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# Phased Array Ultrasonic Testing of Welded Joints in Plastic (PE) Pipes

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**Abstract**
A reliable Non-Destructive Testing approach is required for the inspection of polyethylene (PE) butt fusion joints in various material grades and pipe sizes. The nature of butt fusion joints is that the fusion zone is relatively small and the inspection solutions are often restricted by the existence of an external weld bead. This weld bead restricts the probe placement and the probe needs to be positioned in a non-optimal position for the weld inspection. The PE material grades have low velocity and high frequency dependent attenuation, which will complicate the inspection of thicker pipes. In this paper, phased array ultrasonic techniques are presented and their capabilities are evaluated. The techniques utilise customised water wedges to be able to generate forward angle beams to cover the weld within the PE pipe. Techniques have been developed for pipes with outer diameters between 220-710mm and thicknesses between 14-45mm. Probe and wedge parameters have been optimised for this range of pipes. The capability of detecting circular defects with diameters between 1.5-8mm on pipes with an outer diameter between 220-710mm using a phased array ultrasonic inspection solution, and the challenges overcome when working with this type of material, are presented.

**Keywords:** Phased array ultrasonic testing, plastic pipe inspection, butt fusion joints

## 1. Introduction

Polyethylene (PE) pipes have been used for gas and water pipework for decades. Due to the material being immune to water corrosion and highly resistant to fouling, it is considered highly desirable to replace coated carbon steel with PE in safety-critical applications in nuclear power stations [1]. However, the regulatory bodies require the welded joints to be inspected volumetrically and currently such a system is not available. Consequently, there is a need for a reliable Non-Destructive Testing (NDT) approach for the inspection of different polyethylene (PE) pipe joints in various material grades and pipe sizes.

Although there are European standards for the volumetric inspection of plastic pipe welds there is a lack of commercially available systems for inspecting these welds. The current best practice for inspection of welds in large diameter steel pipes uses ultrasonic testing. One of the main reasons why this is not implemented in the plastic pipe industry is because plastic is a difficult material to inspect due to its acoustic properties of high attenuation and low velocity.

Several studies have been conducted to develop reliable NDE methods for the inspection of butt fusion (BF) joints. They have been examined with several different techniques using conventional ultrasonic transducers [2,3]; including pulse-echo, tandem, creeping waves, and time-of-flight diffraction (TOFD). In recent years, work has been extended to also inspect BF joints using phased array ultrasonic testing (PAUT) [4-7].

There are commercial ultrasonic inspection systems for plastic pipes in North America and South Korea [8,9]. However, none of the systems provide a complete solution to the inspection problem. The American system is limited to BF joints and uses conventional TOFD rather than phased array and is not applicable to more complex weld configurations. The Korean system is limited to EF joints and does not record data.

The work presented in this paper is part of the TestPEP project, which is a European funded project on the development and validation of an automated NDT approach for testing welded PE pipe joints. The project will develop phased array ultrasonic NDT procedures, techniques and equipment for the volumetric examination of welded joints in PE pipes. In this paper the progress in developing the inspection techniques for BF joints in different pipe sizes is presented. To assess the joints several individual ultrasonic techniques need to be applied to fully cover the weld fusion zones. A comprehensive development of the techniques has been undertaken, and the techniques have been evaluated on test samples. Detection results from the pipe samples and initial evaluation of the capability of the inspection techniques are presented.

## 2. Materials and equipment

In this section acoustic properties of the polyethylene material used in the plastic pipes are described, together with the weld configuration examined in this paper. The test specimen, the equipment such as the probes, wedges and the designed and manufactured scanner system are also presented.

### *2.1 Material and weld configuration*

PE is a complicated material to inspect due to its low velocity and high attenuation. Shear waves are not supported in PE due to the material properties leaving longitudinal waves as the only inspection mode. The longitudinal velocity will vary depending on the grade of PE, but also from different batches of pipe material. It is also believed that the velocity can vary depending on the depth in the pipe wall and also on the angle of the sound travelling through the crystalline structure [10]. This implies that for accurate inspection solutions the acoustic properties need to be determined for each pipe range.

Initial work involved the determination of the ultrasonic properties of a generic PE pipe material [11], showing the velocity to be slightly frequency dependent and the attenuation to be strongly frequency dependent. The grades involved in this study are both PE80 and PE100. The pipes with an outer diameter (OD) of 355mm were manufactured from PE80 and the pipes with ODs of 220mm and 450mm were from PE100. The velocities of ultrasonic longitudinal waves in different parts of the pipe were determined. It was estimated by measurement of the delay time of ultrasonic signals in the special test samples using cross-correlation techniques. The overall average longitudinal wave velocity for PE80 was 2349.5m/s with a standard deviation of 0.75% of the average value. The overall average value for PE100 was 2385.8m/s with a standard deviation of 0.75%. The attenuation in the PE material is very high and frequency dependent, measured as 0.5dB/mm at 2MHz and 1.1dB at 4MHz.

The BF joint is created by using a heating plate to melt the ends of two pipes which are then fused together by a pressure applied for a certain time (Figure 1(a)). The process then creates a weld bead of the excess pipe material on both the inner and outer surface (Figure 1(b)).

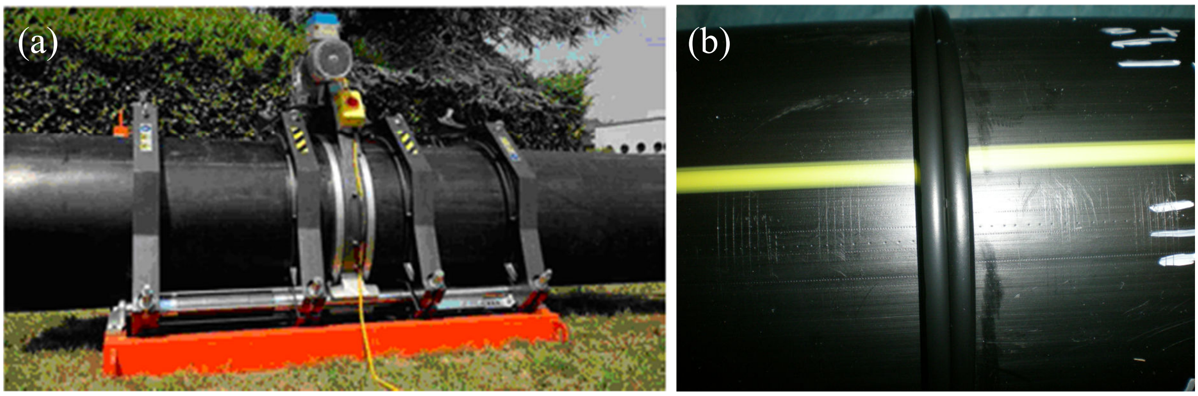


**Figure 1** Butt Fusion pipe joint. (a) An onsite welding tool and (b) a completed weld with the outer surface weld bead.

A severely bad weld can be identified by visual inspection of the external weld bead. However, the weld bead can be intact without deformations and the weld can still contain flaws. In some industries and countries, the weld bead is removed after the welding cycle is completed. However, in some instances, especially in the utilities industry, the weld bead is kept intact. The techniques developed in this study are aimed at the inspection of BF joints with the weld bead intact, which will have some practical implications on the developed inspection techniques and the probe and wedge selections, especially since the weld bead width will vary depending on pipe geometry and welding procedures (Figure 2).

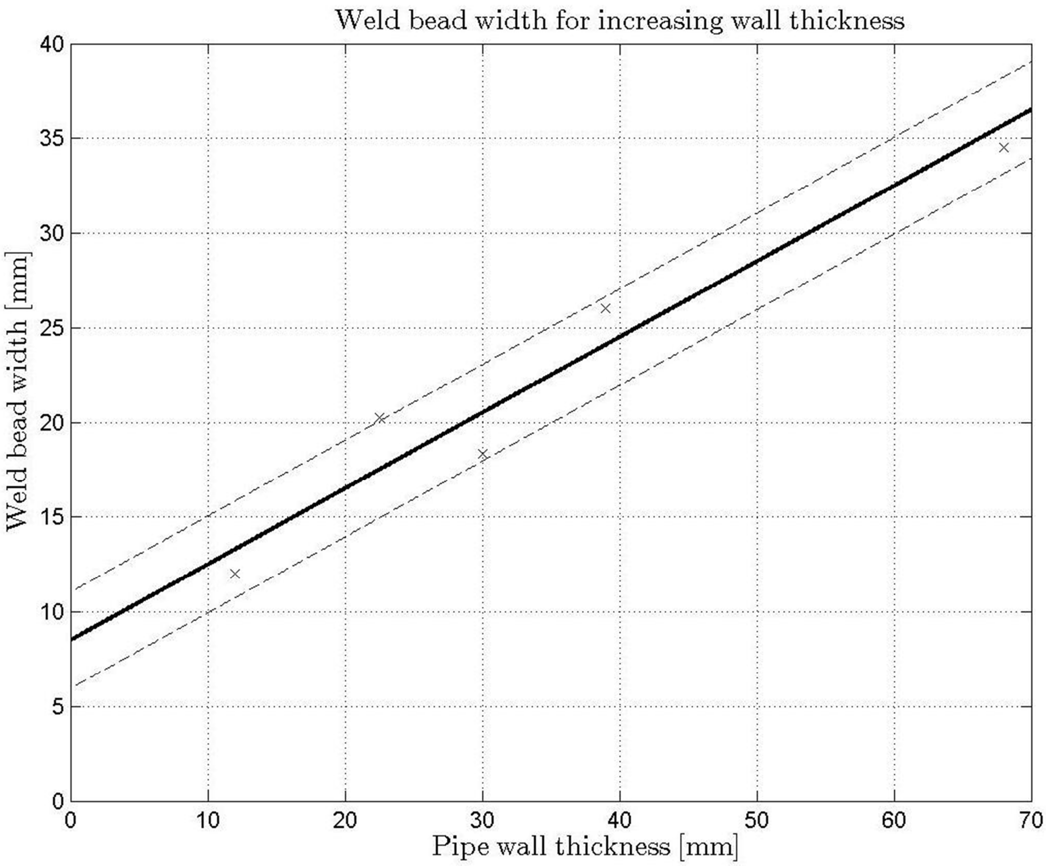


**Figure 2** Average weld bead versus the pipe wall thickness. The distance between the front of the probe wedge and the weld centreline needs to be greater than half the weld bead width.

## *2.2 Test specimen*

When developing the inspection techniques for BF joints, test samples with artificial flaws were used, covering a range of pipe sizes between 220mm and 450mm OD. Flat bottom holes (FBHs) were considered sufficient to evaluate the performance of the proposed techniques. The FBHs were used to evaluate the tandem and the sector pulse-echo techniques and they were machined at the pipe ends. The arrangement of the FBHs for the 220mm OD pipe are shown in Figure 3(a) and the FBHs inserted in all pipes are given in Table 1. In Figure 3(b) the probe position when inspecting the FBHs on the 220mm OD pipe is shown. The FBHs are 40mm deep from the pipe end and the probe is positioned 47mm from the pipe edge leaving the extra 7mm to simulate half of the weld bead.

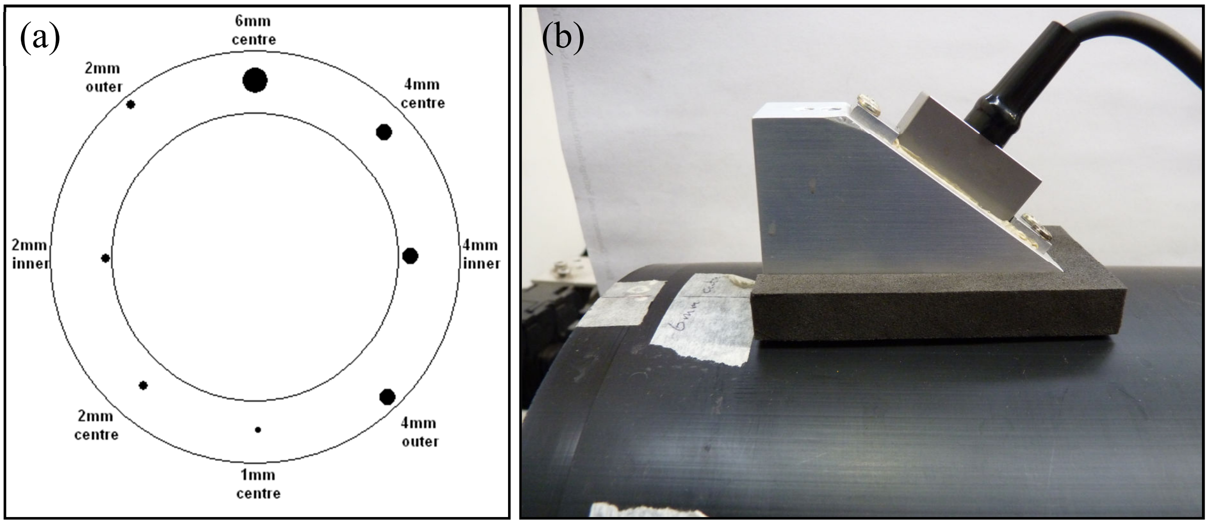


**Figure 3** (a) Arrangement of FBHs in the pipe end. (b) Probe position inspecting the pipe with the FBHs.

**Table 1** Diameter and position of all FBHs in the four different pipe sizes

| 220mm OD 14mm thick | 450mm OD 28mm thick | 355mm OD 33mm thick | 710mm OD 45mm thick |
|---|---|---|---|
| 6mm centre | 6mm outer | 6mm outer | 8mm outer |
| | 6mm centre | 6mm centre | 8mm centre |
| | 6mm inner | 6mm inner | 8mm inner |
| 4mm centre | 8mm outer | 8mm outer | 6mm outer |
| 4mm inner | 8mm centre | 8mm centre | 6mm centre |
| 4mm outer | 8mm inner | 8mm inner | 6mm inner |
| 1.5mm centre | 2mm outer | 2mm outer | 4mm outer |
| | 2mm half outer | 2mm half outer | 4mm half outer |
| | 2mm centre | 2mm centre | 4mm centre |
| | 2mm half inner | 2mm half inner | 4mm half inner |
| | 2mm inner | 2mm inner | 4mm inner |
| 2mm centre | 4mm outer | 4mm outer | 2mm outer |
| | 4mm half outer | 4mm half outer | 2mm half outer |
| | 4mm centre | 4mm centre | 2mm centre |
| | 4mm half inner | 4mm half inner | 2mm half inner |
| | 4mm inner | 4mm inner | 2mm inner |

*2.3 Probes, water wedge and scanner system*

For the evaluation of the inspection techniques two different sets of 1D linear phased array probes were used. For the smaller sized pipes 4MHz probes with 32 elements were used and for the larger pipes a 32 element 2MHz probe was used. Angled beams are required to inspect BF joints and since the steering capability is limited with these probes, angled wedges were used to minimize the steering by the transducer elements.

To perform the inspection on plastic pipes, novel open face water wedge prototypes have been designed and manufactured. The advantages of using a water wedge are low attenuation and a velocity ratio enabling the steering of angled beams to the fusion zone. High angles are required since the weld bead prevents optimal positioning of the probes. The wedges with the probes are shown in Figure 4, the 4MHz probe is shown in (a) and the 2MHz probe is shown in (b). The figure also shows the flexible sealing skirt that is used to effectively keep the water in the probe wedge.

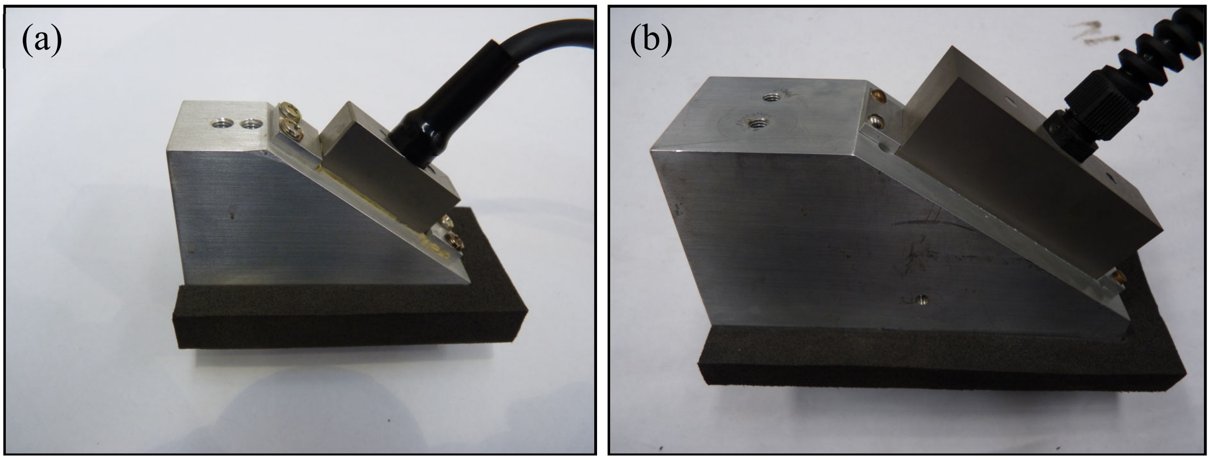


**Figure 4** Angled water probe wedges. (a) 4MHz and (b) 2MHz.

A scanner system has been designed that will be used for inspection of the welded pipes, see Figure 5. The scanner system comprises a main plate that is held in position around the pipe by several links and an adjustment mechanism. This flexible system should allow the scanner to inspect pipes with an OD from 90mm to 1m. The main plate will contain the encoder and also the support for the probe holders. In Figure 5(a) and 5(b), the flexible scanner system and the two probe holders for the BF joints are shown. The probes are kept in contact with the pipe using pre-loaded springs and the coupling is maintained using constant water supply.

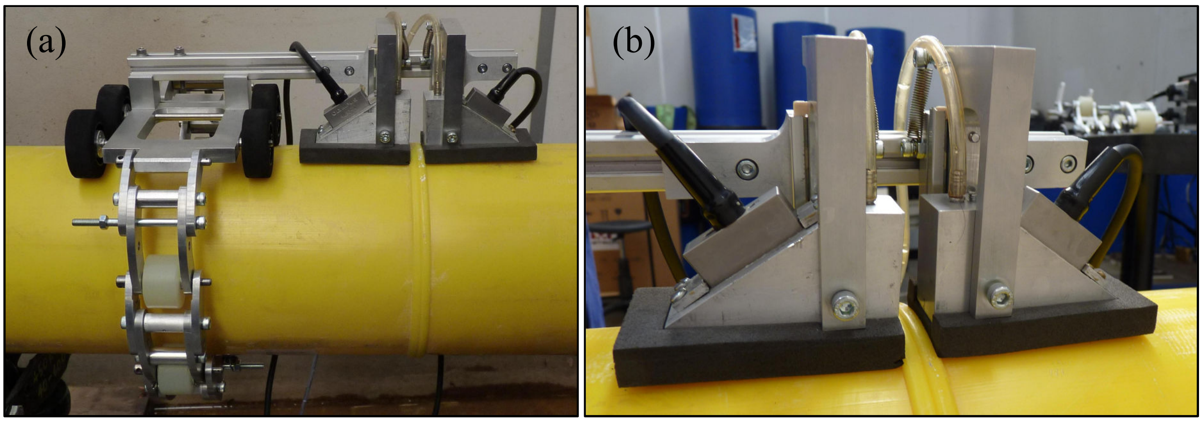


**Figure 5** (a) The flexible chain link scanner with the 4MHz probes. (b) BF probe holder.

## 3. Inspection techniques

For the inspection of BF joints four different techniques were investigated; self-tandem; sector pulse-echo; creeping wave, and TOFD (Figure 6). The techniques are, in most cases, complimentary, both in terms of coverage and also types of defect detected.

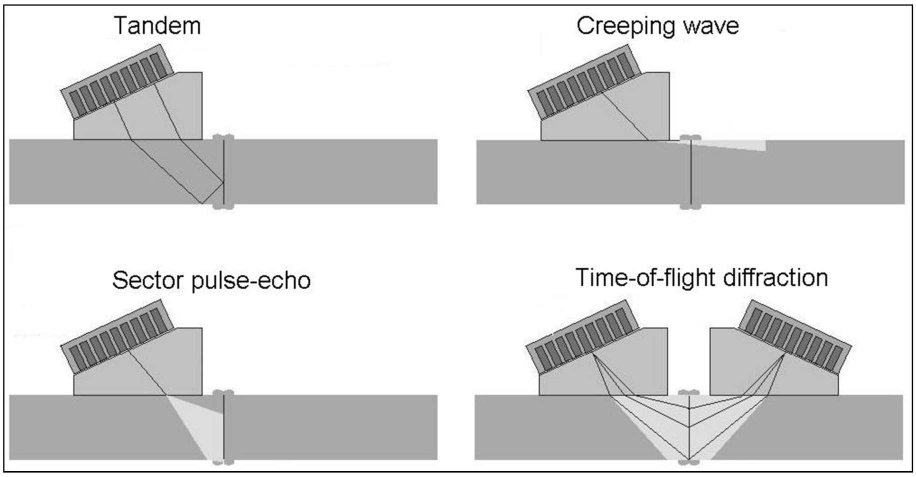


**Figure 6** Schematic drawings of the developed inspection techniques for BF joints.

The sector pulse-echo uses all the elements in the array to create an aperture, sweeping the beam from the lower angle to the higher angle. The technique gives an overview of the weld, and aims to cover most of the weld fusion zone, except for a few millimetres close to the outer surface.

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

The creeping wave technique aims to cover the region close to the outer surface, 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 under the inspection surface, to detect surface-breaking and near-surface defects.

The TOFD technique aims to cover the entire fusion zone. The technique utilises forward diffraction and is sensitive to vertical flaws. The technique uses two probes and the configuration evaluated at this stage of the project is a pitch-catch technique using two sector scans. With this technique, both transducers use a large aperture to transmit beams covering the entire weld.

## 4. Results

This section presents results using the sector pulse-echo and the tandem techniques on pipe samples of different outer diameters and thicknesses. The pipes all have FBHs inserted in one pipe end with different diameters and at different locations, see Table 1 for details. All FBHs are circular, but are in some of the schematic drawings shown as elliptical, due to the change in length-height ratio, for display purposes only.

In all figures in this section three images are shown; a schematic drawing of the cross-section of the pipe; the inspection results using the sector-pulse echo technique; and the inspection results using the tandem technique. To the left of the cross-section drawings two bars are shown to indicate the theoretical coverage of each technique. The black bar indicates the direct coverage of the sector pulse-echo technique and the dark grey bar indicates the direct coverage of the tandem technique. The light grey on the ends of the bars indicates the beam spread contributing to the coverage. The actual coverage during the inspection will always vary to some extent depending on probe misalignment, varying pressure and varying standoff distance.

### *4.1 Pipe size: 220mm OD and 14mm thick*

In Figure 7 the inspection results for a 220mm OD, 14mm thick PE100 pipe are presented. In the top image a schematic drawing of the cross-section of the pipe with FBHs is shown. The inspection result from the sector pulse-echo technique shows that the technique detected all the FBHs. With the tandem technique six out of the eight FBHs are detected.

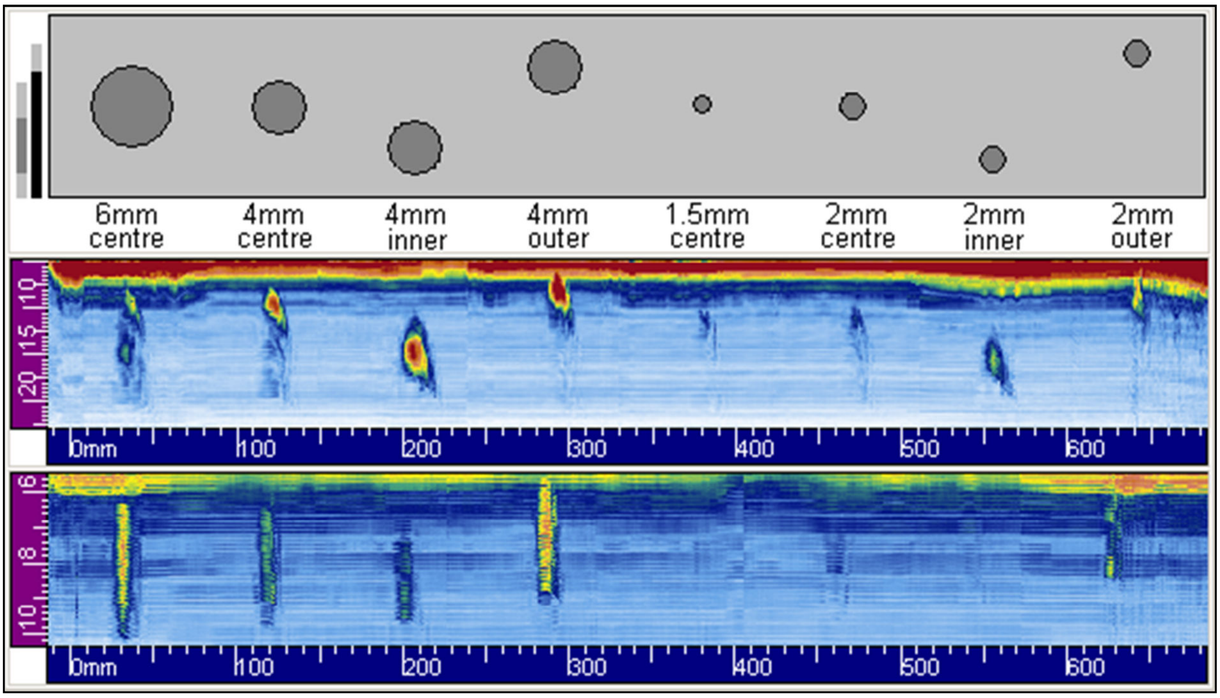


**Figure 7** Schematic drawing of the cross-section of the 220mm OD and 14mm thick pipe with FBHs and the sector pulse-echo and tandem inspection results.

### *4.2 Pipe size: 450mm OD and 28mm thick*

In Figure 8 the inspection results for a 450mm OD, 28mm thick PE100 pipe are given. The sector pulse-echo technique managed to detect all the FBHs, while the tandem technique reliably detected ten out of the 16 FBHs. Weak indications are shown from some of the other FBHs. The undetected FBHs are the ones closest to the outer surface.

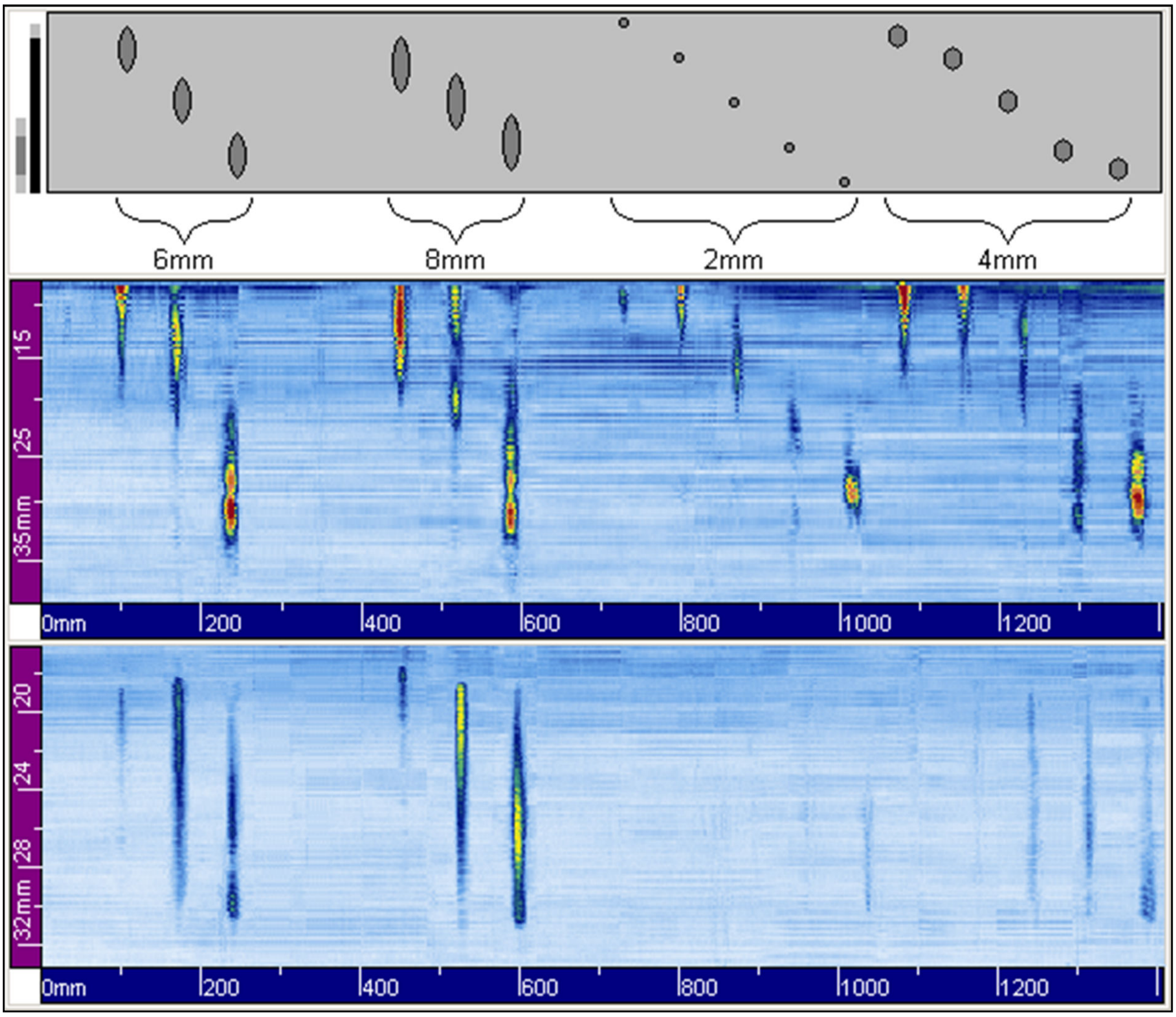


**Figure 8** Schematic drawing of the cross-section of the 450mm OD and 28mm thick pipe with FBHs and the sector pulse-echo and tandem inspection results.

### *4.3 Pipe size: 355mm OD and 33mm thick*

In Figure 9 the inspection results for a 355mm OD, 33mm thick PE80 pipe are presented. The sector pulse-echo technique managed to detect ten of the 16 FBHs, while the tandem technique reliably detected eight out of the 16 FBHs. Some weak indications are shown from some of the other FBHs and the undetected FBHs are again the ones closest to the outer surface.

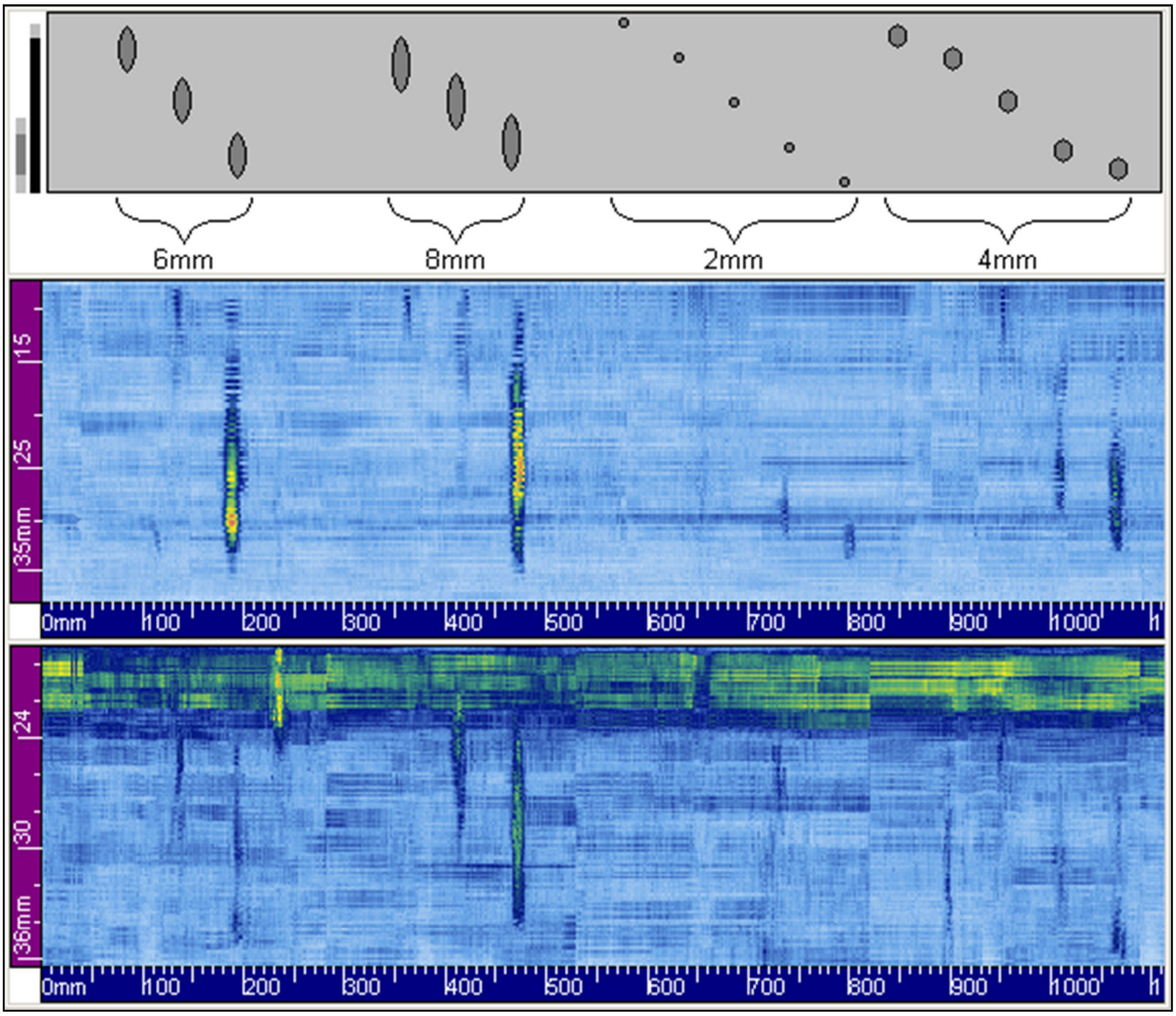


**Figure 9** Schematic drawing of the cross-section of the 355mm OD and 33mm thick pipe with FBHs and the sector pulse-echo and tandem inspection results.

*4.4 Pipe size: 710mm OD and 45mm thick*

In Figure 10 the inspection results for a 710mm OD, 45mm thick PE100 pipe are presented. The sector pulse-echo technique managed to detect 15 of the 16 FBHs, while the tandem technique reliably detected seven out of the 16 FBHs.

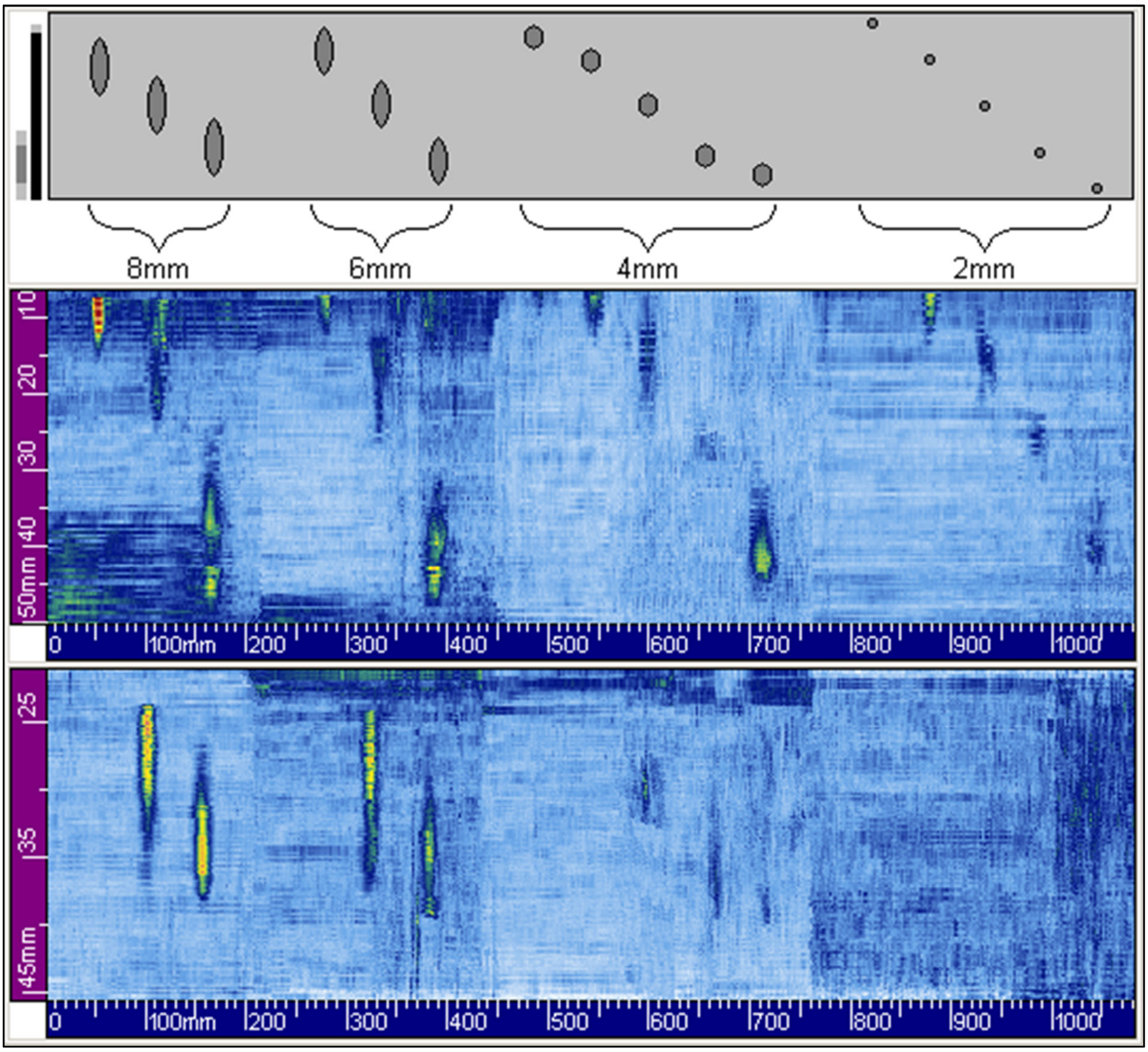


**Figure 10** Schematic drawing of the cross-section of the 710mm OD and 45mm thick pipe with FBHs and the sector pulse-echo and tandem inspection results.

*4.5 Summary of inspection results*

In Table 2 the detection results of the evaluated techniques are presented. Overall, the sector pulse-echo technique detected 49 out of 56 FBHs (88%) and the tandem technique detected 31 out of 56 FBHs (55%). The lower detection capabilities with the tandem technique are expected, due to the smaller coverage area. All FBHs detected by the tandem technique were also detected by the sector pulse-echo technique. If the FBHs located outside the theoretical coverage area are ignored then the detection capabilities for the two inspection techniques are higher than the overall results; 91% for the sector pulse-echo and 84% for the tandem technique. The percentage of undetected FBHs are of the smaller sizes and usually closer to the outer surface.

**Table 2** Summary of inspection results

| FBH (size) | Technique | 220mm OD | 450mm OD | 355mm OD | 710mm OD |
|---|---|---|---|---|---|
| **1.5mm** | Sector PE | 1/1 | - | - | - |
| | Tandem | 0/1 | - | - | - |
| **2mm** | Sector PE | 3/3 | 5/5 | 2/5 | 4/5 |
| | Tandem | 2/3 | 1/5 | 1/5 | 0/5 |
| **4mm** | Sector PE | 3/3 | 5/5 | 3/5 | 5/5 |
| | Tandem | 3/3 | 3/5 | 2/5 | 3/5 |
| **6mm** | Sector PE | 1/1 | 3/3 | 2/3 | 3/3 |
| | Tandem | 1/1 | 3/3 | 2/3 | 2/3 |
| **8mm** | Sector PE | - | 3/3 | 3/3 | 3/3 |
| | Tandem | - | 3/3 | 2/3 | 2/3 |
| **Total** | Sector PE | 8/8 | 16/16 | 10/16 | 15/16 |
| | Tandem | 6/8 | 10/16 | 8/16 | 7/16 |

## 5. Discussion

The developed PAUT techniques are part of a project which aims to incorporate them in a scanning system for on-site inspections, covering a range of PE grades and pipe sizes. Hence, performance on individual material and sizes may need to be optimised. Another part of the project is to design and manufacture probes and wedges for specific joint configurations and pipe sizes. Furthermore, the detection capabilities evaluated in this paper do not consider the entire system, merely the two techniques investigated. It also has to be noted that only a few FBHs of the same size and position have been inspected, and the shapes and locations of the FBHs have not been verified. In order to obtain more statistically correct data, it would be beneficial to perform a more quantitative experimental study on a larger sample size.

## 6. Conclusions

Inspection techniques have been developed for butt fusion joints with outer diameters between 220-710mm and thicknesses between 14-45mm. The capabilities of the techniques have been qualified on test specimens containing artificial defects in the form of flat bottom holes drilled in the pipe end. The overall detection capabilities were 88% for the sector pulse-echo technique and 5% for the tandem technique. All sizes of FBH were detected by both techniques in all pipe sizes. The main reason for undetected FBHs was due to the location being outside the coverage area of the technique. The detection capabilities within the coverage area for each technique were 91% for the sector pulse-echo technique and 84% for the tandem technique.

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## References


1. ASME Boiler and Pressure Vessel Code Case N-755, “Use of Polyethylene (PE) Plastic Pipe. Section III, Division I, and Section XI”.
2. M.J. Troughton, *"Welding with integrated non-destructive examination of polyethylene pipes"*, Plastics Pipes XI Conference, Munich, Germany, 3-6 September 2001.
3. I.J. Munns and G.A. Georgiou, *"Ultrasonic and radiographic NDT of butt fusion welded polyethylene pipes",* Insight, vol. 41, no. 5, May 1999.
4. C. Frederick, D. Zimmerman, and A. Porter, *“High-density polyethylene piping butt-fusion joint examination using ultrasonic phased array”,* Pressure Vessels and Piping, Prague, Czech Republic, 26-30 July 2009.
5. S L Crawford, S E Cumblidge, S R Doctor, T E Hall and M T Anderson, “Preliminary assessment of NDE methods on inspection of HDPE butt fusion piping joints for lack of fusion”, PNNL, May 2008.
6. D. MacLennan, I.G. Pettigrew and C.R. Bird, *“Plastic Fantastic? – An NDE inspection solution for HDPE butt welds”*, 18th World Conference in Non-Destructive Testing, Durban, South Africa, 16-20 April 2012.
7. C. Hekun, C. Zheng, C. Hong and F. Yang, *“Ultrasonic phased array inspection on PE pipe heat fusion joints and electr-fusion joints”*, 18th World Conference in Non-Destructive Testing, Durban, South Africa, 16-20 April 2012.
8. B. Messer, M. Yarmuch and P. den Boer, *“Novel High Resolution Defect Detection for Thermoplastic Butt -Welds”,* Pipeline and Gas Journal, March 2003.
9. H.J. Shin, Y.H. Jang, J.R. Kwon and E.J. Lee, *"Nondestructive Testing of Fusion Joints of Polyethylene Piping by Real Time Ultrasonic Imaging".* Plastics Pipes XII Conference, Milan, Italy, 19-22 April 2004.
10. J.Q. Zhao, L.Daigle and D. Beaulieu, *“Effect of joint contamination on the quality of butt-fused HDPE pipe joints”,* Canadian Journal of Civil Engineering, vol. 29, no. 5, pp. 787-798, October 2002.
11. L. Mazeika, R. Sliteris and A. Vladisauskas, *“Measurement of Velocity and Attenuation for Ultrasonic Longitudinal Waves in the Polyethylene Samples”,* Ultragarsas, vol. 65, No. 4, 2010.