TestPEP Report Summary

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Final Report Summary - TESTPEP (Development and Validation of an Automated Non-destructive Evaluation (NDE) Approach for Testing Welded Joints in Plastic Pipes)

Executive Summary:
Polyethylene (PE) has many advantages over metals or concrete. It does not corrode, has good chemical resistance, low weight and a 50-year predicted service life. However, although welds of high integrity can be achieved in these materials, installation of PE pipes is often carried out in the field, where it is difficult to eliminate the possibility of flaws getting into the joint.

Currently, there are no accepted non-destructive evaluation (NDE) methods for the examination of welds in PE pipes. Normally, the welded joints are only examined visually followed by a pressure test or destructive testing. However, removing a weld for mechanical testing and replacing it with a weld of unknown quality can be detrimental to the integrity of the pipeline. In addition, visual inspection can only examine the external surface of the weld; it cannot detect embedded flaws or incomplete fusion.

The two most common welding techniques for PE pipes are butt fusion (BF) and electrofusion (EF) and, according to the industry survey that was carried out at the beginning of the project, the most likely types of flaws that can occur in these types of weld are planar flaws (such as fingerprints, grease, rain droplets), fine particulates (such as airborne dust), coarse particulates (such as sand or grit), cold welds and pipe under-penetration (in EF joints). In the TestPEP project, procedures have been developed for inserting simulations of each of these types of flaw into BF and EF joints in a consistent and reproducible manner, and a large number of welds containing flaws have been made in pipes with outside diameters between 180 and 710mm.

The project has developed phased array ultrasonic testing (PAUT) techniques and procedures for the examination of BF and EF welds in these pipe sizes, and new PAUT probes, probe wedges and a scanning system have been specified, designed and manufactured. In addition, a new lightweight, compact and robust ultrasonic instrument has been designed and manufactured. The device has a large internal memory for data storage, is battery operated and Wifi compatible.

Algorithms and software have been developed for analysing the inspection data collected from EF joints. The software generates a map of the weld, estimates the size of any flaws in the weld and sentences the joint based on a comparison between the measured flaw size and the acceptance criteria, which have been determined based on short-term and long-term mechanical testing of the flawed joints.

The complete prototype phased array ultrasonic inspection system has been assessed, both in the laboratory/factory and in the field, and excellent results were obtained in all of the assessment trials. All of the key flaw types highlighted by the European plastics pipes industry can be detected with the developed system.

The project website, www.testpep.eu, contains over 25 publications, including press releases, flyers, magazine articles and conference papers as well as videos of presentations of the results and a demonstration of the prototype equipment.

The procedures developed in the TestPEP project are currently being incorporated into ISO and ASME standards, and training guidelines have been developed for trainers, developers of the inspection system and for operators.

The results from the TestPEP project will hopefully enable a wider adoption of PE pipes for more safety-critical applications. This, in turn, will result in cost reductions in the installation and maintenance of pipelines, due to the fact that PE pipes are less expensive to install and have better corrosion and chemical resistance than metallic or concrete pipes. In addition, the project provides a system capable of detecting defective welds just after the welding process, which means that these welds can be cut out and replaced before they are buried, which should result in a reduction in leaks occurring in PE pipe systems.

Project Context and Objectives:

Every year an estimated 40million holes are dug up in Europe's roads and streets to access the subterranean maze of 30million kilometres of pipes and cables. The resulting annual delay to road users, disruption to business, environmental damage, additional fuel usage and safety costs add up to a minimum of €10bn for gas and water supply services alone, in addition to the €3bn direct costs to utility companies and local authorities for the same services. Most new gas and water supply distribution pipelines in the EC are now made of plastic or are planned to be upgraded to plastic over the next few years.

Plastic materials have many advantages over metals or concrete. They do not corrode, have good chemical resistance, low weight and long predicted service life (polyethylene pipes have a predicted service life of at least 50 years). Welds of high integrity can be achieved in these materials, but installation of plastics pipes is often carried out in the field, where it is difficult to eliminate the possibility of flaws getting into the joint and, for this reason, most leaks in plastic water and gas supply distribution pipelines arise from improperly fused pipe welded joints.

The two main techniques for welding plastics pipes are butt fusion welding and electrofusion (EF) welding. In butt fusion welding the pipe ends, which have been cut square and flat, are pushed against a heated metal plate until they melt; the plate is then removed and the pipes are pushed together and allowed to cool, forming a weld. In EF welding the pipe ends are pushed into either end of an injection moulded fitting, 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 fitting and the outside of the pipes, producing a weld.

The best method of alleviating the risk of leaks and maintaining the quality of welded joints in plastics pipes is to inspect them prior to service. However, there is no accepted non-destructive evaluation (NDE) method for the examination of welded joints in plastic pipes. The current QA practice is to destructively test the welds on a sample basis using tensile tests or bend tests, supplemented with visual inspection of every weld. However, removing a weld for mechanical testing and replacing it with a weld of unknown quality can be detrimental to the integrity of the pipeline. In addition, visual inspection can only examine the external surface of the weld; it cannot provide evidence of a weld with incomplete fusion or cold fusion. Volumetric NDE will not destroy perfectly good welds, which will result in reduced waste.

The primary method for the inspection of metallic welds in the field in Europe is ultrasonic testing. However, due to the challenges associated with ultrasonic inspection of plastic pipes, other methods have been investigated. Radiography is a possibility and significant research has been carried out in this area. However, this technique cannot be deployed in the field for safety reasons. Thermal inspection methods have been examined but were found to be insensitive to the types of flaws found in plastic welds due to the low thermal conductivity of these materials. Microwave interferometry has similar restrictions in that the wavelength is greater than the size of flaws that need to be detected.

Phased array ultrasonic testing (PAUT) has been used widely in the steel pipeline industry and PAUT inspection systems are commercially available from many companies. However, none of these systems has either the software or hardware to provide volumetric examination of plastic welds. Furthermore, there are no sealed PAUT instruments available for rugged application in a trench environment and there are no manipulators integrated with the specific ultrasound transducers required to cope with the highly attenuative plastic material properties.

There is a company in North America that uses ultrasonic time-of-flight-diffraction (TOFD) inspection of polyethylene (PE) pipe welds and there is a Korean company that markets a PAUT system for PE pipe weld examination, but this system does not record data. Furthermore, these systems require trained operators to interpret the results and neither have flaw acceptance criteria data, without which the examination of welds has no quality or financial benefit.

Two previous EC projects, WINDEPP and Polytec Systems, developed the basic concept of the ultrasonic inspection of butt fusion and EF welds in plastics pipes, respectively. However, these projects only investigated the inspection of welds in a relatively small range of pipe sizes (outside diameters of between 125 and 315mm) in PE pipes. Each project developed a prototype ultrasonic inspection system dedicated to one particular joint type and pipe size. In addition, they did not investigate NDE of joints between pipes and fittings (e.g. reducers, tees). The TestPEP project builds on the work carried out in these earlier projects to develop an NDE system for inspecting pipes in a wide range of sizes and between pipes and fittings as well as pipe-to-pipe joints.

The main challenges in the ultrasonic inspection of plastics pipes are:
- The velocity of the ultrasound is much lower than that for metals, which makes it more difficult to generate angled beams in the plastic material; angled ultrasonic beams are generated by refraction from a slower medium and there are very few materials that will support velocities lower than plastics.
- The attenuation of ultrasound in plastics is very high and very dependent on frequency.
- The inspection system will need to operate from one side of the welded joint only, since the other side may be an elbow, reducer or flange.
- In butt fusion welds, the flaws are perpendicular to the inspection surface whereas, in EF welds, the flaws are parallel to the inspection surface but beneath the coil of heating wire.
- The inspections will need to be carried out in harsh environments, i.e. in a muddy trench.

The main objective of the TestPEP project is to design and manufacture a single, compact, rugged NDE system that can inspect a wide range of pipe sizes and joint configurations in the field. The instrument will need to have sufficient memory to store a number of inspections and download to a computer plus drive complex PAUT probes. The data will need to be analysed semi-automatically so that a red/green (yes/no) answer can be provided for the quality of the welds so that the system can be operated by normal pipe laying technicians. This will lead to a longer average service life of plastics pipe systems and lower leakage rates, resulting in reduced risk of serious accidents and pollution, which in turn will lead to significant economic benefits, as more widespread use of these material occurs.

In summary, the main objectives of the TestPEP project are:
- To develop ultrasonic phased array NDE techniques for the inspection of welded joints in plastics pipes over a wide range of diameters.
- To determine the limits of detection for the above NDE techniques.
- To determine critical defect sizes and contamination levels.
- To develop defect recognition and automatic defect sentencing software to allow the equipment to provide a pass/fail indication.
- To produce a prototype PAUT NDE system that can inspect welded joints in plastics pipes over a wide range of diameters.
- To assess the prototype NDE equipment in the field.

Project Results:
Introduction

The TestPEP project is divided into eight technical work packages:

Work Package 1: Project Specification
- To survey the European plastics pipes industry to determine the plastics materials, pipe size ranges, joint types and flaw types that are of most interest and also the dimensional and time constraints for the inspection system.
- To develop a functional specification for the NDE system.

Work Package 2: Manufacture of Welded Joints
- To develop procedures for inserting simulated flaws into welded joints in plastics pipes in a reproducible and consistent manner.
- To manufacture a range of welded joints containing the various flaws defined in Work Package 1, together with control welds containing no deliberate flaws.

Work Package 3: Development of NDE techniques
- To measure the basic ultrasonic material properties of the plastics materials defined in WP1.
- To develop inspection procedures for the joint geometries and pipe dimensions defined in WP1.
- To design and manufacture phased array probes and probe wedges specifically for the inspection of welds in plastics pipes.
- To develop data analysis algorithms and automatic defect recognition software.

Work Package 4: Development of Acceptance Criteria
- To perform short-term and long-term mechanical testing of the welds produced in WP2.
- To quantify the levels of particulate contamination in the welded joints.
- To compare the results of the mechanical tests on welds containing flaws and welds containing no flaws in order to determine critical defect sizes and contamination levels.

Work Package 5: Development of NDE Instrument
- To design and manufacture a new low weight, compact, robust ultrasonic instrument and associated software for collection and processing of the ultrasonic data.

Work Package 6: Development of Scanning System
- To design and manufacture a flexible system for scanning the ultrasonic phased array probe(s) over the surface of the welded joints, allowing full 360° rotation around the joint whilst providing detailed positional data, and accommodating a wide range of pipe sizes and joint geometries.

Work Package 7. Assembly and Assessment of Complete Prototype System
- To assemble and assess the complete NDE system, including instrument, probe(s) and scanning system, both in the laboratory and in the field, to evaluate the sensitivity, reproducibility and ease-of-use of the system.

Work Package 8: Development of Training Guidelines
- To develop guidelines for the training of trainers, process developers and operators.

WP1 - Project Specification

Industry questionnaire
The overall objective of this work package was to arrive at detailed specifications for the other work packages in the project. It was essential that the needs of the plastics pipes industry in Europe were met by this project and therefore, at the start of the project, a questionnaire was developed and sent out via the SME-AGs and other partners in order to determine the weld configurations, welding processes, pipe sizes and materials that the industry was most interested

in inspecting, the main types of flaws that can occur when welding plastics pipes in the field, together with the dimensional and inspection time constraints required by the industry for the inspection system.

72 responses were received from the following types of companies in 10 countries:
- Water suppliers.
- Gas suppliers.
- Oil and Gas suppliers.
- Other energy suppliers (nuclear, renewables).
- Solution providers for water transport.
- Solution providers for gas.
- Inspection companies.
- Polymer resin manufacturers.
- Pipe manufacturers.
- Polymer welding equipment suppliers.
- Consultants.
- Welding/training institutes.

The results showed that by far the main plastic material of interest was polyethylene (Figure 1). Regarding pipe sizes, from Figure 2 it can be seen that 72% of the pipes of interest to the industry had a diameter between 110 and 1000mm and the main welding processes of interest were butt fusion and electrofusion (EF) (Figure 3).

The main types of flaw that were of interest to the industry (Figure 4) were:
- Cold welds.
- Fine particulates.
- Planar flaws.
- Pipe under-penetration (EF only).
- Coarse particulates.

Regarding the inspection system, an important parameter is the size of the equipment. From Figure 5 it can be seen that 54% of the responses to the questionnaire specified a minimum working distance around the pipe of more than 200mm.

Figures 6 and 7 show the breakdown of the answers regarding the maximum time people were willing to wait for the inspection to be completed, either after the welding cycle (Figure 6) or as a retrospective technique (Figure 7). The results show that, in both cases, the majority of people were prepared to wait longer than 2-5 minutes for the inspection to be completed.

Based on the above results, the following variables for the welds to be made in the project were agreed:
- Materials
  - PE only (PE80 and PE100).
- Pipe sizes
  - 180mm SDR17.
  - 225mm SDR11.
  - 355mm SDR11.
  - 450mm SDR17.
  - 710mm SDR17.
- Welding processes
  - Butt fusion.
  - Electrofusion.
- Flaw types
  - Fine particulates.
  - Coarse particulates.
  - Cold welds.
  - Planar flaws.
  - Pipe under-penetration (EF joints).

Functional specification of the inspection system

Also defined in this work package were the functional specifications of the inspection system. The system consists of a number of parts, including:
- Phased array probe(s)
  - For emitting the ultrasound into the pipe/fitting and detecting the reflected signals.
- Probe wedge(s)
  - For transferring the ultrasound from the probe to the pipe/fitting and directing the ultrasound.
- Manipulator
  - For holding the probe and moving it around the pipe surface.
- Ultrasonic instrument
  - For defining the ultrasound to be emitted and collecting and presenting the data received back.

Phased array probes

The geometrical structure of butt fusion and EF joints in PE pipes and the acoustic properties of the material, together with the requirements of a rapid and robust system, demanded a phased array device. Longitudinal waves have to be used due to the high attenuation of shear waves in PE. Also, a linear array was more appropriate than a 2D system since it required less complex programming and instrumentation and was less expensive.

Designing phased array probes is always a compromise between selecting the proper pitch, element width and aperture. A high number of small elements increases steering, reduces side lobes and provides focusing but can be limited by cost of manufacture and instrument complexity. Separating elements with a greater distance can gain aperture size, but this creates unwanted grating lobes. In Figure 8 an illustration of a phased array probe and some of its properties is given. Other probe features include centre frequency and bandwidth.

The inspection of EF joints can be carried out using only one probe, whereas the inspection of butt fusion joints may require two probes (for the TOFD technique). Since the total number of channels will be 128 this implies that 128 elements are possible for the EF probe, whereas for the butt fusion joints the maximum number of elements is 64.

Probe wedges

Independent of the experimental configuration in this project, a type of coupling media is required for both examinations. The coupling can be water or a wedge of an appropriate material. In previous work on EF joints carried out at TWI, a water gap was used as the coupling media. The benefits of using water instead of a contact probe are the low ultrasonic attenuation and the preserved measurement configuration. Additionally, the obstacles on the EF coupler complicate the use of a solid wedge.

For the inspection of the butt fusion joints, the probe can be used with either a water or solid plastic wedge in order to generate waves that can inspect the entire weld. Water has lower attenuation than plastic wedges but the mismatch in acoustic impedance between water and PE is greater, implying that a higher amount of sound will be reflected at the top pipe surface. Figure 9 shows a schematic view of an example of a solid wedge. The European standard, EN 13100-3 (Non-destructive testing of welded joints in thermoplastics semi-finished products. Ultrasonic testing), suggests using a polytetrafluoroethylene (PTFE) wedge. The PTFE material has low velocity of sound propagating inside it, enabling high angles for the sound entering the material. However, the main drawback is the high ultrasonic attenuation inside the PTFE compared to water.

Using a 1-D linear array, the primary axis of the device runs along the pipe, while the secondary axis runs along the curvature of the pipe. This means that the wedge surface facing the pipe must have a curvature similar to the pipe. Another result of this is that different wedges must be used for different pipe diameters for a sufficient match between wedge and pipe. According to EN 13100-3, a curved wedge is not required when the outside diameter (OD) of the pipe is greater than 15 times the width of the wedge. For example, for a wedge with a width of 15mm all pipes with larger diameter than 225mm can be inspected with a plane wedge, but smaller pipes need a curved wedge. The wedge dimensions depend on the dimensions of the probe. This limitation can be relaxed if a water wedge is used.

Manipulator

A flexible system for scanning the ultrasonic phased array probe(s) over the surface of the welded joints, allowing full 360° rotation around the joint, whilst providing detailed positional data, and accommodating a wide range of pipe sizes and joint geometries, is required for this project. The manipulator will need to be designed in modular form with simple changes for different configurations and should allow the ultrasonic instrument to be mounted directly on to the scanner. The probe holders will be required to hold the probes in a very precise position around the pipe and any loss of water from the wedges will need to be minimised.

Ultrasonic instrument

The specification for the ultrasonic instrument was:

- 128 channels
- Maximum dimensions: 250 x 200 x 70 mm
- Maximum weight: 4kg
- Protected to IP67
- Two connections for conventional probes
- SSD memory: 128 GB
- Multi Salvo capability to chain various testing configuration
- Embedded PC board

There will be higher demands on the instrument software since the same probes and channels will need to be used for different measurement techniques. Also, due to the complexity of the material under investigation, with varying acoustic properties, the system will be required to have flexibility in the focal law configuration for each inspection location. Focusing at different depths will require pre-set updates in the parameter configuration. The software will need to incorporate four phased array NDT techniques (pulse-echo, tandem, TOFD and creeping waves) in a single parallel system. The system will also need to be adapted for compact data storage and transmittal to an external computer. Because of the environment, both a wireless connection to a remote computer and the possibility to use a cable will be required.

WP2 – Manufacture of Welded Joints

Development of flaw insertion procedures

This work was carried out to develop procedures to insert flaws in a reproducible and consistent manner into both butt fusion and EF welds. In order to develop inspection procedures, determine the limits of detection and also develop flaw acceptance criteria it is important to know the position and size/concentration of any embedded flaw, which means that simulations of real flaws should be inserted into the joints. The three types of embedded flaw of interest to the plastics pipes industry are fine particulates, such as airborne dust; coarse particulates, such as sand or grit; and planar flaws, such as fingerprints, grease or rain droplets. In this work, fine particulates were simulated using micronised talc with an average particle size of 10.4μm; coarse particulates were simulated using graded silica sand with a particle size of between 150 and 300μm; and planar flaws were simulated using aluminium discs, with a thickness of 25μm and diameters between 1 and 50mm.

Fine particulates

For butt fusion welds, talc was applied to the trimmed end of one of the pipes to be welded using a soft-haired brush. The amount and uniformity of contamination was determined visually, by comparing with standard samples. Three nominal contamination levels were produced for each pipe size, denoted “light”, “medium” and “heavy” (Figure 10).

For EF welds, talc was applied to the scraped pipe surface of both of the pipes to be welded using a soft rubber roller (Figure 11). Again, the amount and uniformity of contamination was determined visually, by comparing with standard samples (Figure 12).

In order to subsequently quantify the amount of talc in the joint after welding, polyimide tape was applied to the trimmed end of the non-contaminated pipe for the butt fusion welds (Figure 13) or to the electrofusion coupler for EF welds (Figure 14). Polyimide was chosen because it does not melt during the welding process and also does not weld to PE.

Coarse particulates

For both butt fusion and EF joints the prepared ends of the pipes to be welded were inserted into a fluidised sand bed for a pre-set time (Figure 15). Again, three nominal contamination levels were produced for each pipe size (Figures 16 and 17). As for the talc contaminated welds, polyimide tape was applied to subsequently quantify the amount of sand in the joint.

Planar flaws

For butt fusion welds, aluminium discs were heat staked to the trimmed end of one of the pipes (Figure 18). The initial radial position of the disc for each circumferential position around the joint, which ensured that it stayed within the joint during welding, was determined by placing discs at different initial through-thickness positions and using X-ray radiography to determine their final positions (Figure 19).

For EF welds, the aluminium discs were heat staked to the scraped pipe surface at the axial position that corresponded to the centre of the fusion zone in the EF coupler (Figure 20).

Cold welds

To produce cold welds in butt fusion joints, the heater plate temperature was reduced and the heater plate removal time was increased until a brittle failure was produced when the weld was subjected to a tensile test in accordance with EN 12814-7 (Testing of welded joints of thermoplastics semi-finished products. Tensile test with waisted test specimen) (Figure 21).

To produce cold welds in EF joints, the heating time was reduced until a brittle failure was produced when the weld was subjected to a peel decohesion test in accordance with EN 12814-4 (Testing of welded joints of thermoplastics semi-finished products. Peel test) (Figure 22).

Pipe under-penetration

Normally in EF welding, the pipes are pushed up to the centre stop in the EF fitting (Figure 23) and then clamped to prevent them from moving during the welding process. However, if the pipes are not clamped then they can move axially during welding. To investigate this type of flaw, three different levels of pipe under-penetration were produced: A) the pipe end was level with the inside of the heating coil (Figure 24), B) the pipe was 10% into the fusion zone, and C) the pipe end was 20% into the fusion zone.

Manufacture of welded pipe samples

The list of welds made in the project is given in Table 1 and photographs of some of the welded pipe samples produced are shown in Figures 25 and 26.

WP3 – Development of NDE Techniques

Measurement of basic material properties

In plastic pipes only longitudinal waves propagate significantly. Transverse waves are highly attenuated due to the properties of the material. The acoustic properties of PE, such as velocity and attenuation of longitudinal waves and their dependency on frequency are necessary for the development of NDT techniques, configuration of NDT equipment and for detecting and measuring wall thickness and flaws.

In this project the pipes were made from different grades of PE80 and PE100. It was therefore necessary to determine the ultrasonic properties for each pipe size to be able to develop and calibrate the inspection techniques.

The principal method for determining the properties was the same regardless of material grade. Square samples 50 x 50mm with thicknesses between 2.5 and 20mm, were machined from the pipe. These were analysed using a contact through-transmission technique in a pitch-catch configuration and wideband ultrasonic transducers with centre frequencies of 1, 3 and 5 MHz. The results showed a small frequency-dependent increase in velocity (Figure 27) and also showed that the estimates were highly dependent on the accuracy of the thickness measurement.

The same samples that were used for the velocity measurements were also used to determine the attenuation in the material. The reductions in the amplitudes of the received signals corresponding to a reference signal were measured. The estimated attenuation against the actual nominal frequency is shown in Figure 28. The estimated dependency is an approximation using a 4th-order polynomial.

Joint geometries

Electrofusion joints

The design of an EF joint comprises two pipe ends, which are attached inside an injection moulded sleeve or fitting. The sleeve contains a heating wire coil either close to or on the inner surface (Figure 29). When a current is applied to the heating wire it heats up and melts the material on the inside of the sleeve and on the outside of the pipe, creating a weld.

Depending on the manufacturer and size, the EF fittings may have different appearances. The most critical parameters for performing ultrasonic testing of an EF joint are:

- Outer surface appearance - general geometry, labelling, connections, etc.
- Wire location relative to the inner surface of the fitting.
- Geometrical dimensions (or at least basic geometry, such as the thickness).
- Wire diameter, number of wires and spacing between adjacent wires.

These parameters will affect both the ability to access the fusion zone with the ultrasound and the physical movement of the probe.

An example of the dimensional parameters of an EF fitting is shown in Figure 30. The wire diameter, Φ, and the spacing between the wires, d7, will vary depending on the pipe size. Normally, the larger the pipe, the larger the wire diameter and the spacing will be.

Butt fusion joints

Butt fusion joints are created by using a metal heater plate to melt the ends of two pipes (Figure 31) which are then fused together under an applied pressure for a certain time. The process creates a weld bead on both the inner and outer surface (Figure 32).

In general, butt fusion joints have surfaces more suitable for ultrasonic testing than EF joints. The critical parameters for performing ultrasonic testing of a butt fusion joint are (Figure 33):

- Wall thickness (d1).
- Weld bead width (average and deviation)(d2).

The width of the weld bead will set the lower limit of the stand-off between the probe wedge and the weld centreline. The stand-off must be greater than half the width of the weld bead. The width of the bead depends on the wall thickness of the pipe and also on the welding parameters.

Manufacture of test samples for the development of inspection procedures

For the development of the inspection techniques, test samples containing artificial flaws were created for the two joint types and for different pipe sizes. For butt fusion joints, flat bottom holes (FBHs) drilled into one end of the pipe and slots machined into the outside surface of the pipe were considered sufficient to evaluate the performance of the techniques. Schematic drawings of the FHBs and slots are shown in Figures 34 and 35.

For the EF joints the unwelded fitting itself was considered sufficient to evaluate the technique.

Design and manufacture of probe wedges

Water wedges were designed and manufactured for both butt fusion and EF joints in PE pipes. The advantages of a water wedge are: low attenuation, good acoustic matching with PE and a velocity ratio enabling the steering of angled beams to the fusion zone in butt fusion joints. The main challenges with a water wedge were possible air bubbles and maintaining the water between the probe and the PE. The aim was to make the wedges as physically small as possible, but still allowing for the desired range of angles to be transmitted into the material.

For the EF joints, new 0° water wedges were manufactured. A photograph of the wedge/probe assembly is shown in Figure 36. A sealing skirt was attached to the bottom of the wedge to reduce the loss of water during the inspection.

The sealing material was flexible and the skirt could be customised to conform to the specific shape of the outer surface of the EF fitting.

For the butt fusion joints, new angled water wedges were manufactured. The angle of these probe wedges was designed to minimize the electronic steering required. A photograph of the wedge/probe assembly is shown in Figure 37.

Description of inspection techniques

Electrofusion joints

For the EF joints a normal focusing sector scan was used, focused on the fusion area between the fitting and the pipe. Since the wires are located just above the fusion area, sufficient resolution to be able to see both the wires and between the wires was required. The main limiting factors that prevented full coverage of the weld area were the several connectors, inscriptions and labelling over the fitting surface. The basic principle of the technique is shown in Figure 38.

The linear scan uses a 0-degree normal scan, focusing on the entire fusion zone. No beam steering was required so the pitch could be increased to increase the aperture and the coverage area.

The most critical areas for the inspection of EF joints are the coverage and the resolution. For pipes with larger diameters, the fitting size increases and the fusion zone is larger. Good resolution is required to be able to inspect beyond the wires. The resolution is mostly dependent on the frequency, and generally, higher frequencies give higher resolution. For smaller pipes, both the wire diameter and the spacing between two adjacent wires is smaller, and a probe with higher frequency must be used. However, PE is a highly attenuating material and attenuation increases with a power factor with frequency. Therefore, the frequency has to be reduced for larger sizes in order to get sufficient propagation of sound. Fortunately, in larger fittings the wire diameter and the wire spacing are larger so the resolution is still sufficient.

Taking the limitations of coverage and resolution mentioned above into consideration it was necessary to use probes with different frequencies for different pipe sizes; a higher frequency probe for smaller pipes and a lower frequency probe for larger pipes.

An example of the configuration of a linear scan on an EF joint is shown in Figure 39. The focus of the beams was slightly below the wires at the fusion zone. A linear electronic scan over the fitting surface was used to cover the entire fusion zone in the axial direction. For thicker pipes, the only change in the configuration was that the focus was further away, but was still on the fusion zone.

The coverage was limited by the aperture, which in turn was limited by the physical size of the probe in relation to the size of the fusion zone. The size of the aperture depends on the number of elements and the pitch. The number of elements was restricted by the hardware to a maximum of 128. The aperture size could then only be changed by changing the pitch. However, increasing the pitch reduces the steering and focussing capabilities of the probe. Increasing the pitch without reducing the probes capabilities is possible if the frequency of the probe is decreased. Therefore, a compromise was required in order to obtain sufficient coverage while maintaining the resolution.

Butt fusion joints

The four techniques used on butt fusion joints are shown in Figure 40.

The tandem technique focuses on a small area close to the inner surface of the weld. It shows good performance on planar flaws within the weld. The main drawback is that a relatively low signal-to-noise ratio is achieved due to several reflections and the longer propagation distance. In conventional ultrasonic inspection, the tandem technique is implemented using two probes, one in front of the other. One probe transmits and the other probe receives the sound. The same set-up using a single phased array probes can be achieved, by using one half of the array as the transmitter and the other half as the receiver. The image is created by sending the sound using an electronic sweep over the elements in the transmitting part and in a similar manner receiving with a sweep in the receiving part. To achieve sufficient steering capability and signal amplitude, more than one element at the time must be used to produce each single beam. For example, eight elements can be used in the aperture to create each beam. If the probe has 32 elements, the transmitter and receiver use 16 elements each. In practice fewer elements could be used, however, more elements imply a larger coverage area. The main challenge with the self-tandem technique is that the receiver elements must be reversed in order to accurately receive the transmitted sound, i.e. the transmitter is set to transmit with start on Element 17 and sweep upwards to Element 32 and the receiver is set to start on Element 16 and sweep downwards to Element 1. The same principle applies on a probe with 64 elements, except that the last 32 elements can be used for transmission and the first 32 elements for reception. The main configuration parameters for the self-tandem technique are the stand-off distance and the angle of the sound. These two properties are defined by the thickness of the pipe and the weld bead width. Thicker pipes imply a larger weld bead and hence the stand-off needs to be increased, but by not as much as the pipe thickness. This means that lower angles can be used for the self-tandem technique of thicker pipes. As an example, the self-tandem configuration for a 225mm SDR11 pipe with a wall thickness of 22mm is shown in Figure 41, where the direct beam path covering the weld centreline is 6mm, which is 27% in the middle of the lower part of the pipe wall thickness. Under ideal inspection conditions the coverage is from approximately 2mm from the inner surface. The beam spread will also contribute, and adding any beneficial reflection within the beam spread, the coverage is 9.6mm (44%) from the inner surface of the pipe. However, the contributions from the beam spread are small and are only seen if there are any beneficial reflections in that region.

The sector pulse-echo technique covers most of the weld fusion zone, except for a couple of millimetres close to the outer surface. The technique provides a good overview of the weld. However, due to the complexity of the structure, caution must be taken when interpreting the scans; direct pulse-echoes will be received together with an angle-swept tandem, which could be hard to interpret. A sector scan, using all the elements in the array to create an aperture is used, sweeping the beam from the lower angle to the higher angle. The transmitted beams are focused at the inner surface distance and dynamic depth focusing is used when receiving the beams. The stand-off for the sector pulse-echo technique is the same as for the tandem technique. The configuration parameter that changes for the different pipe sizes is the range of inspection angles. The sector pulse-echo configuration for a 225mm SDR11 pipe is shown in Figure 42; the coverage is approximately the lower 75% of the weld. However, the beam spread will increase this.

The creeping wave technique covers the region close to the outer surface of the pipe. The technique, combined with high angle pulse-echo signals, covers the upper part of the weld that the sector pulse-echo and tandem techniques cannot see. Creeping waves are compression waves propagating immediately beneath the inspection surface, to detect surface-breaking and near-surface defects. As creeping waves propagate, mode conversions at the surface cause secondary shear waves to be emitted. However, shear waves do not travel any significant distance in PE and are effectively cancelled out. This continuous transfer of energy results in high attenuation of the waves and inspection is only effective over a relatively short range. Creating creeping waves with a phased array probe is achieved using a sector scan between angles of around 83 to 90 degrees. The creeping waves are effectively only produced by the higher angles, and the response will be a combination of creeping waves and high angle pulse-echo signals. As with the sector pulse-echo technique, the sector scans are created by all elements in the aperture. The coverage is slightly larger for thicker pipes, since the stand-off is larger. The configuration for a 225mm SDR11 pipe is shown in Figure 43. The beam spread indicates that there are possibilities to receive sound outside the range of angles used in the configuration.

The time-of-flight-diffraction (TOFD) technique covers most of the weld fusion zone. There is a possibility that a couple of millimetres close to the outer surface will be missed, depending on how the technique is implemented. The conventional technique uses forward diffraction from the flaw tips and is sensitive to flaws perpendicular to the pipe surface. Using the steering and focusing capabilities of phased array ultrasonic testing, several different configurations can be considered:
1) Imitating conventional TOFD. With this technique the aperture is used to transmit one beam and the sound is received in the same way. The main advantage is that it imitates conventional TOFD and can easily be used to produce TOFD-like B-scans. The main limitation is that it produces weak signal amplitude, since the focusing capabilities of the phased array probe are not used.
2) Pitch-catch with two sector scans. With this technique, the transmitter uses a large aperture to transmit focused beams at the weld centreline. Angles that cover the entire pipe through wall thickness are used. The receiver is set up in the same way. The main advantage is that good signal amplitude is achieved at each location due to the focusing. The main limitation is that the mechanical set-up is highly important to be able to receive the transmitted sound. The transducers also have to be positioned carefully at the same distance from the weld centreline.
3) A combination of conventional TOFD and sector scan. This technique transmits one beam with beam spread like Technique 1. The sound is then received with focused beams using a large aperture like Technique 2. The advantages with this technique are that the mechanical set-up is less important and it has greater flexibility. The main limitations are that the technique is demanding for the instrument to perform and the received signal must be weighted according to the transmitted sound.
The stand-offs for each probe for this technique are the same as for the other techniques. The TOFD configuration for a 225mm SDR11 pipe with a wall thickness of 22mm is shown in Figure 44.

Evaluation of the inspection techniques

Electrofusion joints

For the evaluation of the inspection technique on the EF joints, a 1D linear 128 element 7MHz probe and a 1D linear 128 elements 5MHz probe were used. The probe covered each fusion zone separately, which meant that two scans around the circumference of the fitting were required to fully cover the whole joint.

The scan on a 180mm EF fitting was performed with the 7MHz probe. A normal linear electronic scan was used with 32 elements in the active aperture. The electronic scan at one position around the fitting can be seen in Figure 45, where it can be seen that, at this frequency and aperture, the resolution at the wires was very good. It was possible to see both the wires and the back wall between the wires. However, the coverage was not enough since the entire fusion zone was not covered.

The scan on a 225mm EF fitting was also performed with the 7MHz probe. The same normal linear electronic scan was used with 32 elements in the active aperture. The resolution at the wires was still very good and both the wires and the back wall were visible. However, since the fitting was larger and the same aperture was used, the coverage was worse. The electronic scan at one position around the pipe can be seen in Figure 46. Since this fitting was thicker, the first repeat of the water path in the wedge was closer to the wires.

The scan on a 710mm EF fitting was performed with the 5MHz probe. The same normal linear electronic scan was used with 32 elements in the active aperture. The resolution at the wires was still good, even where the outer surface of the fitting was irregular. The electronic scan at one position around the pipe can be seen in Figure 47. The first repeat of the water path in the wedge can be seen just below the wires.

Butt fusion joints

For the evaluation of the inspection techniques on the butt fusion joints, two identical 1D linear 32 element 4MHz probes were used. All techniques in this section were evaluated using a 200mm diameter pipe with a wall thickness of about 14mm. Photographs of the two different probe experimental set-ups are shown in Figure 48.

The B-scan of the FBHs using the tandem technique is shown in Figure 49. All FBHs that were within the coverage area of the technique were detected and also, due to beam spread, some of the FBHs that were located slightly outside the coverage area were also detected. The B-scan of the FBHs using the sector pulse-echo technique is shown in Figure 50 and shows that all eight FBHs were detected.

The B-scan of the slots using the creeping wave technique is shown in Figure 51, where one signal is marked from the 8mm slot. Signals from this slot were received between approximately 53mm to 133mm. This means that the slot was ultrasonically measured to be 80mm long. A physical measurement of the slot revealed that the actual distance was 84mm. Comparisons between the location and size of the slots in the circumferential direction from the creeping wave technique and from physical measurements are given in Table 2. On average the creeping wave technique underestimated the circumferential size by 14%. The error in estimating the location was less than 2%.

The TOFD technique was evaluated using the slots on the pipes. The B-scan of the slots is shown in Figure 52. Again, the slots could be located and circumferentially sized, and compared with physical measurements. These results are shown in Table 3 where, on average, the TOFD technique had an estimating error in the circumferential size of 13%. The error in estimating the location was just over 1%.

Data analysis algorithms and software including automatic defect recognition

Phased array ultrasonic inspection of EF joints gives the opportunity of rapid scanning of the weld in the axial direction, with mechanical scanning in the circumferential direction. As a result, a large amount of data is acquired, typically between 700 and 2000 individual images per joint, which depends on the dimensions of the pipe and the parameters set in the inspection electronics. In general, the acquired data are obtained as a three-dimensional array, the dimensions of which are defined by the number of samples in the signal, the number of scans performed and the number of measurement positions around the pipe. The analysis of such a large data set is not an easy task, even for modern computers.

Algorithms and software were developed for the inspection of EF welds which perform the following steps:
1. Determination of the validity of the acquired data, i.e have all the images been recorded.
2. Determination of the amplitudes of the signals from the heating wires, i.e. is the signal-to-noise ratio sufficient to allow the analysis to take place.
3. Detection of the positions of the heating wires.
4. Detection of the inner cold zone.
5. Generation of maps of the fusion zone, cold zone and any defects.
6. Estimation of the boundaries of the fusion zone.
7. Estimation of the size of the defects.
8. Comparison of the calculated defect size with the acceptance criteria.
9. Sentencing of the weld as acceptable or not acceptable.

An example of the display from the software is given in Figure 53, where it can be seen that both C-scan and B-scan images are shown, as well as a sentencing box, which classifies the weld as either unacceptable (red), acceptable (green) or yellow, where the data provided is insufficient for the software to be able to sentence the weld and either the weld must be rescanned or manual interpretation of the images is required. In the C-scan image in Figure 53 areas where B-scans were missing, normally due to scanning too fast, are marked in green and areas where the signal-to-noise ratio was too low are marked in blue.

The software can also generate three-dimensional images of the joint, displaying the heating wires and defects (Figure 54).

Inspection of welded samples

All of the welds made in WP2 were inspected to determine whether the inserted flaws could be detected using the inspection techniques developed in this work package. The results showed that all of the flaws could be detected:
- In butt fusion joints
  - Planar flaws down to 2mm diameter;
  - Fine particulates down light loadings;
  - Coarse particulates down to light loadings;
  - Cold welds.
- In electrofusion joints
  - Planar flaws down to 2mm diameter;
  - Fine particulates down to light loadings;
  - Coarse particulates down to light loadings;
  - Cold welds;
  - Pipe under-penetration down to Level A.

B-scan images of butt fusion joints in 225mm and 355mm pipes containing aluminium discs are shown in Figures 55 and 56, respectively. B-scan images of EF joints in 180, 225 and 450mm pipes containing aluminium discs are shown in Figures 57, 58 and 59, respectively and an image of an electrofusion joint in 225mm pipe with pipe under-penetration is shown in Figure 60. A cold EF weld in 225mm pipe is shown in Figure 61, where it can be seen that the indication from the heat affected zone boundary in the cold weld is much closer to the indications from the heating wires than for the standard weld. The distance from the indication of the HAZ boundary to the plane of the heating wires can therefore be used to detect cold welds, i.e. there will be a minimum distance, below which the weld will be cold.

WP4 – Development of Flaw Acceptance Criteria

Various mechanical tests were performed in the TestPEP project to determine the effect of different types, sizes and concentrations of defects on the short-term and long-term performance of butt fusion and EF welds in PE pipes. These tests, the majority of which are currently used by the European plastics pipes industry, using either specimens cut from the weld or whole pipe samples, are listed below.

- Tests on butt fusion welds
  - Tensile test, according to EN 12814-7.
  - Specimen creep rupture test, according to EN 12814-3.
  - Whole pipe tensile creep rupture test, according to Annex B of prEN 12814-3:2012.
- Tests on electrofusion welds
  - Peel decohesion test, according to EN 12814-4.
  - Crushing decohesion test, according to ISO 13955.
  - Specimen creep rupture test, according to Annex C of EN 12814-3.
  - Whole pipe tensile creep rupture test, according to Annex B of prEN 12814-3: 2012.
  - Hydrostatic pressure test at 80°C, according to ISO 1167.

Tests on butt fusion welds

Tensile test

The tensile test specified in EN 12814-7:2002 uses a waisted specimen (Figure 62), which is cut from across the joint. This is subjected, via loading pins, to a constant crosshead speed of 5mm/min. The weld beads are left intact. This specimen geometry was chosen because it ensures that fracture occurs in the weld and not in the parent pipe, as is often the case with specimens with a dog-bone geometry. It has also been found that by measuring the energy to break the weld in this test it is possible to differentiate between welds made under different conditions.

In order to ensure that the energy measured was only that required to break the weld and did not include the energy used to elongate the holes for the loading pins, metal side plates were bolted to the test specimens either side of the loading pin holes (Figure 63). The experimental set-up is shown in Figure 64.

Specimen creep rupture test

This test involves machining dog-bone specimens from across the welded joint (Figure 65). The specimens were inserted into a creep test rig (Figure 66), where they were immersed in an aqueous detergent solution at 90°C and subjected to a constant tensile stress, which was chosen to produce slow crack growth failure in the specimen. The time to rupture was measured, and the type and position of failure recorded.

Whole pipe tensile creep rupture test

This test involves subjecting a welded whole pipe sample to a constant axial tensile stress in water at 80°C (Figure 67). A tensile load was applied to the pipe sample via a stainless steel push rod, which was passed down the inside of the pipe. The top of the push rod was in contact with the ram of a hydraulic jack and the bottom end was attached to the bottom end plate, which had a hole in it to allow the inside of the pipe sample to fill with water when it was inserted into the water bath. The load was calculated to produce slow crack growth failure in the sample. The time to failure was measured and the position of failure recorded.

Tests on electrofusion welds

Peel decohesion test

This test involves cutting specimens (Figure 68) from various positions around the circumference of the welded EF joint. The specimen length is equal to half of the length of the EF coupler and the width is 20mm for joints with a nominal outside diameter between 90 and 180mm, and 30mm for joints with a nominal outside diameter greater than 180mm. The specimens are grooved to promote failure at the joint line. The specimens were subjected to a force perpendicular to the weld at a constant rate of displacement of 25mm/min (Figure 69). Separation of the pipe from the fitting was taken to completion and the parted surfaces were inspected for evidence of ductile and/or brittle failure along the joint interface. The percentage area of the weld that failed through the weld interface between the pipe and coupler was calculated using the equation given in Figure 70.

Crushing decohesion test

The welded EF joint was sectioned in the axial direction in either two or four equal parts, depending on the pipe size. The pipe section of each specimen was squeezed close to the mouth of the fitting using a compression speed of 100mm/min until the internal pipe surfaces touched (Figure 71). The socket was then separated from the pipe using a lever. The weld interfaces were inspected and the percentage of ductile or no failure was calculated (Figure 72). The minimum acceptable value for percentage ductile or no failure, according to standards such as ISO 8085-3, is 66.7%.

Specimen creep rupture test

Pre-specimens (“corks”) were cut from the welded joint using a hole-cutter. Extension bars were then hot plate welded on either end and the specimen was machined to remove the hot plate weld beads and reduce the cross-sectional area at the EF joint line (Figure 73). The final specimen was then inserted into the creep test rig (Figure 66), where it was immersed in an aqueous detergent solution at 90°C and subjected to a constant tensile stress, which was chosen to produce slow crack growth failure in the specimen. The time to rupture was measured, and the type and position of failure recorded.

Hydrostatic pressure test at 80°C

The long-term internal pressure test according to ISO 1167 was used for assessing the long-term behaviour of EF joints under internal pressure at elevated temperature. This test method is specified in the relevant standards for gas and water pipelines (eg EN 12201-3 and EN 1555). Welded 125mm pipe samples were closed using butt fusion welded end caps, filled with water and subjected to an internal pressure of 10 bar, producing a circumferential stress in the pipe wall of 5MPa, at a test temperature of 80°C. The time-to-failure was measured and the position of failure recorded.

Results

Tests on butt fusion welds

The load vs displacement curves for the short-term tensile tests on unflawed and talc contaminated welds in 225 and 450mm diameter pipes are shown in Figures 74 and 75, respectively. Curves for unflawed and sand contaminated welds in 180 and 225mm diameter pipes are shown in Figures 76 and 77, respectively, and curves for standard and cold welds in 355 and 450mm diameter pipes are shown in Figures 78 and 79, respectively. As can be seen, talc contamination, even at light loadings, had a dramatic effect on the ductility of butt fusion welds in PE pipes for all the pipe sizes investigated in the project. It reduced the energy to break values by up to 87% for light loading and by up to 96% for heavy loadings. The effect of sand contamination was also significant but not as pronounced, with reductions in the energy to break values of up to 60% for light loading and up to 87% for heavy loading. Cold welds reduced the energy to break values by up to 99% compared with standard welds. Photographs of the fracture surfaces from the flawed and unflawed butt fusion welds in 180mm pipe are shown in Figure 80.

A summary of the results of the specimen creep rupture tests is given in Table 4, where it can be seen that both talc and sand contamination caused a significant reduction in the long-term performance of butt fusion welds, with reductions in the failure times of up to 97% and failures all occurring in the fusion plane. However, as was seen in the short-term tensile tests, the results for the 710mm pipes were inconclusive, with the light talc loading giving times to failure similar to the uncontaminated weld. Cold welds also had much shorter times to failure than standard welds and resulted in failures through the fusion plane. Photographs of the fractured specimens from flawed and unflawed butt fusion welds in 225mm pipe are shown in Figure 81.

The results of the whole pipe tensile creep rupture (WPTCR) tests on butt fusion joints in 180mm diameter PE80 pipes are given in Table 5 and suggest that at least medium and heavy talc contamination has a significant effect on the long-term performance of butt fusion welds and generates brittle fractures, as do cold welds.

Tests on electrofusion welds

The results of the peel decohesion tests are given in Table 6, which show that even a light loading of sand in 225mm EF joints caused brittle failure through the weld interface and is therefore not acceptable. However, in 355mm EF joints a light loading of sand caused partial failure through the interface and partial failure through the plane of the heating wires. Cold welds produced a brittle failure through the weld interface in all the pipe sizes tested. However, there were some areas where the weld was good in the 225mm joint, which suggests that the weld quality may not be uniform around the weld circumference. This may well be due to a slight ovality of the pipe.

The results from the crushing decohesion tests are given in Table 7 and show that aluminium discs of diameters up to 50mm had no effect of the integrity of the weld according to this test. However, pipe under-penetrations of around 20% into the fusion zone (Level C) generated unacceptable failure modes.

A summary of the results of the specimen creep rupture tests is given in Table 8. Where the failure was in the plane of the heating wires, the cracks were initiated by the stress peak due to the notch produced by the wires. The typical fracture surface of an EF tensile creep rupture test specimen where rupture has occurred in the plane of the heating wires is shown in Figure 82. The typical appearance of an EF tensile creep rupture test specimen where rupture has occurred in the fusion plane due to talc and sand contamination is shown in Figures 83 and 84, respectively. The fracture surface of a cold weld is shown in Figure 85 and the fracture surface of the 710mm EF joint containing no flaws, where the failure was partly in the plane of the heating wires and partly in the fusion plane, is shown in Figure 86. These results show that both talc and sand contamination caused a significant reduction in the long-term performance of EF welds, with reductions in the failure times of over 99% for heavy contamination, and failures all occurring in the fusion plane, even for light loadings. Cold welds also tended to have much shorter times to failure than standard welds although, in the 355mm joint, there was an area where the weld was good which, similar to the peel test results, suggests that the weld quality may not have been uniform around the weld circumference. As suggested previously, this may well be due to ovality of the pipe.

The whole pipe tensile creep rupture tests on cold welds in 180mm and 225mm EF joints all failed during loading, which suggests that cold EF welds have a dramatically reduced long-term, as well as short-term, performance.

A summary of the results of the hydrostatic pressure tests on EF welds in 180mm and 225mm PE pipes containing various flaws are given in Table 9. For the pipe under-penetrated welds in the 225mm EF joints, the crack initiated from the stress concentration produced by the melt bead formed in front of the pipe end due to it not being pushed up to the centre stop in the coupler and the crack travelled through the wall of the coupler. Therefore, for these particular EF couplers, pipe under-penetration, even at Level A, reduced the long-term integrity of the joint. However, it can be seen in Table 9 that pipe under-penetration had no effect on the long-term integrity of the 180mm EF joints. This suggests that the effect of pipe under-penetration is dependent on the resistance to slow crack growth of the material that the EF fitting is made from. It can also be seen in Table 9 that failure also occurred through the EF coupler for welds containing a 50mm diameter aluminium disc. However, since the crack initiation point was remote from the disc this suggests that the disc had no influence on the long-term integrity of the joint. The cold EF welds failed during the filling stage which, in agreement with the whole pipe tensile creep rupture tests, shows that cold welds have a greatly reduced long-term performance.

Quantification of particulate contamination levels

Some of the welded joints containing particulate contamination had polyimide tape inserted into the joint at various positions. This was to allow specimens containing the tape to be cut from the welded joint and then broken open to reveal the weld interface. The surface that was contaminated with either talc or sand was then analysed using X-ray photoelectron spectroscopy in order to quantify the percentage area of the weld that had been contaminated. A summary of the percentage talc and sand contamination levels in the different joint types and pipe sizes is given in Table 10.

Determination of acceptance criteria

Typical graphs of the log of the percentage contamination level, from Table 10, against log of time to failure from the specimen creep rupture tests on butt fusion welds are shown in Figures 87-89, where the vertical red line is the time to failure for the uncontaminated weld. The critical contamination levels predicted from the above graphs assume that the activation energy of the crack growth in contaminated welds is the same as that for uncontaminated welds. Further work will need to be performed in order to confirm whether or not this assumption is valid.

Based on these data, a summary of the critical flaw sizes and contamination levels for each pipe size and joint type is shown in Table 11. However, it must be remembered that the values given in this table are only valid for the PE resins, pipe dimensions and welding procedures used in this study. The effect of different PE resins and welding procedures on the acceptance criteria will need to be determined but is outside the scope of this project.

WP5 – Development of Ultrasonic Instrument and Data Processing

The objectives of this work package were to design and manufacture a small rugged phased array instrument capable of rapidly scanning both butt fusion and EF joints in PE pipes with diameters between 110 and 1000mm, and to develop data collection and processing software that can incorporate all NDE techniques in a single parallel system.

Ultrasonic instrument

A UT instrument (Figure 90) has been designed and manufactured with the following hardware specifications:
- Integrated UT device and PC
- 64 phased array channels, 4 conventional channels
- Wireless capability for remote control
- IP67 protection for full water immersion
- SSD hard drive (100GB) for data storage
- Battery operated
- Weight: 5kg
- Dimensions: 320x 240x 100mm
- Magnesium alloy body

This instrument has the capability of being attached directly to the scanner (Figure 91).

Data collection and processing software

Software has been developed that allows focal law computations (using CIVA) and parameter setup. In addition, it also supports data acquisition and imaging, together with Multi Salvo capability to chain various testing configurations.

A software user interface has also been finalised that will be used to setup, calibrate and perform the inspections. Individual applications for different pipe sizes and joint types have been pre-defined in the user software, which allows the user to select the appropriate application and follow the steps in the software.

WP6 – Development of Scanning System

Current pipe scanners are designed for metallic pipes and are frequently held in place with magnets, which are not applicable for PE pipes. Furthermore, the space around PE pipes is very limited and the inspection conditions are often wet and dirty. Therefore a low cost hardy system is desired. Also, as described in WP5, the ultrasonic instrument is to be mounted on the scanner for the larger pipe sizes.

A scanning system has been designed that encompasses the full range of weld geometries and pipe sizes specified in

WP1. To extend the use of the manipulator and minimise costs it was designed in a modular form with simple changes for different configurations.

The scanning system consisted of three main parts:

- Chain links and tightening mechanism.
- Main carriage.
- Holders for probe/wedge assembly.

To encompass the range of pipe sizes from 180 to 710mm, three sizes of chain links were designed (Figure 92). Different combinations of links are used for the different pipe sizes (Table 12). In addition, a tightening mechanism (Figure 93) is required to allow for the dimensional tolerances on the outside diameter of the pipes. Figure 94 shows the scanner system mounted on the 180mm pipe and Figure 95 shows the system mounted on a 710mm pipe.

Two main carriages were designed and built: one for small diameter pipes (up to 355mm), where the ultrasonic instrument and water feed system were remote (Figure 96); and one for large diameter pipes (above 355mm), where the instrument and water feed system were mounted directly on the carriage (Figure 97).

Both carriages had a mounting bar attached, on to which the probe/wedge assembles were attached, via probe holders. The purpose of the probe holders is to hold the probe/wedge assembly in a very precise position around the pipe and to ensure that good contact is maintained between the wedge and the pipe/fitting surface to minimise the loss of water from the wedge. Two types of probe holder were designed and built: one for butt fusion joints (Figure 98) and one for EF joints (Figure 99).

WP7 – Assessment of Complete NDE System

Development of final inspection procedure

A procedure for inspecting both butt fusion and EF joints in PE pipes of diameters between 90 and 1000mm using phased array ultrasonic testing (PAUT) has been developed. Although the procedure is specifically for PE80 and PE100 materials, other types of PE and other plastics may be inspected by taking into consideration the possible changes in ultrasonic velocity and impedance. The inspections detailed in the procedure may be undertaken in the workshop or on-site, and either during installation, as long as the joint has cooled to ambient temperature, or on pipes that have been in service.

The inspections are designed to detect defects along the fusion face and in the heat affected zone for the full circumference of the pipe weld joint. The types of reportable defect are: planar lack of fusion, joint contamination (fine and coarse particulates), cold welds, axial misalignment, pipe under-penetration and porosity/voids.

The procedure specifies the use of an open architecture PAUT array controller with a minimum of 64 channels, capable of addressing 32 elements in one focal law. The frequency range should be between 2MHz and 5MHz. It also specifies the use of one-dimensional linear PAUT probes with a centre frequency of between 2MHz and 5MHZ and either 64 or 128 elements, for inspecting butt fusion and EF welds, respectively. The probes should be coupled to the plastic pipe or EF coupler by the means of a water wedge.

The procedure defines two types of inspection, one for EF welds and one for butt fusion welds. The EF welds should be inspected using a single technique: a zero degree technique where the weld is examined using an ultrasonic beam that is normal to the fusion face. The beam is electronically scanned axially along the fusion zone and mechanically scanned circumferentially around the fusion joint. The butt fusion welds should be inspected using a combination of three or four techniques, dependent on the coverage required. As a minimum, three techniques should be employed: a sectorial pulse echo scan with beam angles between 35º and 70º, a self-tandem scan and a high angle ‘creeping wave’ scan. In addition, a TOFD scan may be employed.

Assessment trials

The finalised inspection system for small diameter pipes is shown in Figure 100. This was assessed both in the laboratory/factory and in the field.

Trials were carried out at Radius Systems in Alfreton, UK on 15-17 October 2012. EF joints in 250 and 450mm PE pipes that had been in service in Belfast, Northern Ireland and had been removed because of concern regarding the integrity of the joints, were inspected in the factory and the results were compared with X-ray radiographs of sections cut from the joints and with mechanical tests. A typical inspection report is shown in Figure 101 and a typical B-scan image is shown in Figure 102. Very good correlation between the ultrasonic inspection results and both the X-ray radiographs and the mechanical test results were obtained. For example, an area where a void was seen in the ultrasonic image was cut out and peel tested and the position of the void on the fracture surface of the peel test specimen was compared with the position in the ultrasonic image (Figure 103).

Further trials were carried out at Plasflow in Rotherham, UK on 5-7 November 2012. Butt fusion joints in 450 and 630mm PE100 pipes that had been made for a power station installation were inspected in the factory (Figure 104). In one of the welds an indication was found at a circumferential position of 240° and a through-wall depth of 20.9mm. The estimated size of the flaw was 5-6mm in the circumferential direction and 2-3mm in the radial direction (Figure 105). This weld was cut out and rewelded. In addition, an indication from an axially misaligned weld was found, due to the step between the internal surfaces of the pipes (Figure 106).

Trials were carried out at EO.N Ruhrgas in Essen, Germany on 19 March 2013. These were blind trials on EF joints in 110mm PE pipes containing various simulated flaws, including aluminium foil, sand and talc (Figure 107). The inspections were very successful at detecting these flaws and distinguishing between good and flawed welds. For example, a comparison of an ultrasonic image of a good weld and one containing sand contamination is shown in Figure 108.

The final trials were carried out in the field between 1 and 5 March 2013. The objective of these trials was to assess the operation of the system in real environments, i.e. in a trench. The first trial was the inspection of EF welds in a 710mm PE pipeline at a hydroelectric power station in Bethesda, North Wales (Figure 109) and the second trial was at a gas pipe installation in Sheffield, UK, where BF joints in 355mm PE pipe and EF joints in 250mm pipe were inspected (Figure 110). In both cases the prototype system operated satisfactorily.

WP8 – Development of Training Guidelines

Training guidelines for the phased array inspection of butt fusion and EF welds in PE pipes have been developed. Three different training schemes have been developed:

- Programme 1 (for the SME-AG members of the consortium)
  - This programme is aimed at providing a core of trained personnel in the SME-AGs who can then deliver training to their member SMEs (training the trainers who will prepare appropriate course notes).
  - The programme will take two days to deliver and the subjects and hours of study are detailed in Table 13. It is aimed at experienced trainers with a minimum of NDT Level 2 in phased array ultrasonic testing, in accordance with ISO 9172.
- Programme 2 (for SME developers of the developed NDE-UT phased array technology and systems)
  - This programme will be delivered nationally by the SME-AGs for training in the use of the equipment and procedures.
  - The programme will take five days to deliver and the subjects and hours of study are detailed in Table 13. The programme is aimed at experienced operators with a minimum of NDT Level 1 in phased array ultrasonic testing, in accordance with ISO 9172.
- Programme 3 (for application engineers and supervisors - service providers and OEM engineers)
  - This programme will be delivered nationally by the SME-AGs for training in the use of the equipment and procedures.
  - The programme will take five days to deliver and the subjects and hours of study are detailed in Table 13. The programme is aimed at experienced operators with a minimum of NDT Level 1 in phased array ultrasonic testing, in accordance with ISO 9172.

All three programmes cover basic principles of the equipment design. Programmes 2 and 3 include understanding applications and any limitations of the techniques developed, developing procedures for specific applications and ensuring quality and safety during operation. This type of training is applicable to staff at an appropriate level in both equipment manufacturers and service providers and will be key to the transfer of the newly developed technology into the marketplace.

Potential Impact:

Potential impact

The expected impacts that the TestPEP project will have on the EU can be divided into three categories:

- Economic
- Societal
- Environmental

Economic impacts

The TestPEP project will enable a wider adoption of plastics pipes for more safety-critical applications. This, in turn, will result in cost reductions in installation and maintenance of pipelines, due to the fact that plastics pipes are less expensive to install and have better corrosion and chemical resistance than metallic or concrete pipes. In addition, the project will deliver a system capable of detecting defective welds just after the welding process, which means that these welds will be cut out and replaced before they are buried. There will therefore be a reduction in leaks occurring in plastic pipe systems, and the resulting repair costs incurred will be reduced. In addition, catastrophic failures will be avoided, which will reduce costs associated with litigation.

Societal impacts

The TestPEP project has developed a system capable of determining the quality of welds in plastics pipes, and if this is adopted by the industry, it will reduce the number of leaks and will therefore reduce the disruption caused by road digging required for repairing leaking joints.

The project has generated new knowledge on the NDE of plastics pipes, which is being incorporated into new European and international standards and codes, for example the draft ISO Technical Report ISO/DTR 16943 ((Plastics piping systems for the supply of gaseous fuels – On-site inspection of PE electrofusion joints using non-destructive testing), which is being developed in the ISO Working Group ISO/TC138/SC5/WG17 (General properties of pipes, fittings and valves of plastic materials and their accessories – Alternative test methods). The results are also being used in the development of the ASME Code Case N-755 (Use of polyethylene Class 3 plastic pipe) for safety-critical applications in nuclear power stations, and in the development of the AFCEN Code Case RCCM-001 (HDPE Piping Systems Design and Construction Rules).

The development of these stadards and codes will require training of operators on the NDE equipment and procedures and will generate new skilled jobs. For this reason, as part of the TestPEP project, training guidelines for phased array ultrasonic testing of BF and EF joints in PE pipes have been developed. Three different training programmes have been defined: Programme 1, a 16 hour course for the SME-AG members of the consortium, aimed at providing a core of trained personnel in the SME-AGs who can then deliver training to their member SMEs; Programme 2, a 40 hour course for SME developers of the PAUT system for PE pipes, to be delivered by the SME-AGs; and Programme 3, a 37 hour course for service providers and OEM engineers.

Environmental impacts
The use of NDE on welded joints in PE pipes as a quality assurance method will reduce the risk of failure and increase the confidence in the use of these materials. This will lead to the more widespread application of plastic pipes, and will allow them to be used for more stringent service requirements. Minor leakage from water pipes has been accepted in the past, but is increasingly penalised as water demand rises and concerns grow for the amount of water abstracted from rivers and boreholes. Failure in sewerage pipes is a hazard to both the environment and to health. Major fracture of gas pipes and the consequent escape of large volumes of flammable gas are potentially life threatening. Any type of leak from a nuclear establishment (either electrical generator or reprocessing) is totally unacceptable.

Main dissemination activities

Project website
The project website, www.testpep.eu, was launched in May 2010 and contains the following pages:
- A project outline page, which provides an introduction to the project, including a list of objectives and deliverables;
- A partners page, which gives a brief description of each of the project partners and links to their websites;
- A videos page, which contains videos of all of the presentations given at the project dissemination seminars as well as a video of the demonstration of the prototype equipment;
- A publications page, which currently list over 25 publications, including press releases, flyers, magazine articles and conference papers;
- A news page, which lists forthcoming event where project results are to be presented.

The website also contains the project logo, which is shown in Figure 111.

Project flyer and posters
The TestPEP flyer was produced in September 2010 (Figure 112) and has subsequently been translated into Italian (Figure 113). In addition, two posters have been produced; one in English (Figure 114) and one in Spanish (Figure 115).

Conferences
The TestPEP project has been presented at the following conferences and events:
- EWF General Assembly, Cambridge, UK, 26 May 2010.
- Wiesbadener Kunststoffrohrtage, Wiesbaden, Germany, 7-8 April 2011.
- 12th Spanish Congress in NDT, Valencia, Spain, 15-17 June 2011.
- International Congress on Ultrasonics, Gdansk, Poland, 5-8 September 2011.
- BINDT Conference, Telford, UK, 13-15 September 2011.
- 5th International Conference on Emerging Technologies in Non-Destructive Testing, Ioannina, Greece, 19-21 September 2011.
- Plastic Pipe Fittings & Joints Conference, Dusseldorf, Germany, 27-29 September 2011.
- 5th Pan America Conference of Non-Destructive Testing, Cancun, Mexico, 2-6 October 2011.
- 14th Congresso AIPnD Biennale PnD-MD, Florence, Italy, 26-28 October 2011.
- SMiRT 21 Conference, New Delhi, India, 6-11 November 2011.
- Pipeline Industries Guild Utilities Panel Meeting, London, UK, 6 December 2011.
- ENDEL/GDF Suez Technical Workshop on Design and Construction of HDPE Piping Systems, Paris, France, 26 January 2012.
- Norwegian University of Science and Technology seminar, Trondheim, 22-24 March 2012.
- Aerospace NDT Symposium, Bristol, UK, 4-5 April 2012.
- 18th WCNDT Conference, Durban, South Africa, 16-20 April 2012.
- 16th Plastics Pipes Conference, Wiesbaden, Germany, 26 April 2012.
- Use of HDPE for Power Plant Piping Systems Seminar, Gloucester, UK, 8-10 May 2012.
- Eurojoin 8 Conference, Pula, Croatia, 24-26 May 2012.
- ASME Pressure Vessels and Piping Conference, Toronto, Canada, 15-19 July 2012.
- Pipeline Industries Guild Utilities Panel Meeting, Cambridge, UK, 6 September 2012.
- ASME Code Week, Washington DC, USA, 13-17 August 2012.
- BINDT Conference, Daventry, UK, 11-13 September 2012.
- Plastics Pipes XVI Conference, Barcelona, Spain, 24-26 September 2012.
- 19th Technical Sessions on Welding, Madrid, Spain, 3-5 October 2012.
- 6th Middle East NDT Conference and Exhibition, Bahrain, 7-10 October 2012.
- 4S Quarterly Meeting, Vaxjo, Sweden, 2 November 2012.
- EWF General Assembly, Porto Salvo, Portugal, 6 November 2012.
- ASME Code Week, Los Angeles, USA, 11-15 February 2013.
- Pipes in Infrastructure Conference, Dusseldorf, Germany, 10-11 April 2013.

Articles
The following papers and articles about the TestPEP project have been published:

- EWF website article (http://www.ewf.be/TestPep.aspx)
- SMART website article (http://www.smartgroup.org/index.php?option=com_content&task=view&id=80)
- EWF Newsletter, March 2010.
- Smarter Newsletter 26, March 2010.
- EWF Annual Report, May 2010.
- AEND Journal, 51, 2010.
- Ultrasound Journal, 65(4), 2010.
- Il Giornale Delle Prove Non Distruttive Monitoraggio Diagnostica, 3, 2010.
- Joining Plastics – Fugen von Kunststoffen Journal, February 2011.
- Smarter Newsletter 30, February 2011.
- Global SMT and Packaging Magazine, March 2011.
- PIG Newsletter, March/April 2011.
- Insight Journal, 53(4), April 2011.
- TWI website article (http://www.twi.co.uk/content/NDT-collab-TestPEP.pdf).
- Il Giornale Delle Prove Non Distruttive Monitoraggio Diagnostica, 2, 2011.
- TWI Connect Magazine, May/June 2011.
- CCR website article (http://www.enterprise-europe-network.ec.europa.eu/src/matching/templates/completerec.cfm?bbs_id=176707).
- Welding and Cutting Magazine, 10(4), July/August 2011.
- AEND Journal, 56, 2012.
- TWI website article (http://www.twi.co.uk/news-events/news/2012-12-testpep-enters-final-year-of-tests-for-nde-of-plastics-pipes/)
- TWI Connect Magazine (Issue 177, March/April 2012).
- TWI Oil and Gas Newsletter, Issue 15.
- British Plastics and Rubber, April 2012.
- Welding and Cutting Magazine, 11(3), 2012

Dissemination seminars
Four dissemination seminars took place in March 2012:
- Hessel Ingenieurtechnik, Roetgen, Germany, 21 March 2013.
- EWF, Lisbon, Portugal, 23 March 2013.
- AIPnD, Brescia, Italy, 28 March 2013.
- AEND, Madrid, Spain, 5 April 2013.

Exploitation of results
The main exploitable products from the TestPEP project are:
- Phased array probes
o Bespoke ultrasonic probes for the inspection of butt fusion and EF welds of particular pipe size ranges.
- Ultrasonic instrument
o Miniaturised, robust flaw detector with internal batteries and integrated PC and hard drive, and wireless connection to an external computer.
- Software
o Advanced signal processing and automated defect recognition software, capable of taking the raw data from the ultrasonic instrument and generating two- and three-dimensional maps of the joint and processing it into a simple “yes/no” system for sentencing flaws.
- In-service inspection of PE pipes
o Inspection procedures, incorporating process acceptance criteria.
- Prototype inspection system
o Complete system, incorporating phased array probes, probe wedges, scanner and flaw detector that have all been optimised for inspecting butt fusion and electrofusion joints in PE pipes of diameters between 110 and 800mm.

List of Websites:
http://www.testpep.eu

Related information

Result In Brief	Non-destructively testing plastic pipe welds
Documents and Publications	final1-figures-for-final-report.pdf

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Subjects

Economic Aspects - Scientific Research

Information source: SESAM

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