SUITABILITY OF NON DESTRUCTIVE TECHNIQUES FOR TESTING POLYETHYLENE PIPE JOINTS.

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Abstract
The suitability of non destructive techniques for testing polyethylene pipe joints are investigated in a GERG (European Gas Research Group, www.gerg.eu) project. The results show that:

- *Both Ultrasonic and Microwave techniques have developed to a mature level.*
- *For electrofusion joints good results are obtained with Ultrasonic Phased Array techniques. These techniques are ready for practice, and in some cases already applied as such.*
- *For butt fusion joints CHORD Ultrasonic testing is showing good results, but this method is only tested to a limited extent in this project. Both Ultrasonic TOFD and Microwave techniques show some indication on the joint quality but both techniques need further development.*
- *The Bead Bend Back test that is used in the UK to examine butt fusion joints shows good results. This technique is quite simple and can be considered as an NDT technique as well*

The different techniques have been assessed on their maturity and suitability to be used in practice. The techniques have been tested on both laboratory made joints and excavated joints, about 180 different joints in total. The laboratory joints are a mix of good joints and joints with certain type of errors introduced deliberately. The joints have been sent to NDT companies for blind testing (without any knowledge about the introduced errors). Afterwards the joints have been destructively tested in accordance with ISO standards. The results of the Non Destructive Techniques have been compared with the introduced errors and the results of destructive tests . This GERG investigation shows the possibilities and performance of current techniques, and what further steps need be to taken to use the techniques in practice.

INTRODUCTION

It is very common to test the quality of steel welds in gas pipe systems using non-destructive techniques, however this is not the case for PE joints, although they are often used at similar pressure levels. Conventional non-destructive testing techniques for steel do not apply to joints in PE piping systems. In the past years several companies developed non-destructive testing techniques especially for PE joints. GERG is monitoring these developments intensively. As these techniques started to show good results, the GERG members decided to start a project where different techniques would be assessed on their suitability to be used in practice.

JOINTS IN POLYETHELENE PIPE SYSTEMS

For Polyethylene Pipe Systems two types of fusion joints are used: Butt Fusion and Electrofusion. For non-destructive testing an important difference between these two techniques is the orientation of the fusion plane. Butt Fusions are created by heating the pipe ends and then pressing both ends together. The fusion plane is perpendicular to the pipe wall.

Figure 1: Butt fusion

Electrofusions concern appendages like sockets, end-caps and saddles. These appendages are made from polyethylene as well. The appendages have wires that form a heating element at the inner surface, touching the pipe wall. After the appendage has been mounted, the wires are connected to a fusion machine. The wires heat up and melt and expand the surrounding plastic. Pipe and joint fuse together. Typically the fusion plane coincides with the pipe wall surface.

Figure 2: Electrofusion socket

TYPICAL ERRORS

Due to human and machine errors it is possible that joints contain errors. The following errors are found in practice:

- Cold Welds or Kissing Bonds
  Though the PE material sticks together; no real fusion has taken place. This is revealed in a destructive test where the parts separate in a brittle way with low strength. This can be caused by a wrong jointing temperature, jointing pressure, or an insufficient pre-treatment such as scraping and cleaning.
- Pollution
  Dirt or grease in the fusion zone prevents locally good fusion.
- Humidity
  During the heating, absorbed water in the PE material can cause voids in the fusion zone, decreasing the strength of the joint.

INVESTIGATED NON-DESTRUCTIVE (NDE) TECHNIQUES

For butt fusions the following NDE techniques have been investigated:

- Ultrasonic Time Off Flight Diffraction (US-TOFD) by Open Grid Europe
- Chord Ultrasonic Test by Polytest
- Microwave by Evisive / Exova
- Bead Bend Back test by National Grid

For electrofusion the following NDE techniques have been examined:

- Ultrasonic Phased Array (US-PA) by Open Grid Europe (and partially by GDF SUEZ)
- Microwave by Evisive / Exova

These techniques are described in short below.

Ultrasonic TOFD

The examination method with Ultrasonic Time of Flight Diffraction (US-TOFD) that has been used in this project has been developed and performed by Open Grid Europe. A common US-TOFD device is used and the test can be performed on-site. TOFD uses the time of flight of an ultrasonic pulse whereas common ultrasonic testing makes use of the amplitude of an ultrasonic pulse.

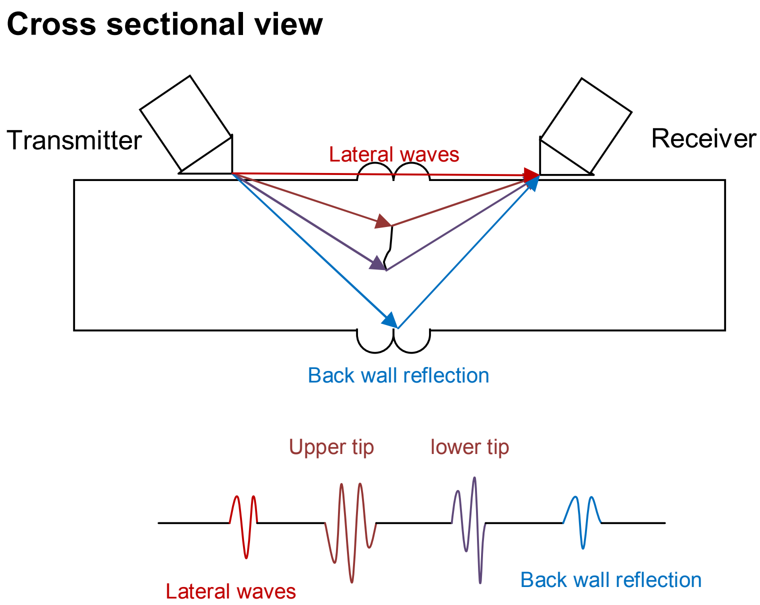

Figure 3: US TOFD Principle

In a TOFD system, a pair of probes (a transmitter and a receiver), are positioned on opposite sides of a weld (see Figure 3). The probe emits compression waves in a pitch catch arrangement. When signals at specified frequencies encounter anomalies, the ultrasonic compression waves are diffracted. Dimensions of the anomaly are measured by calculating the time of flight of the diffracted waves from the transmitter to the receiver. Software displays cross sectional views with defects superimposed on the pipe image.

Chord Ultrasonic Test

The Chord ultrasonic test that has been used for this project has been developed and performed by Polytest. The Chord ultrasonic test uses a so called Chord probe with separate functions for transmittance and receival of ultrasonic waves [1]. The transmitter and the receiver are placed in an angle in such a manner that the main energy of an emitted beam is concentrated in the cross section of the fusion zone.

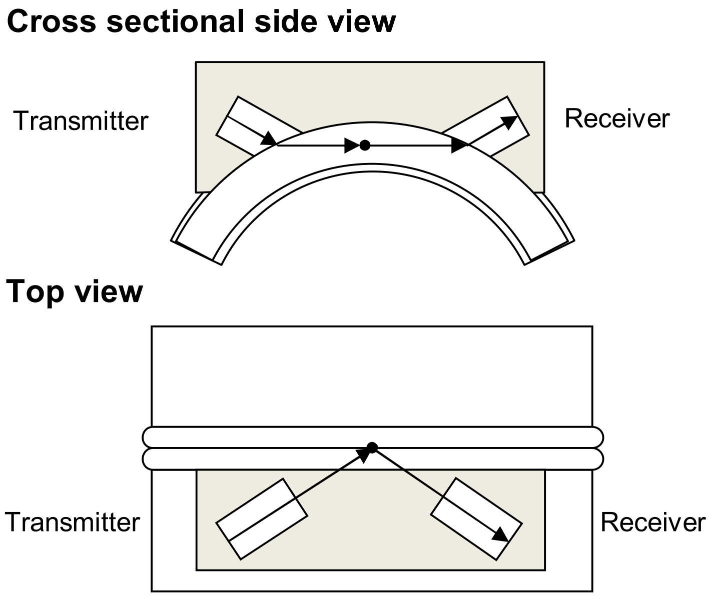

Figure 4: Schematic drawing of the ultrasonic Chord probe, side view and top view

Special about the probe is that the receiver and transmitter are fit in an elastic protector to solve problems related to excitation of high-power surface waves along an inspected surface. The technique is used for steel welds as well as for polyethylene butt fusion joints. For each diameter a different probe is necessary. The Ultrasonic device can be any standard ultrasonic flaw detector for general purposes. However there are also specially designed flaw detectors available. The system can be used on-site and is suitable for diameters from 63 up to 315 mm with wall thicknesses from 6 up to 25 mm.

Microwave
For this project the Microwave system developed by Evisive has been used (the tests have been performed by Exova). The system has been specially designed for butt fusions and at a later stage also for electrofusions. Both systems can be used on-site. The Microwave inspection technique is based on monochromatic, phase coherent electromagnetic radiation, preferably in the 5-50 gigahertz frequency range (i.e. microwaves). The sample to be examined is exposed to microwave radiation at discrete locations along a path of which the location coordinates are known and are returned as part of the data field, thus creating a map of the specimen. A detectable microwave signal is also returned everywhere along the path and a differing signal is generated at each interface where the dielectric constant changes (e.g. - where there are de-laminations, cracks, holes, impurities, or other defects). The return signal is generated based on the angle of incidence, the differential in the dielectric constants between the materials, the surface geometry, and other factors.

Bead Bent Back Test
The bead bent back test is a test that is commonly used in the United Kingdom. For this project the test has been performed according to the procedure followed by National Grid. After the common visual examination of the bead, the bead is cut-off

using a tool that leaves the bead in one piece. Then the bead is bended backwards. The dual bead should not separate at any point while bending it back.

Figure 5: Bead Bend Back Test. The beads separate indicating a bad fusion.

A separation at any point indicates a bad fusion. This test can be considered as a non-destructive test as well, since the joint is not affected although the bead has to be cut-off.

Ultrasonic Phased Array

The non destructive examination of electrofusion joints using Ultrasonic Phased Array (US-PA), as is performed in this project, has been developed by Open Grid Europe, especially by Mr Sievering. For the saddles a similar technique has been performed by GDF SUEZ as well. An US-PA transducer contains multiple elements in a row generating longitudinal ultrasonic waves. The waves may be emitted in different directions using different element combinations and timing delays of firing each element. The emitting ultrasound beam can be steered and focused.

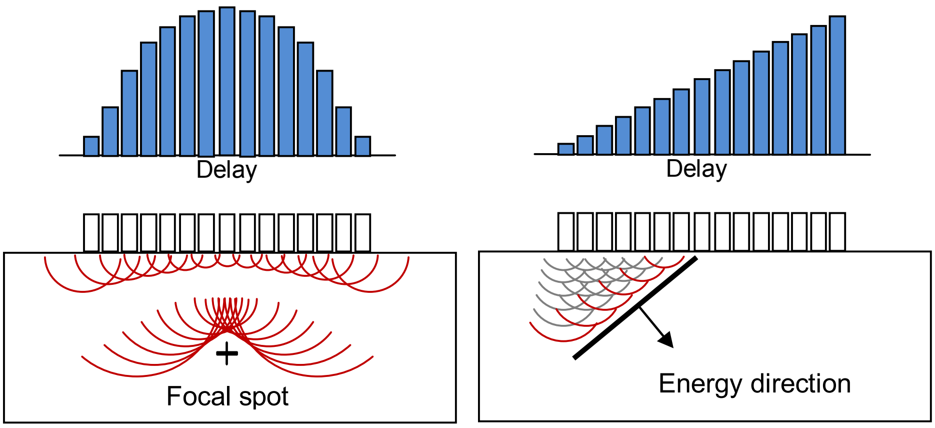

Figure 6. Principle of US Phased Array

The device generates real time 2D imaging, and deviations become visible. However, with the test procedure of Open Grid it is not possible to determine what type of defect is present.

ASSESSMENT OF THE NDE TECHNIQUES

The NDE techniques have been assessed using a large set of joints. This set contained in total 86 butt fusions, 74 electrofusion sockets and 20 electrofusion saddles. More than 50% of these samples have been newly made. Part of these newly made joints contained certain type of errors. Although the errors have been artificially introduced, they refer as much as possible to errors that occur in practice, as described above in chapter “TYPICAL ERRORS”. The following errors have been added:

- Cold weld
- Pollution (big, normal, small and grease)
- Water and drilled holes (representing voids)
- Wrong fusion procedure (from not scraping to premature abort of the fusion process).

The excavated joints have been taken out of practice by the participating companies. As a consequence these samples are a mix of all kinds of joint types originating from United Kingdom, Spain, France and Germany. The joints have different designs, ages, brands, and diameters.

The suitability of the different techniques has been assessed by their maturity and their performance. In this case maturity refers to the development stage: is the technique still in laboratory stage or is it field ready, and is it already applied in practice. The performance has been assessed by the Probability Of Detection (POD) and Falls Call Rate (FCR). The POD is the probability that an error is detected by the technique, also referred to as the sensitivity. The FCR is the chance that a good joint is misjudged as a bad joint. The POD can be calculated with following formula:

$$\text{POD} = \frac{\text{Found bad joints}}{\text{All bad joints}}$$

The higher the POD, the better the performance. For the FCR it is just the other way around: the lower the FCR, the better the performance. The FCR is calculated with following formula:

$$\text{FCR} = \frac{\text{Misjudged good joints}}{\text{All good joints}}$$

It is clear that the POD and FCR depend on the definition of a good joint and a bad joint. And this is rather difficult. In case of PE pipe joints this could be defined as: Leak tight and at least as strong as the pipe itself during the lifetime of the piping system. However, how do you assess whether this is the case?
For this project two different definitions of a good joint have been used:

1. Fusion made in accordance with prescriptions
   A good joint is a joint made in accordance with the prescribed procedure. Joints that are made in a non-prescribed way are defined as bad joints.
2. Fusion complies with destructive test requirements
   When no errors are found using the destructive test, the joint is a good joint.

The reason for this is that in this project both excavated and newly made joints have been used. The first definition can only be used for the newly made joints. The latter definition can be used for all samples; both excavated and newly made samples. For the destructive testing of butt fusions the tensile test as described in ISO 13953 has been used. For electrofusions the peel test as described in ISO 13954 has been used and for smaller diameters the crush test in accordance with ISO 13955. For the saddles a peel test has been performed by GDF SUEZ in accordance with ISO 13956 using their own specially designed equipment.

RESULTS

As explained above the POD and FCR have been calculated based on two different definitions of a good joint: according to prescribed procedure and according to the destructive test results. The results for each technique for butt fusions are shown in the following table.

Table 1: Assessment results of different NDT techniques for butt fusions.

NDT technique	Joint type	Maturity	POD (procedure / destructive)	FCR (procedure / destructive)
US TOFD	Butt fusion	+	35% / 38%	0% / 22%
US Chord [2)]	Butt fusion	++	87% / 100%	0% / 60%
BBBT	Butt fusion	++	53% / 65%	0% / 12%
Microwave [3)]	Butt fusion	++	80% / 70%	57% / 63%
Microwave [1)]	Electrofusion sockets	++	89% / 100%	100% / 88%
US PA	Electrofusion sockets	++	84% / 62%	0% / 28%

1) tested with a limited set of samples

2) tested with a limited set of samples with mainly big errors

3) tested with a limited set of samples without any big errors

The destructive tests do not detect every type of error that has been introduced. Therefore different POD and FCR values are found using the 2 different criteria for a good joint quality. Compared to the introduced errors, a probability of detection of 61% for butt fusions (ISO 13953), and 45% for electrofusions (ISO 13954/ISO13955) has been calculated. All joints that were intended as good joints passed the destructive test showing a FCR of 0%.

Results Ultrasonic TOFD for butt fusion

The technique is almost mature. A common commercially available TOFD device has been used. The technique can be used on site. The scanning and analysis takes about a quarter of an hour. However, since Open Grid is not a NDT service company, the assessment of joints with TOFD as performed by Open Grid is not commercially available. Therefore the maturity is ranked as + instead of ++. Only large errors have been detected. This is reflected in a low POD. Small errors like pollution with dust or even sand keep undetected. The FCR of 0% is excellent but may be not surprising regarding the low sensitivity. In using the destructive test results as a criterion for joint quality the POD becomes a little better since fewer errors are found by the destructive test. The FCR becomes higher since the TOFD technique finds pollutions that did not give a failure in the destructive test.

Results Chord Ultrasonic testing of butt fusions
The technique was not witnessed for this project. But as understood from Polytest, the technique is used in practice for years in Russia and is commercially available. Due to project limitations, the technique was tested on a limited scale with samples having mainly large errors. It performed well with a high POD and low FCR. However, it is not tested with smaller errors and neither with cold welds. The FCR of 0% is excellent. When the results are compared with the results of the destructive test, the FCR becomes much higher since the technique finds all the pollutions that did not give a failure in the destructive test. For all other types of errors the technique corresponds well with the destructive test, showing a POD of 100%.

Results Microwave Technique
The technique is mature. It is used in practice and commercially available. The device is customized for pipe systems and can rotate around the pipe. The hardware is CE compliant. The scanning and analysis takes about a quarter of an hour.
For butt fusions, normally the microwave test is combined with the bead bend back test. However, for this project the purpose was to show what the performance of the technique is on itself. Therefore the Microwave test has been performed separately from the bead bend back test. For butt fusions, the POD seems to be very good; however the FCR value of 57% is much too high. Many good joints have been misjudged as bad joints. Combining the Microwave results with those of the bead bent back test, does not make the results any better. For electrofusions similar results are obtained; a good POD but a FCR value of even 100%. It seems that the pass/fail criteria that are currently used, are too strict, not accepting any deviation.

Results Bead Bent Back Test for butt fusions
This technique is mature. The bead bend back test has been performed in the United Kingdom for years and can be performed by anyone after some instructions. After removing the bead with a special tool it takes only several minutes to perform the test. The performance of this technique is quite good. The POD is high and the FCR value of 0% is excellent. The bead bend back test also corresponds well with the destructive test results.

Ultrasonic Phased Array
For the examination standard ultrasonic phased array equipment is used. The technique is suitable for on-site testing, takes about a quarter of an hour, and is as such already deployed. In Germany this technique is commercially available and offered as an service. Therefore the technique is to be considered as mature.

For US-PA and ultrasonic testing in general, the probes have to make good contact with the surface. This is accomplished by using contact fluids. However, the design of the outside shape of electrofusion appendages could also be improved for US-PA application. Current designs sometimes limit the inspection possibilities due to irregularities at the outer surface. The best design would be a smooth and plane surface.

The US-PA technique shows very good results. In some way it even performs better than destructive testing since it detects pollution that is not (always) detected by destructive testing. The expert that developed the examination with US-PA, Mr Sievering, did not expect that cold welds could be detected, due to the nature of cold welds and ultrasonic testing. Ultrasonic testing is based on reflections of surfaces (of the errors), but in case of a cold weld there are no surfaces present. Surprisingly all the cold welds have been detected by the test as well. The reason for this is unclear, since the test is only able to detect an error without the possibility to determine the type of error. The FCR is 0%, which is excellent. Compared with the results of the destructive test, the POD is lower and the FCR is higher. This is due to the fact that pollution does not always lead to failure in the destructive test, where phased array will detect it.

Twenty saddles have been tested both by Open Grid and GDF SUEZ using the same phased array technique. These saddles have been excavated, but it was known that many of these saddles contained errors. The experimental difficulty with saddles is that there is little room for the US-PA detector, making it hard to examine the saddle. The saddles have been destructively tested in accordance with ISO 13956. In the following table the results are presented:

Destructive test result	**Amount**	**U-PA by GDF SUEZ**		**U-PA by Open Grid**	
		Found	**Performance**	**Found**	**Performance**
Pass	2	2	FCR=0%	2	FCR=0%
Fail	18	1	POD=6%	0	POD=0%

Clearly US-PA does not perform as well with saddles as it does with sockets. This is most probably caused by the difficult geometry of saddles.

CONCLUSIONS

Non-destructive techniques for joints in PE piping systems have developed to a mature level. The techniques are field ready and in many cases already applied as such. The POD and FCR values are comparable to those that are common for NDT techniques for steel pipes. Regarding the specific techniques for butt fusions that have been investigated in this GERG project, the following conclusions can be drawn:

- The Bead Bend Back test that is used in the UK to examine butt fusion joints shows good results. This technique is quite simple and can be considered as an NDT technique.
- The Chord Ultrasonic testing for butt fusions is showing good results too, but was only tested on a limited scale in this project.
- Ultrasonic TOFD for butt fusions is showing some indication of the joint quality, but the technique needs further development.
- Microwave testing shows a good POD but a very high FCR. Most probably the pass/fail criteria for this examination need further development.

Regarding the specific techniques for electrofusions that have been investigated in this GERG project, the following conclusions can be drawn:

- Good results are obtained with Ultrasonic Phased Array techniques. The technique is mature, ready for practice, and already applied as such.
- As for butt fusions the Microwave technique still has a too high FCR. Further development of the pass/fail criteria is necessary.

- Currently the designs of electrofusion appendages do not take non-destructive testing into account. For non-destructive testing, especially for ultrasonic testing, a smooth and plane surface would improve the possibilities.

For a fully accepted non-destructive testing of joints in PE piping systems, still some steps have to be taken. Pass and fail criteria have to be clear and agreed upon. Also certified training has to become available. However, this GERG project has shown that techniques are available and non-destructive testing is ready for the next step.

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