DEVELOPMENT OF ULTRASONIC INSPECTION TECHNIQUES AND ACCEPTANCE CRITERIA FOR BUTT FUSION JOINTS IN POLYETHYLENE PIPES

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ABSTRACT

Cooling water intake pipework in nuclear power stations is often required to operate in highly corrosive and fouling environments, transporting organically rich seawater. Under these conditions, stainless steels may only last a few months. Titanium is an alternative material but is prohibitively expensive. For this reason polyethylene (PE) is being considered for this application. However, one of the main reasons why this material has not been introduced to any great extent is that the regulatory bodies require the welded joints to be inspected volumetrically and currently there is no validated inspection system commercially available.

TWI has been carrying out research on the ultrasonic inspection of butt fusion joints in PE pipes for over 20 years and this paper describes some of the results of this work, together with a summary of a current research project to develop and validate a phased array ultrasonic inspection system specifically for welded joints in PE pipes.

INTRODUCTION

Polyethylene has been used successfully for natural gas and municipal water distribution pipework for many decades. It has also been incorporated into non-safety piping systems in some nuclear facilities both in the UK and the USA. Due to the fact that this material is immune to service water corrosion and is highly resistant to fouling, it is currently being considered as a replacement for stainless steel in safety-critical applications such as cooling water intake pipework in nuclear power stations [1].

The presence of joints in any pipeline can affect the overall structural integrity of the system. There is, therefore, especially in Class 3 safety-related applications, a need for a reliable and validated non-destructive examination (NDE) system for inspecting the welded joints. Unfortunately, at the present time, there is no such system available for inspecting welded joints in PE pipes.

This paper describes the work that has been carried out at TWI, and also work that is planned, to develop an ultrasonic NDE system specifically for inspecting welded joints in PE pipes.

BUTT FUSION WELDING PROCESS

Butt fusion welding, also known as hot plate, heated tool, mirror or platen welding, is the most cost effective method for joining large diameter (>500mm) PE pipes and welding machines are commercially available for pipes of outside diameter (OD) up to 1600mm (Fig. 1).

Fig.1: Butt fusion welding of PE pipes.

The technique uses a heated metal plate, known as a hot plate or heating platen, to heat and melt the ends of the PE pipes. Once the ends are sufficiently melted the hot plate is removed and the pipes are brought together under pressure to form the weld.

The welding sequence begins when the pipe ends are pushed against the hot plate, typically at 230°C, using hydraulic rams. The pressure is increased to give good thermal contact. The pipe ends melt and the pressure forces the molten material outwards to form weld beads at the outside and inside pipe surfaces. This is known as the bead-up stage. When either a pre-set displacement or bead size is reached the pressure is reduced to a value sufficient only to maintain the pipe in contact with the hot plate. This is called the heat soak stage and allows the melt depth to increase without increasing the size of the weld beads. At the end of this stage the pipe ends are pulled away from the hot plate, which is then removed and the two molten pipe ends are pushed together. This is the plate removal, or changeover, stage, which should be as short as possible to prevent premature cooling and recrystallisation of the pipe ends before they are brought together. In the final fusion/cooling stage the molten pipe ends are pushed together to produce a welded joint and are held at a constant pressure until the joint solidifies.

There are a number of industry, national and international standards that define the butt fusion welding procedure and welding parameters for PE pipes of different OD, including the international standard ISO 21307 [2], the UK Water Industry Specification WIS 4-32-08 [3], the German Welding Society Directive DVS 2207-1 [4] and the American Plastics Pipe Institute Procedure TR-33 [5].

MANUFACTURE OF WELDED SAMPLES

In order to determine both the limits of detection of the ultrasonic NDE system and the critical defect sizes and contamination levels, a number of welds were made in PE pipes of 125mm and 315mm OD containing the following idealised flaws:

- Aluminium discs – to simulate planar flaws, such as fingerprints, oil and grease.
- Micronised talc – to simulate fine particulate contamination.
- Graded sand – to simulate coarse particulate contamination.

Welds Containing Particulate Contamination

There are two main types of particulate flaw that may contaminate butt fusion welds: fine airborne dust and coarse particles. In the laboratory, these were simulated using talc (particle size < 45μm) and graded natural silica sand (particle size 150-300μm). These flaws were inserted into the joint by applying them to the end of one of the pipes with a soft-haired brush, before the welding operation. Three different loadings, nominally described as heavy, medium and light, were applied. The uniformity of coverage was assessed visually.

In order to determine critical particulate levels, above which the long-term integrity of the joint is reduced, it was necessary to quantify the actual percentage area of the weld contaminated. In order to do this, polyimide tape was applied to the pipe end that had not been contaminated, at four equidistant positions (see Fig. 2). After welding, parallel-sided strips from each of the four positions and each containing polyimide tape, were cut from the weld and carefully broken open. The interface surface was then analysed using X-ray photoelectron spectroscopy (XPS) to quantify the percentage area of contamination. Specimens for mechanical testing were also cut from the same weld and the contamination levels in these specimens were determined by interpolation. Polyimide tape was chosen for this application because it had the required temperature resistance and produced a clean break at the interface.

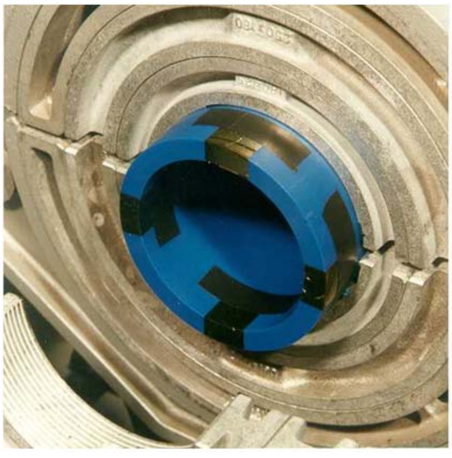

Fig. 2: Location of polyimide tape.

Welds Containing Planar Discs

In order to determine critical planar flaw sizes, it was necessary to produce simulated planar flaws of known size. Previous work [6] had shown that, for ultrasonic NDE, thin (25μm) aluminium discs provided a good simulation of real planar flaws.

Discs of five different diameters (1, 2, 3, 4 and 8mm) were adhesively bonded to one end of one of the pipes before the welding operation. Each disc was placed at the mid-wall position. Some of the joints contained a single disc; others contained eight discs of different sizes placed equidistantly around the circumference (see Fig. 3).

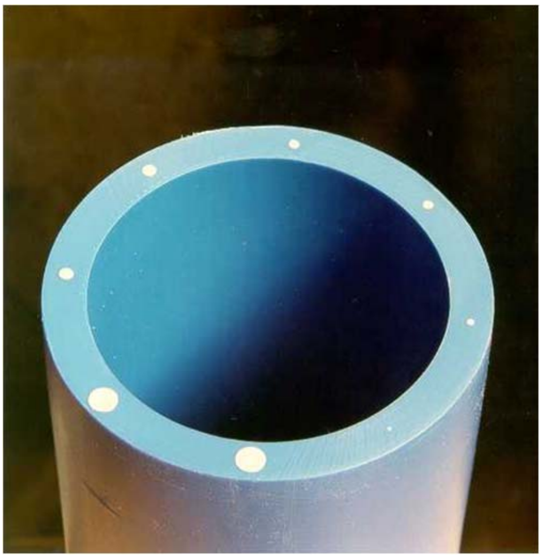

Fig. 3: Location of planar flaws.

DEVELOPMENT OF CONVENTIONAL ULTRASONIC NDE TECHNIQUES

Previous work [6,7] has shown that ultrasonic creeping wave, time-of-flight diffraction (TOFD) and tandem techniques are most sensitive to flaws in butt fusion welds. It was also believed that by combining these techniques it should be possible to achieve full through-thickness coverage of the weld for a wide range of wall thicknesses.

A number of experiments were carried out to optimise the above three ultrasonic techniques for both the 125mm and 315mm PE pipes, in terms of ultrasonic frequency, probe type (single-crystal or multi-element composite), probe size, probe angle and probe separation distance. The optimised ultrasonic NDE techniques were then used to examine the welded samples containing deliberate flaws. The results, which are given in Table 1, show that the detectability of planar flaws was generally good, with 29 of the 36 planar flaws being detected by at least one of the ultrasonic techniques and confirm that flaw detectability was improved by using all three techniques. However, rather surprisingly, it appears that the non-detectability of the planar flaws did not depend greatly on flaw size. For example, in 4 out of 5 cases, 1mm diameter flaws were detected, yet in other cases flaws as large as 4mm diameter were not detected. To establish the reason for this, one of the undetected flaws was sectioned and examined under an optical microscope and also using scanning electron microscopy and energy dispersive X-ray analysis. Results indicated that this flaw had broken up during the welding process, which suggests that the actual detectability of planar flaws with diameters down to 1mm is greater than the 81% given in Table 1.

It can also be seen in Table 1 that sand contamination (down to 3% contamination level, as determined by XPS) was detected with a high reliability, with TOFD detecting contamination in all 12 welds. However, talc contamination did not produce a detectable ultrasonic response.

The difficulty in detecting the talc contamination is believed to relate to particle size. Krautkrämer et al [8] suggested that particle sizes less than about 0.1 of the ultrasonic wavelength do not produce a strong scattering effect and would therefore appear transparent to the incident ultrasound. At the ultrasonic frequencies used in this study, a wavelength of around 1-2mm is generated in PE pipes. Therefore, the sand, which has a particle size of between 0.15 and 0.3mm, produced scattering that was sufficiently strong to be detected by ultrasonic NDE; whereas the talc, which has a particle size of less than 0.05mm, produced little or no effect. Although the talc contamination was not detected reliably by any of the ultrasonic NDE techniques, it was detected by removing the external weld bead and bending it back on itself (see Fig. 4) – a slit being clearly visible between the two halves of the weld bead.

Table 1: Summary of ultrasonic testing results

Flaw type	Size / level of contamination	Actual number of flaws	Number of flaws detected			Flaws detected by at least one technique	
			Creep	Tandem	TOFD	Number	%
Planar (Al foil inserts)	1mm diameter	5	0	2	3	4	80
	2mm diameter	5	2	3	3	3	60
	3mm diameter	8	2	4	5	6	75
	4mm diameter	9	4	7	7	7	78
	8mm diameter	9	6	8	9	9	100
	Total:	36	14	24	27	29	81
Sand	Heavy (19%)	4	0	4	4	4	100
	Medium (6%)	4	0	1	4	4	100
	Light (3%)	4	0	2	4	4	100
	Total:	12	0	7	12	12	100
Talc	Heavy (9%)	4	0	0	1	1	25
	Medium (8%)	4	1	0	1	1	25
	Light (7%)	4	0	0	1	1	25
	Total:	12	1	0	3	3	25

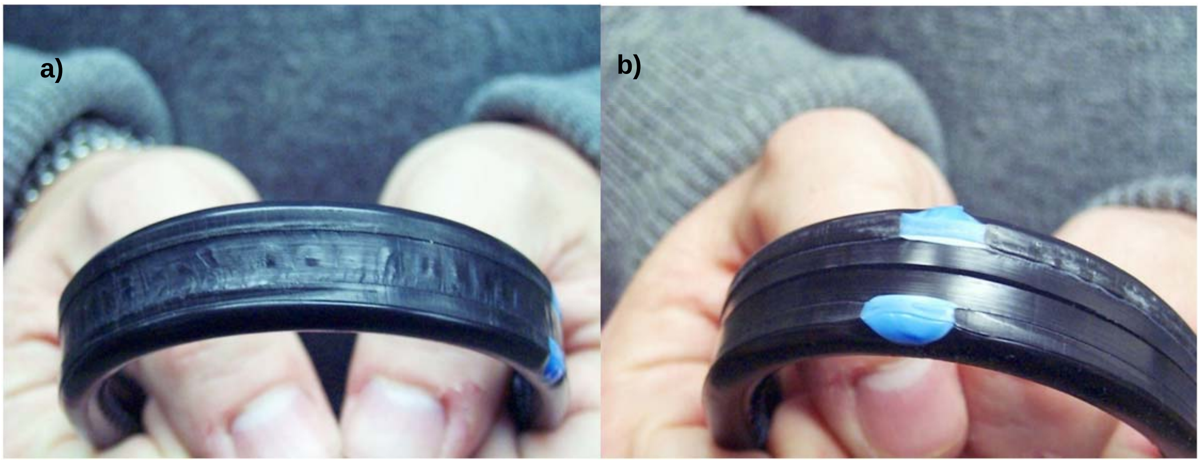

Fig. 4: Bend-back test on the external bead from welds in 315mm OD PE pipe a) containing no particulate contamination and b) containing 6% talc contamination.

DETERMINATION OF ACCEPTANCE CRITERIA

Determining the limits of detection provides only half of the information that is required for an NDE technique to be effective. It is equally important to determine the minimum size of flaw or level of particulate contamination that reduces the quality of the welded joint. Since PE pipelines are designed to last for at least 50 years, the most important property of the weld is its long-term durability under stress. For this reason, the acceptance criteria (critical defect sizes and contamination levels) were determined by measuring the creep rupture performance of the joint.

Two types of creep rupture test were performed in this work. Whole pipe tensile tests were carried out to determine the effect of planar flaw size in 125mm OD welds, using the equipment shown in Fig. 5. However, due the cost of performing these whole pipe tests, specimen tests, according to EN 12814-3 [9], were carried out to determine the effect of levels of particulate contamination in both 125mm and 315mm OD welds. In both tests, the test temperature was 80°C and the applied tensile stress was 5.5MPa. An example of a failed whole pipe sample is given in Fig. 6.

Fig. 5: Whole pipe tensile creep rupture test rig.

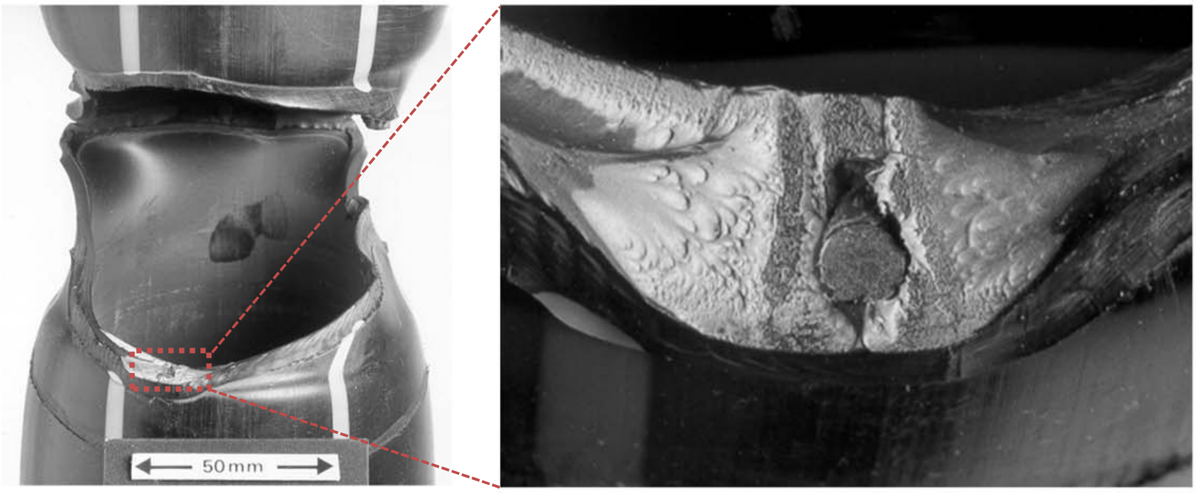

Fig. 6: Photographs of a failed weld in 125mm OD pipe containing a 4mm diameter aluminium disc.

In order to determine the critical defect sizes and contamination levels, graphs of flaw size/contamination level against time to failure were produced and the values compared with welds that contained no deliberate flaws. A schematic of the type of graph produced is given in Fig. 7.

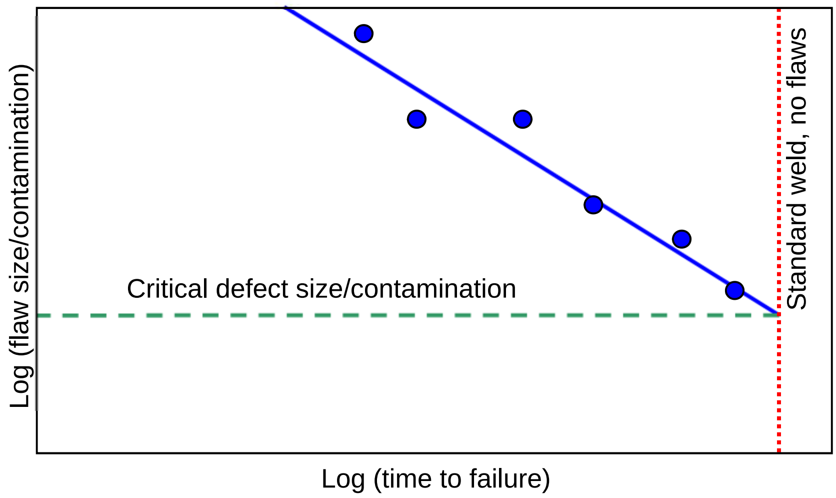

Fig. 7: Schematic of the type of graph produced to determine critical defect sizes and contamination levels.

THE TESTPEP PROJECT

Following on from the above research, TWI is leading a European (FP7) funded project, involving 15 organisations from seven European countries, with the objective of developing phased array ultrasonic NDE procedures, techniques and equipment for the inspection of welded joints in PE pipes and fittings of diameters between 90 and 1000mm.

The advantage of phased array probes is that they can collect ultrasound data very rapidly and the inspection can be performed with a single pass around the weld without any mechanical axial movement. This simplified mechanical concept will solve many of the required economic and ergonomic challenges. The instrument, which will be attached directly to the scanning system, will therefore be required to have sufficient memory to store an inspection and download the data to a computer, plus drive complex ultrasonic phased array probes.

The data will be required to be analysed semi-automatically so that a red/green (yes/no) answer can be provided for the quality of the welds so that the system can be operated by existing pipe laying technicians.

In parallel, the significance of flaw size and quantity will be established in relation to service requirements. This will be achieved, as before, by long-term mechanical testing of joints containing known flaws, and comparison with results for welds containing no flaws.

The prototype NDE equipment, designed and built as part of this project will be assessed under both laboratory and field conditions.

The main objectives of the TestPEP project are:

- To develop ultrasonic phased array NDE techniques for the inspection of both butt and socket joints in PE pipes with wall thicknesses up to 70mm in various plastics materials.
- To determine the limits of detection for the above techniques/pipe sizes.
- To determine critical defects sizes and contamination levels for the above pipe sizes.
- To develop defect recognition and automatic defect sentencing software to allow the equipment to provide a pass/fail indication.
- To produce a prototype ultrasonic NDE system that can inspect both butt and socket joints in pipe sizes up to 1m diameter.

The anticipated project deliverables will include:

- A new compact phased array flaw detector with the ability to drive phased array probes in a harsh compact environment.
- An integrated scanner and phased array probes providing a mechanically rugged system.
- Novel data analysis and processing software enabling the system to be used rapidly in the field by pipe laying technicians.
- Inspection procedure including flaw reporting criteria and flaw acceptance levels.
- Rugged phased array sensor design that is adaptable for a wide range of pipe sizes and fitting geometries.

The structure of the TestPEP project is shown in Fig. 8, where it can be seen that it is divided into eight work packages.

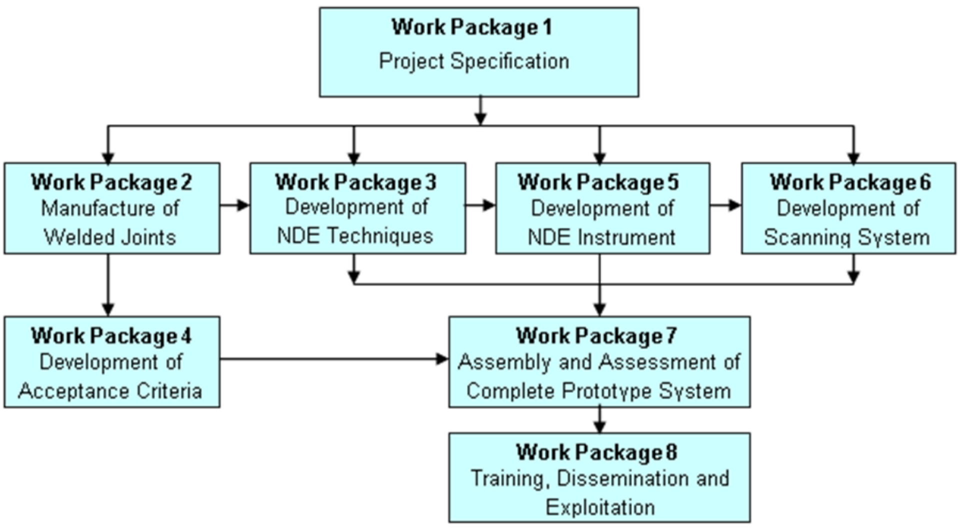

Fig. 8: TestPEP project flow diagram showing the interdependencies of component work packages.

Work Package 1: Project Specification

The Industry Associations in the consortium will survey their members in order to define the types of PE, pipe size ranges and joint types (e.g. pipe-to-pipe, pipe-to-fitting) that are of most interest to European companies involved in the plastics pipes industry. Based on the information provided, up to four pipe sizes and four joint types will be assessed. The Industry Associations will also survey their members in order to define the main types of flaws that can occur when welding plastics pipes in the field.

It is also essential that the developed NDE system (equipment, phased array transducers, techniques and data processing software) is directly relevant to the market needs. The Industry Associations will therefore also survey their members in order to develop a functional specification for the NDE system.

Work Package 2: Manufacture of Welded Joints

A range of welded joints containing the various flaws defined in Work Package 1 will be made in the PE materials, joint types and pipe sizes also defined in Work Package 1. Since, for both the NDE assessment and the acceptance criteria, it is necessary to know the exact size and/or quantity of each flaw, most of the flaws chosen will be idealised simulations of actual flaws that may be encountered in the field.

Work Package 3: Development of NDE Techniques

The ultrasonic phased array NDE techniques will be developed for the detection of defects in the joint types and PE pipe materials defined in Work Package 1. This will include the technical and functional specifications of phased array probe design and the technical specification of the ultrasonic instrument and scanning system. The material properties of the chosen PE materials will be defined as well as the methods to overcome the very slow acoustic velocity and highly attenuative nature of these materials. These two factors will be incorporated into the ultrasonic probe specification.

Specialist ultrasonic probe shoes will be designed and manufactured. These will either be manufactured from very low velocity ultrasonic materials or will be specialised water wedges. The capability of the optimised NDE system will be determined using the welded pipe joints produced in Work Package 2. Following optimisation, outline inspection procedures will be generated.

Work Package 4: Development of Acceptance Criteria

The welds inspected in Work Package 3 will be mechanically tested using both specimen and whole pipe creep rupture tests. The results from these tests will be analysed for each of the different flaw types and compared with the results from tests on welds containing no deliberate flaws. The actual size of the flaws in the joints, as opposed to the size of the flaw inserted into the joint before welding, will be determined by sectioning a set of test samples. The actual particulate contamination levels will be determined using surface analysis techniques on the weld interfaces. Graphs of flaw size/particulate contamination level against time-to-failure will be generated in order to calculate the critical sizes/levels of defects for each pipe material, pipe size and joint type that reduce the long-term integrity of the weld. This information will be compared with the flaws detected using the prototype NDE equipment to enable the inspected weld to be accepted or rejected.

Work Package 5: Development of NDE Instrument

The prototype ultrasonic phased array NDE data acquisition and analysis systems will be developed in this work package. Extensive design of the ultrasonic beam control electronics and the data processing within the instrument will be undertaken. This will require the implementation within the instrument of the algorithms developed in Work Package 3. Significant effort will be implemented into cost reduction of the deployed instrumentation.

Work Package 6: Development of Scanning System

A flexible prototype system for scanning the ultrasonic phased array probe(s) over the surface of the welded joints, allowing full 360° rotation around the joint whilst providing detailed positional data, and accommodating a wide range of pipe sizes and joint geometries, will be designed, developed and manufactured.

Work Package 7: Assembly and Assessment of Complete Prototype System

The complete NDE system, including instrument, probe(s) and scanning system, will be assembled and assessed in the field by the end users in the project, as well as by interested members of the Industry Associations, to evaluate the sensitivity, reproducibility and ease-of-use of the system. This work package will include the validation of the system for the range of welds specified in Work Package 1. For the validation a series of pipe welds will be produced, where the location and number of flaws will remain blind to the NDE operator.

Work Package 8: Training, Dissemination and Exploitation

The knowledge generated during the course of the project will be disseminated both to SMEs responsible for providing the new inspection service and to end users. This will be done via the project website (www.testpep.eu), training guidelines, awareness campaigns, workshops, publications and newsletters.

CONCLUSIONS

Work has been carried out to optimise the TOFD, tandem and creeping wave ultrasonic NDE techniques for butt fusion welds in PE pipes of 125mm and 315mm OD, and has shown that a system incorporating these three techniques is capable of detecting planar flaws of diameters down to at least 1mm and sand contamination at levels down to at least 3% by area, in butt fusion welds in these sizes of PE pipe. Neither of these types of flaw can be detected reliably by visual examination or manual testing of the external weld bead.

The work has also shown that ultrasonic NDE cannot detect fine particulate contamination. However, this type of flaw can be detected using a manual bend-back test on the removed external weld bead.

The minimum size of planar flaw and minimum levels of fine and coarse particulate contamination that cause premature failure of butt fusion welds in PE pipes of 125mm and 315mm OD have also been determined.

A current European-funded project is being carried out to extend this work to phased array ultrasonics and pipe sizes up to 1000mm OD.

ACKNOWLEDGEMENTS

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