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The use of tensile tests to determine the optimum conditions for butt fusion welding certain grades of polyethylene, polybutene-1 and polypropylene pipes

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The optimum conditions for butt fusion welding certain grades of polyethylene, polybutene-1 and polypropylene pipes have been determined on the basis of tensile test results. The effect of the welding bead has been discussed and the conclusion reached that removal of the welding beads enables a clearer picture to be obtained of weld performance when this is judged from a tensile test. An examination of the microstructures of each weld has shown the presence of different zones. The importance of these zones is discussed in relation to the short- and long-term strength of the welds.

1. Introduction: the butt-welding process

In the butt-welding process, the pipe ends to be joined are cut so that they are smooth and plane and wiped with an acetone swab to remove any grease. The ends are brought up to a Teflon-covered heating plate and heated for a short time. The heating plate is then removed and the two ends pushed together and held in contact. A small bead forms on the inside and outside surfaces (see the section shown in Fig. 1) thereby indicating overall melting and some flow at the surfaces joined.

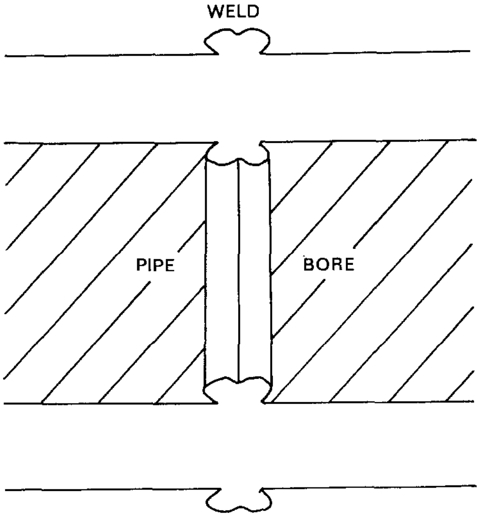

Figure 1 Section through a butt-welded pipe.

The welding process can be broken down into the following stages each of which must be carried out correctly if a satisfactory weld is to be obtained.

(i) *The preparation of the ends to be welded.* If the pipe comes in long lengths it is easy to clamp the pipes on to the welding machine so that the two lengths of pipe lie in the same plane, but if the pipe comes in coils this becomes more difficult. Jointing is facilitated if the curvature of the second coil is reversed, with respect to the first coil, so as to form an 'S' bend [1]. The wall thickness of plastic pipes tends to vary round the circumference and welding slightly different wall thicknesses together will cause problems which could result in premature failure. To overcome this difficulty it is best to clamp lengths of pipe together so that the manufacturers' markings on the outer surfaces are aligned.

A square, flat, surface finish is essential and it is important to have it free from grease and dirt. Therefore, premachining should, if possible, be carried out immediately prior to welding. In principle premachining can be carried out by means of various cutting tools, but in practice only two-sided smoothing planes are used. The plane is inserted on the welding machine between the two pipe ends. The main advantage of this is that both pipe ends can, simultaneously, be peeled by means of parallel knives. This ensures that the pipe ends are flat and square to each other, so that when they are pushed together the gap between them does not exceed 0.3 mm. In the laboratory, where shorter lengths of pipe are welded together, the machining of the pipe ends can be carried out on a lathe to achieve the same effect. After machining, the pipe ends are wiped with a swab of acetone to remove any grease or dirt.

(ii) *The heating of the ends to be welded.* The heating plate is set so that its surface reaches the required temperature and the pipe ends are then brought up to it and heated for a short time. The correct welding temperature varies not only from one polyolefin to another, but also between different grades of the same polyolefin.

Too high a welding temperature can result in the generation of large shrinkage stresses when the pipe cools down. If the welding temperature is too low, there will be insufficient heat to fuse the pipe ends together. The welding temperature is, of course, related to the time of application of this temperature.

The heating time depends upon the diameter and wall thickness of the pipe, and also upon the weather conditions if welding takes place in the field. Longer heating times are required if air temperatures are low or there are strong winds. If the heating time is too short, only a thin layer of polymer becomes molten and complete fusion is unlikely to occur: such welds are prone to cracking. If the heating time is too long, thermal degradation of the polymer may occur and this again leads to a poor weld.

In practice, the heating is carried out in two stages. During the first stage the pipe ends are brought up to the heating plate under a very slight pressure, usually of the order of 0.02 MPa, and held there until a bead of about 1 mm diameter begins to form. The pressure is then released although the heating is continued for a further period of time. The initial pressure is required to ensure complete surface contact between the pipe ends and the heating plate. Once this has been established, the pressure is released so as to keep the diameter of the bead to a minimum.

(iii) *The removal of the heating plate.* After the pipe ends have been heated for a sufficient time, the heating plate is removed extremely carefully so as not to damage them. The interval between the times when the heating plate is removed and when the pipe ends are pushed together (known as the change-over time) must be as short as possible to prevent the fall in temperature at the pipe ends from being too large. It is desirable to have a change over time of less than 3 sec.

(iv) *The welding and cooling under pressure.* After the removal of the heating plate, the pipe ends are pushed together with the desired welding pressure. This pushes molten material out from the pipe ends resulting in the formation of a welding bead on the inside and outside surfaces. Too high a pressure will expel too much molten material from the welded region. With too low a pressure, cavities will form at the weld interface due to shrinkage on cooling. An experienced welder can determine the correct welding pressure by simply watching the formation of the welding bead when the pipe ends are pushed together. This pressure must be maintained for a sufficient length of time to ensure that the welded region has cooled down enough to prevent the formation of any shrinkage cavities.

(v) *Welding parameters.* The welding conditions may, therefore, be described in terms of the following parameters:

T_W, the welding temperature (the temperature at the surface of the heating plate);

t_p, the heating time with pressure applied to the pipe ends;

t_q, the heating time with no pressure applied to the pipe ends;

p_W, the welding pressure used to push the pipe ends together after heating;

t_W, the time of application of the welding pressure.

2. Methods for evaluating weld strength

All welds should be examined visually to check that the bead is the correct shape and size, and that no misalignment of the pipes has occurred. Unfortunately, however, it is possible to produce welds which look perfectly satisfactory but which fracture easily in a brittle fashion.

Destructive testing enables one to obtain an estimate of either the life expectancy or the strength of the welded joint. The two commonest types of test are tensile tests and stress rupture or burst tests.

If tensile tests are used, a welding factor, f, can be defined [2]:

$$f = \frac{\text{yield strength of welded material}}{\text{yield strength of basic material}}\,.$$

Tensile specimens are cut across the welded

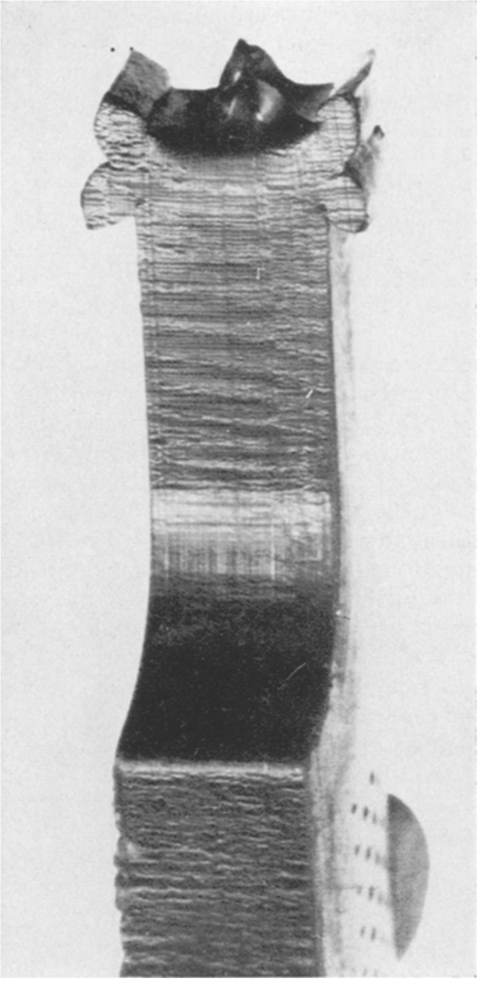

Figure 2 Fracture of a Plastronga PE weld caused by a tensile stress. Failure has been initiated by the notch between the welding bead and the gauge length.

region and the usual procedure is to carry out a tensile test with the welding bead left on (see for example Fig. 2). Fracture is almost always initiated by the notch between the welding bead and the gauge length. In practice the welding bead will, of course, remain on pipes fusion-welded together.

The most popular testing method for plastics pipes is the stress rupture test [3]. Short lengths of pipe are sealed and subjected to an internal pressure, and the time to failure noted. This time to failure is reduced if the test is carried out at an elevated temperature (usually 353 K), but then there is the question of whether the increased temperature has some effect on the microstructure and, hence, on the mechanical properties of the material. It is the authors' opinion that it is dangerous to predict life expectancies for welded plastic pipes on the basis of stress rupture tests at elevated temperatures. Stress rupture tests will, however, indicate the quality of a given weld, because the time to failure of the welded pipe may be compared with that of the basic pipe.

3. Microstructural changes caused by welding

It is unlikely that the microstructure in the weld will be the same as that of the rest of the material in view of the large thermal gradients caused by the welding process. Certain microstructural features of polyethylene welds have been identified by Menges and Zohren [2], and by Barber and Atkinson [4] who explain the nature of the different zones found in terms of the flow of material and the consequent temperature distribution. With polyethylene and polybutene-1 welds, a columnar zone is formed which could have serious effects on the long term performance of the plastic pipe (Fig. 3).

4. Experimental

4.1. The welding machine

In our experiments a Bielomatik welding machine (Model HV 493) supplied by Bielomatik Lenze Company, West Germany, was used. The temperature at the surface of the heating plate was determined accurately using a thermocouple. The welding pressures quoted are calculated from the welding forces applied, which may be read off the gauge on the instrument, and the areas of the pipe ends.

Before welding, the pipe ends to be joined were turned until they were smooth and plane and wiped with an acetone swab to remove any grease.

4.2. The materials studied

The following materials were used:

1. Plastronga polyethylene of outer diameter 60.1 to 60.6 mm and wall thickness 6.6 to 7.3 mm. This was supplied by Yorkshire Imperial Plastics, Leeds, UK.
2. Aldyl "A" polyethylene of outer diameter 60.2 mm and wall thickness 5.8 mm. This was supplied by Dupont Co UK Ltd, Derbyshire, UK.
3. Vestolen BT 1711 polybutene-1 of outer diameter 63.5 mm and wall thickness 3.5 mm.

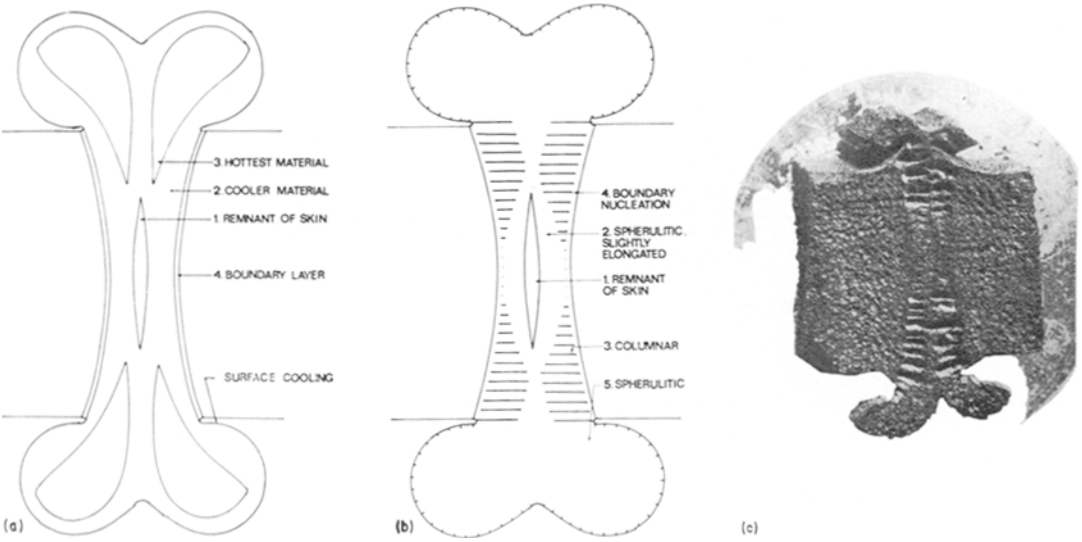

Figure 3 (a) Diagram showing the distribution of hot material in a section through the pipe wall during the final stage of welding. (b) The expected microstructures. (c) The actual microstructures revealed by chromic acid etching in a section through the pipe wall of a Plastronga PE weld.

TABLE I Properties of materials used

Property	Plastronga	Aldyl "A"	Vestolen BT 1711	Propathene GSE 108	Propathene 112/00/Grey 9897
Density (kg m^{-3})	0.957×10^3	0.939×10^3	0.925×10^3	0.904×10^3	0.921×10^3
Yield strength MPa	23.8	18.4	20.8	28.0	25.0
Elongation %	790	1030	190	870	840
Softening point (K)	398	388	398	417	417
Melt flow index	0.05[c]	1.9[a]	0.5[b]	0.8[a]	0.5[a]

[a] Tested according to ASTM D1238-65T
[b] Tested according to DIN 53 735
[c] Tested according to method 105C of BS 2782

This was supplied by Polva Nederland, Enkhuizen, Holland.

4. Propathene GSE 108 polypropylene of outer diameter 60.1 mm and wall thickness 5.8 mm. This was supplied by Paragon Plastics, Doncaster, UK.

5. Propathene 112/00/Grey 9897 heat-stabilized polypropylene of outer diameter 48.3 mm and wall thickness 5.4 mm. This was supplied by Paragon Plastics, Doncaster, UK.

Table I shows some of the more important properties of these materials.

4.3. The tensile test procedure

Tensile test pieces were cut from the welded pipe using a high speed, air driven router. A 25.4 mm gauge length was used and the breadth was governed by the thickness of the pipe wall. It was possible to use the router to machine off the welding bead. After machining, the surfaces were polished with fine emery paper. Tensile tests were carried out on an Instron testing machine at room temperature. The cross-head 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}.

5. Results

5.1. Plastronga polyethylene

A series of welds was made over a wide range of welding temperatures (see Table II). The welding pressure and the heating times were kept constant except for the weld AF made at the lowest temperature, when a slightly longer heating time was used to ensure that a welding bead of reasonable size was obtained. From each weld

TABLE II Welding factors and elongation values for Plastronga PE welds made over a range of welding temperatures. For all welds except AF, $t_p = 20$ sec, $t_q = 35$ sec, $P_w = 0.1$ MPa, $t_w = 180$ sec. For AF, $t_p = 35$ sec, but t_q, P_w and t_w were as listed above

		Welding bead machined off		Welding bead left on	
Welds	T_w (K)	Average welding factor, f (4 tensile specimens)	Average elongation to break (%) (4 tensile specimens)	Average welding factor, f (2 tensile specimens)	Average elongation to break (%) (2 tensile specimens)
AA	533	1.00	695	0.99	397
AB	518	0.99	600	0.99	388
AC	508	1.00	728	1.00	340
AD	498	0.98	660	0.98	375
AE	488	0.97	668	0.98	460
AF	458	0.95	481	0.98	253

six tensile specimens were cut and from four of these the welding beads were removed. The welding factors determined at a given temperature varied little (less than 2%), but the elongations to break varied to the extent of ± 20% of the average values quoted. Even so, these elongations to break were sufficiently reproducible to indicate trends caused by the variation in the welding temperature.

Table II shows that at a temperature of 508 K the welding factor and the elongation to break have reached maximum values for those tensile specimens where the bead has been machined off. When the welding bead is left on, the welding factor is less influenced by the welding temperature. It appears that the increased thickness of the tensile specimen due to the bead masks any slight weakness in the weld. This weakness, at the lower welding temperatures, shows up in a lower welding factor when the bead is machined off. With the bead on, the elongation values are much smaller. Necking always occurs away from the weld, but failure is initiated by the notch between the welding bead and the gauge length (Fig. 2), so necking cannot continue through the weld. Thus, welding factors and elongation values obtained from tensile tests with the beads left on the specimens do not provide much information on the quality of the welds. The results obtained when the beads are machined off suggest that the optimum welding temperature is 508 K.

A second series of welds was made varying the other welding parameters. The results are presented in Table III. It can be seen that the welding factor alone is not a good guide to weld quality. Specimens AG, AI, AK and AL have good welding factors but their elongation characteristics are unsatisfactory. Unless the elongation was greater than 570%, failure occurred at the weld and the weld was deemed unsatisfactory. Specimens AH and AJ show that

TABLE III Welding factors and elongation values for Plastronga PE welds made over a range of welding conditions

						Welding bead machined off	
Welds	T_w (K)	t_p (sec)	t_q (sec)	P_w (MPa)	t_w (sec)	Average welding factor (4 tensile specimens)	Average elongation to break (%) (4 tensile specimens)
AG	548	20	35	0.3	180	0.99	339
AH	458	35	35	0	0	0.82	43
AI	508	20	35	0.1	180	0.99	362
AJ	508	20	35	0	0	0.89	31
AK	508	20	0	0.1	180	1.00	88
AL	508	20	120	0.1	180	1.01	442
AM[a]	508	20	35	0.1	180	0.94	83
AN[b]	508	20	35	0.1	180	1.00	659
AO[c]	508	20	35	0.1	180	0.96	58

[a] This specimen was rapidly cooled after welding

[b] This specimen was heated up to 393 K for 22 h before welding

[c] This specimen was welded with cylindrical metal inserts to prevent an inside bead

if the welding pressure is zero, or very low, with the molten pipe ends held gently in contact, there is a large fall in both the elongation at break and the welding factor. If the weld is cooled rapidly after welding, by immersion in cold water, there is a reduction in weld quality (specimen AM). If the pipes to be welded are preheated and maintained at a temperature of 393 K for 22 h before welding, and then welding is carried out using the optimum conditions, a good weld is obtained. The purpose of this experiment was to prevent the large temperature gradients which usually arise at the pipe ends during welding. These welds had different microstructures to those seen normally, there being no columnar zone 3. However, we are not yet certain that zone 3 is necessarily a weakening feature and preheating prior to welding would obviously not be a practical proposition in the field. If tight-fitting metal inserts are placed inside the ends of the pipes before welding, to prevent the formation of an inside bead, there is a large drop in welding factor and in elongation. The metal inserts probably acted as heat sinks and prevented complete adhesion at the inside edges.

These results suggest that the optimum welding conditions for Plastronga polyethylene are: $T_W = 508$ K, $t_p = 20$ sec, $t_q = 35$ sec, $P_W = 0.1$ MPA, $t_W = 180$ sec.

Examination of the fracture surfaces showed that when the bead is left on, failure is initiated by the notch between the welding bead and the gauge length, and a fracture surface similar to that in Fig. 2 is observed when optimum welding conditions are used. When the weld is made under optimum conditions and the bead removed, failure occurs at the end of the gauge length (Fig. 4) after necking has occurred through the weld. When welds are made under non-optimum conditions, the fracture surfaces show weakening features such as blow holes, caused by localized shrinkages on rapid cooling, or voids indicating incomplete adhesion due to too low a welding temperature.

5.2. Aldyl "A" polyethylene

As for Plastronga PE, a series of welds was made in which the welding parameters were varied systematically, and each weld was tensile tested. The optimum welding conditions were found to be as follows:

$$T_W = 443\text{ K},\ t_p = 20\text{ sec},\ t_q = 30\text{ sec},\ P_W = 0.1\text{ MPa},\ t_W = 180\text{ sec}.$$

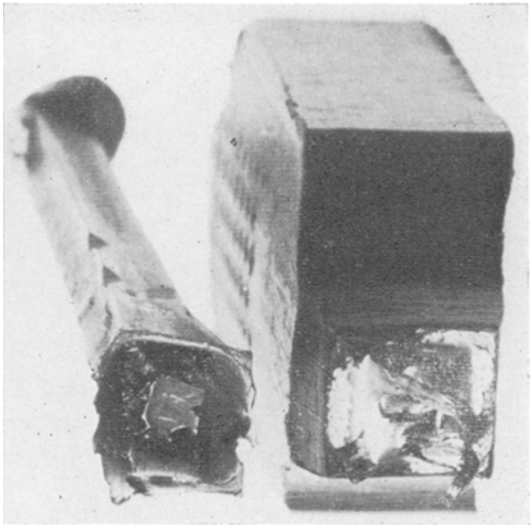

Figure 4 With the welding beads machined off, failure occurs at the end of the gauge length for Plastronga PE specimens welded using optimum conditions.

The optimum welding temperature was lower than for Plastronga PE, presumably because of the higher melt flow index, and the value of the welding temperature was not so critical. Acceptable welds were obtained in the welding temperature range 433 to 488 K, although the optimum temperature was 443 K. It was found that it was important to have a sufficiently long heating time and that it was better to have too long rather than too short a heating time. This observation also applied to Plastronga PE. Reducing the welding pressure did not have as large an effect as for Plastronga PE, again presumably because Plastronga PE has a much lower melt flow index. All the Aldyl "A" PE welds had longer elongation values (900% using optimum conditions) than the corresponding Plastronga PE welds, and welding factors of 1.00 were achieved.

5.3. Polybutene-1

Isotactic PB-1 may exist in at least three distinct crystalline modifications [5]. On cooling molten PB-1, a modification II results and this changes into modification I at room temperature after about 1 week [6]. (Modification III is obtained by precipitating the polymer from various solvents [7], it is stable at room temperature but at elevated temperatures is transformed into either modification I or II.) Hence, testing PB-1 welds presents problems as full weld strength is not obtained until at least a week after the weld has been made [3a].

A series of PB-1 welds was made in which the welding parameters were varied systematically. These welds were left for at least 1 week and then tested. The following optimum conditions were found:

$$T_W = 518\text{ K},\ t_p = 15\text{ sec},\ t_q = 22\text{ sec},\ P_W = 0.15\text{ MPa},\ t_W = 180\text{ sec}.$$

These conditions are similar to those for Plastronga PE, the main difference being that PB-1 needs a shorter heating time.

Unlike the two grades of PE, it was more difficult to obtain a welding factor approaching 1.00 for PB-1. Using optimum welding conditions a factor of 0.99 was obtained, but this soon decreased as changes were made in the welding parameters. With the two grades of PE a longer heating time was preferable to a shorter heating time, but this was not the case for PB-1 which appeared to suffer from heat ageing or thermal degradation at elevated temperatures. Hence it was essential not to exceed either the optimum welding temperature or the optimum time which the pipe ends were in contact with the heating plate. An increase in welding pressure also resulted in a fairly dramatic decrease in weld quality.

PB-1 is more defect sensitive than PE and PB-1 tensile specimens always failed in the weld even when the welding bead was removed. The elongation at break values were, therefore, much lower, being about 230% for the optimum conditions. Using transmission electron microscopy it was possible to follow the path of the fracture through the weld and relate it to the zones discussed in a previous publication [4]. When the bead was left on, failure was always initiated by the notch between the bead and the gauge length and fracture proceeded straight across the pipe wall to the corresponding notch at the other surface (Fig. 5). When optimum welding conditions were used and the bead was removed, failure was always initiated at the junction of zone 3 with zone 2 (Fig. 6). The fracture propagated through the weld and failed at the edge of zone 3 on the opposite side to that where fracture was initiated. It appears that there is an intrinsic weakness at the zone 3–zone 2 boundary. When non-optimum welding conditions were used, fracture was again initiated at the edge of zone 3, but propagated at the weld interface.

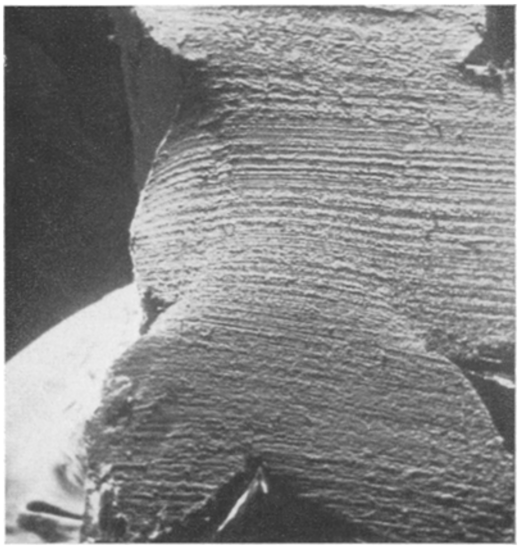

Figure 5 With the welding beads left on, failure is always caused by the notch between the welding bead and the gauge length in PB-1 welds. Optical micrograph.

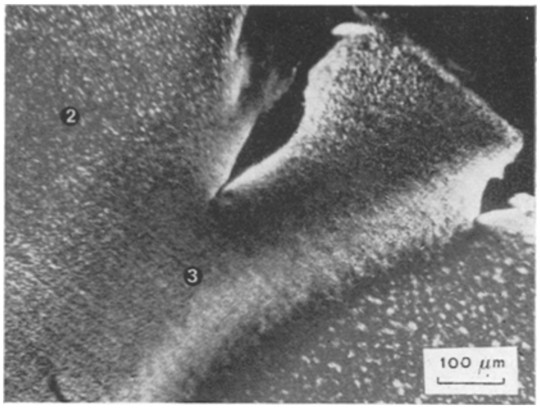

Figure 6 Failure at the junction of zones 2 and 3 for a PB-1 weld from which the welding beads have been removed. Optical micrograph.

5.4. Propathene GSE 108 polypropylene and Propathene 112/00/Grey 9897 (heat-stabilized) polypropylene

We found great difficulty in obtaining good welds of either of the above materials. The problem is that, even for the heat-stabilized polypropylene, the temperature at which thermal degradation begins is very close to the temperature required to produce a good weld. Microstructural examinations of the welds, either by chromic acid etching followed by scanning electron microscopy, or by microtome sectioning and trans-

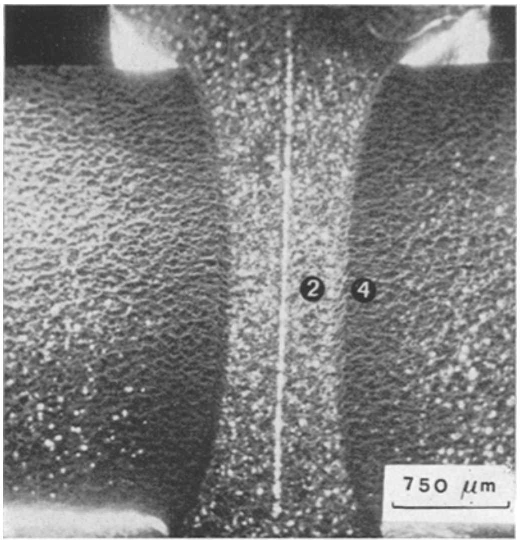

Figure 7 Section through a Propathene 112/00/Grey 9897 polypropylene weld. The microstructure has been revealed by a $5\frac{1}{2}$ h etch in chromic acid at 340 K. Two zones can be distinguished and the weld interface is clearly visible. Scanning electron micrograph.

mission optical microscopy, showed that in every case the weld interface was distinguishable and different from the rest of the material (Fig. 7). When specimens were fractured, the fractures occurred at the weld interface with low elongations.

For Propathene GSE 108 polypropylene, the following conditions gave the best welds: $T_w = 513$ K, $t_p = 25$ sec, $t_q = 35$ sec, $P_w = 0.1$ MPa, $t_w = 180$ sec. Welding factors of 0.99 could be obtained, but elongations to break were only about 30% irrespective of whether the bead was left on or machined off.

For Propathene 112/00/Grey 9897 heat-stabilized polypropylene, the situation was somewhat better and it did appear that thermal oxidation at the weld had been reduced. When the welding bead was machined off, welding factors of 0.97 were obtained with elongations to break of about 33%. With the bead on, the welding factors obtained were 0.98 but the elongations to break increased considerably to about 450%: necking occurred and failure was initiated at the notch between the bead and the gauge length. The following conditions gave the best welds: $T_w = 523$ K, $t_p = 25$ sec, $t_q = 25$ sec, $P_w = 0.1$ MPa, $t_w = 180$ sec.

For both types of polypropylene it was noticed that the fracture surfaces showed unusual features (Fig. 8). These were circular fibrous pits in the bottom of each of which an impurity particle could be seen (Fig. 9). When there was no necking and failure occurred at the weld interface, the fracture appeared to be initiated at these particles. There was evidence that, initially, failure was ductile, but eventually the fibres holding the particles in place were severed and brittle fracture then resulted. The

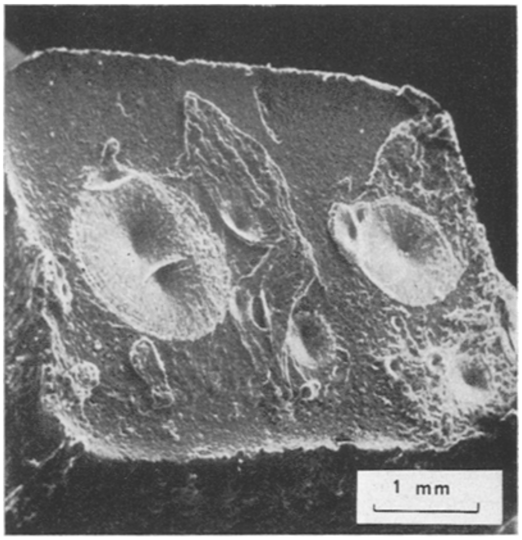

Figure 8 Failure has occurred across the weld interface for this Propathene GSE 108 polypropylene weld. Scanning electron micrograph.

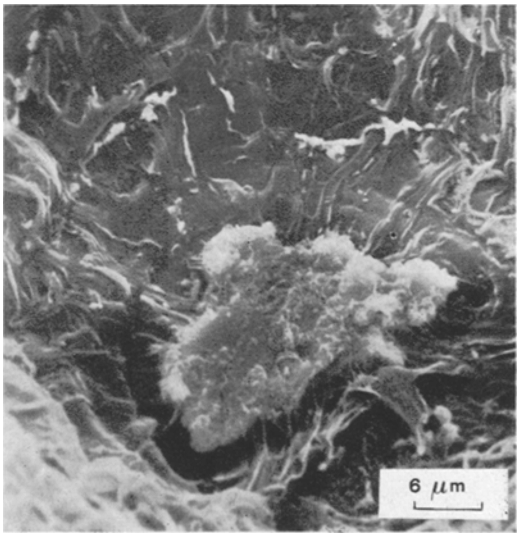

Figure 9 At the bottom of one of the pits shown in Fig. 8, a "foreign" particle can be seen. Scanning electron micrograph.

reason for these impurity particles being at or near to the weld interface is uncertain. It seems probable that they result from welding, for we could find no evidence of similar particles in surfaces produced by fracturing non-welded pipe material at liquid nitrogen temperatures. In addition, when the pipe material was melted at 493 K, allowed to cool and then fractured, no particles were observed in the fracture surfaces. Thus the particles are not degradation products. It is possible that the combination of heat and pressure used in a normal welding operation causes some finely-divided additives in the polypropylene to agglomerate and form larger particles. These particles weaken the weld and failure occurs almost immediately at the weld unless it is strengthened by an increased thickness of material due to the bead.

6. Microstructures of the welds

The different cooling rates in the welded region cause a number of different zones to form [4] (Fig. 3). These zones can be identified either by etching the weld in chromic acid and then viewing the etched surfaces in the scanning electron microscope, or by viewing thin sections of the weld in transmitted polarized light. The number of zones to form will depend on the welding temperature, the melting point of the plastic and, to a lesser extent, on the welding pressure.

With Plastronga PE welds and PB-1 welds, a columnar zone 3 is formed (see Figs. 10 and 11) which could have serious effects on the long term performance of the plastic pipe. In the short term no ill effects are noticed, except in those tensile specimens of PB-1 welds for which the welding bead has been removed. For these welds, the junction between the columnar zone 3 and the spherulitic zone 2 is a line of weakness and failure is always initiated at this particular point for a weld made under the optimum welding conditions (Fig. 6). For Plastronga PE welds, failure did not occur at the weld when welding was carried out using the optimum conditions. Zone 3 formation occurs because of the large temperature gradient set up on cooling. The size of zone 3 can be reduced by lowering the welding temperature, but then, for both materials, the join between the two interfaces (zone 1) becomes apparent and it is obvious that complete adhesion has not occurred (Fig. 12). In conclusion, the microstructures of welds of these two materials will show zones 2, 3, 4 and 5, but the appearance of zone 1 is an indication that the weld is unsatisfactory.

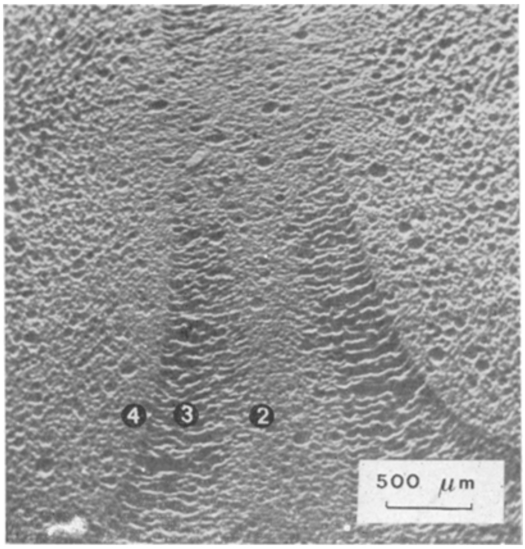

Figure 10 Plastronga PE weld after etching for 12 h in chromic acid at 340 K. Scanning electron micrograph.

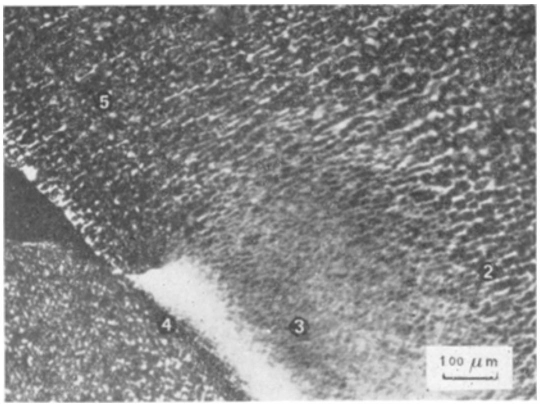

Figure 11 Microtome section of PB-1 weld showing the different zones. The base material is in the bottom left corner, a whitened region (zone 3) in the centre of the picture is separated from the base material by a boundary layer (zone 4); zone 2 is on the right and the bead (zone 5) at the top. Optical micrograph.

Aldyl "A" PE had a much higher meet flow index than Plastronga PE and a lower welding temperature was used. The temperature gradients produced during welding were, therefore, much lower and their effect on the microstructure much less: no columnar zone 3 was observed. For this material it was difficult to decide the quality of the weld from a study of the microstructure, except for those welds showing pronounced

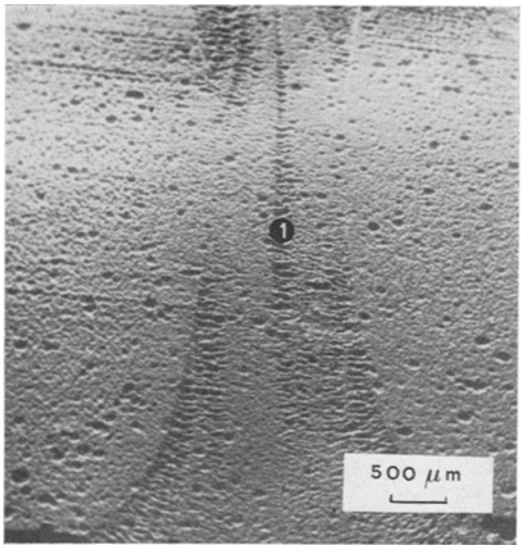

Figure 12 Plastronga PE weld after etching for 12 h in chromic acid at 340 K. A zone 1 is visible. Scanning electron micrograph.

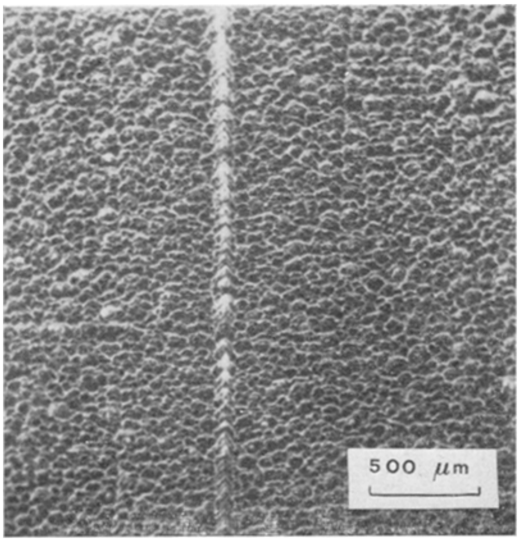

Figure 13 Aldyl "A" PE weld after a $4\frac{1}{2}$ h etch in chromic acid at 340 K. The weld interface has been severely etched due to incomplete adhesion Scanning electron micrograph.

interfaces (Fig. 13) which were obviously unsatisfactory.

For both grades of PP, zones 1, 2 and 4 could be seen in the welds (Fig. 7) with zone 1 (the weld interface) always present and clearly distinguishable.

7. Conclusions

The optimum welding conditions are collected together in Table IV. The particular problems associated with each material have been discussed in detail in the appropriate sections and will not be repeated here. However, the following general points emerge.

We believe that tensile tests can be used as a guide at least to short term weld reliability, providing that welding factors are used in conjunction with elongation to break values. The removal of the welding bead enables a clearer picture to be obtained of weld performance, since with the welding bead left on failure in a tensile test is always initiated by the notch between the welding bead and the gauge length. We do not suggest that a tensile test represents the situation encountered by a weld in a pipe in service, where the welding beads will always remain and the pipes will be subjected to hoop as well as to tensile stresses. The tensile test does, however, indicate the intrinsic quality of the weld and highlight defects caused by deviations from optimum welding temperatures, pressures and times.

An examination of the microstructure of each weld has shown the presence of the zones discussed in a previous publication [4]. In the short term we find no evidence that zones 2, 3, 4 and 5 are harmful, although the presence of zone 1 indicates poor adhesion at the weld interface. These results, together with those obtained from a study of the fracture surfaces, support the conclusions from the tensile tests and provide additional information on the reasons why failure occurred at the welds.

In the long term the presence of zone 3 could affect the stability of the weld. When subjected to a hoop stress caused by an internal pressure, the columnar crystals may separate at their boundaries where lower molecular weight material is rejected. We could not detect any weakness in short term burst tests, but it has been found [3d] that in long term stress rupture tests, failure does sometimes occur at the weld. These "long-term" test results are, however, questionable as the tests were carried out at elevated temperatures. One way of producing a weld with no zone 3 formation is to use a lower welding temperature. But with a low welding temperature a weld with poor strength is obtained unless the material has a high melt flow index.

It may well be that the molecular weight distribution is the most important characteristic

TABLE IV Optimum welding conditions

Pipe material	T_w (K)	t_p (sec)	t_q (sec)	P_w (MPa)	T_w (sec)	Comments
Plastronga PE	508	20	35	0.1	180	Optimum conditions fairly critical
Aldyl "A" PE	443	20	30	0.1	180	Welding temperatures acceptable between 443 and 488 K: better to have longer rather than shorter heating times
Vestolen PB-1	518	15	22	0.15	180	Optimum conditions critical
Propathene GSE 108	513	25	35	0.1	180	No satisfactory welds obtained
Propathene 112/00/Grey 9897	523	25	25	0.1	180	Difficult to obtain satisfactory welds

of the pipe material and that it is better to have a fairly narrow distribution rather than a broader distribution with a pronounced low molecular weight tail. With a narrow distribution the rejected material would still consist of reasonably long polymer chains and, therefore, still possess relatively good creep properties and reasonable toughness.

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