A'; welding pressure constant at 0.1 MPa.

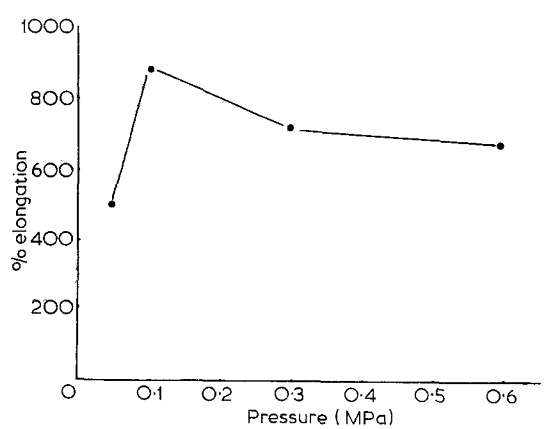

Figure 14 Graph of percentage elongation versus welding pressure for welds between Muntz HDPE and Aldyl 'A'; welding temperature constant at 518 K.

TABLE II The effect of using different initial heating times for the two pipes on the quality of Muntz HDPE/Aldyl 'A' welds

Specimen	Welding Temperature (K)	Welding Pressure (MPa)	Heating time for Muntz HDPE (sec)	Heating time for Aldyl 'A' (sec)	Average percentage elongations (4 specimens), welding beads removed (%)
E11	518	0.1	70	60	981
E12	518	0.1	80	60	876
E13	518	0.1	90	60	932
E14	518	0.1	60	50	958
E15	518	0.1	60	40	791
E16	498	0.1	80	60	840
E17	498	0.1	90	60	991
E18	473	0.1	90	60	714
E19	473	0.3	90	60	928

details of the welding conditions and the elongation values are given in Table II. The results here may be summarized as follows. Increasing the heating time for Muntz HDPE does not appear to result in any thermal degradation and, whilst the elongation values do not vary significantly, the microstructural observations indicate an improvement in weld quality. On the other hand, decreasing the heating time for Aldyl 'A' (specimen E15) results in a significant decrease in elongation and therefore in weld quality. The results also show that a lower than optimum welding temperature (473 K, specimens E18 and E19) may be compensated for by heating the Muntz HDPE for a longer time (90 sec), keeping the heating time for Aldyl 'A' at 60 sec, and raising the welding pressure from 0.1 to 0.3 MPa. Overall, there is a clear indication that an increase in the heating time for the Muntz HDPE is beneficial.

Two types of fracture behaviour were observed for those specimens tested with the welding bead removed. If the welding temperature or pressure was too low, fracture occurred at the weld and the elongation was less than 500%. Initially, yielding occurred in the Aldyl 'A' part of the specimen, but when the neck reached the weld, failure occurred without any yielding of the Muntz material. For welds made under or near optimum conditions, elongations of more than 700% were obtained and the neck again initiated in the Aldyl

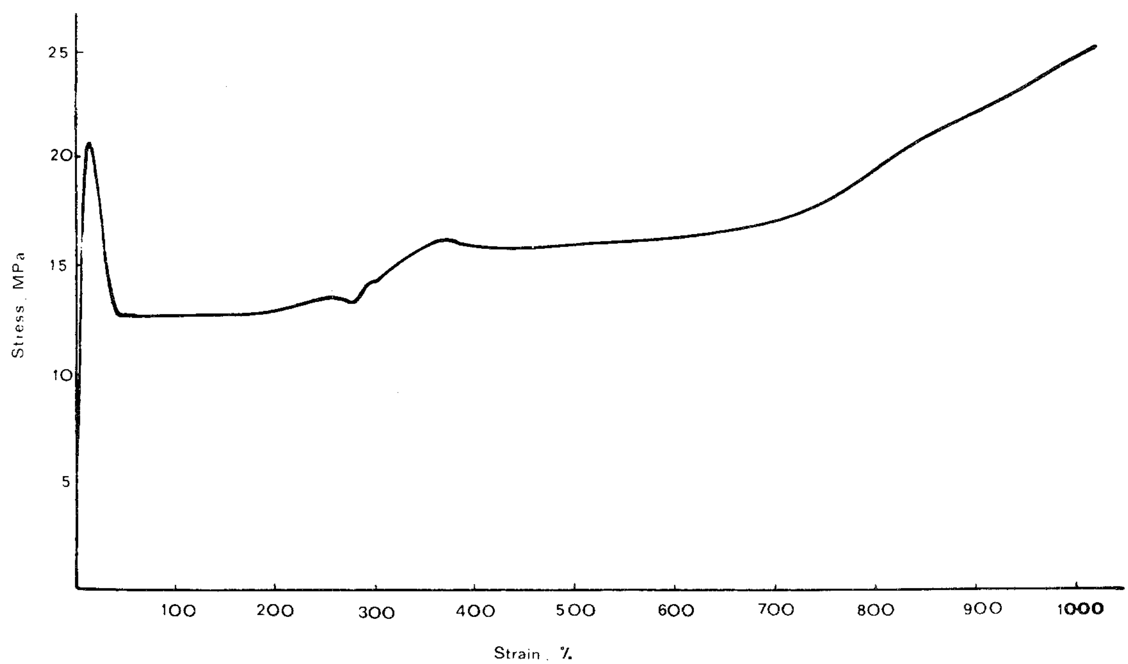

Figure 15 Stress–Strain curve for a specimen taken from a weld between Muntz HDPE and Aldyl 'A'. Failure occurred away from the weld.

Figure 16 At low welding temperatures, when specimens were tested with the welding bead remaining, a large amount of fibrillation was observed. Bar = 1 mm.

'A' and ran through the weld. Fracture finally occurred at the end of the gauge length in the Muntz HDPE. Although the yield stress is lower for Aldyl 'A' PE, the fracture stress is higher (25.5 MPa compared with 21 MPa for Muntz HDPE), so final fracture occurs in the Muntz material. A typical stress–strain curve is shown in Fig. 15. The initial yielding and subsequent drawing of the Aldyl 'A' can be seen, followed by the yielding and drawing of the Muntz HDPE. As the neck passes through the weld there is a slight drop in stress which may be associated with the actual weld interface.

Those specimens which were tensile tested with the welding beads on were found to be less sensitive to weld quality and, as in the case of welds between similar materials, failure was always initiated by the notch between the bead and the gauge length. However, the tensile results and the appearances of the fracture surfaces support the conclusions reached for those specimens for which the beads were removed. Poor welds were produced at low welding temperatures and at both extremes of welding pressure, and in these cases the incomplete adhesion at the interfaces was indicated by the fibrillar nature of the fracture surfaces (Fig. 16).

Sections from welds were etched in chromic acid to reveal the microstructures. The Aldyl 'A' PE etched more rapidly than the Muntz material and this made it impossible to etch the complete weld correctly. However, some useful information was obtained. Fig. 17 is a scanning electron micrograph of specimen E4 (welding conditions within the permissible ranges but no additional heating period for the Muntz pipe) etched for 12 h in chromic acid at 340 K. Two features are noteworthy: first the large size of the bead on the Aldyl 'A' (upper) half of the weld, and secondly the preferential attack at the interface. Both are undesirable. The large bead size could impede the flow of gas through the pipe and the attack at the interface implies poor adhesion. Most specimens exhibited microstructures similar to this. However, a rather better weld is indicated by Fig. 18 for specimen E13, where extra heating time before welding was given to the Muntz HDPE. The welding beads are more nearly equal in size and the attack at the interface is less pronounced.

3.2.2. Welds between Rigidex PE and Aldyl 'A' PE

As before, a series of welds was made over a range of temperatures and pressures and the duration of the heating time was also varied. The results previously obtained for welding each material to itself provided a good indication of the range in which satisfactory welds could be expected.

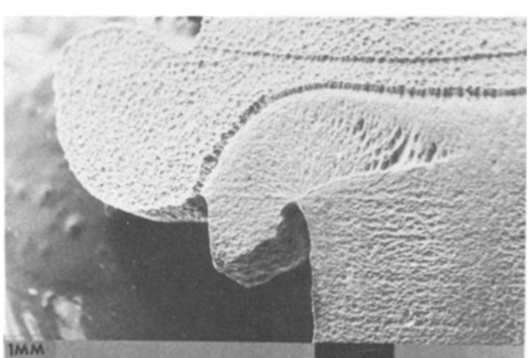

Figure 17 Specimen E4 etched in chromic acid. The upper half of the weld is Aldyl 'A'. There has been preferential attack at the interface and the welding bead is very uneven (scanning electron micrograph). Bar = 1 mm.

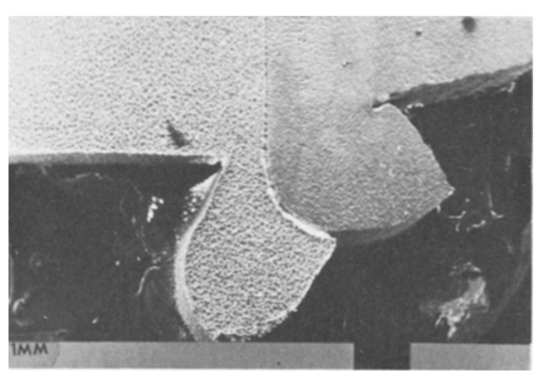

Figure 18 Specimen E13 etched in chromic acid. The right-hand side of the weld is Muntz HDPE. A longer heating time for Muntz HDPE reduces the amount of interfacial attack and results in a more even welding bead (scanning electron micrograph). Bar = 1 mm.

Once again, the Aldyl 'A' PE had the lower yield stress and the welding factor could not be used as a criterion of weld quality.

Fig. 19 shows the effect on percentage elongation of varying the welding temperature using a constant welding pressure of 0.1 MPa, and Fig. 20 illustrates the effect of varying the welding pressure. It is apparent that good welds are obtained in the temperature range 493 to 523 K and in the pressure range 0.05 to 0.3 MPa. There is a significant drop in weld quality at low welding temperatures and at high welding pressures. Table III shows the effect of using different heating times for the two materials, all other variables remaining constant. The sizes of the welding beads are made more nearly equal if either the heating time for the Rigidex PE is increased or the heating time for the Aldyl 'A' is reduced; in both cases high elongation values indicate good welds.

The fracture behaviour of specimens tested with the beads removed was similar to that of specimens from welds between Muntz HDPE and Aldyl 'A'. If the welding conditions were far removed from the optimum, fracture always occurred at the weld and the elongations were less than 464%. Yielding occurred in the Aldyl 'A' half and the neck extended until it reached the weld. The surface showed some fibrillation, indicating poor adhesion (Fig. 21). For good welds, with elongations of more than 590%, the neck ran through the weld and the Rigidex PE was also drawn. Failure finally occurred at the end of the gauge length in the Rigidex material. The stress–

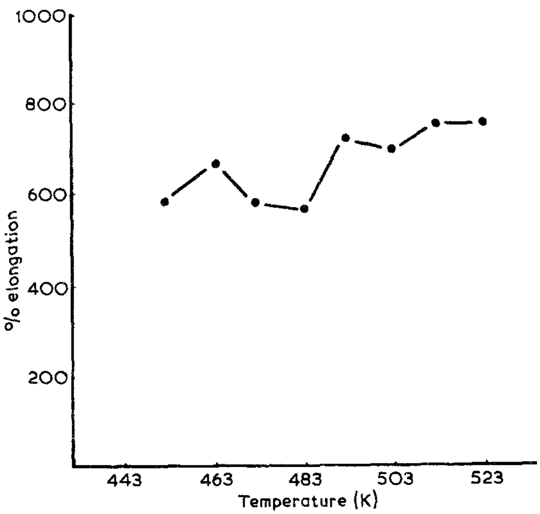

Figure 19 Graph of percentage elongation versus welding temperature for welds between Rigidex and Aldyl 'A'; welding pressure constant at 0.1 MPa.

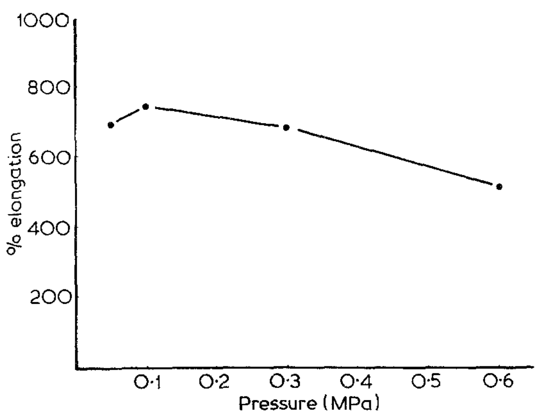

Figure 20 Graph of percentage elongation versus welding pressure for welds between Rigidex and Aldyl 'A'; welding temperature constant at 503 K.

Figure 21 For specimens welded away from the optimum conditions failure occurred at the weld with some fibrillation (scanning electron micrograph). Bar = 1 mm.

TABLE III The effect of using different initial heating times for the two pipes on the quality of Rigidex/Aldyl 'A' welds

Specimen	Welding Temperature (K)	Welding Pressure (MPa)	Heating time for Rigidex PE (sec)	Heating time for Aldyl 'A' PE (S) (sec)	Average percentage elongation (4 specimens) welding beads removed
F13	513	0.1	70	60	884
F14	513	0.1	80	60	722
F15	513	0.1	90	60	711
F16	513	0.1	60	50	789
F17	513	0.1	60	40	767

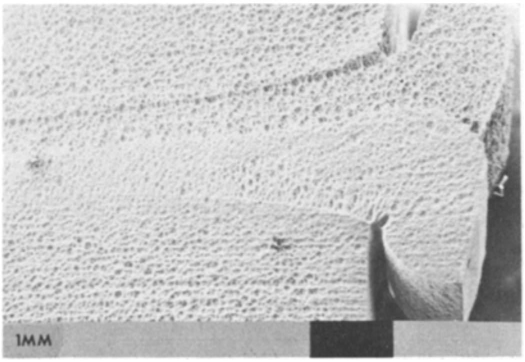

Figure 22 Specimen F15 etched in chromic acid. The lower half of the weld is Rigidex PE. This specimen was welded under suitable conditions and no attack at the interface is visible. The welding bead is uniform (scanning electron micrograph). Bar = 1 mm.

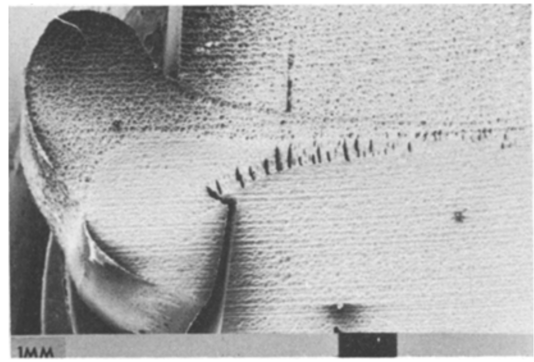

Figure 24 Specimen F9 etched in chromic acid. The lower half of the weld is Rigidex. High welding pressure results in a heavily etched zone 3 in Rigidex, some interfacial attack, and a narrow weld region (scanning electron micrograph). Bar = 1 mm.

strain curves obtained from good welds showed the same effects as those seen for the Muntz HDPE/Aldyl 'A' system.

The results obtained from specimens tested with the welding beads left on were largely insensitive to variations in the welding conditions. The fracture surfaces showed an increase in fibrillation and sometimes cavitation if the welding conditions were not correct.

Etching specimens from Aldyl 'A'/Rigidex welds was reasonably successful because both materials were etched at about the same rate. An etching time between 8 and 12 h in concentrated chromic acid at 340 K produced good results. Fig. 22 shows the result of etching specimen F15. There is no preferential attack at the interface and the welding beads are approximately equal in size due to the extra heating time for the Rigidex PE.

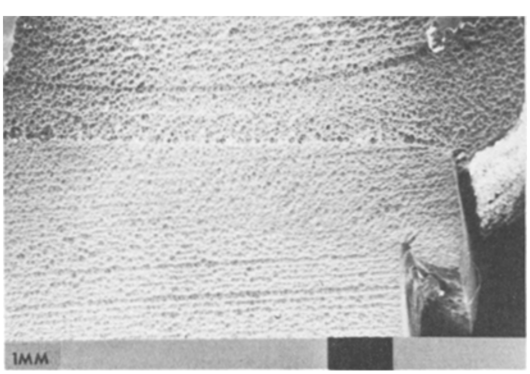

Figure 23 Specimen F12 etched in chromic acid. The lower half of the weld is Rigidex. Due to the use of a low welding pressure some etching of the interface has taken place (scanning electron micrograph). Bar = 1 mm.

As also observed in Aldyl 'A'/Muntz welds, each material exhibits its own characteristic microstructure which is not affected by the other.

Zone 3 in the Rigidex part of the weld (Fig. 22) is less heavily etched than usual. This may be because there is less flow than usual in this part of the weld: the Aldyl 'A' is at a temperature well above its normal welding temperature and consequently most of the flow probably occurs in this material. This is indicated by the fact that the weld region in Aldyl 'A' is slightly thinner than in Rigidex. Another possibility is that, because of the unusually long heating period, the viscosity of the Rigidex melt is correspondingly reduced and only a small amount of frozen-in stress is produced in the weld. We have shown elsewhere [8] that frozen-in stress causes preferential etching.

Fig. 23 shows the microstructure of a specimen where the welding pressure is too low. If, on the other hand, the welding pressure is too high (Fig. 24) a pronounced zone 3 is formed in the Rigidex half due to the excessive flow, and most of the molten polymer is squeezed into the beads, resulting in a narrow weld and large beads. Preferential etching of the interface also occurs.

Welds between Rigidex PE and Aldyl 'A' could also be examined using transmission optical microscopy, for both components were yellow and thin transparent sections could be cut. This allowed the flow patterns visible in the Rigidex part of the weld to be studied. Fig. 25 is a micrograph of a specimen welded under optimum conditions, i.e. there is no preferential etching at the interface and all the tensile tests gave large elongations. The Aldyl

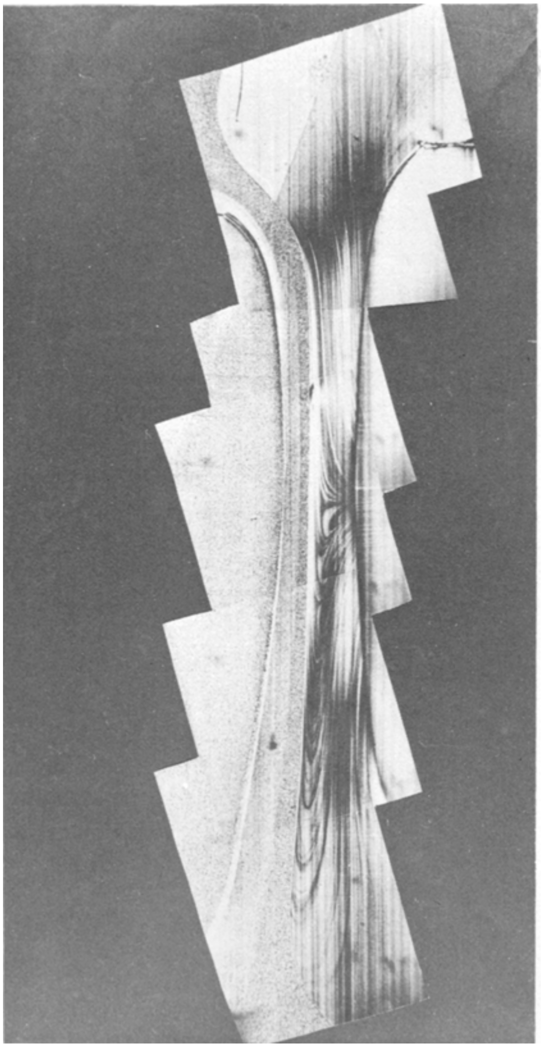

Figure 25 This shows the appearance of a weld made at near optimum conditions (transmission optical micrograph). × 12.

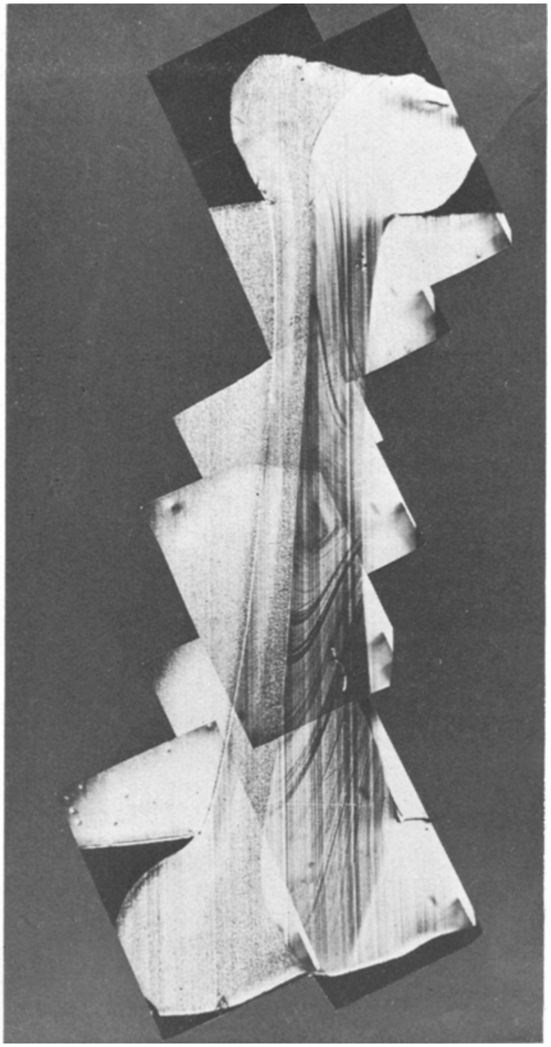

Figure 26 This shows the appearance of a weld made using a welding pressure which is too low (transmission optical micrograph). × 12.

'A' side of the weld is on the left and has its usual appearance. The interface is similar to that found previously in Aldyl 'A' welds, i.e. a chill skin containing crystallite nuclei. The Rigidex portion shows the flow patterns discussed elsewhere [5] but now there is no "dead-zone". Indeed, the flow lines are densely packed near the interface. This could explain why the interface appears to be more readily etched than in similar welds in either component material, particularly at slightly higher pressures. It also may explain why many of the welds between Aldyl 'A' and Muntz HDPE appeared to be preferentially etched in this way. Muntz HDPE having a very low melt flow index is more likely to contain residual stresses than Rigidex, though these would be reduced somewhat by the extra period of heating which would lower the melt viscosity. It was not possible to see any flow lines in the Muntz HDPE as this was black.

The reason for the presence of these flow lines near the interface is not clear. It may be that the Aldyl 'A' melt, which will flow quite readily at this temperature, tends to drag the Rigidex along with it. Alternatively, it may be that the more fluid Aldyl 'A' is rapidly squeezed from the weld and then what deformation occurs in the more viscous Rigidex melt must be accommodated in a relatively small region, resulting in more severe flow than usual.

Fig. 26 is a micrograph of a specimen made using a welding pressure of 0.05 MPa. The Aldyl 'A' side of the weld (on the left) is unchanged but now a "dead" zone is present in the Rigidex material. The relative widths of the two sides of the weld and the small number of flow lines visible in the Rigidex PE indicate that the amount of flow in the Rigidex melt has been less than that for Aldyl 'A'. This specimen was preferentially etched at the interface and though the lack of adhesion cannot be detected directly from this micrograph, it can be inferred from the flow pattern in the Rigidex which indicates little flow and therefore little pressure. As the welding pressure is increased up to a value of 0.6 MPa the flow lines in the Rigidex become denser and the weld narrower.

The effect of welding temperature on the appearance of optical micrographs was very slight until relatively low temperatures were reached and there was little flow in the Rigidex PE. Then the welds were very similar to that shown in Fig. 26.

4. Discussion

Using tensile tests, optimum welding conditions have been found for Muntz, Rigidex and Aldyl 'A' polythenes for welds made between pipes of the same material. The welds have short term strengths equal to those of the unwelded materials. These conditions are summarized in Table IV and it can be seen that the optimum welding pressures are about the same for all these materials but the welding temperatures vary. This is a reflection of the different melt flow indices. It has been found that welding temperatures below the optimum are much more harmful than those above, at least in the short term.

It has been shown that satisfactory welds cannot be made with Muntz LDPE. The highest welding factor obtainable was 0.95 and all the welds were brittle. Butt fusion welding must therefore be discounted as a joining technique. These results indicate the harmful effects that could result if low density fractions are present in polyethylene pipes.

Tensile tests can be used to assess the quality of welds between dissimilar materials and to observe the effect of variations in welding parameters, providing the welding bead is removed. The welding factor is no longer a useful criterion of weld quality because yielding always occurs in the weaker material and the welding factor defined in terms of the weaker material is always unity. However, the fact that fracture occurs away from the weld shows that this is at least as strong as the weaker component. The quality of the weld can be assessed in terms of the percentage elongation at fracture, particularly when consideration is also given to the weld microstructure. In this respect, when the weld is etched in chromic acid there should be no preferential etching at the interface as this indicates a lack of adhesion.

Good welds are possible between Muntz HDPE and Aldyl 'A' polythene, and between Rigidex and Aldyl 'A'. As the Muntz/Aldyl 'A' system provides the greatest difference in melt flow indices, it is expected that no difficulty will arise in welding other materials within this range. The optimum welding pressures are very similar for all three materials so the problem is essentially one of determining optimum welding temperatures and heating times.

TABLE IV Summary of optimum welding conditions

Materials	Optimum Welding Temperature (K)	Optimum Welding Pressure (MPa)	Permissible Range of Welding Temperature (K)	Permissible Range of Welding Pressure (MPa)
Muntz LDPE	473	0.25	Small deviations from the optimum values produce large decreases in weld quality	
Muntz HDPE	518	0.1	508–538	0.1–0.6 Welding pressures lower than 0.1 MPa must be avoided
Rigidex	503	0.1–0.3	493–523	0.05–0.6
Aldyl 'A'	473	0.1	453–518	0.1–0.6
Muntz HDPE/Aldyl 'A'	508	0.1	488–518 (An additional 30s heating period for the Muntz pipe is beneficial	0.1–0.3 Welding pressures lower than 0.1 MPa must be avoided
Rigidex/Aldyl 'A'	503	0.1	493–523	0.05–0.3

The best results (see Table IV) are achieved by using welding conditions appropriate for the material with the lower melt flow index. The other component will then be welded at a temperature higher than its optimum but this does not appear to be harmful, at least in the short term. If the material of lower melt flow index is heated for a longer time than usual before welding, whilst the other material is not, the welding bead becomes nearly symmetrical. This produces a slightly larger bead than normal but there are no other detrimental effects.

In conclusion, it has been shown that by using the correct conditions it is possible to achieve welds between polyethylene pipes of widely different melt flow index which are, in the short term at least, as strong as the weaker component. However, there is a need for more long-term testing.

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