HARMONISATION OF POLYETHYLENE PIPE BUTTFUSION PROCEDURES AND TEST METHODS – FINAL CONCLUSIONS

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ABSTRACT

Polyethylene, Pipes, Buttfusion, Joining, Testing

Several well established procedures are used for butt fusion welding of PE pipes globally. The most widely used are the European Single Pressure, UK Dual Pressure, and the USA High Pressure procedures. In the future it may be possible to rationalise these procedures. Materials and machinery developments are resulting in an increasing size range of pipe. Confirmation of the appropriate test methods is required to assure weld quality, to fully understand the properties of the welds, and to confirm the suitability of the fusion procedure used for such pipes. The PE 100+ Association established this project to evaluate welds in large diameter thick walled pipe. The results of this programme are discussed and conclusions made.

INTRODUCTION

The advantage and ease of fusion welding of polyethylene was recognised during the early days of the introduction of PE pipeline systems. Fusion welding creates a fully end load resistant joint, resulting in a flexible pipeline system which will resist ground movement and even earthquakes, Nishimura et al (1). The introduction of ‘low sag’ PE materials is allowing thicker walled pipe to be produced with accurate control of thickness. It is important to confirm the suitability of butt fusion procedures for such pipe, and that test methods are appropriate.

This paper outlines the efforts being made by the PE100+ Association and the industry to further develop and harmonise global standards for fusion procedures, test methods and non destructive techniques (NDT), verifying suitability for thick walled large diameter pipes. This paper finalises the results and conclusions of the project, presented at Plastics Pipes XV held in Vancouver in 2010, Beech et al (2).
CURRENT SITUATION

There are several well established procedures and variations of these used for butt fusion welding PE pipes. There are distinct differences between the procedures which have been developed mostly on a national basis. It is recognised that the industry needs accepted international standards for harmonised fusion procedures, test methods, and site codes of practice including NDT techniques in order to promote the use of large diameter PE systems.

The ISO 21307 (3) Butt fusion procedures standard has been developed, which brings the European Single Pressure, the UK Dual Pressure, and the USA High Pressure procedures into one document. There is a significant difference between each of these procedures, but they each have a successful track record. These will be referred to as the Single Low Pressure (SLP), Dual Low Pressure (DLP), and Single High Pressure (SHP) fusion procedures in the future revision of ISO 21307 currently being discussed. For the SLP procedure, the pipes are brought together and held at a pressure of 0.15 MPa whilst cooling. The DLP fusion procedure is performed at the same pressure, but the pressure is reduced to 0.025 MPa during cooling. The SHP procedure has some similarity to the SLP procedure but a much higher pressure of 0.517 MPa is used for fusion and during cooling.

Test methods for butt fusion welds are perhaps more confusing and potentially more misleading than the procedures used! Methods exist in ISO, European and many national and industry standards. Short term destructive tests used include a variety of tensile tests on small specimens cut from the weld, impact tests, pressure tests and tensile tests on whole pipe assemblies. Long term tests include creep tests on full thickness specimens, Full Notch Creep Tests and pressure tests.

TEST PROGRAMME TO EVALUATE TEST METHODS

The key to success for this PE 100+ Association project has been the evaluation of test methods to fully understand short term and long term properties of the welds. Some of the test methods currently used are misleading, and may not be applicable to the full range of wall thickness of pipe used nowadays. An important aim of this project is to evaluate welds in large diameter thick walled pipe with a range of wall thicknesses.

A 1200 mm SDR 17 (70.6 mm nominal wall thickness) pipe produced from a PE 100+ listed material was kindly supplied by Egeplast DE. Rings of full 70.6 mm, 50 mm, and 30 mm wall thickness ends were machined by Reinert Ritz. Welds were prepared from the rings using the Single Low Pressure (SLP) (DVS 2207-1) (4), the UK WIS 4-32-08 Dual Low Pressure (DLP) procedure (5), and the Single High Pressure (SHP) USA procedure as specified in ISO 21307 (3). In addition, for comparison a ‘Poor Weld’ was produced using a lower temperature and heat soak time.
SHORT TERM TESTS

The Project Steering Group selected the UK Water Industry Specification Tensile test specified in WIS 4-32-08 (5) and the German DVS Technological Bend test specified in DVS 2203-5 (6) and equivalent EN 12814-1 (7).

The WIS test includes energy measurement as well as an assessment of the fracture surface. Fig.1 shows the basic geometry of the test specimen. Results for absorbed energy are dependent on the aspect ratio of width of the waist to thickness as reported by Hill et al (8). This means that data obtained for absorbed energy at any aspect ratio may be corrected for the effects of aspect ratio by dividing results for absorbed energy by aspect ratio. This may then be used to compare results in all sample sizes. For thicker walled pipe the overall width of the grip area is increased to avoid slippage. The test is carried out at a speed of 5 mm/min at 23°C.

The Bend tests are carried out on both inner and outer weld beads. Decreasing temperature can be used to assess the onset of brittle behaviour. The wall thickness of the test pieces with reduced thickness (50 mm and 30 mm) were milled to the same thickness over the total length of the test piece. Distance between the supports for thickness 70 mm, 50 mm and 30 mm was respectively 375 mm, 260 mm, and 160 mm to give the same outer fibre stress. The specimen as shown in fig.2 is deflected at a crosshead speed of 50 mm/min and the test is stopped after reaching a maximum angle of 100° if no failure has occurred. Tests were carried out at 0 °C, and -10 °C in some cases to try to promote or confirm brittle behaviour.
LONG TERM TESTS

The Tensile Creep test in accordance with EN 12814-3 (9) and DVS 2203-4 (10), is used extensively in Germany and Scandinavia, and was selected as the principle test to evaluate the long term properties of the welds. In addition the ISO 16770 Full Notched Creep Test (FNCT) on 10 mm by 10 mm square bars with the notch located at the centre of the heat affected zone of the weld has been used to develop a correlation of failure time of the Creep test with lifetime. It is noted that another version of the FNCT test carried out on cylindrical test specimens cut from welds to assess crack initiation is being developed by GDF SUEZ Research and Innovation Division for the evaluation of the slow crack growth performance of buttfusion welds, Gueugnaut et al (11).

The Creep test specimen is subject to a constant tensile load of 2.5 MPa at 90 °C, in an aqueous solution with 2% wetting agent to accelerate failure, ie a mixture of anionic and cationic detergents termed ‘NM5’. For this test programme, the specimen was milled to give a parallel gauge length of full wall thickness and equal width, both weld beads being retained. Initiation normally occurs in the notch formed between the weld bead and the pipe, and should propagate into the pipe material, see fig.3. However in poor welds the crack tends to propagate into the fusion zone, Hessel et al (12). The examination of the mode of crack propagation is used to assess the weld but time to failure is taken into account also.

![Fig. 3 Tensile Creep test specimen showing crack propagation and growth initiating at the weld bead and propagating into the pipe material before fracture](image)

Test Results

Results of the programme using the WIS Tensile tests and the Bend tests on the full range of welds produced are shown in Table 1. The energy values given for the WIS tests are an average of 5 or 6 tests. For the Bend tests 4 samples with the inner bead and 4 samples with the outer bead were tested. In both cases samples have been evenly spaced around the circumference of the welds. A comparison of weld yield stress with parent pipe measured by using WIS Tensile specimen is given in Table 2. The results of the Creep tests carried out are given in Table 3.
<table>
<thead>
<tr>
<th>Weld</th>
<th>Thickness</th>
<th>WIS Energy (KJ/m²)</th>
<th>Bend Failure Mode (at 0 °C)</th>
<th>Bend Failure Mode (at -10 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLP</td>
<td>70 mm</td>
<td>383 - Mixed</td>
<td>X 1 Inner – Ductile</td>
<td></td>
</tr>
<tr>
<td>SLP</td>
<td>50 mm</td>
<td>375 - Mixed</td>
<td>No failure</td>
<td></td>
</tr>
<tr>
<td>SLP</td>
<td>30 mm</td>
<td>329 - Ductile</td>
<td>X 1 Outer – Ductile</td>
<td></td>
</tr>
<tr>
<td>DLP</td>
<td>70 mm</td>
<td>817 - Ductile</td>
<td>No failure</td>
<td></td>
</tr>
<tr>
<td>DLP</td>
<td>50 mm</td>
<td>580 - Ductile</td>
<td>No failure</td>
<td></td>
</tr>
<tr>
<td>DLP</td>
<td>30 mm</td>
<td>306 - Ductile</td>
<td>No failure</td>
<td></td>
</tr>
<tr>
<td>SHP</td>
<td>70 mm</td>
<td>481 - Mixed</td>
<td>No failure (x 4)</td>
<td>No failure (x 4)</td>
</tr>
<tr>
<td>SHP</td>
<td>50 mm</td>
<td>366 - Mixed</td>
<td>No failure (x 4)</td>
<td></td>
</tr>
<tr>
<td>SHP</td>
<td>30 mm¹</td>
<td>180 - Brittle</td>
<td>X 1 Outer – Brittle</td>
<td>X 1 Inner - Brittle</td>
</tr>
<tr>
<td>Poor</td>
<td>50 mm</td>
<td>218 - Brittle</td>
<td>X 1 Inner – Mixed</td>
<td>X 2 Outer - Brittle</td>
</tr>
<tr>
<td>Poor</td>
<td>50 mm</td>
<td>271 - Brittle</td>
<td>X 1 Inner – Mixed</td>
<td>X 1 Inner - Brittle</td>
</tr>
</tbody>
</table>

¹ Weld contaminated (see discussion of test results)

Table 1 Results of the short term tests.

![Dual Low Pressure](image1)

![Single Low Pressure](image2)

![Single High Pressure](image3)

!['Poor' weld](image4)

Fig.4 WIS Tensile test fracture surfaces for 50 mm welds
<table>
<thead>
<tr>
<th>Test specimen</th>
<th>Yield stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent pipe</td>
<td>28.3 MPa</td>
</tr>
<tr>
<td>Single Low pressure</td>
<td>27.0 MPa</td>
</tr>
<tr>
<td>Dual Low pressure</td>
<td>26.7 MPa</td>
</tr>
<tr>
<td>Single high Pressure</td>
<td>25.9 MPa</td>
</tr>
<tr>
<td>Poor Weld</td>
<td>26.1 MPa</td>
</tr>
</tbody>
</table>

Table 2 Comparison of weld yield stress with parent pipe

<table>
<thead>
<tr>
<th>Weld</th>
<th>Thickness</th>
<th>Failure Mode</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLP</td>
<td>70 mm</td>
<td>Propagation from both beads, partly into fusion zone</td>
<td>7384</td>
</tr>
<tr>
<td>SLP</td>
<td>50 mm</td>
<td>Propagation from outer bead¹</td>
<td>2352</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Propagation from inner bead¹</td>
<td>2855</td>
</tr>
<tr>
<td>SLP</td>
<td>30 mm</td>
<td>Propagation from inner bead¹</td>
<td>3306</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Propagation from inner bead¹</td>
<td>4624</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Propagation from defect in fusion plane²</td>
<td>997</td>
</tr>
<tr>
<td>DLP</td>
<td>50 mm</td>
<td>Propagation from inner bead¹</td>
<td>1554</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Propagation from inner bead¹</td>
<td>1976</td>
</tr>
<tr>
<td>DLP</td>
<td>30 mm</td>
<td>Propagation from inner bead¹</td>
<td>1303</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Propagation from both beads¹</td>
<td>2829</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Propagation from inner bead¹</td>
<td>1817</td>
</tr>
</tbody>
</table>

¹ Propagation into parent pipe indicating good fusion
² Subject to further investigation

Table 3 Failure mode and time to failure in the DVS Creep test

**FNCT Lifetime Correlation**

To achieve this aim, FNCT tests were carried out on samples cut from the centre of the welds to make a correlation with Creep test results and to assess lifetime. This method is outlined in DVS 2203-4 Supplementary Sheet 3 (13). Three FNCT specimens are tested from each weld at 4 MPa in NM5 detergent at 90°C.

The results are given in Table 4, and fig.5 shows a lifetime correlation by relating test conditions to service conditions.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>SLP</th>
<th>DLP</th>
<th>SHP</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 mm</td>
<td>36.2</td>
<td>43.7</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td>50 mm</td>
<td>41.4</td>
<td>35.7</td>
<td>32.7</td>
<td>21.1</td>
</tr>
<tr>
<td>70 mm</td>
<td>57.9</td>
<td>47.7</td>
<td>32.8</td>
<td></td>
</tr>
</tbody>
</table>

¹ Defect in one test piece

Table 4 FNCT results for the range of welds (4 MPa, 90 °C, 2% NM5)
The minimum service life of the butt welds tested has been estimated in accordance with Vogt et al (14). The lifetime correlation is based on the lowest result of 1303 h for the DLP 30 mm Creep test specimen. The curve for FNCT stress versus failure time on samples from pipe has been determined, see fig.5 (Step 1). A similar curve is assumed for Creep testing using the selected result as a basis. A minimum curve has been determined by conservatively lowering the latter curve by a time factor of 3 to take into account scatter in accordance with DVS 2203-4 (13), see fig.5 (Step 2).

Equation of Activation Energy:-

\[ E_A = 1,9152 \times 10^{-2} \cdot \log \left( \frac{t_1}{t_2} \right) \cdot \left( \frac{1}{T_1} - \frac{1}{T_2} \right) \]

- \( E_A \) - Activation Energy (90 kJ/mol)
- \( t_1, t_2 \) - Rupture time (h)
- \( T_1, T_2 \) - Absolute temperature (K)
The prediction is based on the maximum longitudinal stress of 4 MPa, a result of the maximum design hoop stress of 8 MPa for an unrestrained PE 100 pipeline. A time of 38 h is predicted at 4 MPa, 90 °C in NM5, see fig.5 (Step 3). Previous work by Hesseltechnik has shown that for the NM5 detergent, a factor of 40 is applicable to estimate the corresponding time in water. This gives an estimated time of 1520 h at 90 °C, equivalent to 215 years at 20 °C in water, see fig.5 (Step 4).

Based on this lifetime calculation, it can be safely concluded that for water and gas applications at 20 °C, a properly made PE 100 butt fusion joint is predicted to achieve a service life in excess of 100 years.

**DISCUSSION**

The WIS Tensile test results show a trend of higher energy values related to more ductile fracture surfaces, with mixed or brittle behaviour indicated by lower energy values. This test is well developed and is suitable for assessing thicker walled pipe, even on site. These findings were confirmed by the Bend test results in which a mixture of mostly no failure and brittle failures were achieved in the welds. When using the Bend test, tests at lower temperatures can be used to find a change in behaviour.

Both the ‘Poor’ and the Single High Pressure procedure 30 mm welds gave the lowest energy values and brittle failure in the WIS tests, confirmed by brittle behaviour in some of the Bend test specimens. The inferior behaviour of the ‘Poor’ weld was expected as it is classed as a cold weld made at a lower temperature and heat soak time. However the behaviour of this SHP procedure weld indicated that something was wrong with the preparation of the weld. Subsequently it was found that the 30 mm rings were machined using a cutting fluid which contaminated the material and was indicated by bubbling in the weld beads. Good quality of the 50 mm and 70 mm SHP procedure welds was indicated by the energy values and no failures in the Bend tests at 0 °C, and even at -10 °C for the 70 mm weld. However the WIS sample fracture surfaces were mixed ductile/brittle in appearance. Similar performance was seen for the 50 mm and 70 mm Single Low Pressure procedure welds, but the 30 mm weld gave higher energy values and a more ductile fracture appearance. The reason for a ductile failure in the Bend test on a 70 mm and a 30 mm test specimen for this procedure cannot be explained, but the fact that ductility was exhibited is reassuring. The Dual Low Pressure 30 mm weld gave a slightly lower energy value, but the 50 mm and 70 mm weld energy values were higher than for the other two procedures. The fracture surfaces for these DLP test specimens were more ductile in appearance compared with those made by the other procedures, and no failures occurred in the Bend tests on these welds, see fig.4. Measurement of yield stress demonstrated that no significant reduction was seen for the all welds compared with the parent pipe.

The failure mode in the Creep tests for the 30 mm and 50 mm test specimens from the Single Low Pressure and Dual Low Pressure welds confirms the expected crack initiation point at the stress concentration between the bead and the parent material.
This was followed by crack propagation into the parent pipe material, and not into the fusion zone or the interface between the heat affected zone and the pipe, indicative of good quality, (12). All specimens show behaviour indicative of slow crack growth accelerated by the detergent media. The test performed on one 70 mm specimen (Single Low Pressure) failed after a much longer rupture time by propagation from both inner and outer beads and partly into the fusion zone, and the failure time is indicative of thermal ageing (13). However the result is not considered reliable because the required load was at the limit of the test equipment. A change of specimen geometry or scaling up of test equipment will be required if the test is to be used for such wall thickness in the future. The times to failure in the Creep tests of the DLP samples were generally lower than the SLP test specimens. FNCT tests have been used to understand what these results mean in terms of lifetime. Table 4 gives the results for the full range of welds. Generally the times to failure for the FNCT tests on the SLP and DLP welds are comparable, but the lower results in the Creep tests of the DLP welds might be explained by the presence of the weld beads on the test specimens. The SHP FNCT times on the 50 mm and 70 mm welds are lower but not significantly. It is reassuring that no reduction in performance was seen for the thicker welds made by all three procedures, and in fact the highest results were obtained for the full 70 mm thickness welds made by each of the procedures.

The FNCT times to failure of the SHP 30 mm weld and the ‘Poor’ weld of 15,9 h and 21,1 h respectively were well below the results of the other welds, > 32,7 h. Therefore it can be assumed that the lifetime of such welds in terms of resistance to slow crack growth are compromised and considered to be unacceptable. The short term tests indicated that there was a problem with these welds and this is confirmed by these FNCT results. Site quality assurance should be used to identify such problems during the initial stages of installation in order to reject such welds. Removal and twisting of weld beads and destructive short term tests on dummy welds made on site should be used to confirm the procedure and quality of the welds.

To assess the meaning of the Creep and FNCT tests in terms of lifetime, a correlation has been carried out by Hesseltechnik (15). Even taking the conservative approach of basing a minimum curve on the lowest failure time of 1303 h in the Creep test lowered by a factor of 3, a lifetime well in excess of design lifetime is predicted. The prediction of 215 years at 20 °C in water for the butt fusion weld gives assurance that a lifetime in excess of 100 years can be safely expected for service. The same correlation based on FNCT of 30 h predicts 168 years. Therefore this prediction can be applied to properly made welds made by all three procedures, demonstrated by the FNCT results all exceeding this level. In reality the joints in a buried pipeline will be restrained by the earth and longitudinal stresses will be significantly lower.

NDT OF PE BUTT WELDS

All the tests discussed in this paper are destructive and therefore only a limited number of welds taken from site could be tested in this way. The question of availability of NDT
techniques for testing of PE welds is often raised by contractors and end users. The establishment of accepted procedures by the industry will be a major benefit for the promotion of use of large diameter polyethylene pipeline systems.

For many years manufacturers of ultrasonic NDT equipment have tried to develop systems to assess plastics welds. Whilst it might be possible to detect voids in PE butt welds, these are not normally an issue. It is the structure and behaviour of the material of the heat affected zone of the weld that is important, Scholten and Jae (15). Examination and analysis of weld beads does provide a deal of information in experienced hands. The size and uniformity of the weld beads can reveal any misalignment of the pipe, twisting or tearing the beads apart can reveal brittle behaviour, and bubbles or protrusions in the weld beads can indicate the presence of moisture or contamination. Thermal analysis techniques may be useful to assess the material properties of the weld bead and any presence of degradation. These topics are being discussed by the Project Steering Group.

Microwave Imaging is a showing promise as an NDT technique for butt fusion welds, and has been tried with some success on welds made for this project, reported by Murphy and Lowe at PPXV (16).

CONCLUSIONS

- Lifetime of properly made welds in a pipeline system using the three procedures evaluated is estimated to be well in excess of 100 years.
- The tests demonstrate that good performance welds can be obtained by the three procedures for thickness up to 70 mm, but the Single High Pressure weld test samples are less ductile in appearance.
- The short term tests used are capable of characterising welds and detecting brittle welds of unacceptable quality.
- Lower resistance to slow crack growth measured by the FNCT test is related to poor performance and brittle behaviour seen in the short term tests.
- There was no deterioration of performance over the thickness range tested of welds made from each procedure.
- With further consideration it should be possible to define limits of acceptability of performance using the test methods described.
- The development of microwave imaging used as an NDT technique for assessing butt fusion welds is showing promise.
- The results of this project indicate that rationalisation and some harmonisation of the three procedures could take place, if the industry is willing to do this.
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