DEVELOPMENT AND ASSESSMENT OF A PHASED ARRAY ULTRASONIC INSPECTION SYSTEM FOR POLYETHYLENE PIPE JOINTS

Mike Troughton, Malcolm Spicer and Fredrik Hagglund, TWI Ltd, Cambridge, UK

Abstract

The development of a phased array ultrasonic system specifically for inspecting both butt fusion (BF) and electrofusion (EF) joints in polyethylene (PE) pipes of diameters up to 1000 mm (39 inches) is described, including development of the inspection techniques, procedures and equipment. Also described are the trials that were carried out to assess the prototype inspection system in both the laboratory and in the field.

This paper describes a European-funded research project, called TestPEP, which involved 17 organizations from seven countries, to design, manufacture and validate a site-rugged phased array ultrasonic testing (PAUT) system for inspecting pipe-to-pipe and pipe-to-fitting (elbows, bends, reducers and tees) BF and EF joints in PE pipes.

Introduction

The current practice in Europe for assuring the quality of BF and EF joints in PE pipes during installation is by recording the fusing parameters used, together with a visual inspection of the fused joint and a short-term hydrostatic pressure test, supplemented by the destructive testing of joint on a sample basis using a short-term test on specimens cut from the joint. However, visual inspection can only examine the external surface of the pipe joint; it cannot provide evidence of embedded flaws or a joint with cold fusion (incomplete or partial fusion caused by inadequate molecular chain penetration and co-crystallization at the interface, resulting in a brittle failure mode when subjected to a short-term mechanical test). Also, previous work at TWI [1,2] has suggested that the hydrostatic pressure test will only cause BF and EF joints containing gross defects to fail. In addition, if a defect exists in a fused joint there is only a small chance that it will be included in a specimen that has been cut for mechanical testing. Finally, mechanically testing a joint and then replacing it with one of unknown quality does not ensure the integrity of the pipeline.

Volumetric non-destructive examination (NDE) can provide a complete analysis of the whole joint and does not destroy perfectly good joints. It is therefore the only technique that has the potential to ensure the integrity of the installed joints in a PE pipeline. However, in order to do this, the NDE technique must be proven to detect all possible types of flaws that reduce the integrity of the joint.

In recent years PAUT has been considered for assessing the integrity of both BF [3-7] and EF [8-10] joints. However, these have been limited to a narrow range of pipe sizes and/or have not included flaw acceptance criteria.

Inspection Techniques

Butt fusion and electrofusion joints require different inspection techniques. In BF joints the joint interface is perpendicular to the surface of the pipe and requires the use of angled ultrasound beams to detect any flaws that may be present at the interface. In order to obtain full wall-thickness coverage of the joint area, four different techniques were used (Figure 1): tandem, creeping wave, sector pulse-echo and time-of-flight diffraction (TOFD).

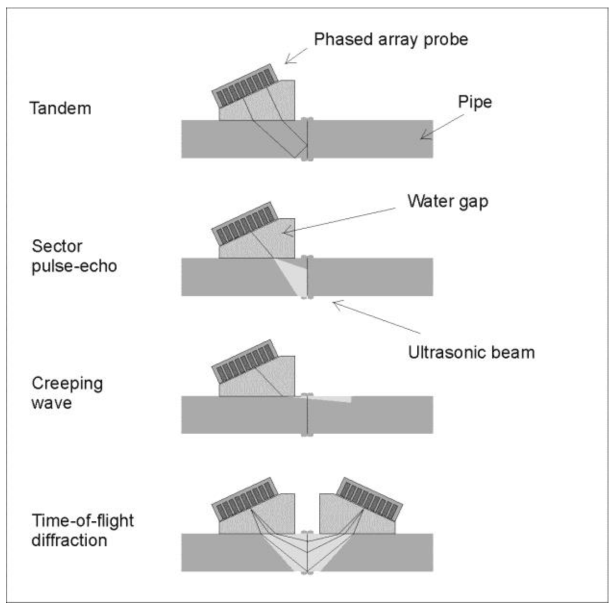

Figure 1. Inspection techniques used for BF joints.

The tandem technique uses one half of the phased array elements in the probe for transmitting the ultrasound and the other half for receiving. The technique is good for detecting planar flaws; however, the coverage is restricted to an area approximately between the mid-wall thickness and 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. This technique gives an overview of the joint and covers most of the fusion zone except for a few millimeters (tenths of an inch) close to the outer surface of the pipe.

The creeping wave technique only covers the region close to the outer surface of the pipe, which is the part not covered by the first two techniques. The 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 was a pitch-catch technique using two sector scans, where both transducers use a large aperture to transmit and receive beams covering the entire joint.

In EF joints, the fusion interface is parallel to the surface of the pipe and a normal (0°) linear scan can be used, with the ultrasound focused at the interface between the pipe and EF fitting (Figure 2).

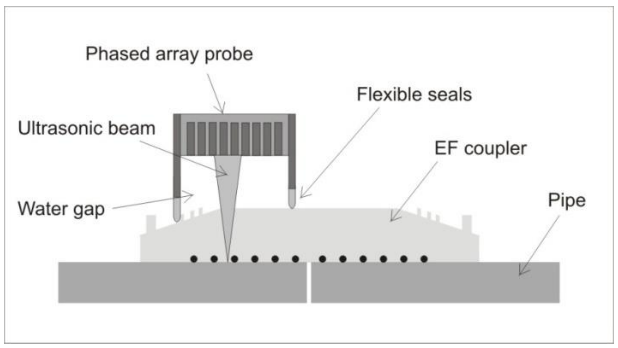

Figure 2. Inspection technique used for EF joints.

Since the heating wire coil is located above the fusion interface, sufficient resolution to be able to see both the wire and between the wire windings is required.

Inspection Equipment

The PAUT inspection system consists of a number of components: a phased array probe, which produces the ultrasonic signal and detects the reflected signals from any flaw in the joint; a probe wedge, which ensures that the ultrasound is transmitted from the probe into the PE pipe or fitting at the correct angle and with the minimal loss of energy; a probe holder, which ensures good contact between the probe wedge and the PE pipe/fitting around the whole circumference; a scanner, which carries the probe assembly around the pipe joint without any movement in the axial direction and records its circumferential position; and a flaw detector, which sends electrical signals to the probe elements and analyses the returning signals.

In this project, the design of each of these components has been optimized specifically for inspecting PE pipes. The specification of the probes for inspecting BF joints, in terms of physical dimensions, ultrasound frequency, number of elements and pitch, was developed based on the ability to detect flat bottomed holes and notches of different sizes, machined into PE pipes of different diameters and wall thicknesses, and the specification of the probes for inspecting EF joints was developed based on the ability to detect the heating wire in unfused EF couplers of different sizes. It was found that the range of pipe diameters from 110 to 1000 mm (4 to 39 inches) can be inspected using only four different probes (two for BF joint and two for EF joints). PAUT probes were designed and manufactured to the specifications developed above.

In order to ensure good acoustic matching with the irregular surface of EF fittings and enable steering of the angled beam for BF inspection the probe wedges were open-faced water wedges, fitted with a flexible sealing skirt to keep the water in the wedge while it passes over the pipe or EF coupler. The angle of the wedges for inspecting the BF joints was optimized to minimize the electronic steering by the probe elements. Photographs of probe/wedge assemblies are shown in Figures 3 and 4.

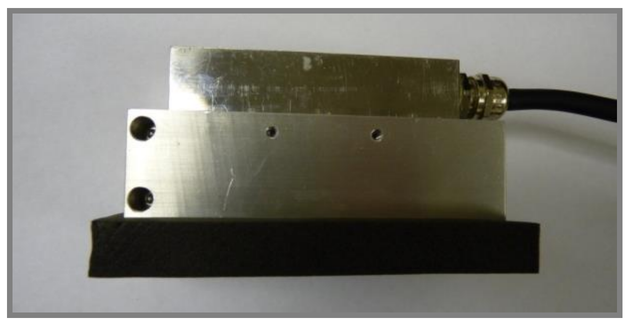

Figure 3. Zero degree water wedge/probe assembly used for inspecting small diameter EF joints.

Figure 4. Angled water wedge/probe assembly used for inspecting small diameter BF joint.

Spring-mounted probe holders were designed to accommodate the different probe/wedge assemblies on the same scanning system. The scanner consisted of a carriage, which contains an encoder to record the circumferential position around the joint and a support for the probe holders, and a series of chain links to hold the carriage on to the pipe (Figures 5 and 6).

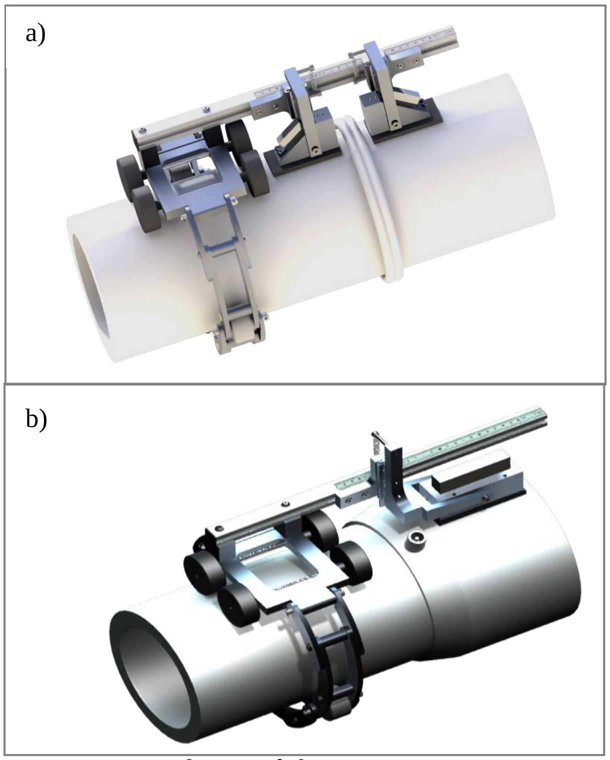

Figure 5. CAD design of the TestPEP inspection system without an encoder on the carriage for: a) BF joints, and b) EF joints.

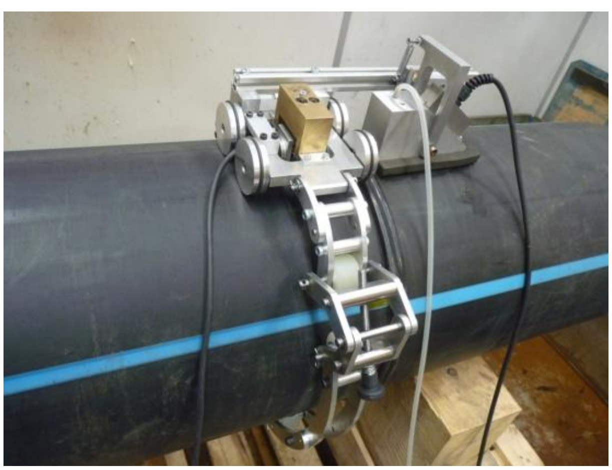

Figure 6. TestPEP inspection prototype system on a BF joint, with the encoder mounted on the carriage.

As part of the TestPEP project a completely new flaw detector, with the ability to operate in harsh environments, was designed and manufactured (Figure 7), with the following features:

- Integrated ultrasonic hardware and PC board;
- Remote access to software application (ethernet or WiFi);
- IP67 protection for full immersion in water;
- 100 GB internal memory for data storage;
- Two rechargeable batteries allowing up to six hours continuous use.

Figure 7. CAD design of TestPEP flaw detector.

Validation of Inspection Procedures

The inspection procedures were validated by inspecting BF and EF joints in pipe sizes up to 710 mm (28 inches) diameter, containing known flaws, including particulate contamination, cold fusions and planar flaws (25 μm (1 mil) thick and 1-50 mm (0.04-2.0 inches) diameter). These joints were made in the laboratory by qualified welding operators, using commercially available pipes and fittings, according to the DVS 2207-1 welding procedure.

Figures 8 and 9 show ultrasonic images of a 225 mm (9 inch) SDR11 EF joint containing a 2 mm (0.08 inch) diameter planar flaw and where the pipe has not been fully inserted into the coupler, respectively. Both types of flaw can clearly be detected. Figures 10 and 11 show images from a standard 450 mm (18 inch) SDR17 EF joint and a cold fusion, where the heating time was reduced to 50% of the manufacturers recommended value, respectively. The line indication above the heating wires has been shown to be the boundary of the melt zone in the EF fitting [9]. The distance between the melt zone boundary indication and the indications from the heating wire can therefore be used to detect cold fusions [9,11, 12].

Figure 12 shows a sector pulse-echo image from a 355 mm (14 inch) SDR11 PE100 BF joint containing a 4 mm (0.16 inch) planar flaw at the fusion interface.

Procedures have been developed that allow the following defects to be detected consistently, in both BF and EF joints:

- Planar flaws/lack of fusion (greater than 1 mm (39 mils) diameter);
- Fine particulates (less than 22 µm; 0.9 mils);
- Coarse particulates (150-300 µm; 6-12 mils);
- Cold fusions;
- Voids (greater than 1mm (40 mils) diameter);
- Pipe under-penetration in EF joints.

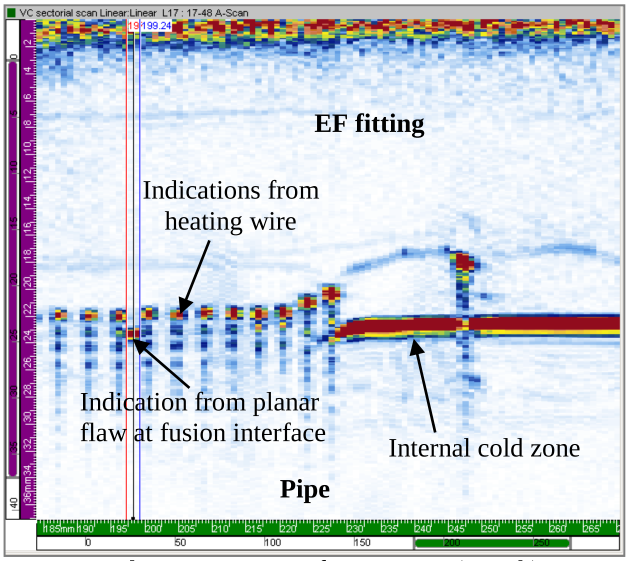

Figure 8. Ultrasonic image of a 225 mm (9 inch) SDR11 EF joint containing a 2 mm (0.08 inch) planar flaw at the fusion interface.

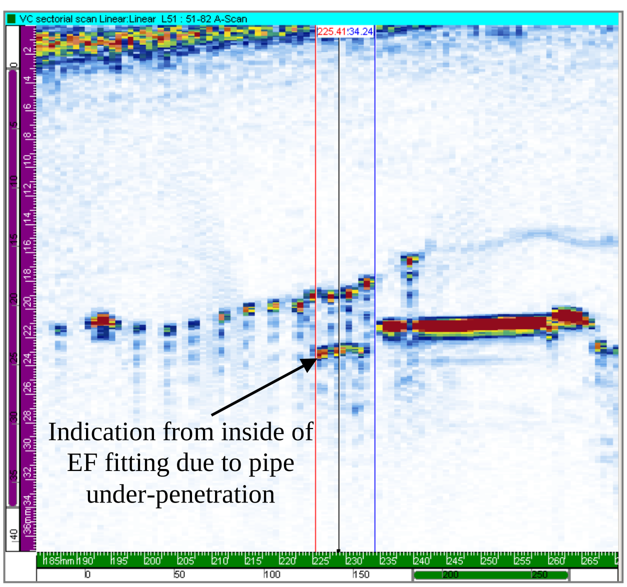

Figure 9. Ultrasonic image of a 225 mm (9 inch) SDR11 EF joint where the pipe has not been fully inserted into the coupler.

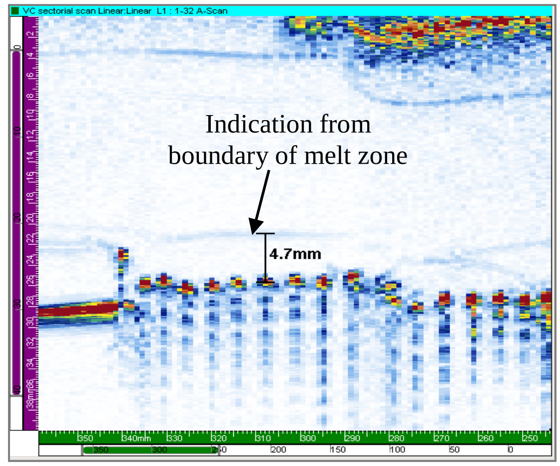

Figure 10. Ultrasonic image of a standard 450 mm (18 inch) SDR17 EF joint.

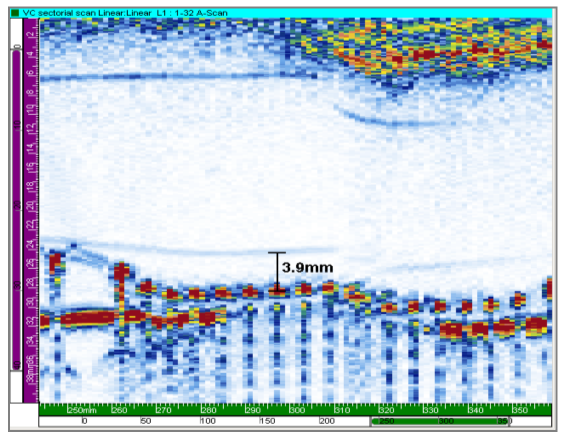

Figure 11. Ultrasonic image of a 450 mm (18 inch) SDR17 EF joint where the heating time has been reduced by 50%, resulting in a cold fusion.

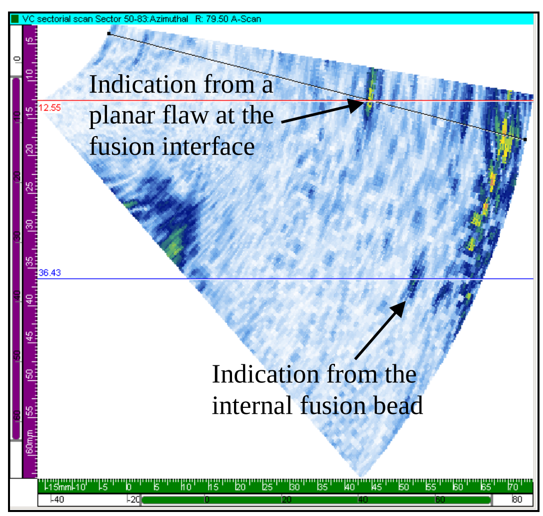

Figure 12. Ultrasonic image of a 355 mm (14 inch) SDR11 BF joint containing a 4 mm (0.16 inch) planar flaw at the fusion interface.

Assessment of Prototype Inspection System

E.ON Ruhrgas, Germany, manufactured nine EF joints in 110 mm (4.3 inch) SDR11 multilayer HexelOne® PE100 monocomposite pipes, some of which contained flaws and some which didn't. These joints were inspected blind in the laboratory and all nine joints were assessed correctly. For example, Figure 13 shows an ultrasonic image of a joint where the inspection suggested that it contained particulate contamination; E.ON Ruhrgas confirmed that sand had been inserted at the interface. It can also be seen in this image that there were indications from within the pipe wall, suggesting that the bond between the layers in the PE pipe was not perfect.

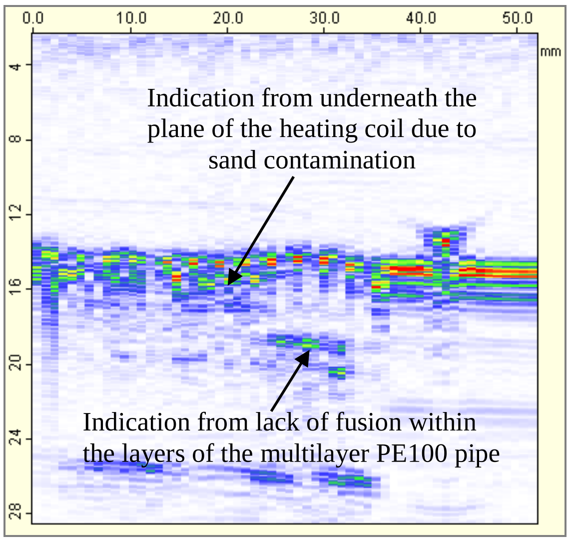

Figure 13. Ultrasonic image of an EF joint produced by E.ON Ruhrgas containing sand contamination.

Field trials were carried out in North Wales, UK, where EF joints in a 710 mm (28 inch) PE100 pipeline being installed for a hydro-electric power station were inspected (Figure 14).

Figure 14. Inspection field trials in North Wales, UK.

In addition, BF joints in 355 mm (14 inch) SDR21 PE80 gas pipe and EF joints in 250 mm (10 inch) SDR11 PE80 gas pipe were inspected in a trench in Sheffield, UK. In both cases no flaws were detected and the prototype system operated perfectly.

Conclusions

Phased array ultrasonic inspection techniques and procedures have been developed for detecting every major type of flaw that can occur in BF and EF joints in PE pipes (lack of fusion, particulate contamination, cold fusions, pipe under-penetration, voids and axial misalignment) and a prototype system has been designed and manufactured specifically for inspecting fused joints in PE pipes of diameters between 110 and 1000 mm (4 and 39 inches) and wall thicknesses between 10 and 60 mm (0.4 and 2.4 inches). This system has been assessed both in the laboratory and in the field and excellent results have been obtained on joints containing both real and artificial defects.

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.

References

1. C.I. Brown and M.J. Troughton, *Plastics Pipes XII Conference* (2004).
2. M.J. Troughton, C.I. Brown, J Hessel and M Piovano, *Plastics Pipes XIII Conference* (2006).
3. I.J. Munns and G.A. Georgiou, *Insight*, **41(5)**, 291 (1999).
4. M.J. Troughton, *Plastics Pipes XI Conference* (2001).
5. B Messer, M. Yarmuch and P. den Boer, *Pipeline and Gas Journal*, March (2003).
6. S.L. Crawford, S.R. Doctor and A.D. Cinson, *ASME Pressure Vessels and Piping Division Conference*, PVP2009-77958 (2009).
7. C. Frederick, A. Porter and D. Zimmerman, *ASME Pressure Vessels and Piping Division Conference*, PVP2009-77783 (2009).
8. H.J. Shin, Y.H. Jang, J.R. Kwon and E.J. Lee, *Plastics Pipes XIII Conference* (2006).
9. C. Bird, D. Caravaca and A. Raude, *Plastics Pipes XIII Conference* (2006).

10. D.S. Caravaca, C. Bird and D. Kleiner, *Insight*, **49(2)**, 83 (2007).
11. M. Troughton, M Spicer and F Hagglund, *ASME Pressure Vessels and Piping Division Conference*, PVP2012-78860 (2012).
12. J Shi, J Zheng, W Guo and C Xu, *ASME Pressure Vessels and Piping Division Conference*, PVP2012-78655 (2012).