Proceedings of the ASME 2012 Pressure Vessels & Piping Division Conference
PVP2012
July 15-19, 2012, Toronto, Ontario, CANADA

PVP2012-78860

DEVELOPMENT OF ULTRASONIC PHASED ARRAY INSPECTION OF POLYETHYLENE PIPE JOINTS

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ABSTRACT

The current practice for assuring the quality of butt fusion joints in polyethylene (PE) pipes during installation is by recording the welding parameters used, together with a visual inspection of the welded joint, supplemented by the destructive testing of welds on a sample basis using a short-term test. However, visual inspection can only examine the external surface of the pipe weld; it cannot provide evidence of embedded flaws or a weld with incomplete fusion or cold fusion. In addition, cutting a specimen from a weld for mechanical testing and then replacing it with a weld of unknown quality does not ensure the integrity of the pipeline. Volumetric non-destructive examination (NDE) will not destroy perfectly good welds and has the added environmental advantage of reduced waste.

This paper describes an ongoing European-funded project to develop ultrasonic phased array techniques for the inspection of butt fusion (BF) and electrofusion (EF) joints in PE pipes of diameters between 90 and 1000mm, and to determine critical defect sizes and particulate contamination levels using accelerated long-term testing. In addition, defect recognition and automated defect sentencing software will be developed to allow the system to automatically sentence detected flaws.

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 BF [2-6] and EF [7-9] joints. However, these have been limited to a narrow range of pipe sizes and/or have not included acceptance criteria.

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).

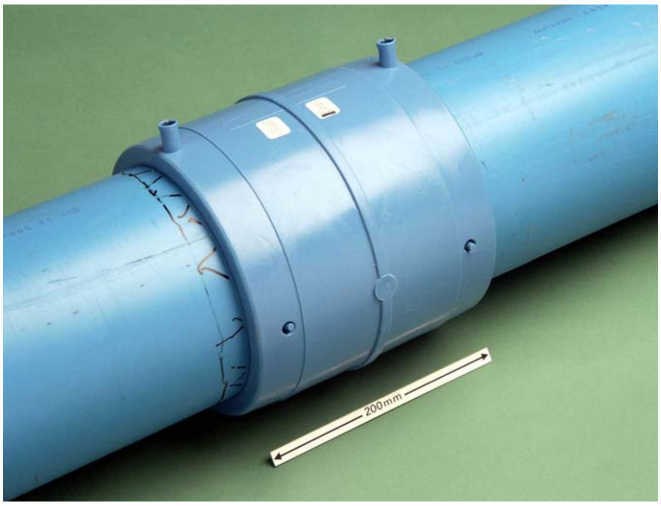

FIG. 2 ELECTROFUSION JOINT

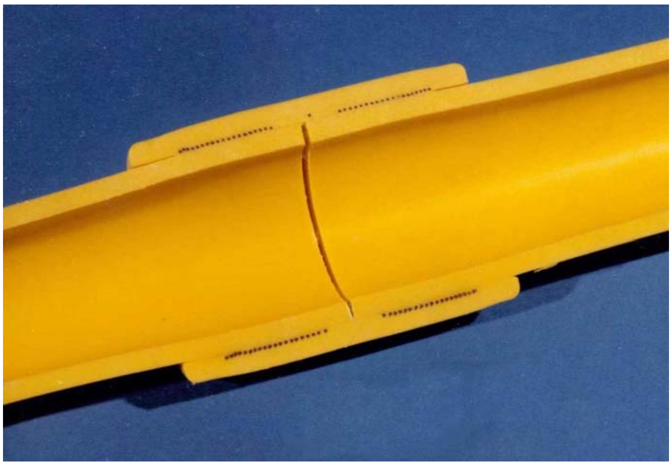

FIG. 3 SECTION THROUGH AN EF JOINT SHOWING THE POSITION OF THE HEATING WIRES

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 2011, 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 seven technical work packages:

WORK PACKAGE 1: PROJECT SPECIFICATION

A questionnaire was sent out to European companies involved in the manufacture or installation of plastics pipes to determine the pipe size ranges and weld flaw types of most interest to the industry, as well as the anticipated physical constraints on the inspection system when working in the field.

A total of 72 responses from ten countries were received, which led to the following specifications for the project:

- 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

WORK PACKAGE 2: MANUFACTURE OF WELDED JOINTS

A number of welded joints containing simulations of the flaw types defined in Work Package 1 is being 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 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.
- Aluminum discs (25µm thick, 1-50mm diameter) – to simulate planar flaws.

Aluminum 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. For example, to investigate the movement of the aluminum discs during the BF welding process, a number of discs were placed at various circumferential and radial positions around the joint before welding (Figure 4).

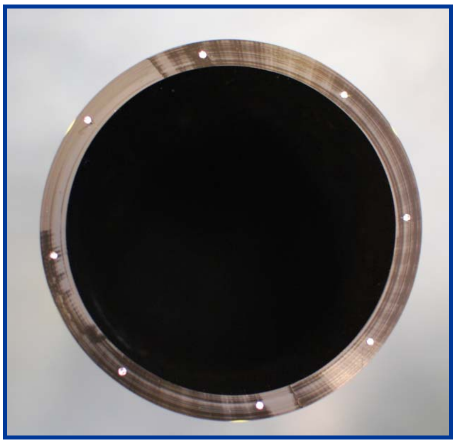

FIG. 4 LOCATION OF ALUMINUM DISCS PRIOR TO BF WELDING

The welded joint was then cut out and machined to a thickness equal to that of the weld beads (Figure 5) before being inspected using X-ray radiography to determine the final positions of the discs after welding (Figure 6).

FIG. 5 MACHINED RING OF BF WELD CONTAINING ALUMINUM DISCS

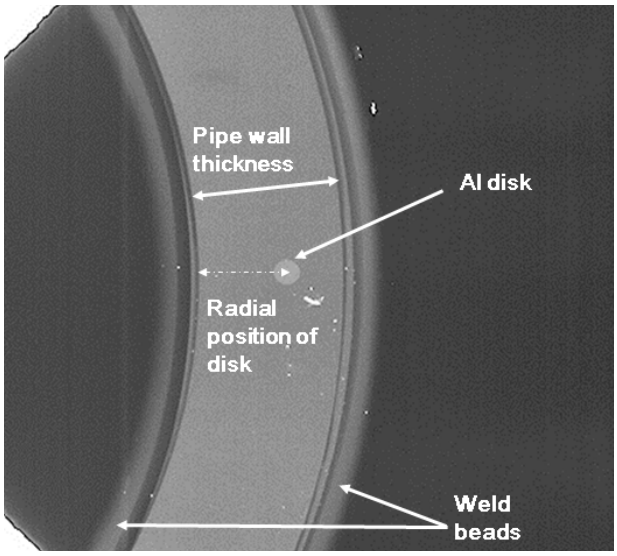

FIG. 6 RADIOGRAPH SHOWING FINAL POSITION OF ALUMINUM DISC AFTER WELDING

WORK PACKAGE 3: DEVELOPMENT OF NDE TECHNIQUES

The objective of this work package is to develop ultrasonic phased array NDE techniques for the detection of defects in the PE pipe materials and pipe sizes defined in Work Package 1, 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] 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.

Also in this work package, 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 7), using a novel open-face water wedge with a sealing skirt that is used to effectively keep the water in the wedge (Figure 8).

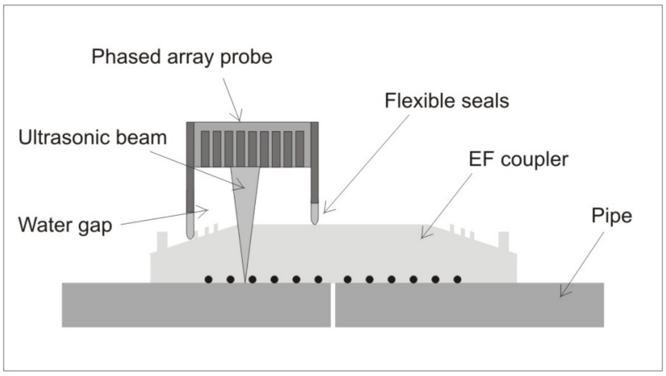

FIG. 7 SCHEMATIC OF THE INSPECTION TECHNIQUE FOR EF JOINTS

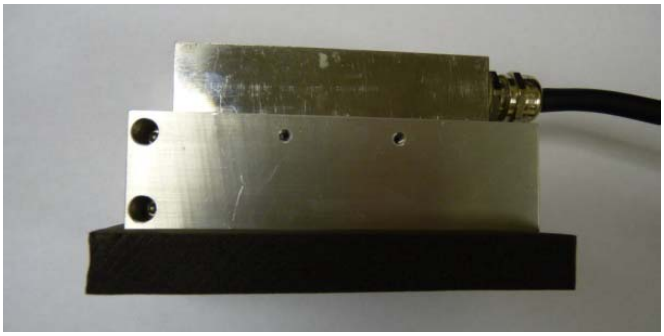

FIG. 8 ZERO DEGREE WATER WEDGE USED FOR EF INSPECTIONS

The ultrasonic image of a 180mm diameter EF fitting is shown in Figure 9 and clearly shows the indications from the heating wires and the reflection from the inside of the fitting between the heating wires.

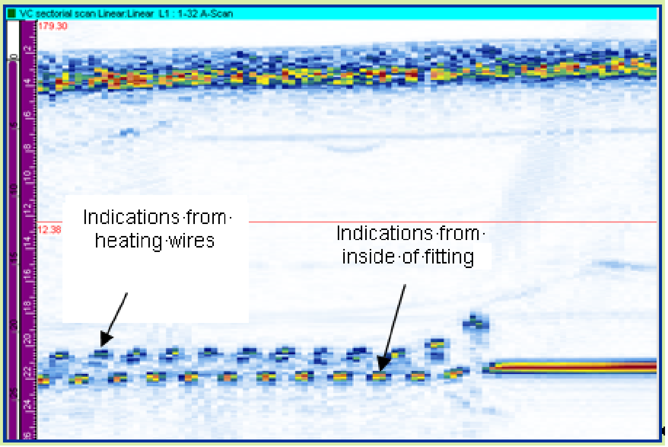

FIG. 9 PHASED ARRAY ULTRASONIC IMAGE OF 180MM EF FITTING

An image of a welded EF joint in a 180mm PE pipe is shown in Figure 10, where the indications from the heating wires can clearly be seen as well as the line indicating the edge of the heat affected zone (HAZ) in the fitting. The distance of the edge of the HAZ to the plane of the heating wires gives an indication of the amount of PE material that has been melted during the welding process and can therefore be used to detect cold welds [8].

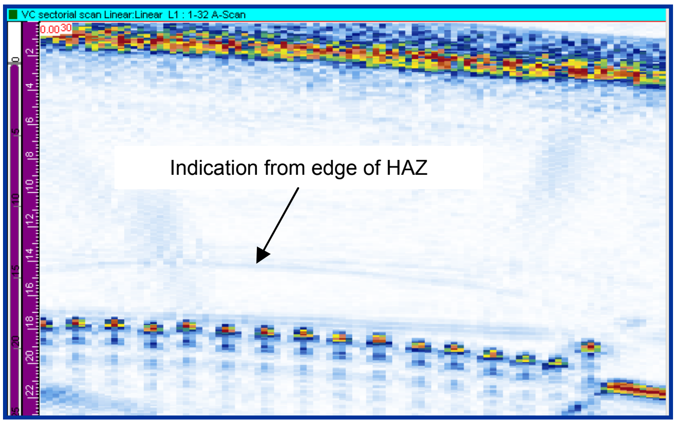

FIG. 10 PHASED ARRAY ULTRASONIC IMAGE OF AN EF JOINT IN 180MM PE PIPE

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 11).

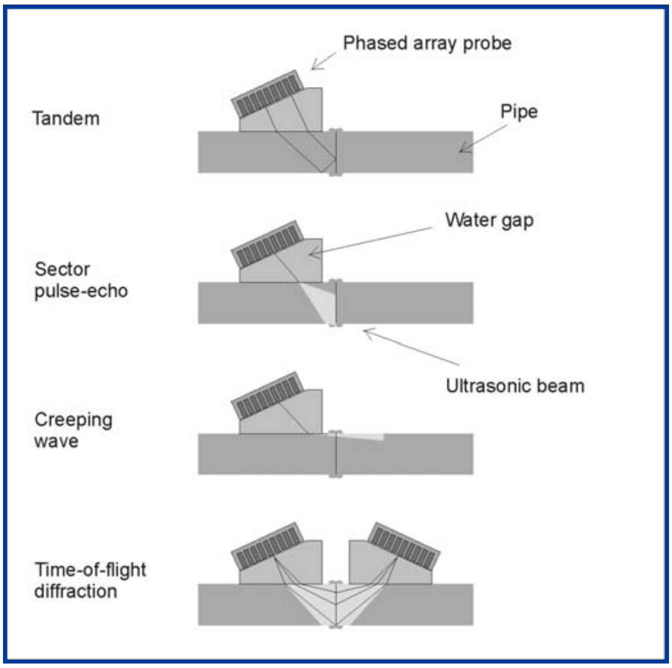

FIG. 11 INSPECTION TECHNIQUES USED FOR INSPECTING BF WELDS

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 millimeters 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 used in this project was a pitch-catch technique using two sector scans, where both transducers 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 transducer elements (Figure 12).

FIG. 12 ANGLED WATER WEDGE USED FOR INSPECTING BF WELDS

For the development of the inspection techniques for BF joints, test pipe samples, covering a range of pipe sizes between 180mm and 710mm and incorporating flat bottom holes (FBHs) of different diameters in the pipe ends (Figure 13) and slots of different depths (Figure 14), were used. The FBHs were used to evaluate the tandem and sector pulse-echo techniques, and the slots were used to evaluate the creeping wave and TOFD techniques.

FIG. 13 FLAT BOTTOM HOLES IN PIPE ENDS

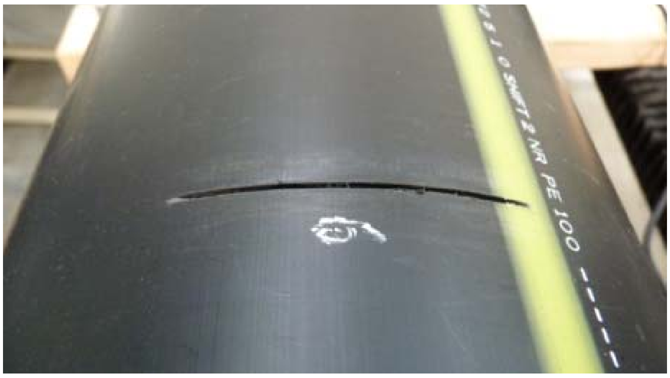

FIG. 14 SLOTS IN PE PIPE

Figures 15 and 16 show data from scans on 225mm pipe containing FBHs and slots, respectively.

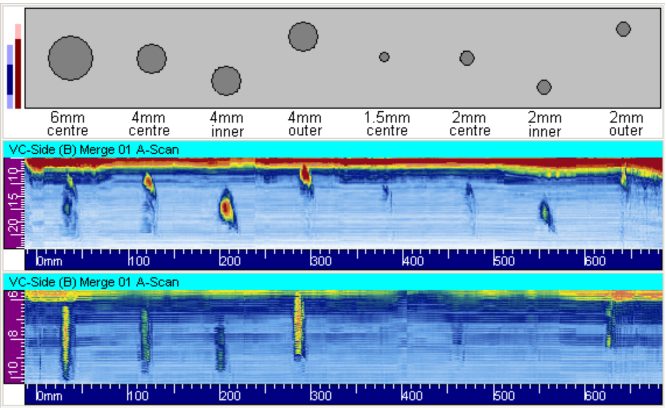

FIG. 15 DEVELOPED VIEW OF FBHS IN THE END OF A 225MM PE PIPE USING THE SECTOR PULSE-ECHO AND TANDEM TECHNIQUES

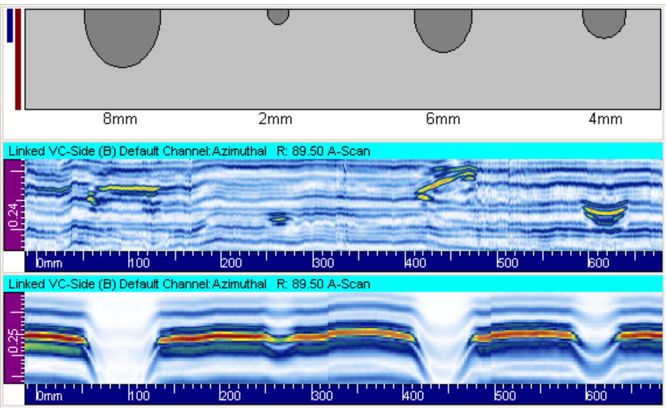

FIG. 16 DEVELOPED VIEW OF SLOTS IN A 225MM PE PIPE USING THE CREEPING WAVE AND TOFD TECHNIQUES

The top part of Figure 15 shows a schematic of the FBH locations in the end of the pipe. The bars to the left of the drawing show the theoretical coverage of the techniques; the red bar showing the coverage with the sector pulse-echo technique and the blue bar showing the coverage with the tandem technique. The lighter areas in the bars show the contributions of the beam spread. In the center part, the B-scan end view of the sector pulse-echo scan, using a 4MHz probe, is shown. The axis on the left shows the through-thickness depth of the indication. In the lower part, the B-scan side view of the tandem scan, using the same probe, is shown. As can be seen, all of the FBHs can be detected using the sector pulse-echo technique and all but the 1.5mm and the 2mm inner FBH can be detected using the tandem technique.

The top part of Figure 16 shows a schematic of the location of the slots in the pipe. The bars to the left of the drawing again show the theoretical coverage of the techniques; the red bar showing the coverage with the TOFD technique and the blue bar showing the coverage with the creeping wave technique. In the center part, the B-scan end view of the creeping wave scan, using a 4MHz probe and a beam angle of 78° is shown, and in the lower part the B-scan end view of the TOFD scan, using two identical 4MHz probes, is shown. As can be seen, both techniques can detect all four slots.

WORK PACKAGE 4: DEVELOPMENT OF ACCEPTANCE CRITERIA

The welds inspected in Work Package 3 will be mechanically tested using both short-term and long-term tests. The results from these tests will be analyzed 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 (Figure 17) 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.

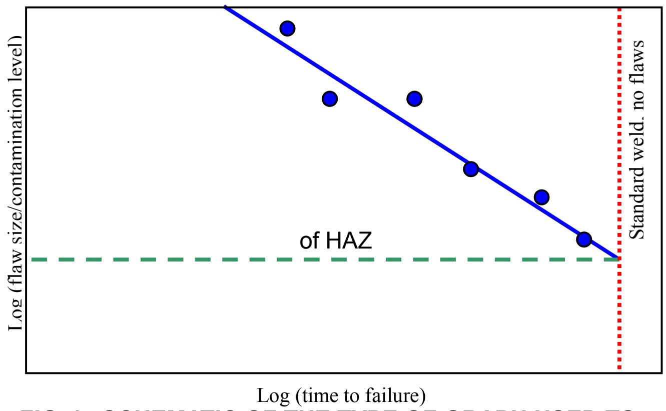

FIG. 17 SCHEMATIC OF THE TYPE OF GRAPH USED TO DETERMINE CRITICAL DEFECT SIZES AND CONTAMINATION LEVELS

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 [11]
  - Specimen creep rupture test to EN 12814-3 [12]
  - Whole pipe tensile creep rupture test (Figure 18) [13]
- EF welds:
  - Decohesion test to EN 12814-4 [14]
  - Crushing decohesion test to ISO 13955 [15]
  - 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 [16]
  - Whole pipe tensile creep rupture test

FIG. 18 WHOLE PIPE TENSILE CREEP RUPTURE TEST RIG

WORK PACKAGE 5: DEVELOPMENT OF NDE INSTRUMENT

A new compact phased array flaw detector with the ability to operate in a harsh environment has been designed (Figure 19). Prototype ultrasonic phased array NDE data acquisition and analysis systems will also 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.

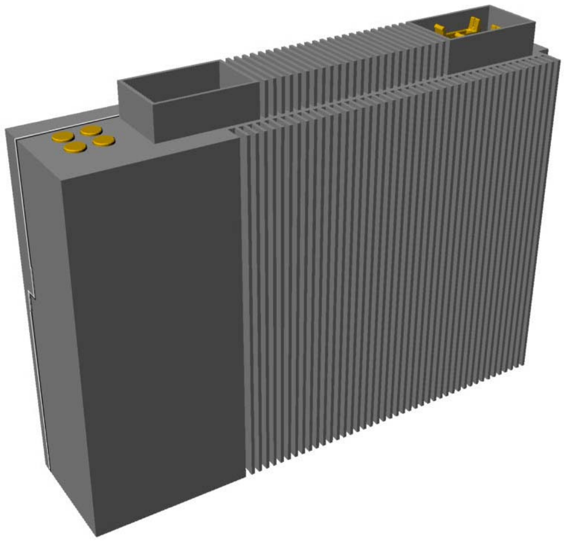

FIG. 19 CONCEPT DRAWING OF TESTPEP NDE INSTRUMENT

The instrument, shown in Figure 19, has the following features:

- Integrated device and remote user interface on separate PC.
- Compact box with IP67 protection for full immersion (<0.5m).
- SSD memory for data storage (100GB).
- Two removable batteries allowing up to 6 hours continuous operation.
- Weight: 4kg.
- Size: 320 x 240 x 100mm.

WORK PACKAGE 6: 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 a wide range of pipe sizes (Figure 20). 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.

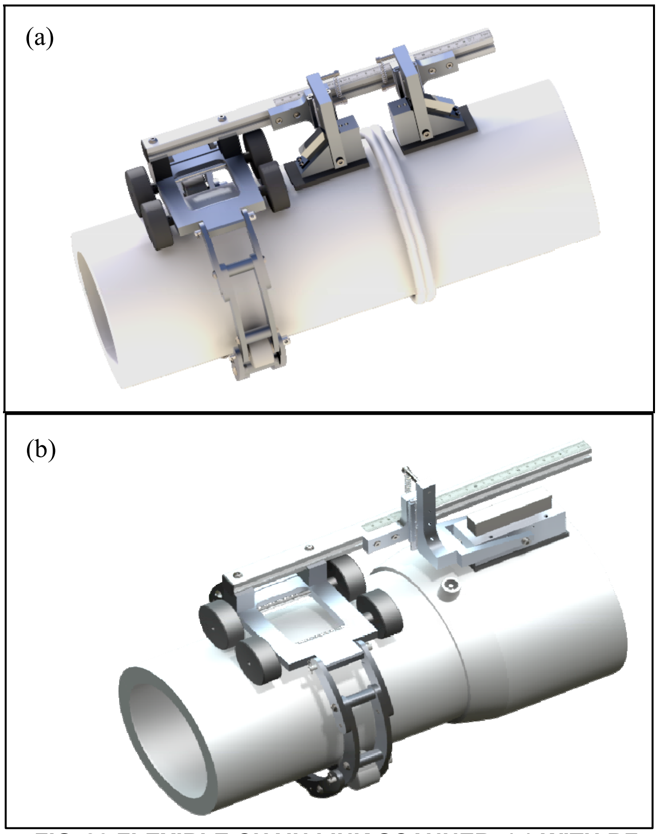

FIG. 20 FLEXIBLE CHAIN LINK SCANNER: (a) WITH BF PROBE HOLDER, (b) WITH EF PROBE HOLDER

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 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, in which a series of pipe welds will be produced, where the location and number of flaws will remain blind to the NDE operator.

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.
- Complete the development of the defect recognition and automatic defect sentencing software.
- Assemble and assess the complete prototype NDE system and perform field trials.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union's Seventh Framework Programme managed by REA-Research Executive Agency [PF7/2007-2013] under grant agreement no [243791-2].

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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