

Development of Phased Array Ultrasonic Inspection Techniques for Testing Welded Joints in Plastic (PE) Pipes

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Abstract

Polyethylene (PE) pipes have been used for gas and water pipework for decades, and have also been incorporated into some non-safety piping systems in nuclear power stations. Due to the material being immune to water corrosion and highly resistant to fouling, it is considered to replace coated carbon steel in safety-critical applications in nuclear power stations. 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. In this paper the progress of developing the inspection techniques for two types of pipe joints and different sizes is presented. The joints require several different techniques to fully cover the weld fusion zones. Detection results from the pipe samples and initial evaluation of the capability of the inspection techniques are presented.

Keyword: Phased array ultrasound, plastic pipe inspection, butt fusion, electrofusion

1. Introduction

Plastic pipes offer significant advantages over other materials for pipework applications. However, their use is being restricted by the lack of reliable NDT method for volumetric inspection, especially for safety-critical applications in nuclear power stations [1]. 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 practise 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 two main types of joint in PE pipes, electrofusion (EF) and butt fusion (BF). These two joints require different inspection methods. In recent years, phased array ultrasonic technology (PAUT) has been considered to assess the integrity of EF joints [2]. However, these studies were limited to pipes with an outer diameter (OD) of 125mm and 250mm. BF joints have been examined with several different techniques using conventional ultrasonic transducers [3, 4]; 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 PAUT [5, 6].

There are commercial ultrasonic inspection systems for plastics pipes in North America and South Korea [7, 8]. 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 such as elbows, reducers and tees. The Korean system is limited to EF joints and does not record data. TestPEP 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 of diameters from 90mm up to 1m. Initial work involved the determination of the ultrasonic properties of PE pipe material [10]. However, several additional tasks need to be solved before reaching the final system. A flexible scanner with probe holder incorporated must be adaptable for the wide range of pipe sizes and joint configurations of interest. Furthermore, a rugged instrument will be developed, capable of performing the advanced procedures required for these materials.

In this paper the progress in developing the inspection techniques and scanner system for EF and BF joints in different pipe sizes are 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 Weld Configurations

The two main joint types investigated in this study have very little in common except that both have fusion zones between two PE materials. An EF joint comprises two pipe ends attached inside a coupler sleeve called a fitting, see Figure 1(a). The fitting has wires around the bore of the sleeve close to the inner surface. When a current is applied to the fitting the wires heat the surrounding pipe and fitting material and the fusion zone is created. The BF joint, see Figure 1(b), 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. The process then creates a weld bead of the excess pipe material on both the inner and outer surface.

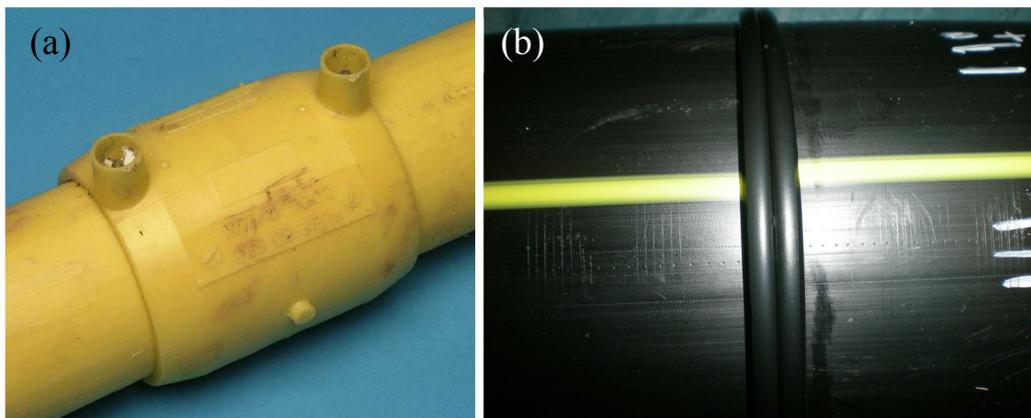


Figure 1. (a) An EF pipe joint. (b) A BF pipe joint with the outer surface weld bead.

In order to develop the PAUT technique for the EF joints initial inspection trials were carried out using unwelded fittings. It was proposed that if sufficient resolution was achieved in detecting the wires, the fusion zone located just below the wires could be inspected. When developing the inspection techniques for BF joints, test samples with artificial flaws were used, covering a range of pipe sizes between 180mm and 710mm OD. Flat bottom holes (FBHs) and slots 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. The slots were used to evaluate the creeping wave and TOFD techniques. The FBHs were machined at the pipe ends and the slots were machined in the middle of the pipe. The arrangement of the FBHs and slots for 225mm OD pipes are shown in Figure 2.

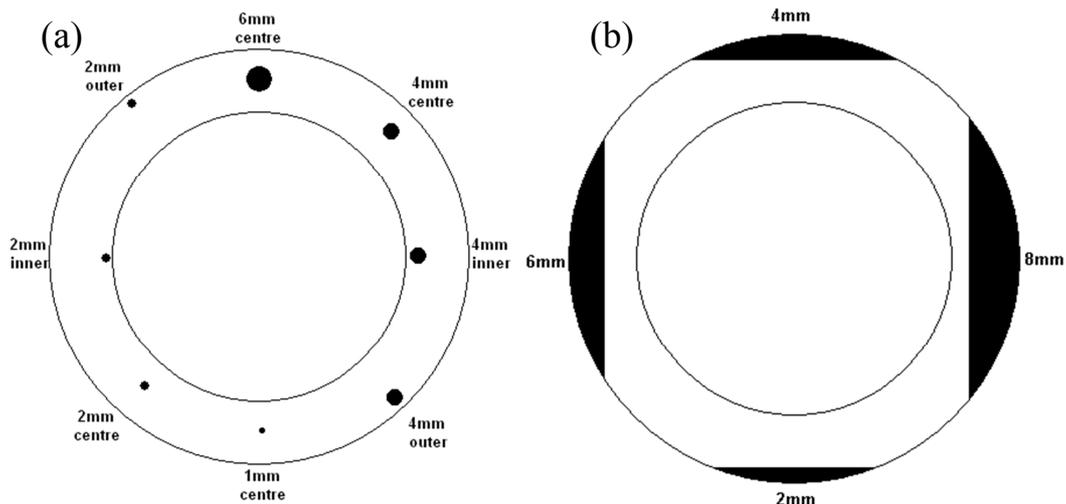


Figure 2. (a) Arrangement of FBHs in the pipe end. (b) Arrangement of slots in the pipe.

3. Development of Scanner System

For the evaluation of the inspection techniques 1D linear probes between 2-7MHz were evaluated. For EF joints, since no steering is required the pitch can be large without reducing the performance of the probe. In this paper 5 and 7MHz probes with 128 elements were used. For the inspections on BF joints 1D linear 4MHz probes with 32 elements were 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. The probes for EF joints required 0° wedges, and the probes for BF joints required angled wedges. The angle of the wedges was optimised to minimize the electronic steering by the transducer elements. The wedges with the probes are shown in Figure 3. The figure also shows the sealing skirt that is used to effectively keep the water in the probe wedge. The sealing material is flexible and the sealing skirt can be customised to specific shapes of the outer surface of EF fittings.

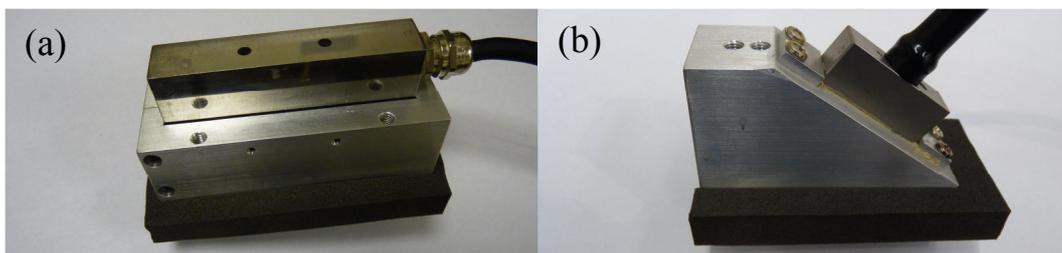


Figure 3. (a) The 0-degree water wedge. (b) The angled water wedge.

A scanner system has been designed that will be used for inspection of the welded pipes, see Figure 4. 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 contains the encoder and also the support for the probe holders. The two different joint configurations require different probe holders. In Figure 4(a) and 4(b) the probe holder for the EF joint and the two probe holders for the BF joint, respectively, are shown.

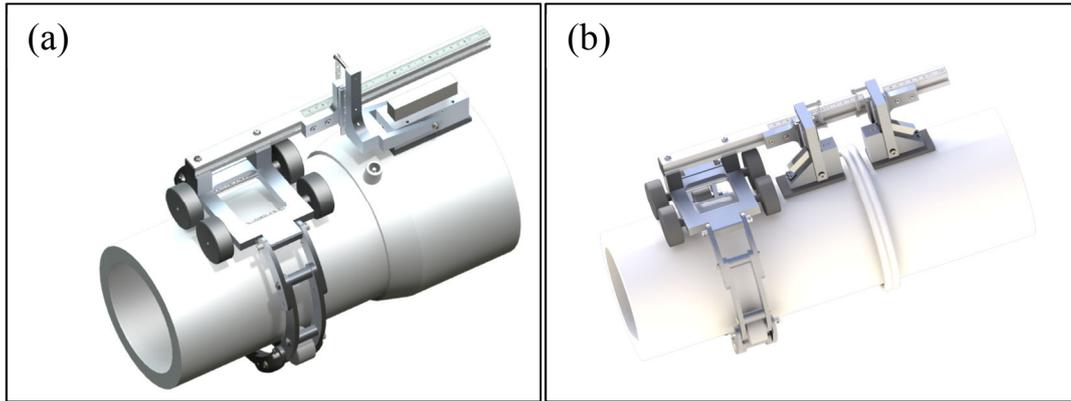


Figure 4. The flexible chain link scanner. (a) EF probe holder. (b) BF probe holder.

4. Development of Inspection Techniques

The joints require different inspection techniques. The techniques used for both types of joints are shown in Figure 5 and are briefly described below.

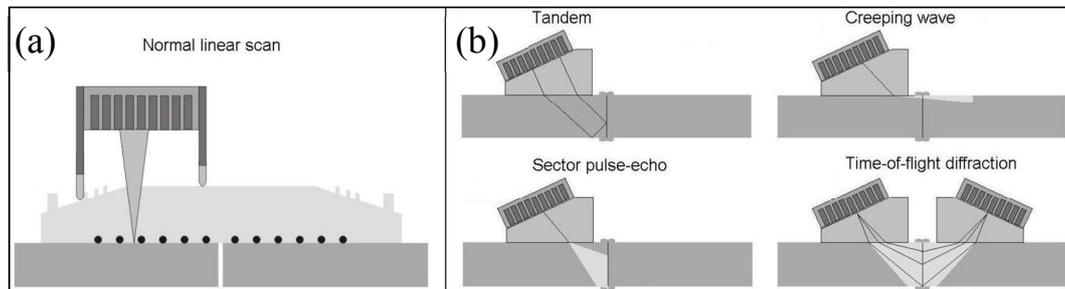


Figure 5. The developed inspection techniques. (a) EF joints. (b) BF joints.

4.1 EF Joints

The inspection technique for EF joints is a normal linear scan, focusing on the fusion zone between the fitting and the pipe; see Figure 5(a). The most critical factors for the inspection of EF joints are the coverage and the resolution. The fusion zone is located below the wires and sufficient resolution for inspection between the wires is required. Generally, the resolution increases with increasing frequency. However, PE is a highly attenuating material and attenuation increases approximately with a power factor with frequency. Thus, the frequency needs to be low for larger pipes to be able to achieve sufficient propagation distance of the sound. In the larger fittings, the wire diameter and the wire spacing are also larger so the resolution is still sufficient. For smaller pipes both the wire diameter and spacing get smaller, and a probe with a higher frequency is required to be able to inspect the fusion zone.

4.2 BF Joints

For the inspection of BF joints four different techniques were investigated; self-tandem; sector pulse-echo; creeping wave, and TOFD; Figure 5(b). The techniques are, in most cases, complimentary, both in terms of coverage and also types of defect to detect. 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 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 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 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.

5. Results

The inspection results on the test specimens are presented. Firstly, results of the development of the technique for EF joints are shown followed by the results for the BF joints.

5.1 EF Results

Electronic sector scans on the EF fitting at one position around the fitting were evaluated. In the scans the top surface of the fitting is visible, along with the bottom surface with the wires located just above. Some parts of the bottom surface are masked by the wires as would be expected. Scans on a 180mm and a 710mm pipe fitting are shown in Figure 6. The electronic scans using the 7MHz probe on the 180mm fitting and the 5MHz probe on the 710mm fitting are shown. In the scans, the first replication of the top surface is shown just under the bottom surface of the fitting. In Figure 6(b), these reflections show the irregular outer surface of the 710mm fitting. This reflection can be avoided by changing the water path in the wedge.

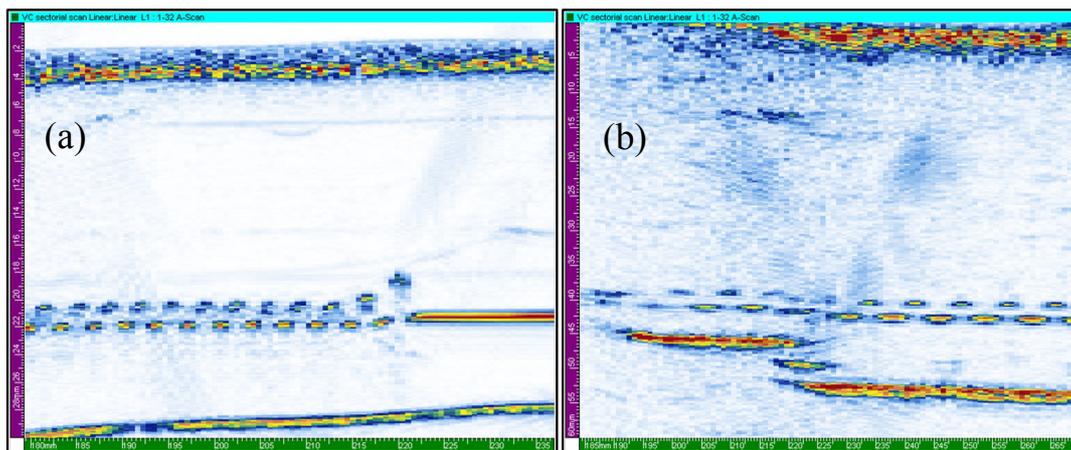


Figure 6. (a) Scanning result of a 180mm fitting. (b) Scanning result of a 710mm fitting.

Scanning results on a 180mm OD EF joint are shown in Figure 7. There are no reflections from under the wires and the fusion zone has been created. Above the wires, it is possible to see a line indicating the heat affected zone (HAZ) [2]. This can be seen clearer in Figure 7(b) where 12dB gain has been added. The position of this HAZ can be used to detect cold welds.

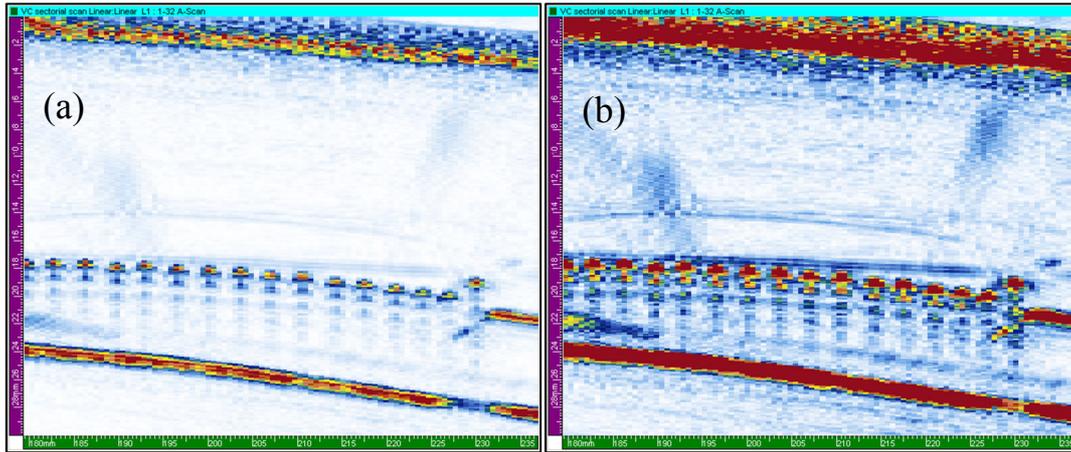


Figure 7. (a) Scanning result of a 180mm EF joint. (b) The same scan, but with +12dB gain.

5.2 BF Results

5.2.1 Single Position Inspection Results on a 225mm OD Pipe

The techniques for BF joints can be evaluated at individual positions around the pipe. In Figure 8 the sector pulse-echo and the tandem scans at the position with the 2mm FBH close to the inner surface are shown. In Figure 8(a), the sectorial scan at one position around the 225mm OD pipe using the 4MHz probe is shown, and in Figure 8(b) the tandem scan at the same position on the same pipe with the same probe is shown. Reflections from the 2mm FBH are achieved with both techniques.

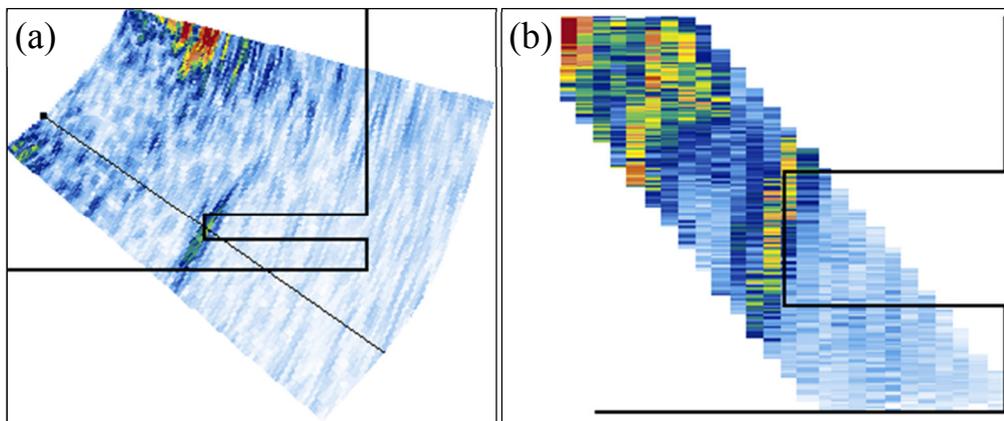


Figure 8. Results on the 225mm OD pipe. (a) Sector pulse-echo scan. (b) Tandem scan.

5.2.1 Circumferential Scans on a 225mm OD Pipe

To assess the inspection zone, circumferential scans were performed. Figure 9 and 10 presents data from scans on the 225mm OD pipe with FBHs and slots. In Figure 9 the results from the sector pulse-echo and the tandem techniques are presented. Figure 9(a) shows a schematic drawing of the FBHs location on the 225mm OD pipe. The bars to the left of the drawing show the theoretical coverage of the techniques (right shows sector pulse-echo and left shows tandem coverage). The lighter areas in the bars show the contributions of the beam spread.

In Figure 9(b) the B-scan side view of the sector pulse-echo scan using the 4MHz probe is shown. The axis on the left reveals at what depths the indications are found. Figure 9(c) shows the B-scan side view of the tandem scan on the same pipe using the same probe. The sector pulse-echo technique detected all the FBHs and the tandem technique detected 6/8.

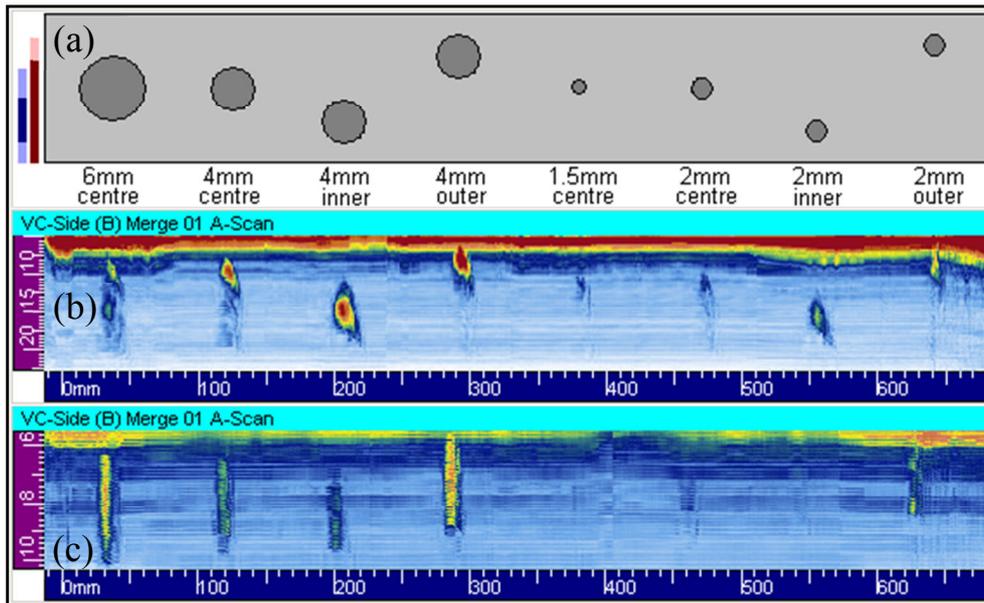


Figure 9. Inspection results on the 225mm OD pipe. (a) Location and size of the FBHs. (b) Sector pulse-echo scan. (c) Tandem scan.

In Figure 10 the results from the creeping wave and the TOFD techniques are presented. Figure 10(a) shows a schematic drawing of the slots location on the 225mm OD pipe. The bars show the theoretical coverage (right shows TOFD and left shows creeping wave). In Figure 10(b) the B-scan side view of the creeping wave scan using the 4MHz probe is shown. Figure 10(c) shows the B-scan side view of the TOFD scan on the same pipe using two identical 4MHz probes. Both techniques detected all of the slots.

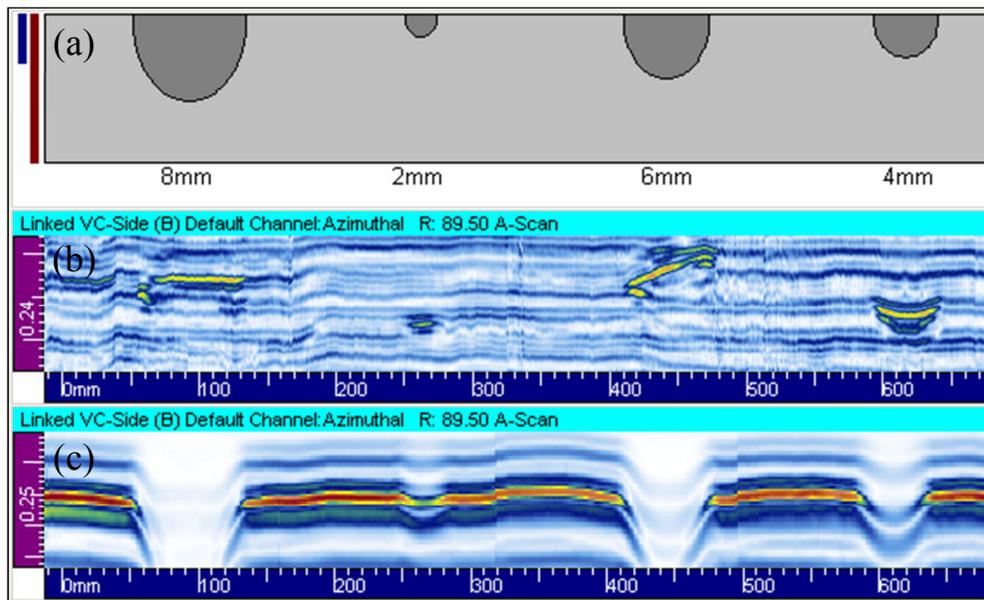


Figure 10. Inspection results on the 225mm OD pipe. (a) Location and size of the slots. (b) Creeping wave scan. (c) TOFD scan.

6.2.2 Circumferential Scans on a 450mm OD Pipe

Figure 11 shows an image from a circumferential scan, using the sector pulse-echo technique with the 4MHz probe, around a 450mm OD pipe with FBHs. Figure 11(a) shows a schematic drawing of the pipe with 4 different diameters of FBHs; 8mm, 6mm, 4mm, and 2mm. The

FBHs are also positioned at different depths in the pipe; three different depths for the two larger holes, and five different depths for the smaller holes. The bar to the left of the drawing shows the theoretical coverage of the technique. In Figure 11(b), B-scan side view from the sector pulse-echo scan is shown with indications from most of the FBHs. When looking at the entire 1.4m scan, some FBHs are difficult to resolve, and closer views are required.

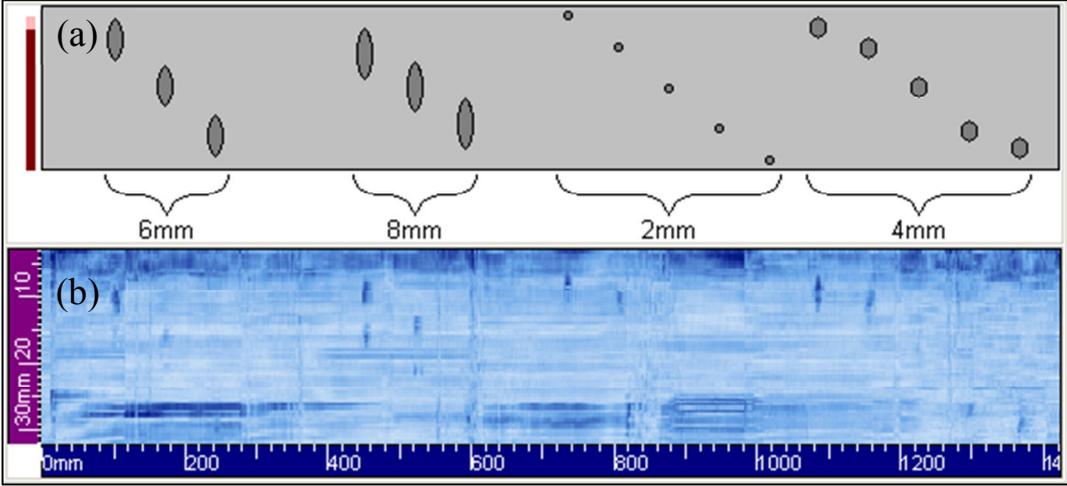


Figure 11. Inspection results on the 450mmOD pipe. (a) FBHs. (b) Sector pulse-echo scan.

Figure 12 show four closer views of the FBHs from the same scan. In Figure 12(a-c), the arrows show where all 8mm, 6mm and 4mm diameter FBHs are detected. Figure 12(d) shows that only two of the five 2mm FBHs are detected. The responses from some of the FBHs are weaker, mainly due to poor scanning results as can be seen in the image.

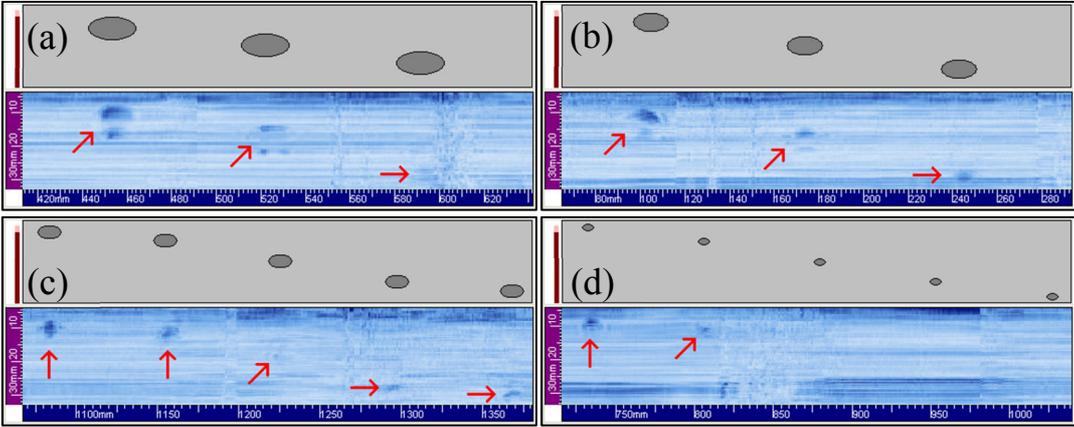


Figure 12. Drawings with the FBHs and inspection results on the 450mmOD pipe. (a) 8mm (b) 6mm (c) 4mm (d) 2mm

In the scans in Figure 11 and 12 it is possible to detect and also size the FBHs in the scan direction. In addition to this, the individual sectorial scans at each position for the FBHs can be used for an initial attempt to size and locate the FBHs in the depth direction. In Figure 13, the sectorial scans at the FBH closest to the outer surface of each size are shown. In all images, it can be seen that signals from the top and the bottom edge makes it possible to size the FBHs. The location and size for all detected FBHs are given in Table 1. In the images, the depth location is biased by 4mm from an error in the wedge delay. This bias has been removed in the table.

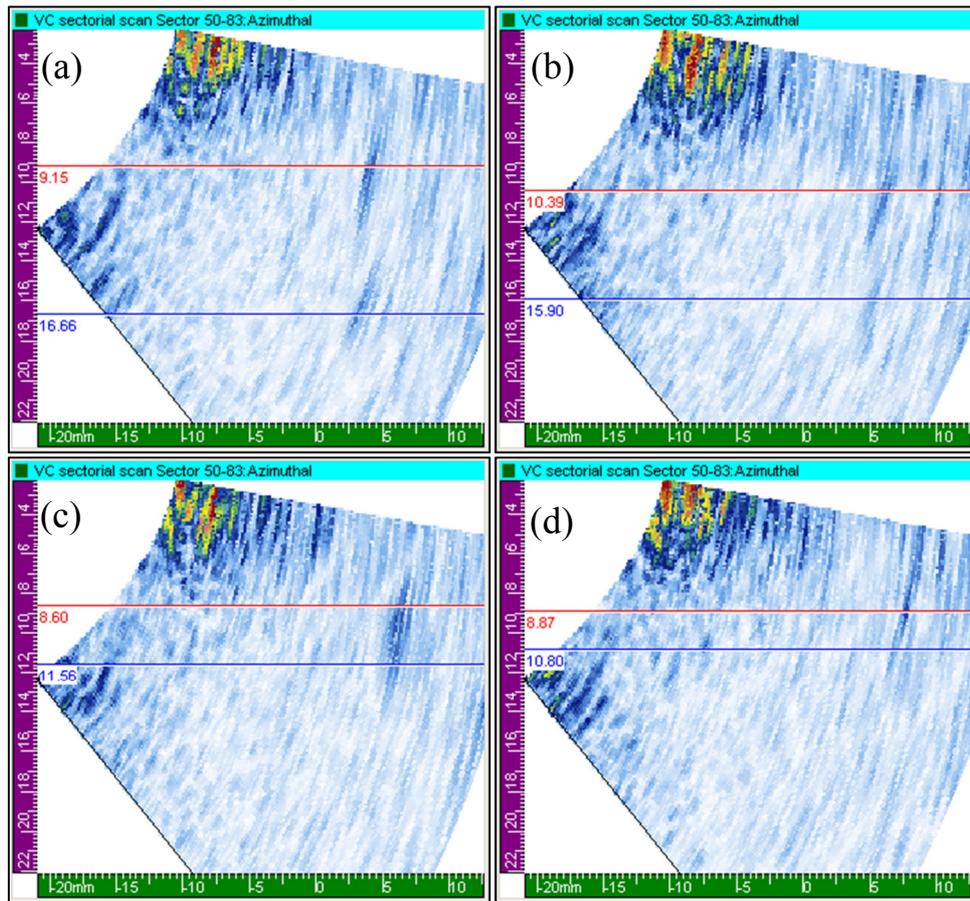


Figure 13. Sector scans at the circumferential positions of the FBHs close to the outer surface on the 450mm OD pipe. (a) 8mm (b) 6mm (c) 4mm (d) 2mm

Table 1. The ultrasonically measured size and location of the FBHs in the 450mm OD pipe, using the sector pulse-echo technique

Properties		Measured properties from scan		
Diameter of FBH [mm]	Depth location [mm]	Size		Location
		Length [mm]	Depth [mm]	Depth [mm]
8	8	9.28	7.51	8.91
8	14	8.25	7.10	14.07
8	20	6.19	8.95	21.20
6	6	8.25	5.51	9.15
6	14	5.16	5.24	14.79
6	22	5.15	2.96	24.61
4	4	6.19	2.96	6.08
4	7	4.12	3.45	8.39
4	14	2.06	2.41	13.32
4	21	5.16	3.03	20.70
4	24	3.12	2.20	25.88
2	2	5.15	1.93	5.84
2	7	2.06	2.00	7.18
2	14	Not detected		
2	21	Not detected		
2	26	Not detected		

6. Discussion

The developed PAUT techniques are part of a project aiming to be incorporated in a scanning system for on-site inspections, covering a range of PE grades and pipe sizes. Hence, performance on individual material and sizes could be optimised. Another part is to design and manufacture probes and wedges for specific joint configurations and pipe sizes. For the development work of optimising the inspection techniques, currently available probes have been used. In many cases these probes are not optimal for the specific inspection.

7. Conclusions

Techniques for inspection of both EF and BF joints have been developed. Initial evaluations of detection and sizing capabilities have been conducted. On the smaller BF size, all defects were detected except two FBHs with the tandem technique. However, all defects can be detected by at least one technique. On the larger BF size, the sector pulse-echo technique was evaluated. All defects except for the three 2mm FBHs closest to the inner surface were detected. These FBHs have a good chance to be detected by the tandem technique. It is also believed that when using the final optimised probes, the detection capabilities will improve.

Acknowledgements

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