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DEVELOPMENT AND ASSESSMENT OF ULTRASONIC INSPECTION SYSTEM FOR POLYETHYLENE PIPES

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ABSTRACT

The American Society of Mechanical Engineers (ASME) is developing a Code Case (N-755) for the use of polyethylene (PE) in nuclear power plant buried pipe systems. However, the United States Nuclear Regulatory Commission (NRC) has not approved this Code Case due to a number of concerns; one of which is the lack of validated non-destructive examination (NDE) techniques for inspecting welded joints in PE pipes. This paper describes the development of an ultrasonic phased array system and procedures for the inspection of welded joints in PE pipes of diameters between 125 and 1000mm. The system includes hardware and software which has been designed specifically for inspecting PE pipe joints. The system has been assessed by a number of organisations and the results of these trials will be presented. Alongside the development of the inspection system, a major programme of work has been carried out to develop acceptance criteria for flaws in PE pipe welds. The types of flaws investigated included particulate contamination, planar flaws and cold fusions. The critical flaw sizes and contamination levels were determined based on both long-term and short-term testing of welded joints in PE pipes.

INTRODUCTION

PE pipes offer significant advantages over other materials, such as cast iron, steel and concrete, for the transportation of fluids such as natural gas and water. They do not corrode, have a longer predicted service life, are less expensive to install due to their light weight and flexibility, and have significantly lower leakage rates due to having an all-welded system. However, their use in safety critical environments, such as cooling water intake pipework in nuclear power stations [1], is being restricted by the lack of a reliable, validated NDE method. Several studies have been conducted to develop NDE methods for both Butt Fusion (BF) [2-6] and Electro-Fusion (EF) [7-9] joints. However, these have been limited to a narrow range of pipe sizes and/or have not included acceptance criteria. This paper describes the progress in the development of the ultrasonic inspection system first presented to the PVP Conference 2012 [10].

BUTT FUSION WELDING PROCESS

Butt fusion welding, also known as hot plate, heated tool, mirror or platen welding (Figure 1), is used for welding PE pipes of sizes typically between 50 and 2000mm diameter.

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.

ELECTROFUSION WELDING PROCESS

In EF welding, the pipe ends are pushed into either end of a fitting (Figure 2), which contains a coil of heating wire in the inside. Current is passed through the coil, which heats up and melts the inside of the fittings and the outside of the pipes, producing a weld (Figure 3).

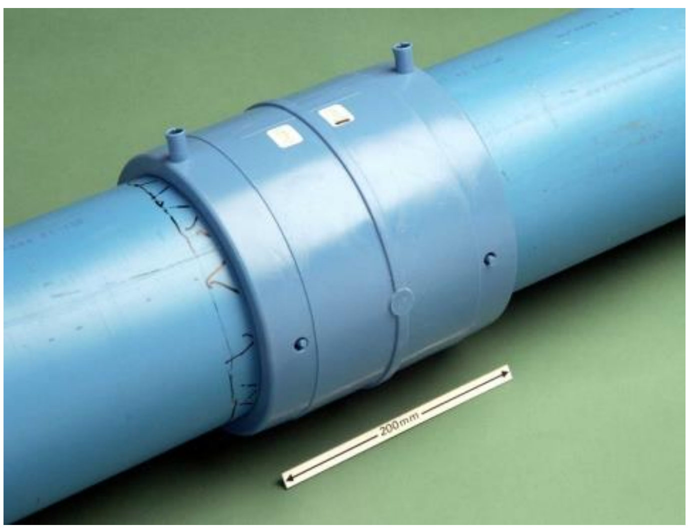

FIG. 2 ELECTROFUSION JOINT

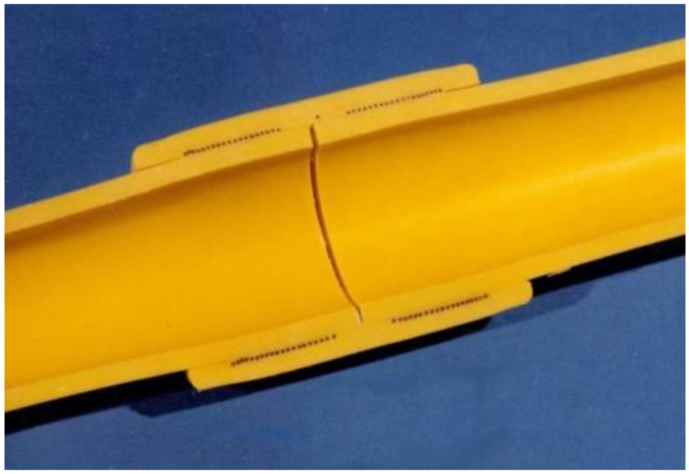

FIG. 3 SECTION THROUGH AN EF JOINT SHOWING THE POSITION OF THE HEATING WIRES

THE TESTPEP PROJECT

The TestPEP European-funded project involves 17 organizations from seven European countries. It is a three year project, which started in February 2010, and has a total value of €3.5M. Its aim is to design, manufacture and validate a phased array ultrasonic system that can be used to inspect pipe-to-pipe and pipe-to-fitting (elbows, bends, reducers, tees) BF and EF joints in PE pipes, which is site-rugged and simple to operate. The concept is to have a black box instrument, directly attached to the scanner, with a simple Ethernet connection to download the recorded data. In parallel, the significance of flaw size and quantity will be established in relation to service requirements, which will be achieved by long-term mechanical testing of joints containing known flaws, and comparison with results for welds containing no flaws.

The project has been divided into several technical work packages based on the following specifications:

- Materials
    - Both PE80 and PE100
- Pipe sizes
    - 180mm SDR 17
    - 225mm SDR 11
    - 355mm SDR11
    - 450mm SDR 17
    - 710mm SDR 17
- Flaw types
    - Fine particulate contamination (dust)
    - Coarse particulate contamination (sand, grit)
    - Planar flaws (fingerprints, oil and grease, rain droplets)
    - Cold welds
    - Pipe underpenetration in EF joints
- Minimum working distance around the pipe joint
    - 200mm

MANUFACTURE OF WELDED JOINTS

A number of welded joints containing simulations of the flaw types defined in the specification have been made in the PE materials, joint types and pipe sizes also defined in the specification.

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 were idealized simulations of actual flaws that may be encountered in the field:

- Micronized talc (particle size < 45µm) – to simulate fine particulate contamination.
- Graded silica sand (particle size 150 - 300µm) – to simulate coarse particulate contamination.

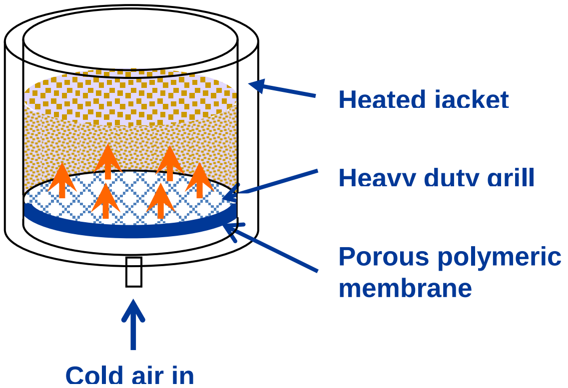

FIG. 4 DIAGRAMATIC REPRESENTATION OF THE FLUIDISED SAND BED

FIG. 5 HEATED FLUIDISED SAND BED

- Aluminium discs (25µm thick, 1-50mm diameter) – to simulate planar flaws.

Aluminium discs were used because previous work had shown that, for ultrasonic NDE, they are a good simulation of real planar flaws [2]. Procedures for inserting the above flaws into both EF and BF joints in a reproducible way have been developed [10]. For example, to introduce a uniformly repeatable level of coarse particulate contamination a fluidised sand bed has been developed to deposit a predetermined level of graded silica sand onto the pipe end prior to welding (Figures 4 and 5).

DEVELOPMENT OF NDE TECHNIQUES

Ultrasonic phased array NDE techniques have been developed for the detection of defects in the PE pipe materials and pipe sizes defined in the specification, including the design and manufacture of bespoke ultrasonic phased array probes and probe shoes. The material properties of the chosen PE materials have been determined [10, 11] as well as the methods to overcome the very slow acoustic velocity and highly attenuative nature of these materials, which were then incorporated into the ultrasonic probe specification.

In addition to this work, defect recognition and automatic defect sentencing software is being developed to allow the inspection system to provide a pass/fail indication.

For inspecting EF joints, the challenge was to achieve a resolution good enough to be able to inspect the fusion zone beyond the heating wires. Since the attenuation of the ultrasound increases rapidly with frequency in PE materials [10] the most appropriate solution is a compromise; the frequency must be low enough to enable the sound to propagate the required distance but high enough to achieve the desired resolution. This required careful parameter choices for the phased array probe. The approach was to use a normal linear scan focused at the fusion zone (Figure 6), using a novel open-face water wedge with a sealing skirt that is used to effectively keep the water in the wedge (Figure 7).

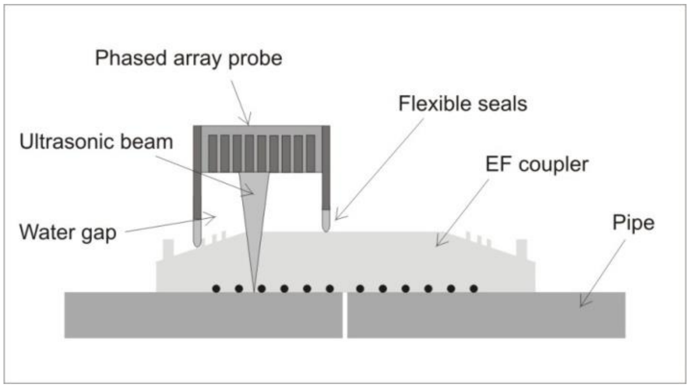

FIG. 6 SCHEMATIC OF THE INSPECTION TECHNIQUE FOR EF JOINTS

FIG. 7 ZERO DEGREE WATER WEDGE USED FOR EF INSPECTIONS

Using the technique that has been already developed in the project [10] a range of EF pipe joints have been inspected which has yielded encouraging results.

Figures 8, 9 and 10 show a series of images of welded EF joints in a 180mm PE pipe. Figure 8 shows a good joint with no discernible flaws. Figure 9 shows a joint with an 8mm aluminium discs and Figure 10 shows a joint with a 2mm aluminium disc demonstrating that a lack of fusion of at least 2mm diameter is readily detectable. The indication from the upper edge of the HAZ is also visible in Figure 8 although it is not so evident in Figures 9 and 10. This feature can be used to detect cold welds [8, 10]. In addition to this, the signal from the inner pipe surface can clearly be seen. Figures 11 and 12 show a good weld and a cold weld respectively in a 450mm EF welded pipe. The measured difference in the distance of the HAZ indication from the wires is illustrated. Also it can be seen in Figure 12 that there are areas of associated lack of fusion at the interface.

A summary of the sizes of EF pipe joints and types of flaw inspected to date is shown in Table 1

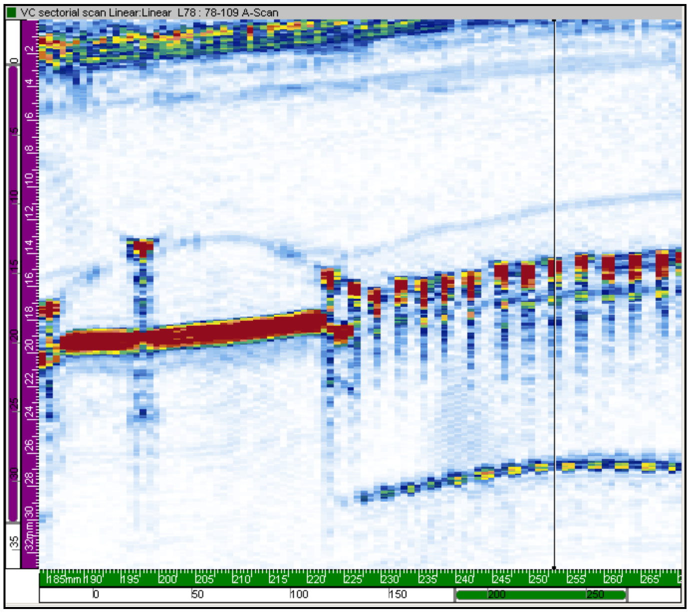

FIG. 8 PHASED ARRAY ULTRASONIC IMAGE OF 180MM EF FITTING CONTAINING NO FLAWS

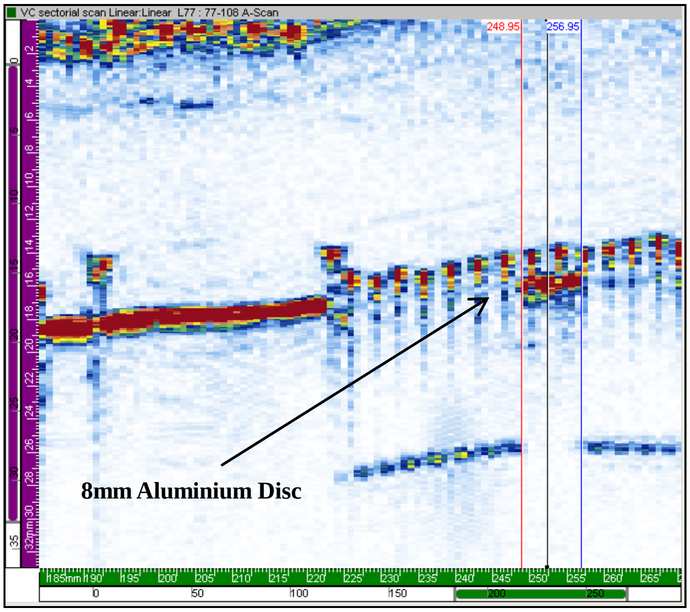

FIG. 9 IMAGE OF AN EF JOINT IN 180MM PE PIPE WITH AN 8mm ALUMINIUM DISC

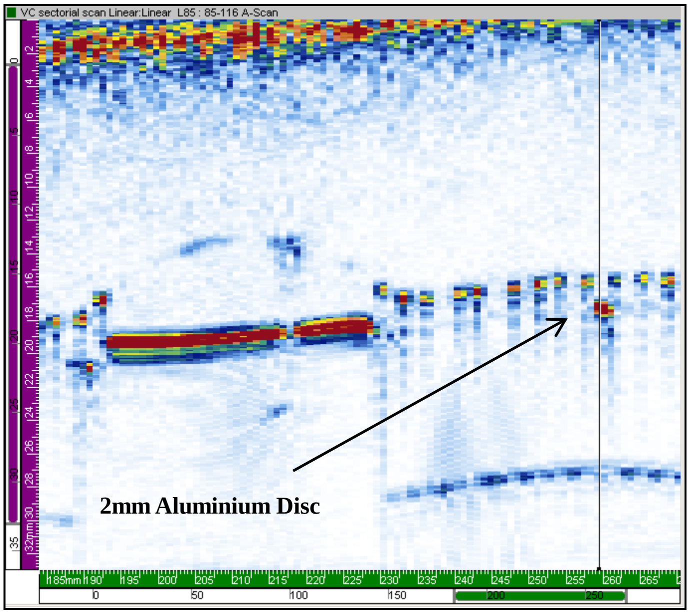

FIG. 10 IMAGE OF AN EF JOINT IN 180MM PE PIPE WITH A 2mm ALUMINIUM DISC

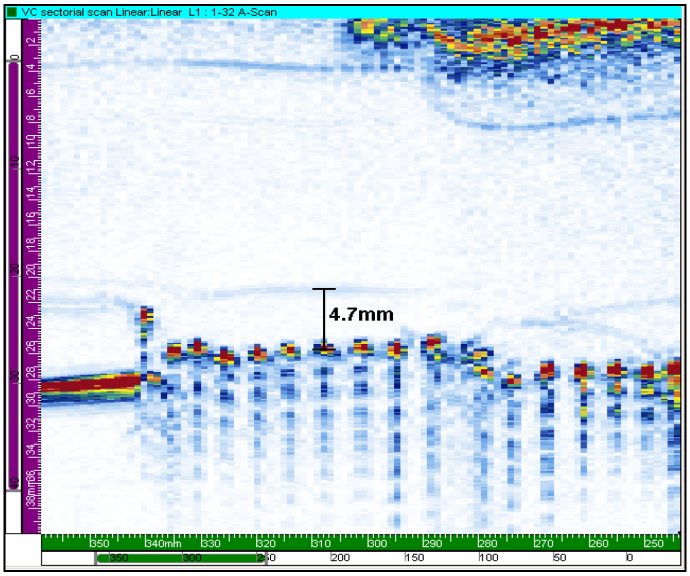

FIG. 11 IMAGE OF AN EF JOINT IN 450MM PE PIPE WITH GOOD FUSION

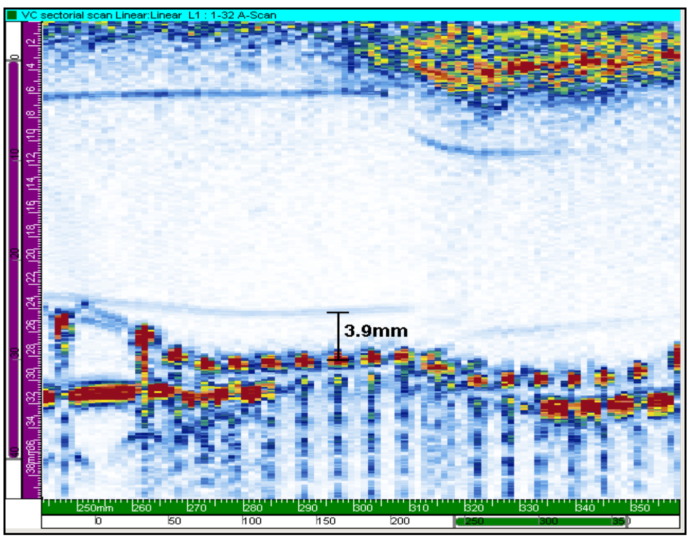

FIG. 12 IMAGE OF AN EF JOINT IN 450MM PE PIPE WITH COLD FUSION

TABLE 1 SUMMARY OF THE SIZES OF EF PIPE JOINTS/TYPES OF FLAW INSPECTED

	Planar	Fine part.	Coarse part.	Cold weld	Under pen.
180	X			X	X
225	X			X	X
355	X			X	X
450	X			X	X
710					

Inspecting BF joints requires the use of angled ultrasound and a combination of four different techniques was used in order to obtain full coverage of the weld area: self-tandem, sector pulse-echo, creeping wave and time-of-flight diffraction (TOFD) (Figure 13).

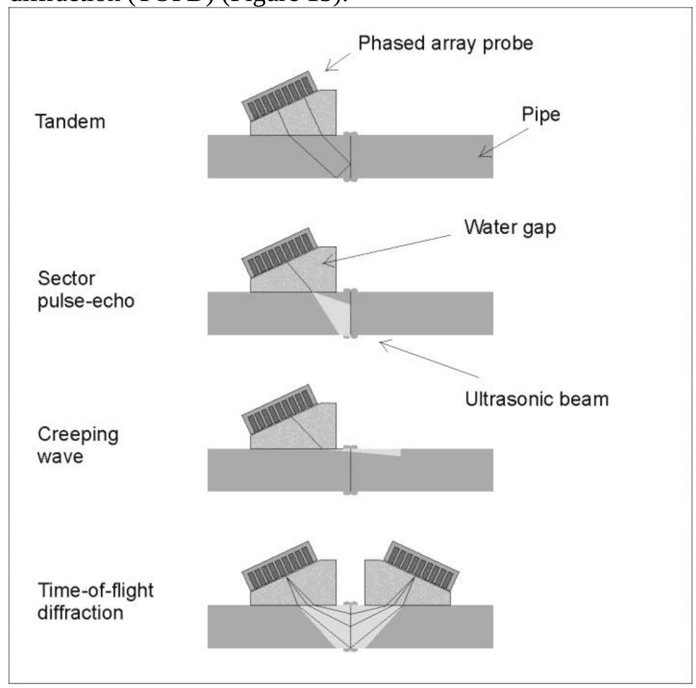

FIG. 13 INSPECTION TECHNIQUES USED FOR INSPECTING BF WELDS

Using three of the four techniques developed in the project [10] and shown in Figure 13 a range of BF pipe joints have been inspected which has yielded encouraging results. The technique which has not yet been employed is the TOFD technique.

The techniques are, in most cases, complimentary. The self-tandem technique uses one half of the phased array elements for transmitting and the other half for receiving. The technique is good for detecting planar flaws but the coverage is restricted to an area closer to the inner surface.

The sector pulse-echo technique uses all of the elements in the array to create an aperture, sweeping the beam over a range of angles. The technique gives an overview of the weld and covers most of the fusion zone except for a few millimetres close to the outer surface.

The creeping wave technique only covers the region close to the outer surface of the weld, which is the part of the weld not covered by the first two techniques. The configuration for the creeping wave technique uses a high-angle sector scan, producing compression waves propagating immediately beneath the inspection surface, to detect surface-breaking and near surface defects.

The TOFD technique covers the entire fusion zone and uses forward diffraction to detect vertical flaws. The configuration that will be used in this project is a pitch-catch technique using two sector scans, where both probes use a large aperture to transmit and receive beams covering the entire weld. Again, open face water wedges were used. The angle of the wedges was optimized to minimize the electronic steering by the probe elements (Figure 14). This Figure shows two BF probes in the TOFD configuration. For the other three techniques only one probe is required.

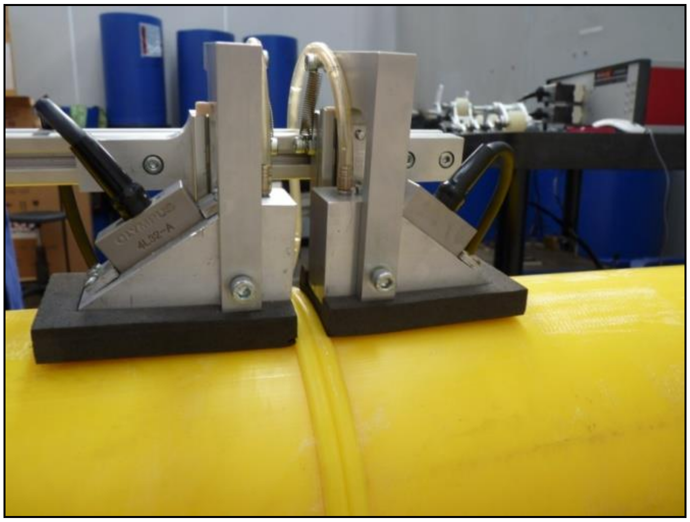

FIG. 14 ANGLED WATER WEDGES USED FOR INSPECTING BF WELDS

The technique which shows the greatest promise when inspecting the BF joints is the sector pulse-echo technique. Figures 15, 16 and 17 show a series of images of welded BF joints in 355mm PE pipes. Figure 15 shows a good joint with no discernible flaws. Figure 16 shows a joint with an 8mm aluminium disc and Figure 17 shows a joint with a 4mm aluminium disc demonstrating that a lack of fusion of at least 4mm diameter is readily detectable. The sectorial scans also show some unwanted areas with a high noise level. These are internal signals from the body of the water wedge and further work is on-going to eliminate these signals. Figure 18 shows the merged B-scans of a sector pulse-echo scan and a self-tandem scan in a 355mm pipe containing aluminium discs.

A summary of the sizes of BF pipe joints and types of flaw inspected to date is shown in Table 2

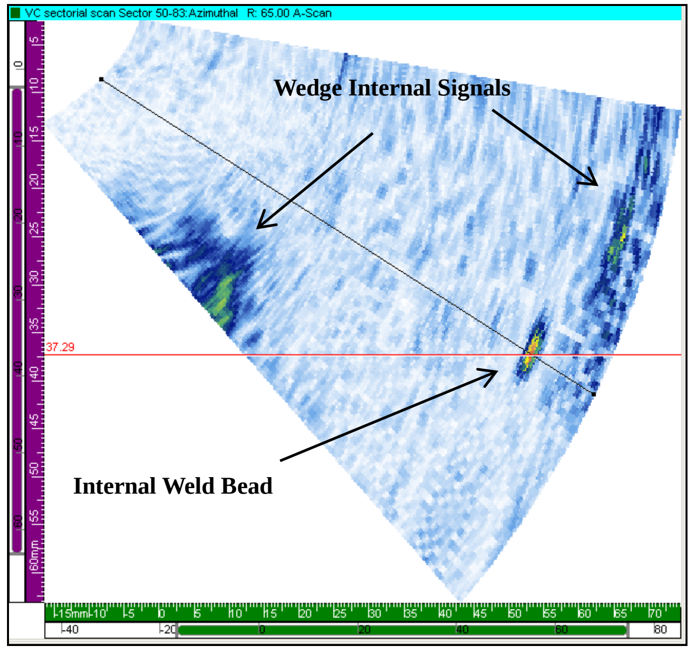

FIG. 15 IMAGE OF A BF JOINT IN 355MM PE PIPE WITH NO FLAWS

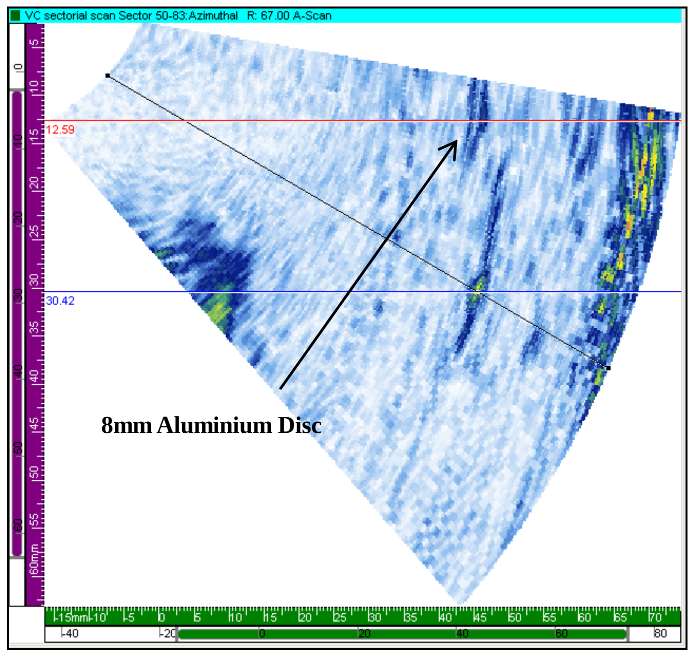

FIG. 16 IMAGE OF A BF JOINT IN 355MM PE PIPE WITH AN 8mm ALUMINIUM DISC

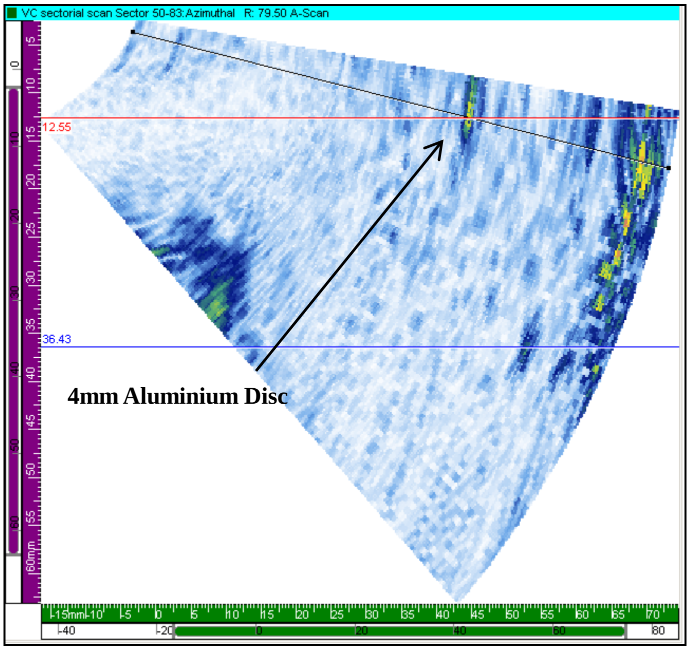

FIG. 17 IMAGE OF A BF JOINT IN 355MM PE PIPE WITH A 4mm ALUMINIUM DISC

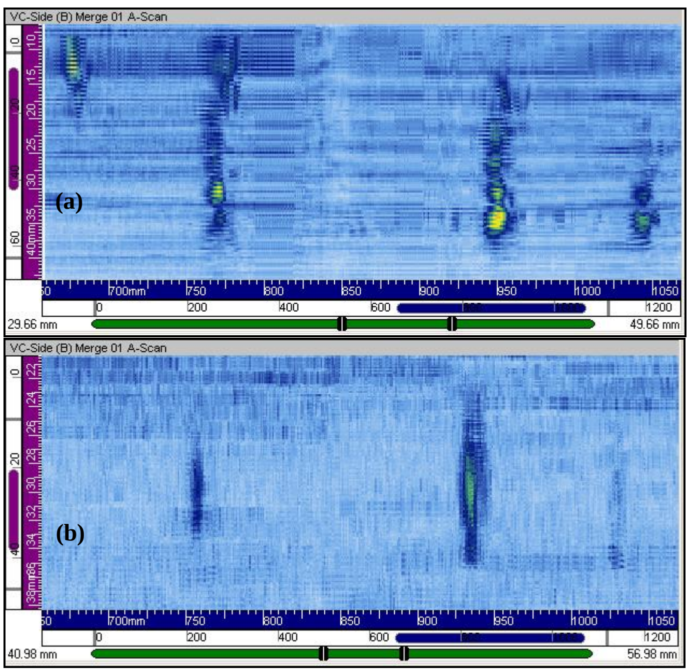

FIG. 18 MERGED B SCAN USING (a) SECTOR PULSE ECHO (b) SELF-TANDEM

TABLE 2 SUMMARY OF THE SIZES OF BF PIPE JOINTS/TYPES OF FLAW INSPECTED

	Planar	Fine part.	Coarse part.	Cold weld
180		X		
225		X		
355	X	X		
450				
710	X	X		

The automatic defect recognition software (ADR) development for the EF weld inspection has made some good progress. There are three main steps in the algorithm:

- Detection of the zones corresponding to the heating wires (Figure 19)
- Determination of the line of wires (Figure 20)
- Determination of the map of the defects (Figure 21)

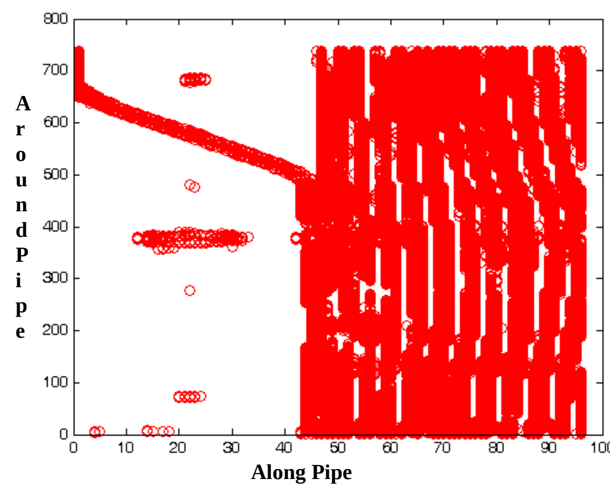

FIG. 19 DETECTION OF THE ZONES CORRESPONDING TO THE HEATING WIRES

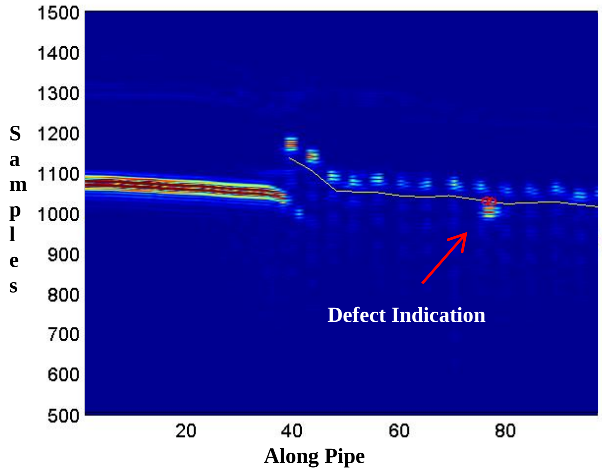

FIG. 20 DETERMINATION OF THE LINE OF WIRES

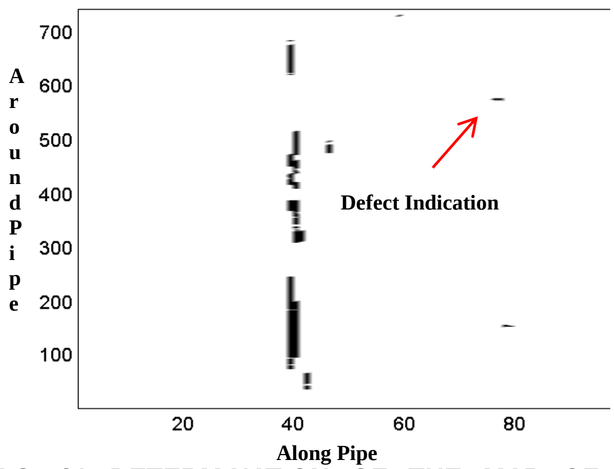

FIG. 21 DETERMINATION OF THE MAP OF THE DEFECTS

DEVELOPMENT OF ACCEPTANCE CRITERIA

The welds that have been inspected in the project are being mechanically tested using both short-term and long-term tests. The results from these tests will be analysed for each of the different flaw types and compared with results from tests on welds containing no deliberate flaws. The actual particulate contamination levels will be determined using surface analysis techniques on the weld interfaces. Graphs of flaw size/particulate contamination level against mechanical performance will be generated in order to calculate the critical sizes/levels of defects that reduce the integrity of the weld, for each pipe material, pipe size and joint type [10].

The mechanical tests that will be used to assess the integrity of the welded joints are:

- BF welds:
  - Waisted tensile test to EN 12814-7 [12]
  - Specimen creep rupture test to EN 12814-3 [13]
  - Whole pipe tensile creep rupture test [14]
- EF welds:
  - Decohesion test to EN 12814-4 [15]
  - Crushing decohesion test to ISO 13955 [16]
  - Specimen creep rupture test for socket joints, according to Annex C of EN 12814-3
  - 80°C hydrostatic pressure test as specified in BS EN 12201-3 [17]
  - Whole pipe tensile creep rupture test

Figure 22 shows a tensile test specimen from a BF joint and Figure 23 shows the fracture surface of tensile test specimens from 225mm PE pipe; the pipe joint with no flaws is a fully ductile failure (Figure 23a), whereas the pipe joint with heavy talc contamination is a fully brittle failure (Figure 23b). Figure 24 shows the fracture surfaces of peel decohesion test specimens from EF joints in 225mm pipe. Figure 24a shows the fracture surface from a joint containing no flaws and shows a ductile fracture through the plane of the heating wires. Figure 24b shows the fracture surface from a joint containing a cold weld and shows a brittle fracture through the weld interface.

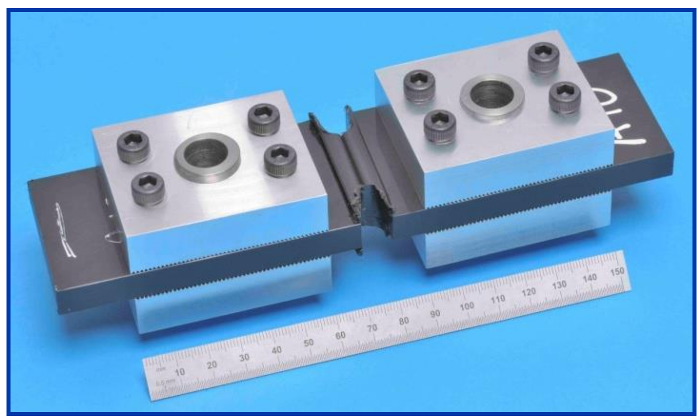

FIG. 22 TENSILE TEST SPECIMEN FROM A BF JOINT.

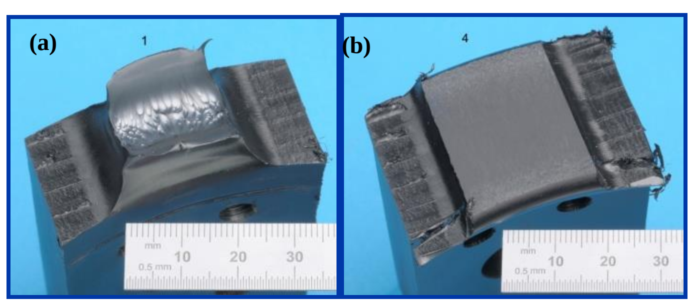

FIG. 23 FRACTURE SURFACE OF TENSILE TEST SPECIMENS FROM 225MM PE PIPE WITH (A) FULLY DUCTILE FAILURE, AND (B) FULLY BRITTLE FAILURE.

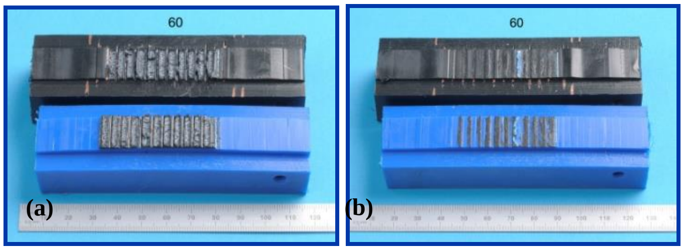

FIG. 24 FRACTURE SURFACES OF PEEL DECOHESION TEST SPECIMENS FROM EF JOINTS IN 225MM PIPE WITH (A) DUCTILE FRACTURE THROUGH THE PLANE OF THE HEATING WIRES, AND (B) BRITTLE FRACTURE THROUGH THE WELD INTERFACE.

DEVELOPMENT OF NDE INSTRUMENT

A new compact phased array flaw detector with the ability to operate in a harsh environment has been designed (Figure 25). Prototype ultrasonic phased array NDE data acquisition and analysis systems are also being developed in this project. Extensive design of the ultrasonic beam control electronics and the data processing within the instrument is being undertaken. In due course the implementation within the instrument of the ADR algorithms will be undertaken.

FIG. 25 CONCEPT PICTURE OF TESTPEP NDE INSTRUMENT

The instrument, shown in Figure 25, has the following features:

- Integrated UT hardware and PC board
- Remote access to software application (Ethernet or WiFi)
- 64 x 64 PA channels
- 4 conventional channels
- Compact box with IP67 protection for full immersion (<0.5m).
- SSD memory for data storage (100GB).
- Two removable batteries allowing up to 4 hours continuous operation.
- Weight: 5kg.
- Size: 320 x 240 x 100mm.

DEVELOPMENT OF SCANNING SYSTEM

A flexible scanner system has been designed and manufactured that will enable full 360° rotation around both BF and EF joints in pipe sizes from 90mm to 1000mm (Figure 26). It comprises a main plate that is held in position around the pipe by several links and an adjustment mechanism. The plate contains an encoder and also the support for the probe holders for the BF and EF joints.

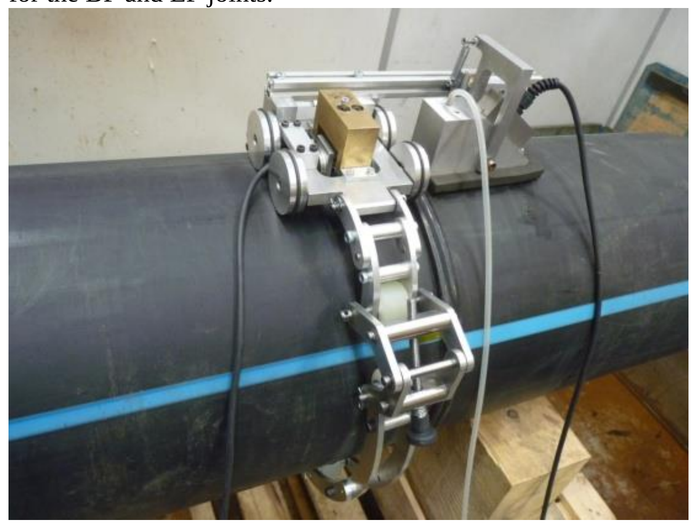

FIG. 26 FLEXIBLE CHAIN LINK SCANNER WITH BF PROBE HOLDER

ASSEMBLY AND ASSESSMENT OF COMPLETE PROTOTYPE SYSTEM

The complete NDE system, including instrument, probe(s) and scanning system has been assembled and assessed in a number of trials to evaluate the sensitivity, reproducibility and ease-of-use of the system. One trial was undertaken on a number of EF joints which had been cut from the pipe and so the scanner system could not be employed. However, by hand manipulating the probe (Figure 27), the joints were successfully inspected and a typical result, showing a void around one of the wires, is shown in Figure 28. In another trial, a small selection of joints destined for the UK power generation industry were examined by this system in parallel with another PAUT system developed by industry. Only one small indication was detected in one joint, by both systems (Figure 29). This joint is under further investigation to determine the cause of the indication. Further field trials are planned on new installations of utility pipelines in Wales and the English midlands.

FIG. 27 HAND MANIPULATION OF PROBE TO INSPECT CUT OUT SAMPLE EF JOINT

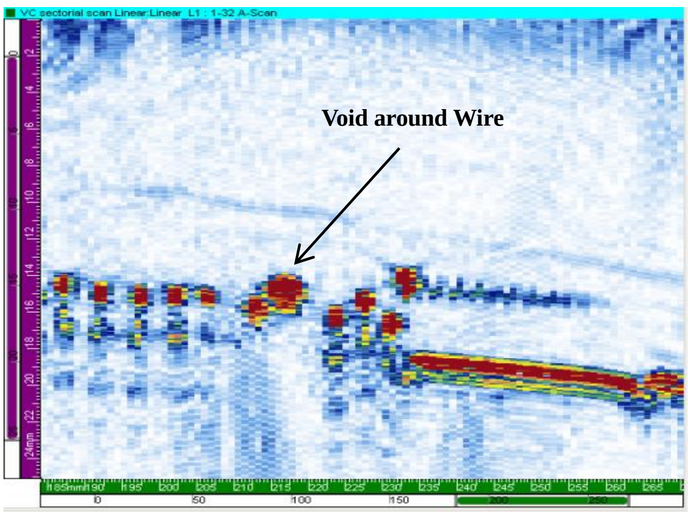

FIG. 28 RESULT FROM HAND SCANNED TRIAL

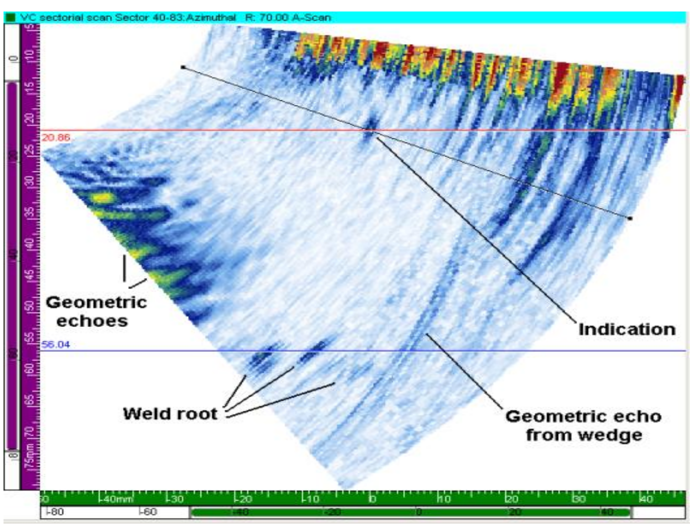

FIG. 29 SMALL INDICATION IN POWER INDUSTRY PIPE JOINT

WORK REMAINING

A summary of the work remaining in this project is given below.

- Complete the manufacture of the BF and EF welds containing deliberate flaws.
- Complete the inspection of the welds containing deliberate flaws in order to determine the limits of detection for the range of pipe sizes investigated.
- Complete the mechanical testing of the welds containing deliberate flaws in order to determine the critical flaw sizes and contamination levels.
- Manufacture the new NDE instrument.
- Finalise the development of the defect recognition and automatic defect sentencing software.
- Continue to assess the complete prototype NDE system and perform field trials.

ACKNOWLEDGMENTS

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The project consortium consists of the European Federation for Welding, Joining and Cutting (EWF), Asociacion espaňola de ensayos no destructivos (AEND), Surface Mount and Related Technologies (SMART Group), Pipeline Industries Guild, Associazione Italiana Prove non Distruttive (AIPnD), Vermon, M2M, Plasflow, Isotest Engineering, E.ON Ruhrgas, British Energy, Hessel Ingenieurtechnik, Kaunas University of Technology, Consorzio Catania Ricerche and TWI.

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