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A COMPARISON OF MECHANICAL TEST METHODS FOR BUTT FUSION JOINTS IN POLYETHYLENE PIPES

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ABSTRACT

There are a large number of different mechanical test methods available to assess the quality of butt fusion welded joints in polyethylene (PE) pipes. These include various short-term tests on specimens cut from the weld, such as bend tests, tensile tests and impact tests, as well as long-term specimen tests and hydrostatic pressure tests. TWI has also developed a whole pipe tensile creep rupture test specifically to determine the long-term performance of butt fusion joints in PE pipes. Unfortunately, little published information exists on the correlations that may or may not exist between the results from these different test methods.

This paper describes a study to compare the results from three short-term mechanical test methods: three-point bend test (according to EN 12814-1), tensile test using a dumb-bell specimen (according to EN 12814-2) and tensile test using a waisted specimen (according to EN 12814-2, Annex B); and three long-term mechanical test methods: specimen tensile creep rupture test (according to EN 12814-3), hydrostatic pressure test (according to ISO 1167) and the whole pipe tensile creep rupture test. These tests were performed on butt fusion joints in 355mm outside diameter PE100 pipes, which were produced using three very different sets of welding parameters, in order to generate joints of nominally different quality.

Results from this study showed that, of the three short-term tests examined, only the waisted specimen tensile test was able to differentiate between welds made under the different welding conditions. In addition, there was no correlation between results from short-term and long-term tests or between results from specimen and whole pipe tensile creep rupture tests.

INTRODUCTION

The presence of joints in any pipeline can affect the overall structural integrity of the system. There is, therefore, a need for reliable standard tests and procedures to evaluate the mechanical properties of the welded joints. At present there are a large number of short-term mechanical test methods, and associated specimen geometries, for assessing the performance of joints in plastics. However, little work has been done to correlate results from one test with those from another.

In addition, although butt fusion weld failures in PE pipes are extremely rare, to confidently predict the service life of a welded pipe system, especially as industries move to more critical and demanding service conditions, it is necessary to have an understanding of the long-term performance of welds such that the whole system is guaranteed to have a 50 year lifetime at the nominal working pressure.

At present, PE pressure pipe systems are designed on the basis of experimental regression curves of hoop stress versus time to failure, generated from laboratory hydrostatic pressure tests on whole pipe sections. Such tests, although satisfactory for determining the performance of the parent pipe, are inadequate for assessing the long-term performance of butt fusion welds. The main reason for this is that butt fusion welds are vulnerable to stresses in the axial direction, which may be generated in service due to bending and thermal contraction. However, in a laboratory hydrostatic pressure test the stress in the axial direction is only half of that in the hoop direction, which means that, in these tests, failure invariably occurs in the pipe wall before the welded joint, giving no quantifiable data on the long-term integrity of the joint.

Short-term tests on butt fusion welds are used typically as a QA/QC measure or to optimise welding conditions. However, there is little published regarding the possible correlation between the results from short-term and long-term tests.

This paper describes a study to establish which of a number of short-term coupon tests, currently used in the plastics pipes industry, are able to discriminate between butt fusion joints made under extremely different welding conditions, and whether these results correlate with those from a number of long-term tests.

WELDING TRIALS

Welds were made in 355mm SDR17.6 black PE100 pipe.

The butt fusion equipment used to weld the pipe was a commercial, semi-automatic, butt fusion machine (model BF400), manufactured by Fusion Group plc, which had been modified to allow the welding parameters to be changed manually.

Three different welding cycles were used, based on advice from industry, in order to produce joints with nominally different weld qualities:

Condition 1: Standard (according to WIS 4-32-08[1]).

Condition 2: As Condition 1, except that the bead-up and fusion cylinder pressures were increased from 19bar to 95bar, and a single pressure cycle was used (i.e. the pressure was maintained at 95bar throughout the cooling stage).

Condition 3: As Condition 1, except that the heater plate temperature was reduced from 230°C to 160°C.

A comparison of the weld bead shape and heat affected zone (HAZ) for welds made using these three conditions is shown in Figure 1.

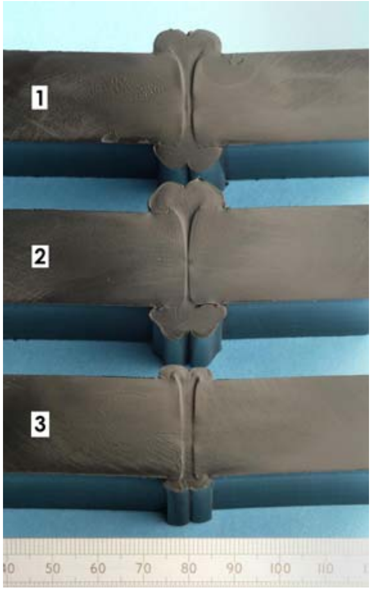

Figure 1 Comparison of the weld bead profiles and heat affected zones for the three welding conditions.

WELD ASSESSMENT

The quality of the welds produced was assessed using three destructive, short-term coupon tests, three long-term tests and also by measuring the dimensions of the external weld bead. These tests and the corresponding properties measured are summarised in Table 1.

Table 1 Summary of tests used

Test	Standard	Properties specified in standard	Additional properties measured
Visual assessment	WIS 4-32-08[1]	Bead width (total/half)	Bead height
Bend test	EN 12814-1[2]	Maximum ram displacement	-
Tensile test - dumb-bell specimen	EN 12814-2[3]	Maximum load Failure mode	Tensile strain at break Energy to break
Tensile test - waisted specimen	EN 12814-2[3] (Annex B)	Maximum load Failure mode	Tensile strain at break Energy to break
Specimen tensile creep rupture test	EN 12814-3[4]	Time to failure	-
Hydrostatic pressure test	ISO 1167[5] EN 1555-2[6]	Time to failure	-
Whole pipe tensile creep rupture test[7]	-	-	Time to failure

Three-point bend test

This test was carried out according to the European standard EN 12814-1[2]. The specimen dimensions are detailed in Figure 2 and a schematic diagram of the test arrangement is given in Figure 3.

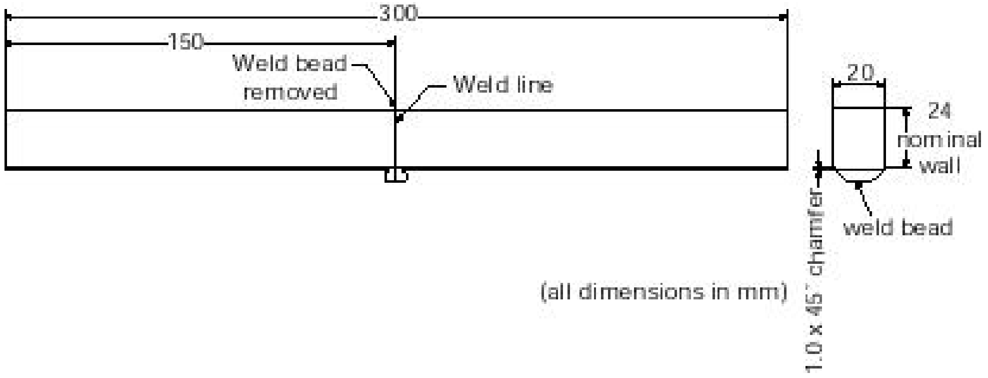

Figure 2 Geometry and dimensions of bend test specimen.

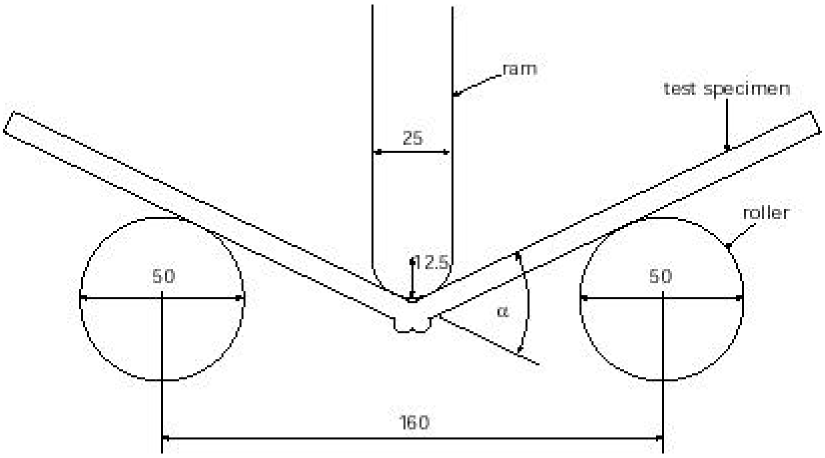

Figure 3 Schematic diagram of bend test.

Five welded specimens were cut perpendicular to the welded joint. The weld bead was removed from the side in contact with the ram end. In addition, five specimens were cut from the parent pipe, for comparison. Tests were performed at room temperature, using a ram rate of 50mm/min. For each test, the ram displacement at which either fracture occurred or a crack appeared was measured. The tests were terminated at a maximum bend angle, α, of 160°.

Tensile test using dumb-bell specimens

The test was carried out in accordance with the European standard EN 12814-2, using the Type 2 test specimen (Figure 4).

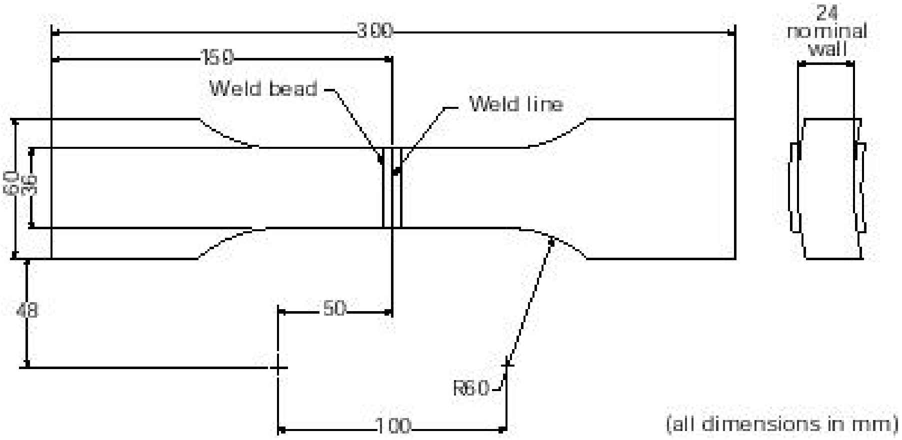

Figure 4 Geometry and dimensions of the dumb-bell tensile specimen.

Five welded specimens were cut perpendicular to the welded joint. The weld beads were left intact. In addition, five specimens were taken from the parent pipe, for comparison. Tests were carried out at room temperature and a crosshead speed of 50mm/min. The distance between the loading jaws was approximately 220mm. The tensile strain at break was as defined in EN ISO 527-1[8] and the energy to break was taken as the area under the force versus displacement curve.

Tensile test using waisted specimens

This test was carried out in accordance with the European standard EN 12814-2, using the specimen geometry defined in Annex B of this standard (Figure 5). This specimen geometry is used because it ensures that fracture occurs in the weld region and not in the parent material, as is often the case with the dumb-bell geometry. A similar test is specified in the International Standard ISO 13953[9] and the European Standard EN 12814-7[10].

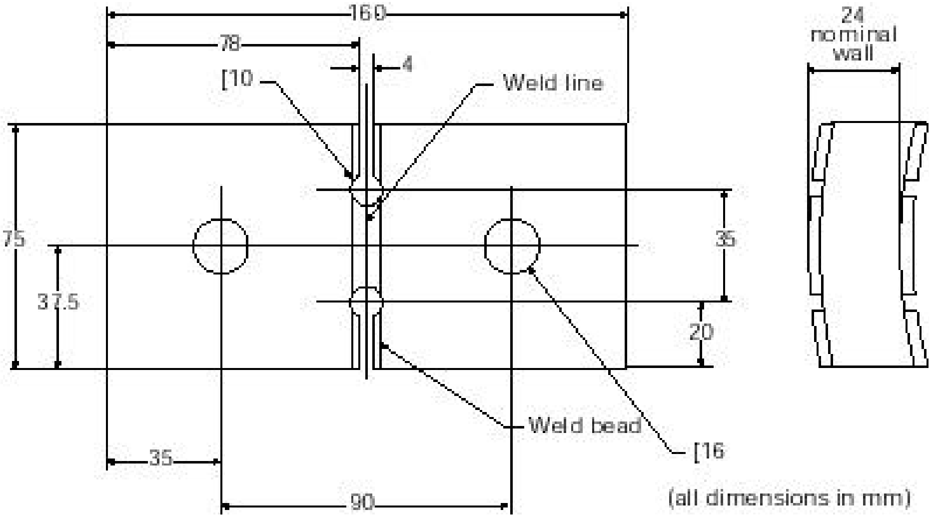

Figure 5 Geometry and dimensions of the waisted tensile specimen.

Five welded specimens were cut perpendicular to the welded joint. The weld beads were left intact. In addition, five specimens were cut from the parent pipe for comparison. Tests were carried out at room temperature and a crosshead speed of 5mm/min. The tensile strain at break was as defined in EN ISO 527-1[8] and the energy to break was taken as the area under the force versus displacement curve.

Specimen tensile creep rupture test

Five welded specimens were cut perpendicular to the welded joint for each welding condition. The weld beads were left intact. Specimens were machined to conform to the Type 2 geometry given in EN 12814-3, except that an additional waisted section was machined at the weld line (Figure 6). This was to ensure that failure occurred at the weld.

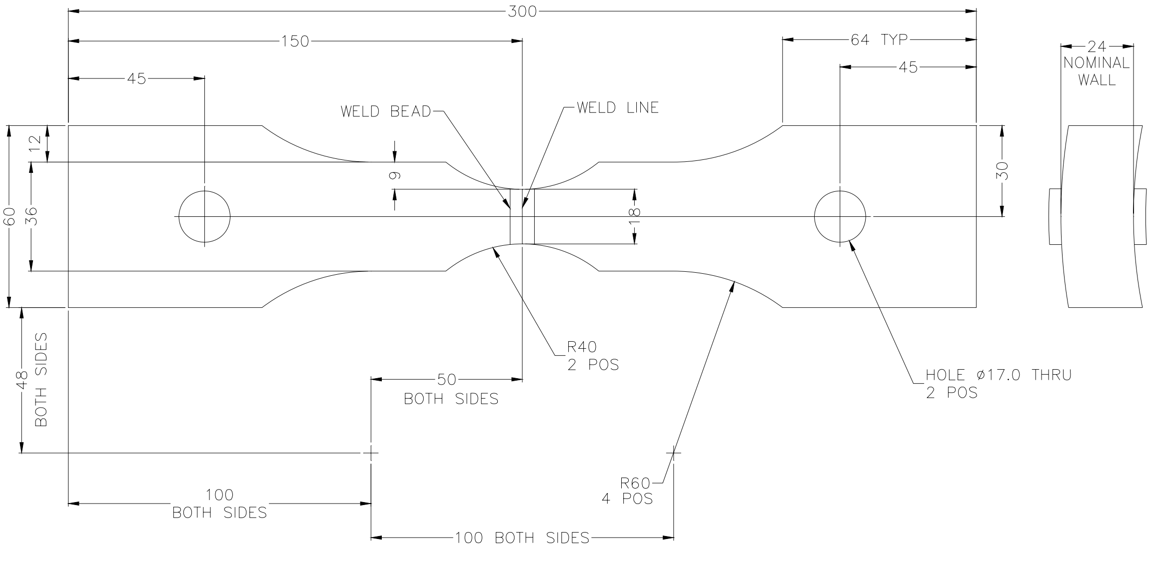

Figure 6 Test specimen geometry for the tensile creep rupture tests.

Tests were carried out at 80ºC in water using the equipment shown in Figure 7. Weights were applied to the hanger on the test station such that an initial tensile stress of 5.5MPa was produced in the narrow section of the specimen at the weld line.

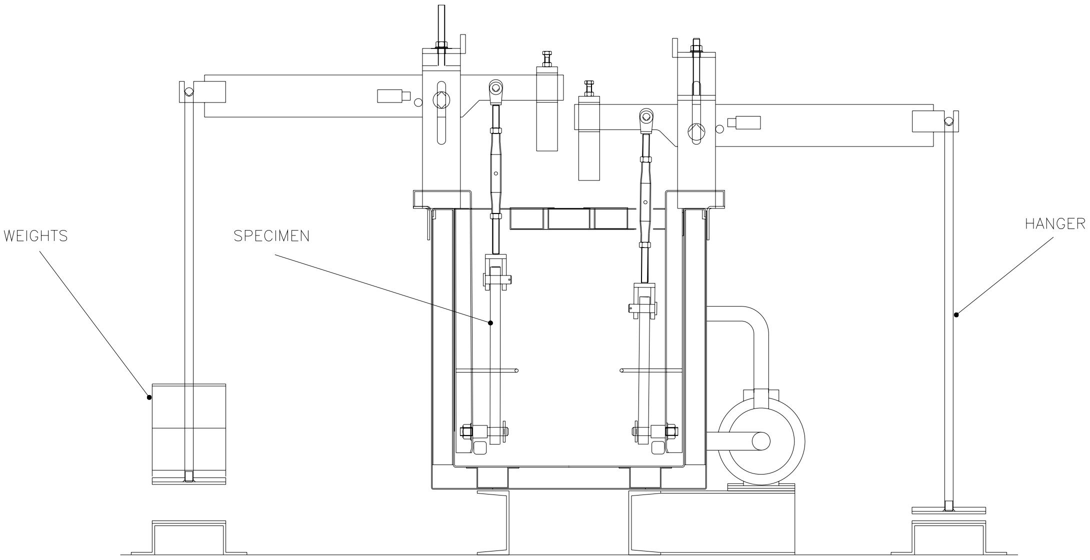

Figure 7 Schematic of specimen tensile creep rupture test rig.

Hydrostatic pressure test

A total of 12 welded samples, four per welding condition, were tested at a pressure of 5.52 bar in water at a temperature of 80ºC for a minimum of 1700 hours. This is ten times the test duration specified in EN 1555-2[6].

For each welding condition, two welded pipe samples had a standard distance between the weld and end fitting of three pipe outside diameters[5] and two had a reduced distance between the weld and end fitting of one pipe outside diameter.

Whole pipe tensile creep rupture test

Currently there is no dedicated whole pipe test available that can be used to generate long-term data on butt fusion welds made under standard conditions. For this reason TWI designed and built a whole pipe tensile creep rupture test rig that subjects welded whole pipe samples to a constant axial tensile load at elevated temperature. Since it is a whole pipe test it maintains the residual stresses in the pipe and weld and should, therefore, be more realistic compared with tests on specimens cut from the weld. For this reason it is believed that this is the most representative test for predicting the long-term performance of butt fusion welds in PE pipes, and the one against which all other tests should be compared. Figure 8 shows a schematic of the pipe loading arrangement for this test.

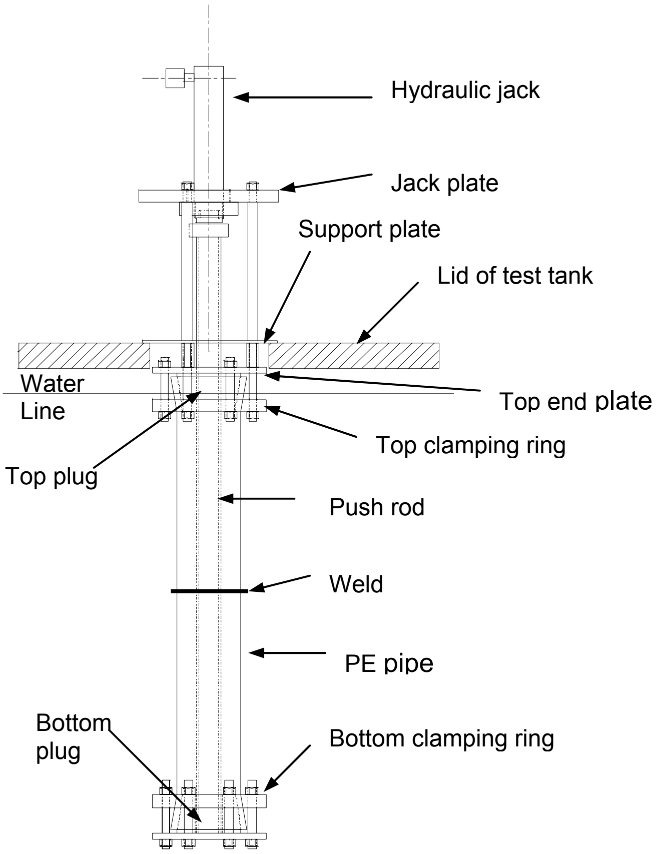

Figure 8 Diagram of the pipe loading arrangement in the whole pipe tensile creep rupture test.

The tensile load was applied to the welded test pipe via a stainless steel push rod, which passed down the inside of the pipe. The top of the push rod was in contact with the ram of a hydraulic jack and the bottom end was attached to the bottom end plate. The end plates were held on to the pipe ends using an internal tapered plug and an external clamping ring. The pressure of oil in each hydraulic jack was generated by a pump, monitored by a pressure transducer and controlled by solenoid and needle valves. There was a hole in the bottom end plate to allow the inside of the PE pipe to fill with water when it was inserted into the bath.

Samples of length 1065mm were tested in water at 80ºC with a tensile load of 120kN, creating an axial stress of 5.4MPa in the pipe wall. Two pipe samples per welding condition were tested. The weld beads were left intact.

RESULTS AND DISCUSSION

Weld bead dimensions

Figures 9 and 10 show the total bead width and bead height, respectively, as a function of position around the circumference of the weld. For all welds produced, the external beads were visually acceptable, as defined in WIS 4-32-08.

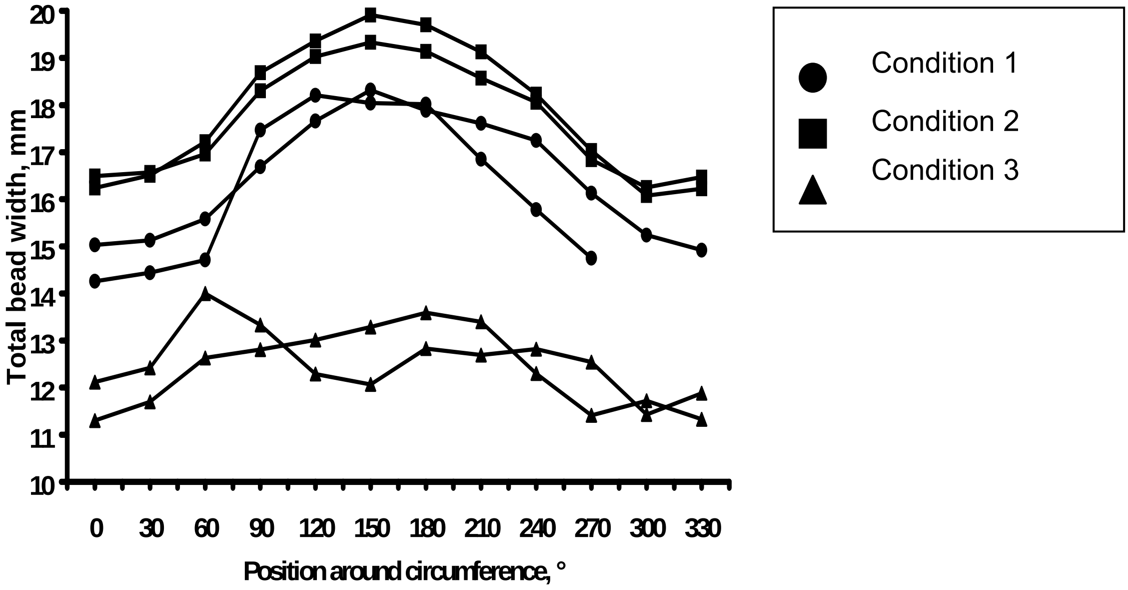

Figure 9 Graph of total bead width versus position around weld circumference.

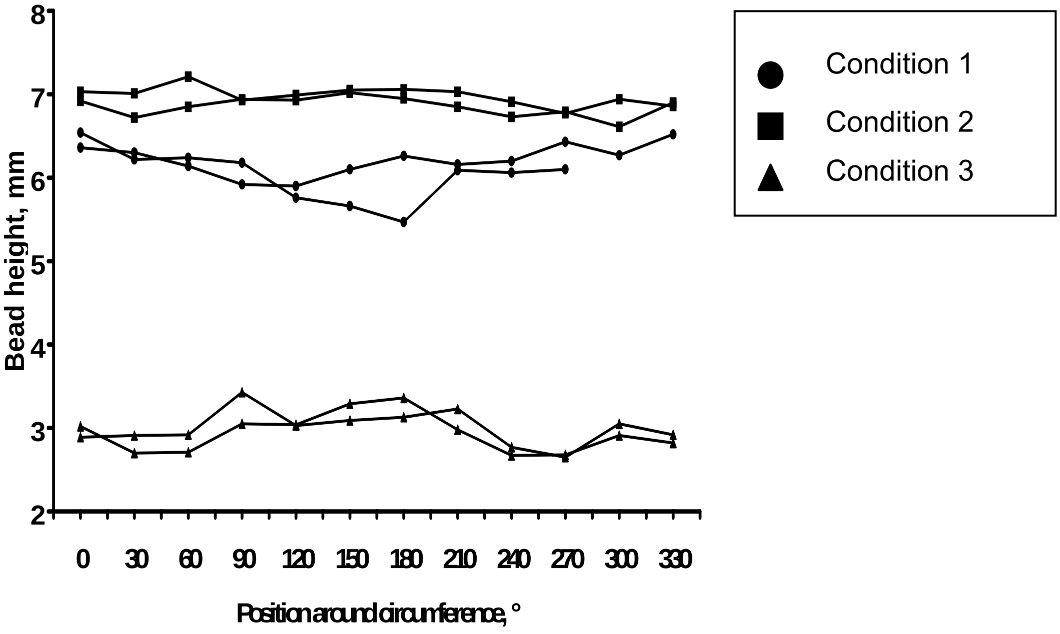

Figure 10 Graph of bead height versus position around weld circumference.

It can clearly be seen in Figure 9 that, for the welds made using Conditions 1 and 2, there was a systematic variation in the total width of the external weld bead around the joint. The minimum width was consistently at the top of the pipe (0°) and the maximum at the bottom (180°). This effect is mainly due to gravity acting on the molten material during welding.

The variation in bead width around the welds was not as pronounced for the welds made using the reduced hot plate temperature (Condition 3), possibly because the polymer melt would be more viscous.

The results given in Figures 9 and 10 suggest that the external weld bead dimensions in polyethylene pipes can discriminate between welds made under different welding conditions. If the total bead width were used, it would be necessary to ensure that measurements were taken from the same relative position around each pipe. However, the range of bead heights for the three different welding conditions did not overlap, which suggests that this dimension may be more useful for QC purposes.

It should be noted that these trends were obtained from welds made in the factory. Such trends may be obscured when welding in adverse conditions in the field.

Three-point bend test

None of the bend test specimens, either welded or parent, failed or showed evidence of cracking when taken to a maximum bend angle of 160º, which suggests that the bend test cannot distinguish between welds made under these different conditions. These results therefore suggest that the bend test should not be used for optimising the welding conditions for butt fusion joints in PE pipes. However, it has been proposed that a bend test performed at low temperatures may give a better differentiation between welds made under different conditions[11].

Tensile test using dumb-bell specimens

The results of the tensile tests using a dumb-bell specimen are given in Table 2. All specimens necked in the parent pipe and did not break before the maximum extension was reached on the tensile testing machine. This meant that neither the extension at break nor the energy to break values could be calculated. The measured values of maximum load were identical, within the errors, for all three welding conditions and also for the parent material. This would be expected since it was the property of the parent pipe that was being measured.

Table 2 Results of tensile tests on dumb-bell specimens

Welding Condition	Maximum Load, kN	Failure Mode
Parent Pipe	19.5 ± 0.2	Necked in parent
1 - Standard	19.5 ± 0.4	Necked in parent
2 – Increased Pressure	19.8 ± 0.5	Necked in parent
3 – Reduced Temperature	19.5 ± 0.2	Necked in parent

These results suggest that this test cannot distinguish between welds made under very different welding conditions and should therefore not be used for QA/QC purposes or for optimising welding conditions in butt fusion joints in PE pipes.

Tensile test using waisted specimens

The results of the tensile tests on waisted specimens are given in Table 3, from which it appears that the energy to break values could discriminate between welds that had been made using the different welding conditions. The values of failure load could not distinguish between Conditions 1 and 2 (standard and increased pressure, respectively), and the failure mode could not distinguish between Conditions 1 and 3 (standard and reduced temperature, respectively).

A possible explanation why the failure load values for Condition 2 were not lower than for Condition 1 is that the bead dimensions were greater for the welds made under Condition 2 than under standard conditions; therefore the actual cross-sectional area at the weld was greater. This would mean that, even if the tensile strength of the weld without the beads made under Condition 2 was lower than under Condition 1, the measured values of failure load could be the same. If this is true, then a waisted tensile test with the weld beads removed might give more information than where the beads are left on.

These results therefore suggest that, in addition to determining the tensile strength and examining the fracture surface as specified in ISO 13953[9], it might be more useful to measure also the energy to break values, as specified in EN 12814-7[10].

Table 3 Results of tensile tests on waisted specimens

Welding Condition	Failure Load, kN	Extension at break, mm	Energy to break, J	Failure Mode
Parent Pipe	14.5 ± 0.2	43 ± 3	488 ± 5	4 ductile/ 1 no failure
1- Standard	15.5 ± 0.1	38 ± 3	449±36	4 ductile/ 1 failure in loading holes
2 – Increased Pressure	15.5 ± 0.2	29 ± 4	345±46	4 mixed/ 1 ductile
3 – Reduced Temperature	14.3 ± 0.1	30 ± 1	320±11	5 ductile

Specimen tensile creep rupture test

The results of the specimen tensile creep rupture tests are given in Table 4 and suggest that welds made under Conditions 1 and 2 had similar average times to failure, whereas welds made under Condition 3 (i.e. low temperature) had, on average, the longest times to failure.

Table 4 Results of the specimen tensile creep rupture tests

Welding condition	Average time to failure, hours
1	3900 ± 900
2	3400 ± 1600
3	>10000 ± 4000

All of the failed specimens displayed a fracture surface that was at least 30% brittle, which is a requirement of EN 12814-3 for the test to be valid.

The specimens made under Conditions 1 and 3 had the same failure mode; slow crack growth (SCG) initiated from the notch between the pipe wall and the outer and inner weld beads. The crack then propagated along the edge of the HAZ until the stress in the remaining ligament exceeded the yield stress of the material and the specimen yielded (Figure 11).

Figure 12 shows a typical fracture surface of a specimen welded under Condition 2 and shows that, again, SCG initiated from the notches between both the internal and external weld beads and the pipe. However, there is also evidence of independent SCG initiating at the centre of the weld.

Figure 11 Fracture surface of a creep rupture test specimen welded under Condition 3.

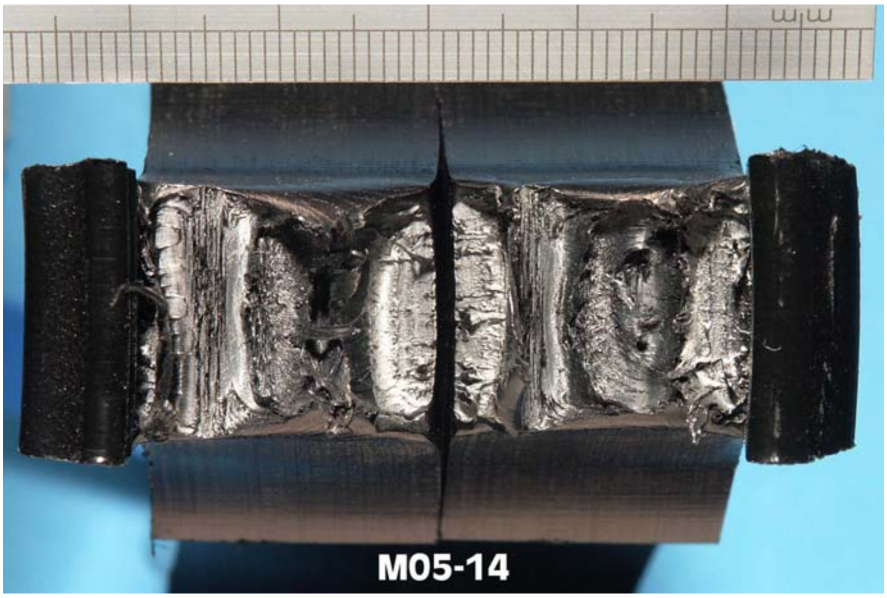

Figure 12 Fracture surface of creep rupture test specimen welded under Condition 2.

Hydrostatic pressure test

All samples were tested for at least 1700 hours. No failures occurred within this time. These tests were carried out at an outside laboratory where, due to commercial time constraints, it was not possible to take the tests to failure. Therefore, no information was obtained from this test about the long-term integrity of the welds. However, as stated in the introduction, it is believed that if these samples had been taken to failure then failure would have occurred in the parent pipe rather than at the weld, due to the dominant stresses in this test being in the hoop direction.

Whole pipe tensile creep rupture test

Table 5 below gives a summary of the test results from the whole pipe tensile creep rupture tests.

Table 5 Whole pipe tensile creep rupture test results

Welding condition	Average time to failure, hours
1	5700 ± 600
2	>8800 ± 1700
3	1700 ± 1400

Samples welded under Condition 1 failed in a brittle manner through the weld interface as shown in Figure 13. The fracture surface shows evidence of micro-ductility, indicating a long-term brittle failure mode from SCG.

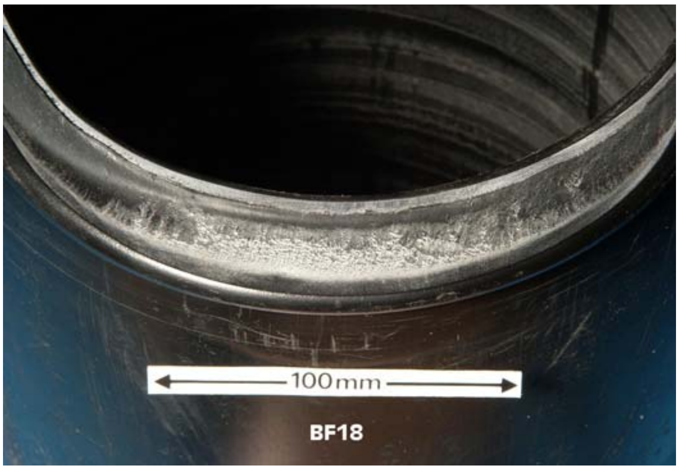

Figure 13 Photograph showing the fracture surface of a weld made under Condition 1.

Samples welded under Condition 2 had the greatest times to failure. For these samples, rather than failing across the interface, the failure appears to have initiated from within the weld (Figure 14). The crack has propagated outwards from the centre of the weld towards the outer and inner pipe wall surfaces.

Figure 14 Photograph showing the fracture of a weld made under Condition 2.

The samples welded under Condition 3 failed along the weld interface in the shortest time. This suggests they were the lowest quality in terms of long-term performance.

Comparison of mechanical tests

Table 6 compares the ranking of the results from all of the mechanical tests.

Table 6 Comparison of ranking of the mechanical tests

<table>
<tr><th rowspan="2">Test</th><th rowspan="2">Property measured</th><th colspan="3">Ranking</th></tr>
<tr><th>Condition 1</th><th>Condition 2</th><th>Condition 3</th></tr>
<tr><td>Bend</td><td>Maximum bend angle</td><td colspan="3">No weld failures</td></tr>
<tr><td rowspan="4">Tensile (dumb-bell specimen)</td><td>Tensile strength</td><td colspan="3" rowspan="4">No weld failures</td></tr>
<tr><td>Extension at break</td></tr>
<tr><td>Energy to break</td></tr>
<tr><td>Failure mode</td></tr>
<tr><td rowspan="4">Tensile (waisted specimen)</td><td>Tensile strength</td><td>H</td><td>H</td><td>L</td></tr>
<tr><td>Extension at break</td><td>H</td><td>L</td><td>L</td></tr>
<tr><td>Energy to break</td><td>H</td><td>M</td><td>L</td></tr>
<tr><td>Failure mode</td><td>H</td><td>L</td><td>H</td></tr>
<tr><td>Specimen tensile creep rupture</td><td>Time to failure</td><td>L</td><td>L</td><td>H</td></tr>
<tr><td>Whole pipe tensile creep rupture test</td><td>Time to failure</td><td>M</td><td>H</td><td>L</td></tr>
<tr><td>Hydrostatic pressure test</td><td>Time to failure</td><td colspan="3">No weld failures</td></tr>
</table>

(H = highest, M = mid, L = lowest)

It can be seen that three of the tests that are commonly used for assessing the quality of butt fusion welds in PE pipes: the tensile test using a dumb-bell specimen, the three-point bend test, and the hydrostatic pressure test, were not able to produce failures in any of the welds made under very different welding conditions.

Therefore, for optimising welding parameters or for QA/QC tests the best short-term specimen test, i.e. the one that gives the best differentiation between different welding conditions, was the tensile test using a waisted specimen. In this test, only the energy to break values showed differences between the UK standard and non-standard welding conditions. The tensile strength and failure mode, as specified in ISO 13953, did not.

The tensile test using a waisted specimen ranked Condition 1 as having the highest quality, which is not surprising since it was this test that was used to establish these welding conditions. However, the whole pipe tensile creep rupture test ranked Condition 2 (high welding pressure) as having the better long-term performance. This tends to agree with butt fusion welding parameters used in North America, where the specified weld pressures are significantly higher than in Europe[12].

The results from the specimen creep rupture test suggest that Condition 3 gives the best weld quality, which also does not agree with the results from the whole pipe tensile creep rupture test. This different ranking order of the specimen and whole pipe creep rupture tests is believed to be associated with the different modes of failure. For example, with welds made using Condition 1, the whole pipe samples failed through the weld interface whereas the specimens failed along the HAZ boundary, initiating from the notch between the weld bead and the parent pipe. The most likely reason for this is a combination of the stress constraints and residual stresses in the whole pipe tests, which are released when the specimens are cut from the pipe.

Most PE pipes exhibit an inward bending of the pipe walls at the end of a pipe, due to residual stresses caused by unequal cooling of the internal and external pipe surfaces during manufacture. When the pipes are welded together, this inward bending is still present. When the axial load is applied during the whole pipe tensile creep rupture test, the pipe wall will want to straighten and, at the weld, will want to expand radially. This will be resisted by tensile hoop stresses leading to a complex triaxial stress state near the weld line, which will have the effect of locally reducing creep strain ductility. No such stresses will be set up in the specimen.

It should be noted that the above rankings are based on a limited number of results and further testing should be carried out in order to confirm these findings. In addition, these tests were only conducted on one pipe size, designed for one pressure rating and produced from one supplier's material. The results will not necessarily be true for all sizes of pipe and grades of PE. For example, larger diameter pipe with thicker walls will contain more residual stress, which could influence the long-term performance of the welds.

CONCLUSIONS

A programme of work has been carried out to compare the results from various standard short-term and long-term mechanical tests that are used to determine the performance of butt fusion welds in PE pipes. Based on the relatively small number of specimens tested by each method, the conclusions are:

- A unique whole pipe test has been developed that can consistently generate long-term failure at the butt fusion weld of PE pipes. This test is believed to be the most representative test currently available for assessing the long-term performance of butt fusion welds in PE pipes.
- Two of the most common short-term tests used for determining the integrity of butt fusion welds in PE pipes, the three-point bend test and the tensile test using a dumb-bell specimen, were not able to discriminate between welds made under three very different conditions and should therefore not be used for QC or QA purposes.
- Hydrostatic pressure tests at 80ºC were also unable to discriminate between welds made under the different welding conditions, for test durations up to 1700 hours and, therefore, again should not be used for QA purposes to assess the quality of butt fusion welds in PE pipes.
- The tensile test using a waisted specimen, as defined in EN 12814-2, EN 12814-7 and ISO 13953, can differentiate between different welding conditions and can therefore be used for QC and QA weld testing. However, the energy to break value should be used rather than the tensile strength or failure mode.
- Short-term testing, which is normally the method used for optimising butt fusion welding parameters, does not appear to give the same results as the whole pipe tensile creep rupture test. This suggests that current welding parameters used in industry may not be the optimum for long-term performance. However, further work will be required to confirm this.
- Long-term creep rupture testing of specimens cut from butt fusion welds in PE pipes does not appear to give the same results as creep rupture testing of whole pipe welded assemblies. This could be due to the different stress fields generated in the two tests.
- The external weld bead dimensions in PE pipes could discriminate between welds made under different welding conditions. Since there was a large systematic variation in total bead width around the weld, a differentiation between different welding conditions could only be made if measurements were taken from the same relative position around each pipe. However, the variation in bead height around the circumference was much smaller than the variation in total bead width, and the range of bead heights for the three different welding conditions did not overlap. This suggests that measuring the bead

height rather than the bead width should give a clearer discrimination between welds made under different conditions, and should therefore be used for QC purposes.

ACKNOWLEDGEMENTS

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REFERENCES

1. Water Industry Specification WIS 4-32-08: "Specification for the fusion jointing of polyethylene pressure pipeline systems using PE80 and PE100 materials", 2002.
2. EN 12814-1: "Testing of welded joints of thermoplastics semi-finished products. Part 1: Bend tests", 2000.
3. EN 12814-2: "Testing of welded joints of thermoplastics semi-finished products. Part 2: Tensile test", 2000.
4. EN 12814-3: "Testing of welded joints of thermoplastics semi-finished products. Part 3: Tensile creep test", 2000.
5. ISO 1167: Thermoplastics pipes, fittings and assemblies for the conveyance of fluids - Determination of the resistance to internal pressure".
6. EN 1555-2: "Plastics piping systems for the supply of gaseous fuels. Polyethylene (PE). Pipes", 2002.
7. Troughton M J and Scandurra A: "Predicting the long-term integrity of butt fusion joints in polyethylene pipes", 17th International Plastic Fuel Gas Pipe Symposium, San Francisco, USA, 19-23 October 2002.
8. EN ISO 527-1: "Plastics - Determination of tensile properties - Part 1: General principles", 1996.
9. ISO 13953: "Polyethylene (PE) pipes and fittings - Determination of the tensile strength and failure mode of test pieces from a butt-fused joint", 2001.
10. EN 12814-7: "Testing of welded joints of thermoplastics semi-finished products. Part 7: Tensile test with waisted test specimens", 2002.
11. Hessel J and John P: "Long-term strength of HDPE welded joints", Kunststoffe, 74(7), p.385, 1984.
12. ISO 21307: "Plastics pipes and fittings - Butt fusion jointing procedures for polyethylene (PE) pipes and fittings used in the construction of gas and water distribution systems", 2009.