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SHORT-TERM AND LONG-TERM MECHANICAL TESTING TO EVALUATE THE EFFECT OF FLAWS IN BUTT FUSION JOINTS IN POLYETHYLENE PIPES

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ABSTRACT

The use of non-destructive examination (NDE) for assessing the quality of butt fusion joints in polyethylene (PE) pipes has been included in the draft Mandatory Appendix XXVI to Section III of the ASME Boiler and Pressure Vessel Code (Rules for construction of Class 3 buried polyethylene pressure piping). However, currently, there are no acceptance criteria for flaws in butt fusion joints in PE pipes. There is an ASME Task Group on flaw evaluation for PE pipe, which is developing a code case using linear elastic fracture mechanics (LEFM) to determine critical flaw sizes. However, the initial experimental crack growth data generated suggests that linear elastic fracture mechanics is not able to adequately describe slow crack growth in PE materials. In addition, this work is only considering planar lack of fusion flaws in the joint; it is not considering other critical flaw types that can occur in butt fusion joints, such as particulate contamination and cold fusion.

TWI has developed procedures using mechanical testing to develop flaw acceptance criteria for butt fusion joints in PE pipes. This is based on inserting lack of fusion flaws of known size and particulate contamination flaws of known concentrations into butt fusion joints and determining the effect of these flaws on both the short-term and long-term integrity of the joints. An important aspect of this work is to determine which of the wide array of mechanical tests available for assessing the integrity of butt fusion joints in PE pipes are the most discriminating.

This paper describes the procedures developed for inserting simulated flaws into butt fusion joints in PE pipes, the experimental work to compare the results from different standard short-term and long-term tests on flawed and unflawed joints and the procedures developed to determine flaw acceptance criteria.

Results have shown that the most discriminating short-term test for butt fusion joints in PE pipes is a tensile test using a waisted specimen, such as those defined in EN 12814-2, EN 12814-7 and ISO 13953, and the most discriminating property is the energy to break the specimen. The most appropriate long-term test for butt fusion joints in PE pipes is the whole pipe tensile creep rupture test, as defined in EN 12814-3; this is the only long-term whole pipe test that consistently generates slow crack growth in the fused joint, even if it contains no flaws.

INTRODUCTION

TWI has developed and validated a phased array ultrasonic testing (PAUT) system specifically for inspecting fused joints in PE pipes of diameters between 90 and 800mm and wall thicknesses between 8 and 65mm (1, 2). However, in order for this system to pass or fail a joint, the flaw acceptance criteria must be known.

The acceptance criteria for planar and volumetric flaws in structural materials are normally based on LEFM, where the stress, σ, perpendicular to an infinitely sharp crack is given by:

$$\sigma = \frac{K}{(2\pi r)^{1/2}}$$

where r is the distance from the crack and K is the stress intensity factor. This equation predicts an infinite stress at the crack tip (r=0). However, in reality, materials develop plastic strains when the yield strength is exceeded in the region near a crack tip, which blunts the crack (3). Although there is a very small amount of yielding at the crack tip, the amount of plastic deformation is restricted by the surrounding material, which remains elastic during loading. This assumption allows the use of LEFM for most metals and some brittle plastics.

However, very tough polymers, such as PE pressure pipe grades, produce very large plastic zones due to crazing, which exceed the stress field around the crack tip. The relaxation of the crack tip stresses caused by this yielding phenomenon removes the stress singularity at the crack tip, which is required by the LEFM theory, and therefore compromises its validity (4). This implies that the elastic stress analysis becomes increasingly inaccurate as the plastic region at the crack tip becomes larger and LEFM is no longer useful for predicting critical flaw sizes (5).

An alternative method for determining flaw acceptance criteria in butt fusion joints in PE pipes, which has been employed at TWI, is to use an empirical approach using mechanical testing of joints containing known flaws. Since PE pipe joints have to survive both the service conditions, which involves long-term loads, and pipeline installation, which involves short-term loads, it is important that the effect of flaws on both the long-term and short-term integrity of the joints be assessed.

The procedure used at TWI to determine critical flaw sizes for long-term joint integrity is to carry out accelerated long-term mechanical tests that generate slow crack growth (the long-term failure mechanism for PE) on butt fusion joints containing flaws of known size and also on joints containing no deliberate flaws and generate graphs of flaw size against time to failure on a logarithmic scale, see Figure 1. Since the critical flaw size may well depend on PE resin, wall thickness and fusing procedure it is necessary to produce such graphs for every combination of these variables.

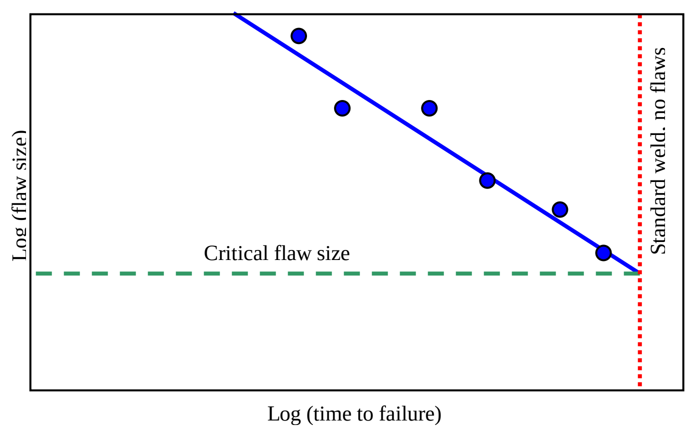

FIG. 1 SCHEMATIC OF A GRAPH USED TO DETERMINE CRITICAL FLAW SIZES FOR LONG-TERM JOINT INTEGRITY

Similarly, the procedure used to determine critical flaw sizes for short-term joint integrity is to generate graphs of a relevant short-term property against log (flaw size), as shown in Figure 2.

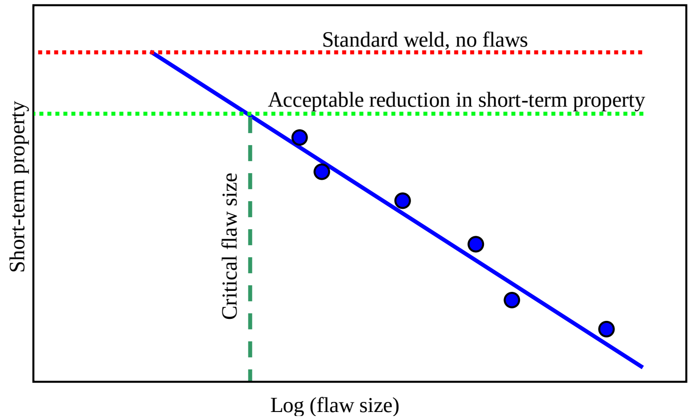

FIG. 2 SCHEMATIC OF A GRAPH USED TO DETERMINE CRITICAL FLAW SIZES FOR SHORT-TERM JOINT INTEGRITY

The question is then, which mechanical tests should be used to determine critical flaw sizes? Obviously, in order to generate graphs such as those shown in Figures 1 and 2, the chosen mechanical test must be able to define a property that changes significantly with the size of the flaw; the more discriminating the test, the better.

MECHANICAL TESTS FOR BUTT FUSION JOINTS

The PE pipes industry uses a number of different mechanical tests to verify the quality of butt fusion joints, depending on the industry and country. For example, in the US a manual bend test is defined in ASTM F2620 (6) and a high-speed tensile impact test is also commonly specified, as defined in ASTM F2634 (7). In the UK, a tensile test using a waisted test specimen is defined in WIS 4-32-08 (8) and in Germany a technological bend test is defined in DVS 2203-5 (9), a tensile test is defined in DVS 2203-2 (10) and a tensile creep test is defined in DVS 2203-4 (11). There are also a number of international standards that specify mechanical test methods for butt fusion joints in PE pipes, including ISO 13953 (12), EN 12814-1 (13), EN 12814-2 (14), EN 12814-3 (15), EN 12814-6 (16) and EN 12814-7 (17). In addition, in most specifications for butt fusion joints in PE pipes, hydrostatic pressure testing, both short-term and long-term, are defined.

Bend Tests

A typical bend test, such as the one defined in EN 12814-1, uses a parallel-sided test specimen, an example of which is shown in Figure 3. This is then subjected to a three-point bend, as shown in Figure 4. In this standard, the tests are performed at room temperature, using a ram displacement velocity of 50mm/min. The ram displacement or bend angle at which either fracture occurs or a crack appears is measured.

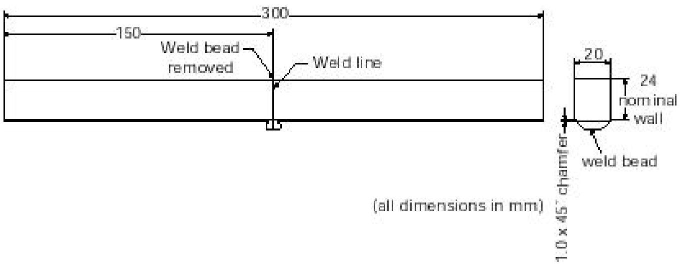

FIG. 3 TYPICAL GEOMETRY AND DIMENSIONS OF BEND TEST SPECIMEN, AS DEFINED IN EN 12814-1

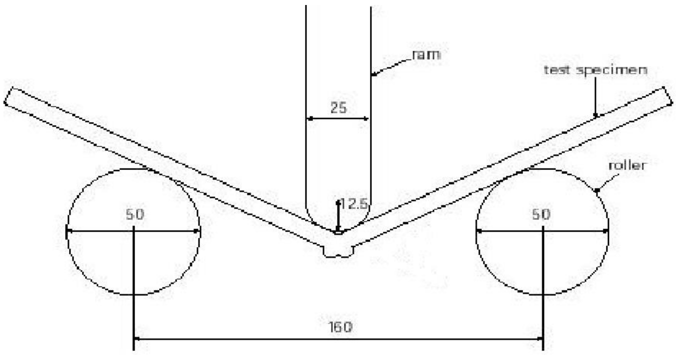

FIG. 4 SCHEMATIC DIAGRAM OF BEND TEST AS DEFINED IN EN 12814-1

Tensile Tests

There are a number of tensile test specimen geometries, the most common are: parallel-sided, dumb-bell or dog-bone, and waisted. A typical dumb-bell specimen geometry is shown in Figure 5.

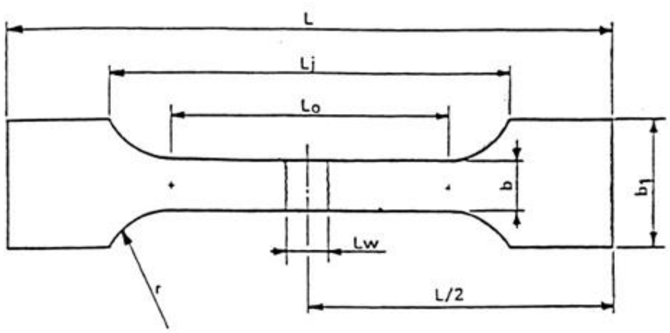

FIG. 5 TYPICAL GEOMETRY OF DUMB-BELL TENSILE TEST SPECIMEN, AS DEFINED IN EN 12814-2

In EN 12814-2 the tests are carried out at room temperature, using a crosshead speed of 50mm/min. Both fused and parent pipe reference specimens are tested and a short-term tensile welding factor, f_s, is then determined, defined as:

$$f_s = \frac{\text{yield strength of fused specimen}}{\text{yield strength of parent material}}$$

A typical waisted tensile test specimen is shown in Figure 6.

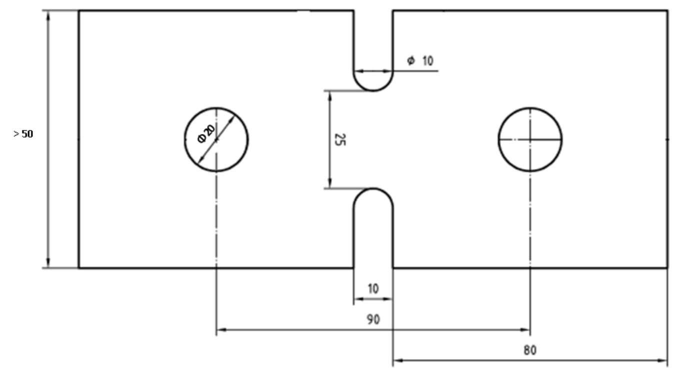

FIG. 6 TYPICAL GEOMETRY OF WAISTED TENSILE TEST SPECIMEN, AS DEFINED IN EN 12814-7

In ISO 13953, the tests are carried out at room temperature and at a constant speed of 5±1mm/min. The failure mode (ductile or brittle – see Figure 7) and tensile strength are used as criteria for the evaluation of the joint.

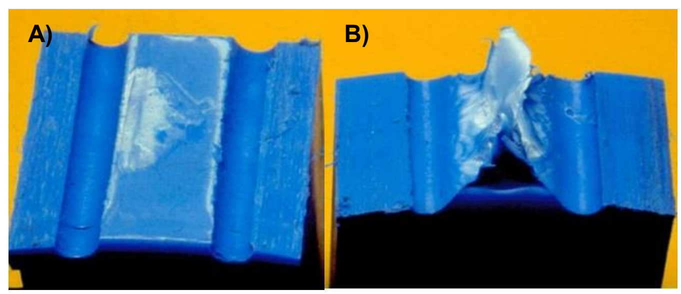

FIG. 7 EXAMPLE OF: A) BRITTLE FAILURE AND B) DUCTILE FAILURE IN A TENSILE TEST WITH A WAISTED SPECIMEN GEOMETRY

In EN 12814-7, the specimen extension is measured using an extensometer and the energy to break the specimen is calculated from the area under the load vs extension curve. Specimens are cut from both the butt fusion joint and the parent pipe and a tensile energy welding factor, f_e, is calculated, where:

$$f_e = \frac{\text{average energy to break of fused specimens}}{\text{average energy to break of specimens from parent pipe}}$$

High Speed Tensile Impact Test

The testing of butt fusion joints in tensile impact mode is defined in ASTM F2634. The specimen geometry and dimensions are given in Figure 8. The speed of the test is 6 inches/s for wall thicknesses between 0.25 and 1.25 inches, and 4 inches/s for wall thicknesses greater than 1.25 inches. Specimens are tested to failure and the energy to yield and to break are calculated, and the failure mode (ductile or brittle) is recorded.

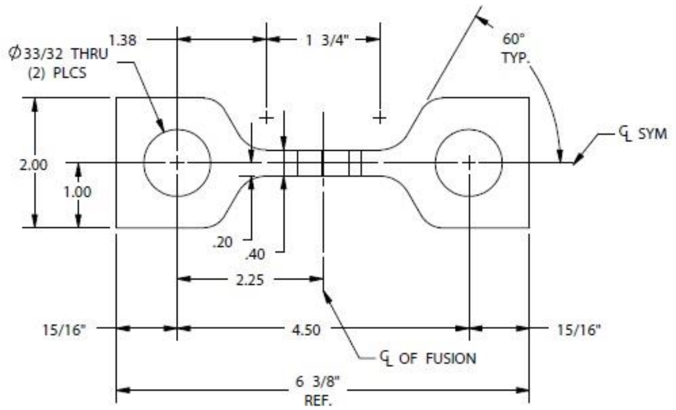

FIG. 8 HIGH SPEED TENSILE IMPACT TEST SPECIMEN GEOMETRY, AS DEFINED IN ASTM F2634

Coupon Creep Rupture Test

The main standardized test method for determining the long-term performance of welded PE specimens is the tensile creep test according to EN 12814-3 or DVS 2203-4. This is basically a stress rupture test in which dumb-bell specimens are subjected to a constant load at elevated temperature (normally 80°C) and the time to failure is recorded. A schematic of the test equipment is shown in Figure 9.

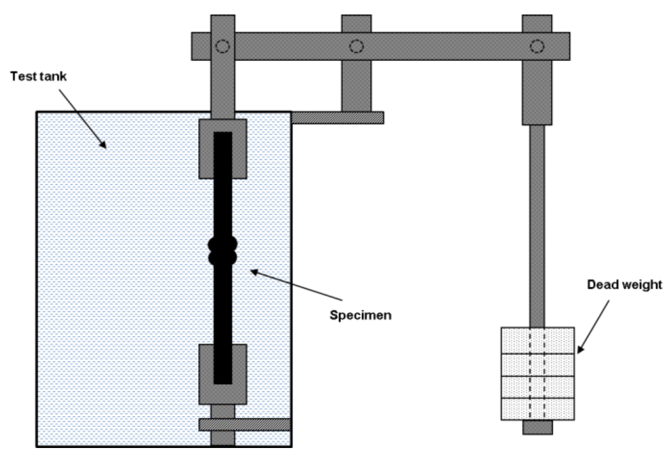

FIG. 9 TENSILE CREEP RUPTURE TEST RIG, ACCORDING TO EN 12814-3

Tests are performed over a range of stresses in order to generate creep rupture curves for both fused and unfused specimens. A long-term welding factor, f_1, is determined from the ratio of the two stress values at which equal lifetime of the fused specimen and specimen from the parent pipe was obtained (see Figure 10).

In order to shorten the duration of the test, a surface active medium and/or higher test temperature can be used.

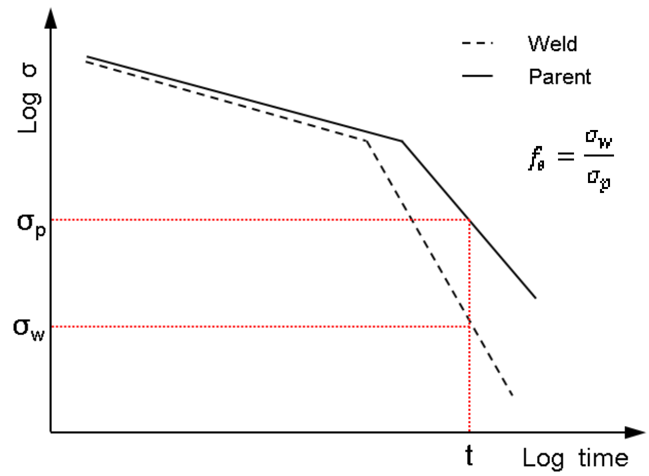

FIG. 10 TYPICAL CURVES FOR THE COUPON CREEP RUPTURE TEST

Hydrostatic Pressure Tests

Short-term hydrostatic pressure tests, or hydro-tests, are normally specified during pipeline installation in order to prove that the system is leakproof (18). These tests typically involve pressurizing the welded pipeline, or section of pipeline, with water to a pre-determined level. This pressure is then maintained for a period of time (typically 30 minutes) by injecting additional water to allow for creep in the material. After this time, the pressure is locked and the decay, due to further creep of the pipeline, is monitored over time (typically 60 minutes). This pressure drop must not be greater than a pre-set value in order to pass the test.

Long-term hydrostatic pressure tests are used for assessing the long-term behavior of pipes containing fused joints under internal pressure at elevated temperature and are defined in the standard EN ISO 1167 (19). Fused pipe samples are closed using end caps, filled with water and subjected to an internal hydrostatic pressure and an elevated temperature (typically 80°C). The time to failure is measured and the position of failure recorded.

Whole Pipe Tensile Creep Rupture Test

This test was developed at TWI (20) specifically to determine the long-term performance of butt fusion joints in PE pipes. In this test, which is defined in Annex B of EN 12814-3, a welded whole pipe sample is subjected to a constant axial tensile load, in water at 80°C. A schematic of the test equipment is shown in Figure 11. The load is applied by a hydraulic jack and transferred to the end of the pipe via a push rod. The time to failure is recorded for a specific test load and the location of failure noted.

The advantage of this test over the coupon creep rupture test is that all of the residual stresses in the joint are retained, which is more representative of the pipe's stress state in service.

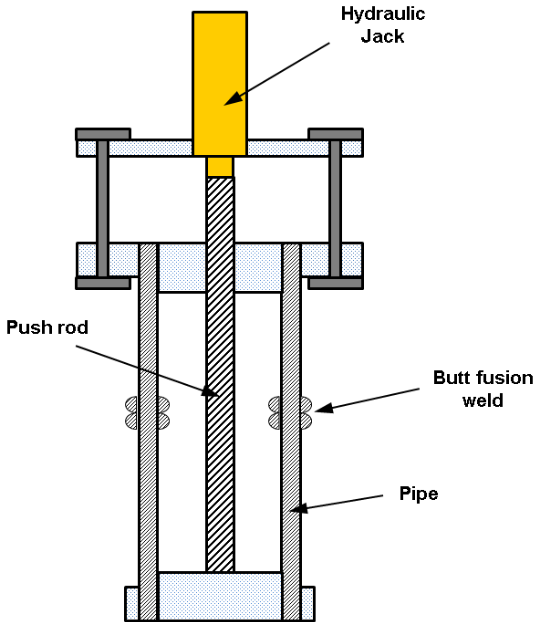

FIG. 11 WHOLE PIPE TENSILE CREEP RUPTURE TEST, ACCORDING TO ANNEX B OF EN 12814-3

TYPES OF FLAWS IN BUTT FUSION JOINTS AND FLAW INSERTION PROCEDURES

The main types of flaws in butt fusion joints that are of interest to the plastics pipes industry (1) are listed below:

- Cold fusion (incompletely fused joint);
- Fine particulate contamination (airborne dust);
- Planar flaws (caused by fingerprints, oil and grease, perspiration, rain droplets, etc);
- Coarse particulate contamination (sand, grit, dirt).

It is useful to note that only one of these types of flaw, planar flaws, is being addressed by the ASME Task Group on flaw evaluation for PE pipe. However, particulate contamination can also be addressed using the empirical approach suggested in this paper, by replacing flaw size in Figures 1 and 2 with contamination level.

In order to determine the flaw acceptance criteria from mechanical tests, it is necessary to know the actual size of the planar flaw or the actual quantity of particulate contamination in the joint. For this reason, TWI has developed procedures for inserting idealized simulations of actual flaws into butt fusion joints in PE pipes.

Fine particulate contamination is simulated using micronized talc, with a particle size < 45µm, this is introduced into the butt fusion joint by applying it to the end of one of the pipes using a soft-haired brush, after the pipe ends have been trimmed. Different nominal loadings of talc are applied (see Figure 12) and the uniformity of coverage is assessed visually.

Coarse particulate contamination is simulated using graded natural silica sand (particle size: 150-300µm). This is introduced into the butt fusion joint by placing the trimmed end of one of the pipes to be fused into a fluidized sand bed (Figure 13). The sand becomes attached to the PE pipe surface due to electrostatic forces. Again, different nominal loadings of sand are applied (Figure 14) and the uniformity of coverage is assessed visually.

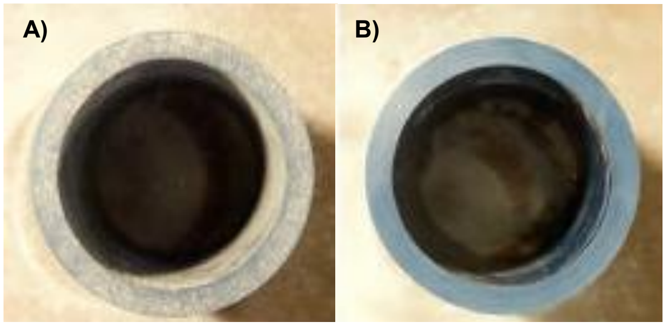

FIG. 12 EXAMPLES OF TALC CONTAMINATION LEVELS: A) HEAVY AND B) LIGHT

FIG. 13 APPLICATION OF COARSE PARTICULATE CONTAMINATION ON TO THE END OF A PE PIPE USING A FLUIDIZED SAND BED

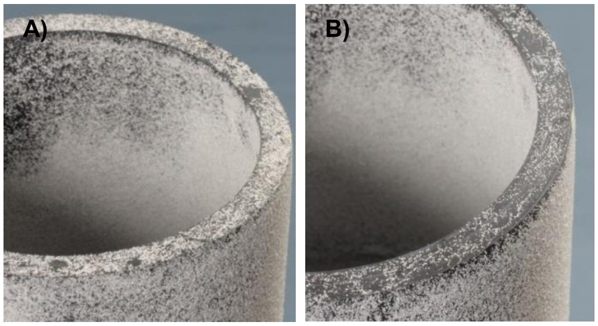

FIG. 14 EXAMPLES OF SAND CONTAMINATION LEVELS: A) HEAVY AND B) LIGHT

QUANTIFICATION OF PARTICULATE CONTAMINATION LEVELS

In order to quantify the actual percentage area of the joint contaminated, full thickness specimens were cut from the fused joint (Figure 15) and analysed using micro computed tomography (μCT).

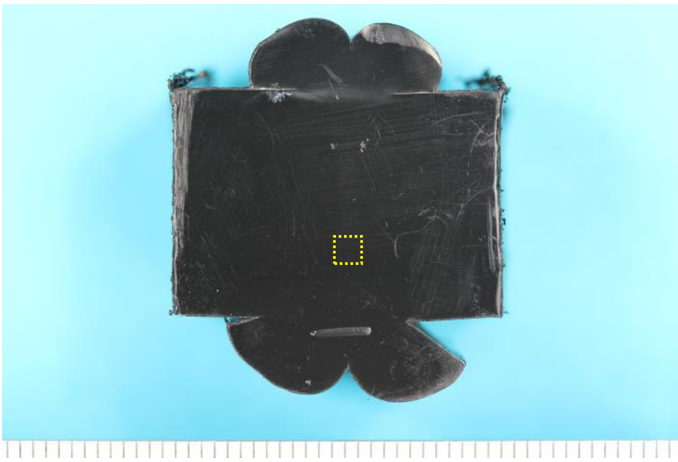

FIG. 15 PARTICULATE-CONTAMINATED BUTT FUSION SPECIMEN FOR μCT ANALYSIS

Micro computed tomography is a powerful analysis technique that produces two- and three-dimensional images of an object, showing up characteristics of its internal structure. The principles of the operation are shown in Figure 16.

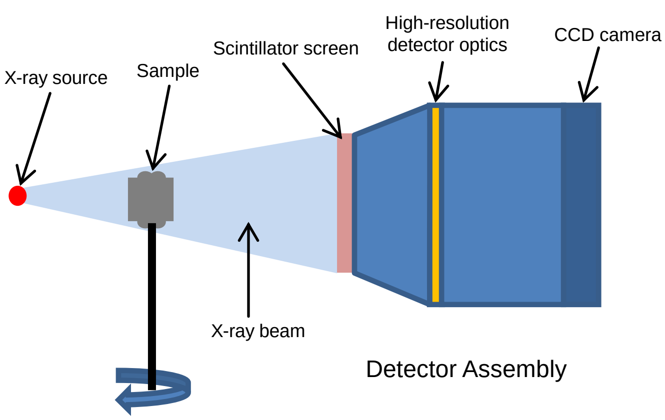

FIG. 16 PRINCIPLE OF COMPUTED TOMOGRAPHY

The specimen is placed on a rotating table between the X-ray source and a detector. X-rays are emitted from the source and penetrate the specimen. Due to internal features within the specimen, such as contamination, some of the X-rays are specifically scattered and absorbed. These effects are recorded by a detector, which contains a scintillator that converts the X-rays into visible light, which is then magnified using high resolution optics and detected using a CCD camera. The rotation of the specimen is divided into a certain number of projections in which the specimen is penetrated by the X-rays. At the end of the scan, all of the projections are combined together and a CT tomograph is generated as a three-dimensional representation of the specimen, through which virtual sections can be taken.

Figure 17 shows a virtual section through the interface of a particulate-contaminated butt fusion joint in the region denoted by the square in Figure 15. Using image analysis software, the percentage area of contamination can be quantified.

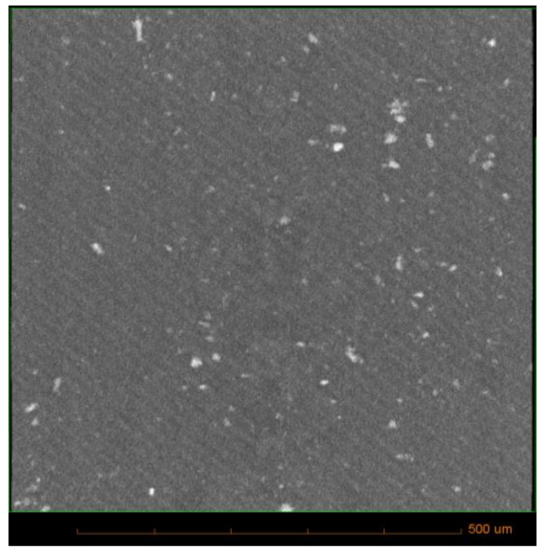

FIG. 17 VIRTUAL SECTION THROUGH A μCT TOMOGRAPH OF A PARTICULATE-CONTAMINATED BUTT FUSION SPECIMEN

COMPARISON OF MECHANICAL TESTS

Previous work at TWI (21, 22) involved making a number of uncontaminated butt fusion joints in 355mm SDR 17.6 PE100 pipe using three very different fusing procedures in order to produce joints with different joint quality:

- Condition 1: Dual pressure procedure, according to WIS 4-32-08 (8);
- Condition 2: As Condition 1, except the bead-up and fusion cylinder pressure was increased from 19 bar to 95 bar and a single pressure cycle was used;
- Condition 3: As Condition 1, except the heater plate temperature was reduced from 230 to 160°C.

These butt fusion joints were then assessed using a number of short-term and long-term mechanical tests. The results of this work are summarized in Table 1 and suggest that the three-point bend test, the tensile test using a dumb-bell specimen and the elevated temperature hydrostatic pressure test are very poor at discriminating between different qualities of butt fusion joint, since none of these tests generated any failures in the joint itself.

Table 1 Results of mechanical tests on butt fusion joints made using different fusing procedures

Test	Property measured	Ranking Cond. 1	Ranking Cond. 2	Ranking Cond. 3
Bend (EN 12814-1)	Maximum bend angle	No weld failures		
Tensile, with dumb-bell specimen (EN 12814-2)	Yield stress	No weld failures, yielded in parent pipe		
	Strain at break			
	Energy to break			
Tensile, with waisted specimen (EN 12814-7)	Maximum load	H	H	L
	Extension at break	H	L	L
	Energy to break	H	M	L
	Failure mode	H	L	H
Coupon creep rupture (EN 12814-3)	Time to failure	M	L	H
Hydrostatic pressure, elevated temperature (ISO 1167)	Time to failure	No weld failures		
Whole pipe tensile creep rupture (EN 12814-3)	Time to failure	M	H	L

H = Highest value, L = Lowest value, M = Middle value

The most discriminating of the short-term tests was the tensile test using a waisted specimen, which, due to the geometry of the test specimen, ensures that failure occurs in the fused joint rather than the parent pipe. All of the properties measured suggested that Condition 1 produced joints with the highest short-term integrity. However, only the energy-to-break value could distinguish between the three different fusing conditions.

Regarding the long-term performance, both the coupon creep rupture test and the whole pipe tensile creep rupture test could distinguish between the different fusing conditions. However, the ranking of the different procedures was different for the two tests. This is probably due to a combination of the stress constraints and residual stresses in the whole pipe test, which are released when coupons are cut from the fused pipe. Most PE pipes exhibit an inward bending of the pipe walls at the end of the pipe, due to residual stresses caused by unequal cooling of the pipe walls during manufacture. When the pipes are fused 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 joint, will want to expand radially. This will be resisted by tensile hoop stresses, leading to a complex triaxial stress state near the joint line. This will have the effect of locally reducing creep strain ductility. Since the stress distributions in the coupons and whole pipes are different, this suggests that using coupon tests to predict the long-term performance of whole pipe butt fusion joints may give misleading results.

It should also be noted that the rankings from the short-term tests do not agree with those from the long-term tests. This suggests that it is not possible to predict long-term performance from short-term tests. The reason for this is that the short-term and long-term failure mechanisms in PE pipe butt fusion joints are different; in the short term, butt fusion joint will fail due to the tensile strength of the joint whereas, in the long term, failure will be due to the resistance of the joint to slow crack growth.

More recent work at TWI has compared the results from two short-term tests: the tensile test using a waisted specimen and the high speed tensile impact test, on butt fusion joints in PE80 and PE100 pipes containing fine particulate contamination. Three different pipe sizes were investigated:

- 180mm SDR17 PE80;
- 355mm SDR11 PE80;
- 450mm SDR17 PE100.

Specimens were cut from joints that had been made containing three different nominal levels of micronized talc (light, medium and heavy), using the procedure given above. Unfortunately, some of these joints had been used for other tests and therefore it was not possible to obtain specimens from every joint.

In both tests, the energy to break was calculated and the failure mode recorded. In both cases, the energy to break was calculated from the graph of load against cross-head displacement and the value was compared to the average value calculated for uncontaminated joints. In order to prevent elongation of the loading holes during the waisted specimen tests, so that the calculated energy to break was only the energy to break the joint, side plates were bolted to the specimen, as shown in Figure 18.

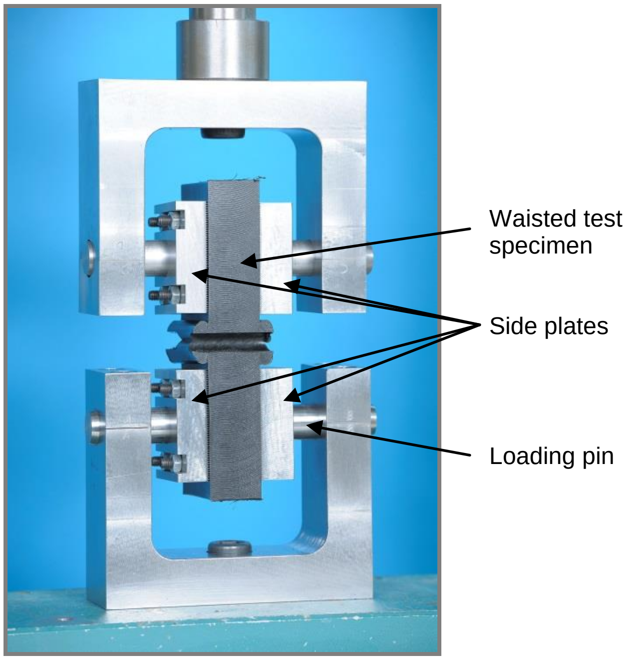

FIG. 18 EXPERIMENTAL SET UP FOR TENSILE TEST WITH WAISTED SPECIMEN

Examples of the failure modes for the high speed tensile impact test are given in Figure 19 and the results of the tests are given in Figures 20-22.

Figure 20 shows that, for the 180mm SDR17 PE80 pipe, even light loadings of fine particulate resulted in a reduction in the energy to break the waisted tensile test specimens by around

70% compared to unflawed joints. This increased to around 90% for higher loadings of talc. In addition, all of the contaminated joints failed in a brittle manner, whereas the unflawed joints all failed in a ductile manner. The results for the high speed tensile impact tests, however, showed that, even with a heavy loading of talc, the specimens still failed in the parent pipe; the energy to break values compared to those for the unflawed joints were related to variations in the parent material properties, not the joint properties. Unfortunately, it was not possible to cut high speed tensile impact test specimens from the joint containing a light loading of talc. However, it would be expected that these would also fail in the parent pipe.

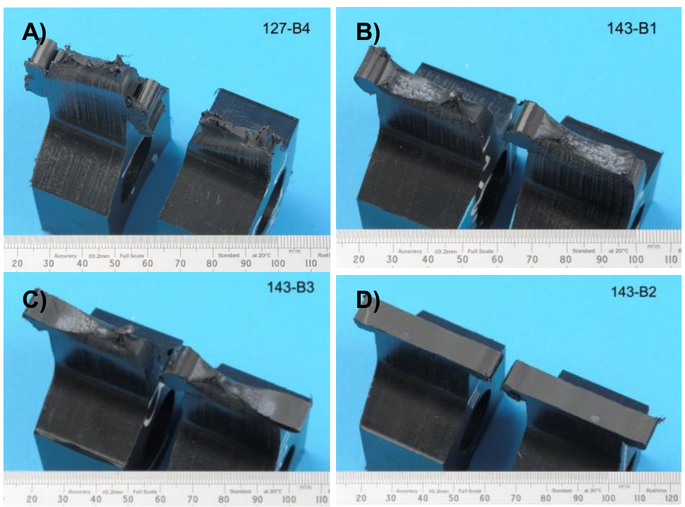

FIG. 19 FAILURE MODES FOR HIGH SPEED TENSILE IMPACT TEST: A) IN PARENT PIPE, B) DUCTILE, C) MIXED AND D) BRITTLE

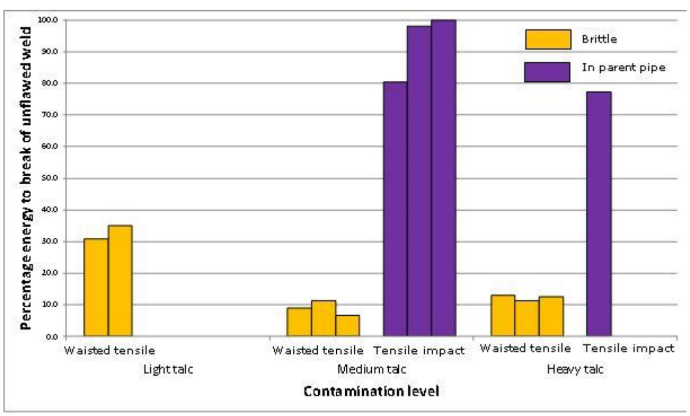

FIG. 20 ENERGY TO BREAK WAISTED TENSILE TEST AND HIGH SPEED IMPACT TEST SPECIMENS FROM TALC-CONTAMINATED BUTT FUSION JOINTS IN 180MM SDR17 PE80 PIPE AS A PERCENTAGE OF ENERGY TO BREAK SPECIMENS FROM UNFLAWED JOINTS

Figure 21 shows the results for the thicker walled 355mm SDR11 PE80 pipe. Again, light loadings of fine particulate resulted in a reduction in the energy to break the waisted tensile test specimens by around 70% compared to unflawed joints, which increased to around 85% reduction for heavy loadings of talc. All of the contaminated joints failed in a brittle manner, whereas all of the unflawed joints failed in a ductile manner. The results for the high speed tensile impact tests, show that, with a heavy loading of talc, the specimens failed in a brittle manner with a reduction in the energy to break of around 65% compared to the unflawed joints. For medium loadings of talc, two of the specimens failed in a brittle manner, with a reduction in energy to break of around 50% and one failed in a ductile manner, with a reduction in energy to break of around 25%. For light loadings of talc, one of the specimens failed in the parent pipe and the other failed in a ductile manner, with a reduction in energy to break of around 20% compared to the unflawed joint.

All of the unflawed joints failed in the parent pipe.

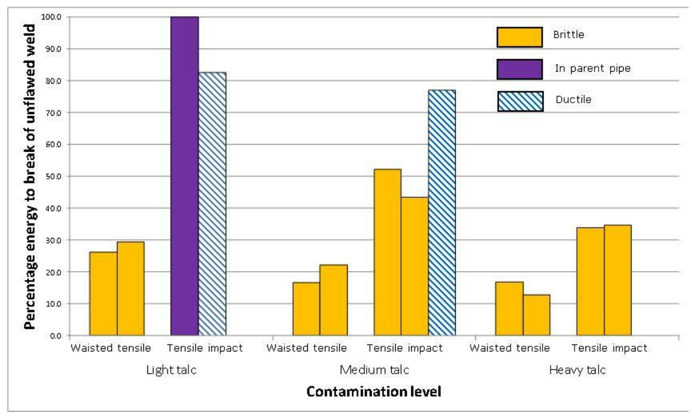

FIG. 21 ENERGY TO BREAK WAISTED TENSILE TEST AND HIGH SPEED IMPACT TEST SPECIMENS FROM TALC-CONTAMINATED BUTT FUSION JOINTS IN 355MM SDR11 PE80 PIPE AS A PERCENTAGE OF ENERGY TO BREAK UNFLAWED JOINTS

Figure 22 shows that, for the 450mm SDR17 PE100 pipe, the waisted tensile test specimens all failed in a brittle manner with a reduction in the energy to break compared with unflawed joints of between 80 and 95%, whereas for the high speed tensile impact test specimens, low levels of contamination had no effect on the test results, with all specimens failing in the parent pipe. For medium loadings of talc, two of the specimens failed in the parent pipe and two failed in the joint in a brittle manner, with a reduction in the energy to break of around 65% compared to the uncontaminated joints. Unfortunately, it was not possible to cut high speed tensile impact test specimens from the joint containing a heavy loading of talc; however, it might be expected that these would have failed in the joint in a brittle manner.

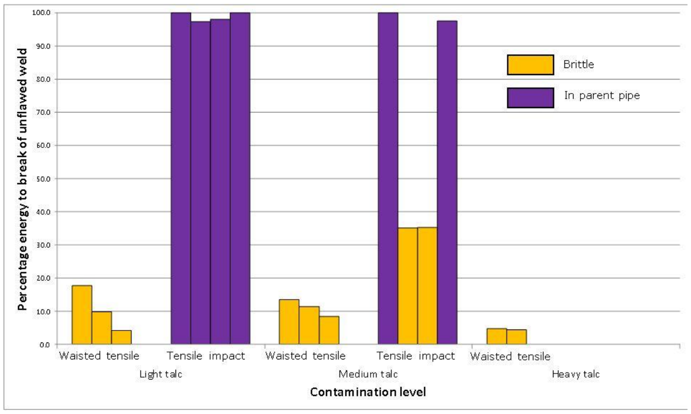

FIG. 22 ENERGY TO BREAK WAISTED TENSILE TEST AND HIGH SPEED IMPACT TEST SPECIMENS FROM TALC-CONTAMINATED BUTT FUSION JOINTS IN 450MM SDR17 PE100 PIPE AS A PERCENTAGE OF ENERGY TO BREAK UNFLAWED JOINTS

CONCLUSIONS

It is believed by the authors that, until a proven fracture mechanics technique has been verified for assessing the significance of flaws in butt fusion joints in PE pipes, the most appropriate method for determining flaw acceptance criteria is an empirical approach where the results of mechanical tests on joints containing planar flaws of different size or particulate flaws of different concentrations are compared with the results of mechanical tests on unflawed joints. Using this method, it is very important to ensure that the mechanical tests chosen to determine the flaw acceptance criteria are able to distinguish between flaws of different size/concentration.

There are a large number of different short-term and long-term mechanical tests available for assessing the integrity of butt fusion joints in PE pipes. Many of these have been compared in this study and the results suggest that the most appropriate short-term test for determining the flaw acceptance criteria is a tensile test using a waisted test specimen geometry, where the cross-sectional area is a minimum at the joint line, and the most appropriate parameter is the energy to break the specimen, and the most appropriate long-term test is the whole pipe tensile creep rupture test.

In order to determine critical particulate contamination levels in butt fusion joints in PE pipes, the concentration of particulates in the joint must be quantified. This study has shown that this can be achieved using micro computed tomography.

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