DEVELOPMENT OF AN AUTOMATED PHASED ARRAY ULTRASONIC INSPECTION SYSTEM AND FLAW ACCEPTANCE CRITERIA FOR WELDED JOINTS IN POLYETHYLENE PIPES

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Abstract

The current practice for assuring the quality of butt fusion and electrofusion welded joints 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 testing 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 both butt fusion and electrofusion joints in polyethylene pipes of diameters between 90 and 710mm (3.5 and 28 inches), and to determine critical defect sizes and particulate contamination levels using accelerated long-term testing.

Keywords: polyethylene, butt fusion, electrofusion, inspection, ultrasonic

INTRODUCTION

Polyethylene (PE) pipes offer significant advantages over other materials such as cast iron, steel, copper and concrete, for the transportation of fluids. They do not corrode; have a longer predicted service life, leading to less frequent replacement; they 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, is being restricted by the lack of a proven, reliable non-destructive testing (NDT) method for the welded joints.

In recent years, phased array ultrasonic testing (PAUT) has been considered for assessing the integrity of both butt fusion (*Munns (1), Troughton (2), Messer (3), Crawford (4), Fredrick (5) and Troughton (6)*) and electrofusion (*Shin (7), Bird (8) and Caravaca (9)*) joints. However, these have been limited to a narrow range of pipe sizes and/or have not included acceptance criteria.

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 PAUT

system for inspecting pipe-to-pipe and pipe-to-fitting (elbows, bends, reducers, tees) butt fusion (BF) and electrofusion (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, which are described below.

Manufacture of welded pipe samples
Over 150 BF and EF welded joints are being manufactured in both PE80 and PE100 materials, in the following pipe sizes:

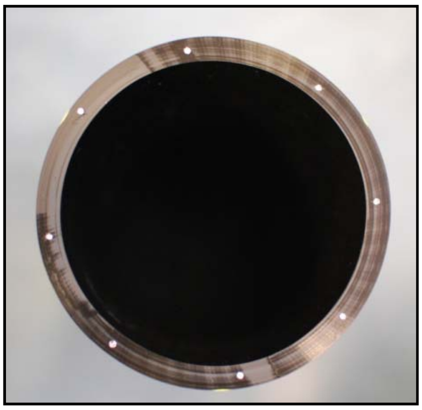
- 180mm SDR17
- 225mm SDR11
- 355mm SDR11
- 450mm SDR17
- 710mm SDR17

Most of these contain deliberate flaws, although some reference samples, containing no flaws, have also been made.
Since, for both the NDT 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 (airborne dust).
- Graded silica sand (particle size 150 - 300μm) – to simulate coarse particulate contamination (sand, grit).
- Aluminium discs (25μm thick, 1-50mm diameter) – to simulate planar flaws (fingerprints, oil, grease, rain droplets).

Aluminium discs were used because previous work had shown that, for ultrasonic NDT, they are a good simulation of real planar flaws. *Munns (1)*
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 aluminium discs during the BF welding process, a number of discs were placed at various circumferential and radial positions around the joint before welding (Figure I).

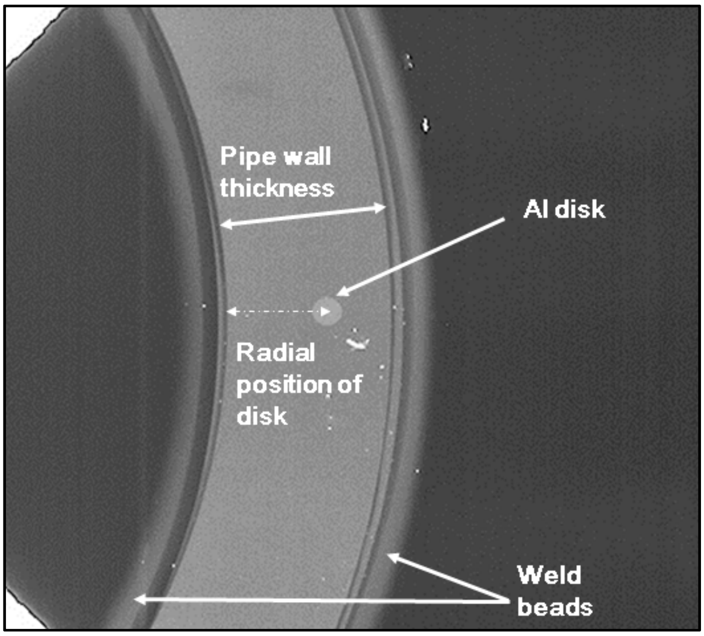
Figure I: Location of aluminium discs prior to butt fusion welding



After welding, the joint was cut out and machined to a thickness equal to that of the weld beads (Figure II) before being inspected using X-ray radiography to determine the final positions of the discs after welding (Figure III).

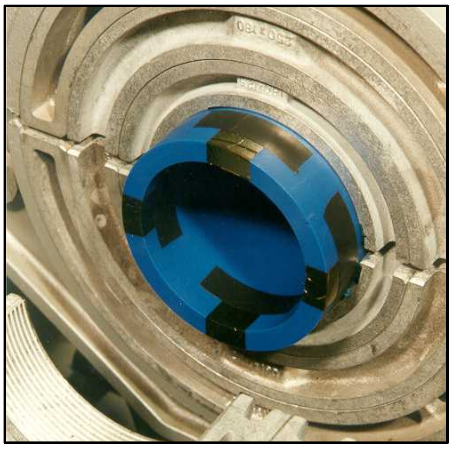
Figure II: Machined ring from butt fusion weld containing aluminium discs

Figure III: Radiograph showing final position of aluminium discs after welding



In order to determine critical particulate levels it was necessary to quantify the actual percentage area of the weld contaminated. In order to do this, one pipe end was contaminated and polyimide tape was applied to the other, at four equidistant positions (Figure IV). After welding, parallel-sided strips containing the 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 estimated by interpolation. Polyimide tape was chosen for this application because it had the required temperature resistance and produced a clean break at the interface.

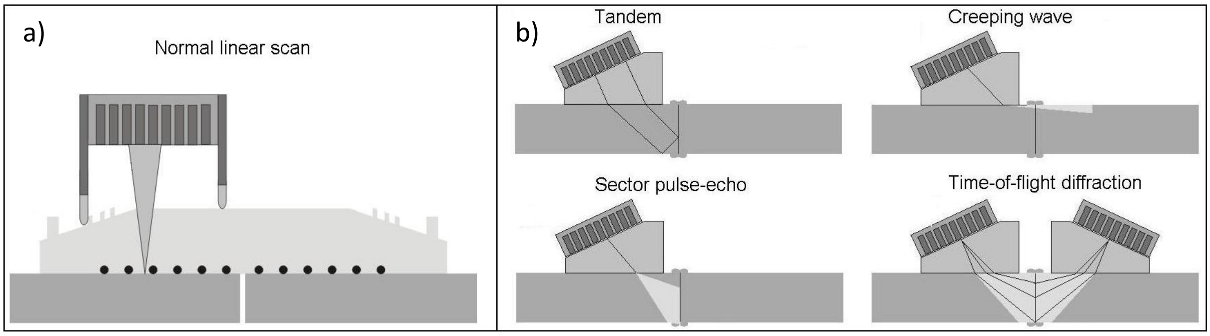
Figure IV: Location of polyimide tape for butt fusion welds containing particulate contamination



Development of inspection techniques

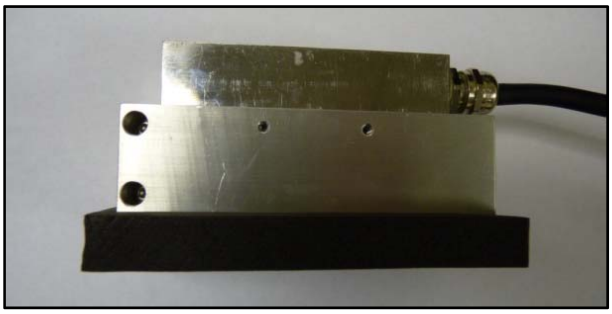
The two different joint types require different inspection techniques. These are shown in Figure V and are described below.

Figure V: Inspection techniques for a) EF joints, and b) BF joints



The inspection technique for EF joints used a normal (0°) linear scan, focused at the fusion zone between the fitting and the pipe (Figure Va). Since the heating wires are located above the fusion zone, sufficient resolution to be able to see both the wires and between the wires is required. A novel open-face water wedge was designed and manufactured in order to achieve good acoustic matching with the PE fitting (Figure VI). The water wedge had a sealing skirt fitted, to keep the water in the wedge while it passes over the surface features on the EF fitting.

Figure VI: Water wedge/probe assembly used for EF inspections



The most critical factors for the inspection of EF joints are the coverage and the resolution. Good resolution is required to be able to inspect beyond the wires. The resolution is mostly dependent on the frequency, with higher frequencies giving higher resolution. For smaller pipe sizes, both the wire diameter and the spacing between two adjacent wires get smaller, and a probe with a higher frequency is required to be able to inspect the fusion zone. However, PE is a highly attenuating material and attenuation increases approximately with a power factor with frequency. Thus, the frequency needs to be reduced for larger pipe sizes to be able to achieve sufficient propagation distance of the ultrasound. Fortunately, in the larger EF fittings, the wire diameter and the wire spacing are also larger so the resolution is still sufficient.

Inspecting BF joints required the use of angled ultrasound beams 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 Vb). The techniques are, in most cases, complimentary. The self-tandem technique uses one half of the phased array elements in the probe 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.

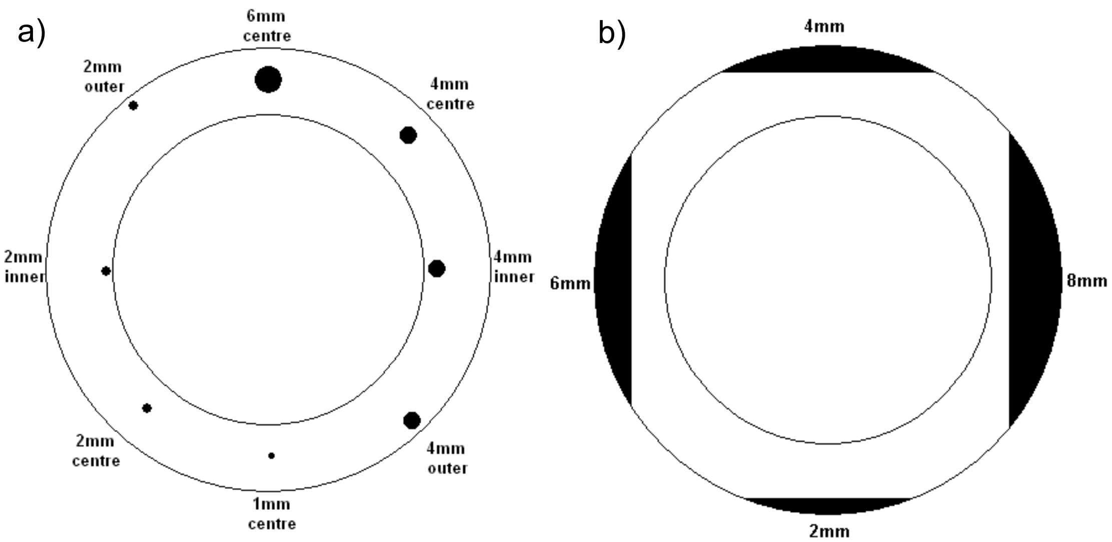
The TOFD technique covers the entire fusion zone and uses forward diffraction to detect vertical flaws. The TOFD configuration used in this project was a pitch-catch technique using two sector scans, where both transducers use a large aperture to transmit and receive beams covering the entire weld.

Again, open face water wedges were used (Figure VII). The angle of the wedges was optimized to minimize the electronic steering by the transducer elements.

Figure VII: Angled water wedge/probe assembly used for BF inspections

In order to develop the PAUT technique for the EF joints, initial inspection trials were carried out using unwelded EF fittings, based on the assumption that, if sufficient resolution can be achieved to detect the wires, the fusion zone located just below the wires can also be inspected.
When developing the inspection techniques for BF joints, unwelded pipe samples with artificial flaws (flat bottom holes (FBHs) machined into the pipe end and slots machined in the middle of the pipe) were used, covering a range of pipe diameters between 180 and 710mm (7 and 28 inches). The FBHs were used to evaluate the tandem and the sector pulse-echo techniques; the slots were used to evaluate the creeping wave and TOFD techniques. The arrangement of the FBHs and slots for 225mm (9 inch) OD pipes are shown in Figure VIII.

Figure VIII: Arrangement of a) FBHs and b) slots in PE pipe test samples



Figures IX and X show data from scans on the 225mm (9 inch) diameter pipe containing FBHs and slots, respectively.

Figure IX: B-scan images from sector pulse-echo and tandem scans on 225mm (9 inch) diameter PE pipes containing FBHs

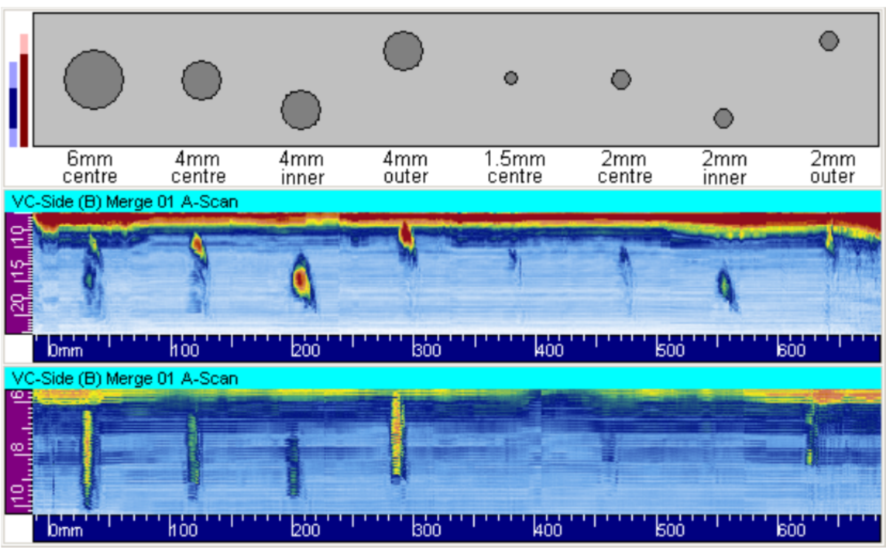
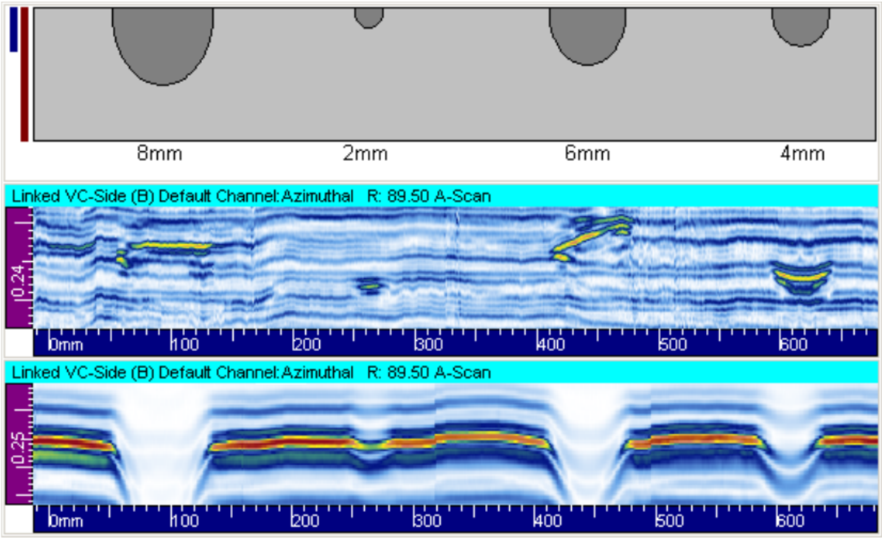


Figure X: B-scan images from creeping wave and TOFD scans on 225mm (9 inch) diameter PE pipes containing slots



The top part of Figure IX shows a schematic of the FBH locations in the end of the pipe. The vertical bars to the left of the drawing show the theoretical coverage of the techniques; the purple 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. The centre image shows the B-scan end view of the sector pulse-echo scan, using a 4MHz probe. The vertical axis on the left shows the through-thickness depth of the indication; the horizontal axis shows the circumferential distance around the pipe. In the lower image, 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 X shows a schematic of the location of the slots in the pipe. The vertical bars to the left of the drawing again show the theoretical coverage of the techniques; the purple bar showing the coverage with the TOFD technique and the blue bar showing the coverage with the creeping wave technique. The centre image shows the B-scan end view of the creeping wave scan, using a 4MHz probe and a beam angle of 78°, and in the lower image 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.

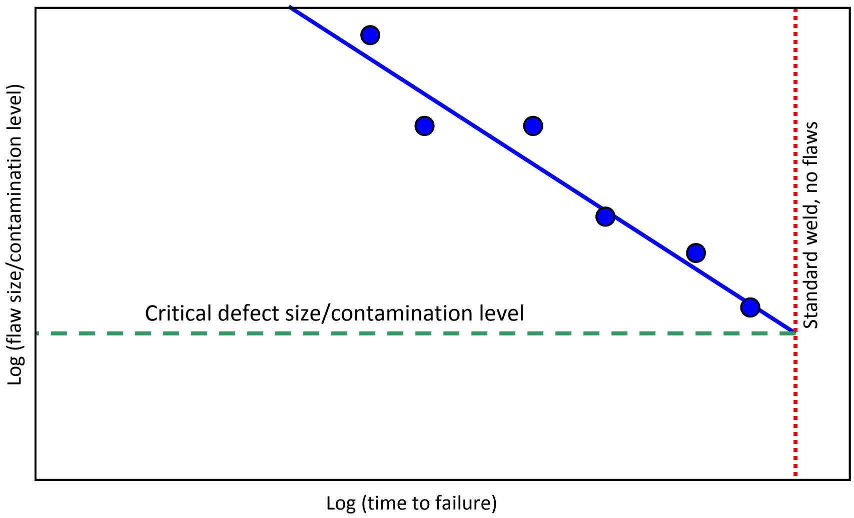
Scans were carried out on the different pipe sizes using probes of different frequencies in order to optimize the PAUT techniques and procedures for pipe sizes between 180 and 710mm (7 and 28 inches). The welded samples containing deliberate flaws are currently being inspected using these procedures in order to determine the limits of detection for each type of flaw, pipe size and joint type.

Development of acceptance criteria

Determining the limits of detection provides only half of the information that is required for an NDT 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 in service, 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) are being determined by measuring the creep rupture performance of the joint.
Two types of creep rupture test are being performed in this project. Whole pipe tensile creep rupture tests are being carried out on pipe diameters up to 225mm. However, due the cost of performing these whole pipe tests, specimen tests, according to the European standard EN 12814-3, are being carried out on larger pipe sizes. In both tests, the test temperature is 80°C (176°F) and the applied tensile stress is 5.5MPa (798psi).
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. Graphs of flaw size / particulate contamination level against mechanical performance (Figure XI) 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.

Figure XI: Schematic example of the graphs used to determine critical defect sizes and contamination levels



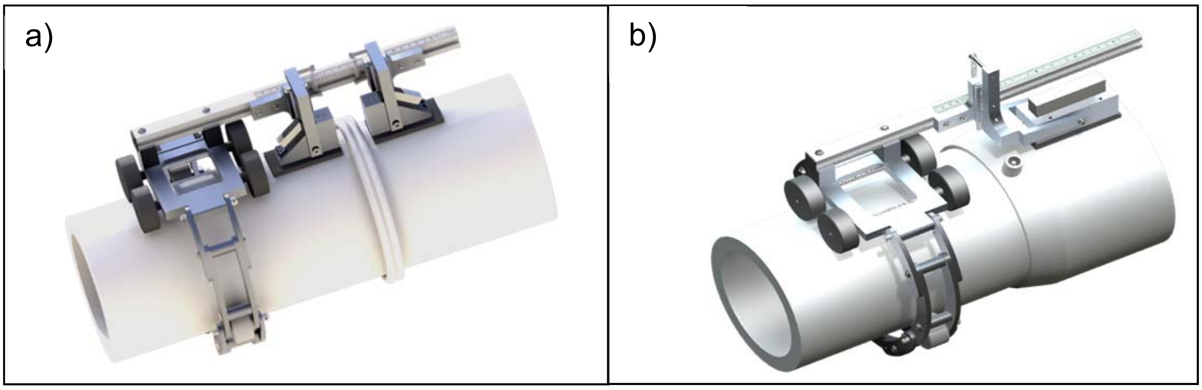
Development of inspection system

A completely new PAUT system is being designed and manufactured, where each component has been optimised specifically for inspecting PE pipes. The system is comprised of the following components:

- Phased array probes
- Probe shoes
- Scanning system with probe holders
- Flaw detector

A flexible scanning 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 XII). It comprises a main carriage that is held in position around the pipe by several links and an adjustment mechanism. The carriage contains an encoder and also the support for the probe holders for the BF and EF joints.

Figure XII: Flexible chain link scanner: a) arrangement for inspecting BF joints, b) arrangement for inspecting EF joints



Since the aim of the project is to have the flaw detector mounted on the carriage of the scanner with wireless connection to a remote computer, a new compact phased array flaw detector with the ability to operate in a harsh environment has been designed and manufactured, with the following features:

- Integrated device and remote user interface on separate PC.
- Compact box with IP67 protection for full immersion (<0.5m, 1.6ft).
- SSD memory for data storage (100GB).
- Two removable batteries allowing up to 6 hours continuous operation.
- Weight: 4kg (8.8lbs).
- Size: 320 x 240 x 100mm (12.6 x 9.4 x 3.9 inches).

In addition to the hardware, prototype ultrasonic phased array NDT data acquisition and analysis software is being developed, including extensive design of the ultrasonic beam control electronics and the data processing within the instrument.

The complete PAUT system, including instrument, probes and scanner will be assembled and assessed in the field at the end of the project in order to evaluate the sensitivity, reproducibility and ease-of-use of the system.

ACKNOWLEDGEMENTS

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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