ULTRASONIC AND RADIOGRAPHIC NDT OF BUTT FUSION WELDS IN POLYETHYLENE PIPE

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1. BACKGROUND

The use of polyethylene in the gas, water and chemical process industries has increased dramatically over the past two decades. This is largely due to the impetus provided by the British and American gas industries who have selected polyethylene as a material to replace metallic distribution pipelines. Apart from distribution pipelines, polyethylene is also used for insertion repairs on leaking cast iron mains.

The popularity of plastic piping can be attributed to its lightness, flexibility and good corrosion resistance, as well as the ease with which it can be joined. Pipes with a diameter <250mm are normally joined using an electrofusion process. For areas where the application is critical or the pipes are of larger diameter (>250mm) and of thicker section, the hot plate butt fusion process is preferred. Both of these heat fusion processes are capable of producing a joint with mechanical properties approximately equivalent to those of the parent material (1).

The quality of butt fusion joints in polyethylene pipe systems is primarily governed by control of the process parameters during welding. However, as new polyethylene materials are introduced (e.g. PE100) and increased demands are placed on existing polyethylene materials, there is an additional need to monitor quality through reliable non-destructive testing (NDT) methods (2,3). At present there are no nationally accepted standards for the NDT of welds in polyethylene. The most widely used technique is a visual inspection of the outer weld bead. This method is sensitive to those embedded flaws which manifest themselves in the weld bead and to gross flaws, such as pipe misalignment. Attempts have been made to use more quantitative methods of weld examination. For example, X-ray radiography has been used to inspect butt welds in large diameter pipe (4) and an automated ultrasonic inspection tool exists for inspecting welds in smaller diameter (50–100mm) gas distribution pipeline (5). At one stage a guideline standard (ASTM F600–78) for the manual ultrasonic inspection of butt fusion welds in polyethylene pipe was introduced. Unfortunately, the results obtained using this standard were so heavily dependent upon the skill of the operator that it was withdrawn in 1991.

This paper summarises work at TWI on NDT of butt fusion welds in polyethylene and compares this work with results from other published literature on this topic. The major objectives of this study were to develop ultrasonic and radiographic testing procedures for the inspection of butt fusion welds in polyethylene pipe systems. The procedures were developed on pipes with diameters greater than 180mm and thicknesses greater than 12mm. The underlying techniques, however, can be used on testpieces other than pipes, and on a range of different polyethylene types and thicknesses.

2. ULTRASONIC NDT

2.1. Background

There are fundamental difference between the ultrasonic inspection of polyethylene and the ultrasonic inspection of metals. Previous work at TWI (6) has shown that the attenuation of ultrasound in polyethylene is a factor of ten higher than for metals. Figure 1 shows that this attenuation is directly proportional to the frequency of vibration of the ultrasound, and also shows that polyethylene attenuates ultrasonic shear waves much more rapidly than compression waves. Essentially, this means that for many practical applications, ultrasonic testing is limited to using low frequency compression waves (i.e. <4MHz) in order to achieve sufficient penetration and sensitivity on typical thicknesses (25mm) and grades of polyethylene.

2.2. Work at TWI

In (7) the authors studied the effect of material composition on ultrasonic wave velocity and attenuation. Separate studies were also included to assess the degree of anisotropy (i.e. differences in elastic properties in different directions) present in the polyethylene materials considered (see Table 1). It was concluded that ultrasonic wave velocity and attenuation do not vary significantly with material composition and that, when inspected ultrasonically, polyethylene exhibits very little anisotropy and no adjustment in sensitivity is required when testing in different directions. This earlier study also reports on the effectiveness of a compression wave pulse–echo technique for inspecting butt fusion welds in polyethylene pipe.

2.2.1. Pulse–echo compression wave technique

The probe configuration for the pulse–echo compression wave technique is shown in Fig.2. A polyethylene wedge is used to couple ultrasonic energy from a 2.25MHz compression wave transducer into the polyethylene specimen. The angle of the wedge is such that compression waves are generated in the polyethylene specimen at an angle of 60°. Additional wedges, designed to generate compression waves at an angle of 45° in polyethylene, have also been evaluated. The ultrasonic procedures developed so far (6,7) have been shown to be largely insensitive to a range of flaws, including inclusions (e.g. material inserts and dust) and cold welds, in 25mm thick butt fusion welded polyethylene pipe. A cold weld can occur when the hot plate temperature is too low, or the delay time between removing the hot plate and joining the pipe ends is too great, causing the pipe ends to crystallise before coming into contact and resulting in a weld with little or no strength. One of the reasons for the poor performance of the pulse–echo technique is the weak response from vertically oriented flaws in a highly attenuative material like polyethylene. This was highlighted in (7) using three 10mm diameter flat bottomed holes drilled at different through–thickness positions at one end of a pipe section, and is illustrated here in Fig.3. Each hole was detected by strong specular reflections from the corner between the hole and the end of the pipe, rather than from backscattered reflections from the face of each hole. This earlier work (7) did, however, identify other ultrasonic techniques such as creeping waves, time–of–flight diffraction (TOFD) and the tandem technique as being potentially more suited to the inspection of butt fusion welded polyethylene pipe.

2.2.2. Pulse–echo creeping wave technique

Creeping waves are high angle compression waves which are normally used on metals to detect surface breaking cracks and other near surface flaws. Unfortunately creeping waves are only effective over a very short range, as energy is continuously being converted into secondary shear waves (Fig.4). TWI have considered a pulse–echo creeping wave technique to inspect the fused area immediately beneath the outer weld bead on butt fusion welded polyethylene pipe (8). The sensitivity of creeping waves to gross discontinuities in the weld such as a lack of fusion and large material inclusions, located close to the surface, has been demonstrated. The pulse–echo creeping wave technique however, has not been able to detect dust contamination of the fused interface or the presence of a nominal cold weld.

2.2.3. The tandem technique

The ultrasonic probe configuration for the tandem inspection technique is shown in Fig.5. On metals, tandem inspection is most commonly applied to welded joints in thick walled vessels. The technique is particularly sensitive to flaws oriented perpendicular to the scanning surface and because of this, is potentially suited to detecting lack of fusion type flaws in butt welded polyethylene pipework. By moving the transmitting probe (T) relative to the receiving probe (R) it is possible to obtain full through–thickness coverage of the welded region. Two, 1MHz transducers, designed to generate compression waves at 60° in polyethylene were found to be most appropriate for the tandem inspection of welds in 25mm thick polyethylene pipe. Figure 6 shows a typical A–scan response from a perpendicular reflector (5mm diameter aluminium foil disc) located in the mid–thickness of such a weld. If a series of these A–scans are collected at consecutive positions around the circumference of a polyethylene pipe, it is possible to construct a composite A–scan image of the welded region. Figure 7 shows a composite A–scan image of a 2mm aluminum foil disc insert in 25mm of polyethylene. The signal to the right of the response from the disc insert is due to the divergence of the ultrasonic beam and corresponds to ultrasound reflected from the inner weld bead. This signal should always be present as the probes are moved around the entire circumference of the pipe, and can be used as a check on whether ultrasound is being coupled into the polyethylene pipe or not.

From the results presented in a recent TWI report (8), the use of the tandem technique to detect planar discontinuities, such as isolated areas of lack of fusion or large planar inclusions, has been demonstrated down to 2mm in through–thickness size. It should be noted that these flaw types were simulated by introducing aluminium foil inserts at the pipe section interface during welding. Also, the technique is sensitive to dust contamination of the welded interface. Areas known to contain chalk dust show some correlation to regions on the composite A–scan results where the amplitude of the signal reflected from the inner weld bead is reduced. The tandem technique has not been able to detect the presence of a nominally cold weld.

2.2.4. Time–of–flight diffraction (TOFD) technique

In weld inspection of metals, TOFD is used to determine the through–thickness height of flaws. The technique is especially sensitive to flaws oriented perpendicular to the scanning surface and, for this reason, its use for butt weld inspection of polyethylene pipes has been explored.

The probe configuration for TOFD is shown in Fig.8. Here two, 2.25MHz, 60° compression wave probes were used. Ultrasound is generated in a broad beam which isonifies the complete thickness of the welded interface. Displayed on a time-trace, the amplitude signals detected by the receiving probe would look similar to Fig.9. Each signal on the A-scan is separated in time according to the distance ultrasound has to travel between the transmitting and receiving transducers. The first ultrasonic signal to be detected is the lateral wave, which travels the most direct route between transmitter and receiver. The final signal detected by the receiver is the reflection from the inner wall of the pipe, termed the backwall echo (Fig.8).

A perpendicular flaw in the weld line will diffract ultrasound from its top and bottom edges and some of this diffracted energy will be detected by the receiving transducer. Diffracted signals appear as low amplitude responses, between the lateral and backwall echo signals on the A-scan. In TOFD inspection of metals, it is possible to accurately measure the through-thickness size of a flaw by scaling the separation between the diffracted signals. Unfortunately, the lower frequencies required for polyethylene inspection mean that it is not always possible to identify the signals diffracted from the top and bottom of a flaw, and accurate sizing of flaws in polyethylene is generally problematic. A-scans collected by the TOFD technique are commonly displayed in composite form as D-scan images. One such image, showing the TOFD response from a 2mm planar discontinuity in 25mm of polyethylene, is shown in Fig.10.

A flaw will only be detected by TOFD if it is capable of diffracting incident ultrasound from its edges. For this reason it is unlikely that TOFD inspection would be sensitive to a cold weld in polyethylene. A nominally cold weld is synonymous with poor fusion across the entire welded interface and there is no local discontinuity from which diffracted signals can originate.The inability of the TOFD technique to detect the presence of a cold weld has been confirmed experimentally (8).

To summarise, the TOFD technique is sensitive to gross planar discontinuities, down to 2mm in diameter, at the fused interface but, as expected, it is not sensitive to the presence of a cold weld. Also, it is reported (8) that the presence of chalk dust at the fused interface causes a variation in the TOFD response detected, although further work is needed before this can be verified.

2.3. Comparisons With Other Studies

One of the difficulties in comparing the TWI results with other research work is the lack of published material on the NDT of large diameter polyethylene pipes.

The notable work carried out by the American Gas Research Institute (GRI) uses a pulse-echo technique with an array of probes and has concentrated solely on testing gas distribution pipes between 50–100mm in diameter, and up to approximately 12mm thick. Attenuation is less of a problem here than for the kind of diameters and thicknesses considered by the work at TWI. The GRI study claims to have developed a technique which is sensitive to a range of manufactured flaws in polyethylene pipe, such as 1mm diameter end-drilled holes but, most importantly, is able to detect the presence of cold welds.

It is important to mention some of the major differences between the work undertaken at TWI and that at GRI. The GRI work uses an array of 18 transducers linked together in a ring, which fastens directly on to the circumference of the pipe to be inspected. Each transducer is angled to interrogate a particular region of the weld in the through–thickness direction. The pulse–echo response from each transducer is monitored automatically and a decision on joint quality is provided by the computer software. The reliability of the GRI system has been proven on polyethylene pipes less than 100mm in diameter and 12mm thick (9), but no reference is made to the suitability of the technique for inspecting pipes of larger diameter and thicker section. The GRI work is based on a pulse–echo technique and experience at TWI on using this technique to inspect pipes of thicker section (25mm) is questionable. TWI have concentrated their efforts on developing alternative ultrasonic inspection techniques, such as tandem and TOFD, suitable for inspecting welds in polyethylene pipe of thicker section.

3. RADIOGRAPHIC NDT

3.1. Background

The radiographic inspection of welded joints in metallic structures is well established. Exposure charts exist which enable the radiographer to select the X–ray energy and exposure necessary to produce a good quality radiograph of a particular thickness and type of metal. The radiographic inspection of plastics is less well established and similar exposure charts are unlikely to exist. In comparison to metals, plastics are much less absorbent of X–ray radiation and require the use of 'softer', lower energy, X–rays to achieve good quality results. To illustrate the point, 50mm of steel would typically be radiographed at an X–ray energy of 300kV, while an identical thickness of polyethylene, under approximately the same exposure conditions, only requires an X–ray energy of 16kV to produce the same density radiograph.

3.2. Work At TWI

TWI have pioneered the use of wire type image quality indicators (IQIs) made from polyethylene to the specifications of BS EN462–1 (10). The existence of such IQIs is a major achievement and significantly helps to overcome the problems of describing image quality of radiographs shot at low X–ray energy (<26kV).

A range of IQIs were manufactured from polyethylene (7). These included an ASME plaque (ASME V, Article 22), a British step wedge with holes (BS EN462–2:1994), and the aforementioned British wire type. The whole range in common use is illustrated in Fig.11. These were assessed and compared for their ability to provide a reliable measure of radiograph quality and sensitivity, and for their practical handling. All IQI types were able to achieve sensitivities better than 2%. The ASME type is small and easy to handle, however, a range of thickness plaques are required for different thickness testpieces. Also, spacers are required to cater for the additional thickness of the weld beads, and these are not easily bent to the pipe's curvature. The British wedge type had similar advantages and disadvantages. The wire type achieved the highest sensitivity (0.67% on 37mm of polyethylene), did not require the use of spacers and was able to cover a much wider range of material thicknesses.

The same programme of work (7) considered the effect of X–ray absorption through different grades of polyethylene. It was concluded that the very low absorption by polyethylene of X–ray radiation can vary significantly from one polyethylene type to another but that, for the range of polyethylene materials shown in Table 1, only two exposure charts are necessary to produce radiographs in the density range specified by BS 2600 (11). Figure 12 illustrates a typical exposure chart. These exposure charts have been used to produce prototype radiographic procedures for the inspection of butt fusion welds in polyethylene pipe (7,8). The procedures make use of two double-wall single image radiographic inspection techniques. When the X-ray source is in the plane of the weld (see Fig.13) the technique is referred to as the 'straight' technique, and the weld fusion face appears as a straight line on the radiograph. When the source is offset from the plane of the weld it is referred to as the 'throwing' technique and the weld fusion face appears as a curve on the radiograph. The straight technique was used as a primary method. The throwing technique was used on occasions to provide additional information regarding the shape and character of the flaw.

The prototype procedures discussed here, have been used to detect reliably a range of manufactured and natural flaws in polyethylene pipes including; dust contamination of the fusion face, planar discontinuities in the fusion zone (aluminium foil discs), lack of fusion and a thinning of the weld bead corresponding to the presence of a cold weld.

3.3. Comparison With Other Studies

In practice, X-ray radiography is used to supplement the visual inspection of larger diameter polyethylene pipe (3,4). The radiographic procedures developed by TWI and those in use at British Gas (12) both stipulate a low energy X-ray, double wall single image technique. British Gas has identified problems with existing IQIs and have sought to overcome the problem by developing their own ERS plastic penetrameter (12). TWI have also addressed this problem by developing polyethylene wire type IQIs in accordance with (10).

4. CONCLUSIONS

The main conclusions are based on the work undertaken at TWI on a range of polyethylene materials and pipes with diameters greater than 180mm and thicknesses greater than 12mm.

- Ultrasonic creeping waves can be used to inspect the fusion area immediately beneath the outer weld bead in polyethylene pipes.
- Ultrasonic tandem and TOFD techniques can be used to detect and image perpendicular planar flaws in butt fusion joints in polyethylene pipes.
- Ultrasonic techniques are currently unable to detect nominally cold welds.
- Radiographic intensities of between 16kV and 26kV are optimum when inspecting thicknesses of polyethylene pipe between 5mm and 50mm.
- With radiography it is possible to infer the presence of a cold weld from local radiographic density measurements.
- Polyethylene wire type IQIs have been proven to achieve radiographic sensitivities at least as good as polyethylene plaques and step wedges with holes, and have other practical handling advantages with regard to pipe inspection.

5. REFERENCES

1 Dodin M G: 'Welding mechanisms of plastics – a review'. J. Adhesion, 12 (1981).

2 Gas Research Institute: 'Quality assurance of heat fused polyethylene plastic pipe joints'. GRI 85/0284. Final report November 1983, June 1986.

3 Ewing L and Richardson W: 'Polyethylene gas pipe systems: An appraisal of joint design and construction methods'. British Gas report no. ERS EZ67, November 1980.

4 Ewing L and Maine L: 'The electrofusion of PE gas pipe systems in British Gas'. 1983, ERS report no. ERS E339.

5 Gas Research Institute: 'Inspection device for heat fused butt joints'. GRI Technology Profile, September 1987.

6 Edwards G R: 'The development of non-destructive test procedures for hot plate butt fusion welds in polyethylene'. TWI Members report no. 370/1988.

7 Georgiou G A and Macdonald I A: 'Ultrasonic and radiographic NDT of butt fusion joints in polyethylene'. TWI Members report no,. 465/1993.

8 Munns I J and Georgiou G A: 'Ultrasonic and radiographic NDT of butt fusion welded polyethylene pipes'. Draft TWI Members report, March 1995.

9 McClinton M: 'How to detect flaws in PE pipe butt fusion joints'. Pipe Line Industry, November 1986.

10 BS EN 462-1:1994: 'Non-destructive testing - Image quality of radiographs. Part 1: Image quality indicators (wire type) - Determination of image quality value'.

11 BS 2600: Part 1: 1983: 'Radiographic examination of fusion welded butt joints in steel. Methods for steel 2mm up to and including 50mm thick'.

12 Lumb R F, Bennett A and Ward C R: 'A review of NDT at British Gas Engineering Research Station'. BJNDT, September 1980, pp.217-225.

Table 1 Product specification of polyethylene materials examined

Product	Colour	Density (g/cm_3)	Application
Dowlex	White	0.937	Heating, installation, irrigation pipes
Finathene 3802 B	Black	0.948	Anticorrosive coatings, cable jackets
Eltex TU B 121	Black	0.958	Gas pipe, industrial fluid transportation
Eltex TU B 124	Dark blue	0.951	Water transportation (drinking)
*Finathene 3802	Light blue		Water transportation (drinking)
Finathene 3802 Y	Yellow	0.941	Gas distribution systems
Eltex TU B 125	Orange	0.951	Gas transportation

* Details not supplied by manufacturers

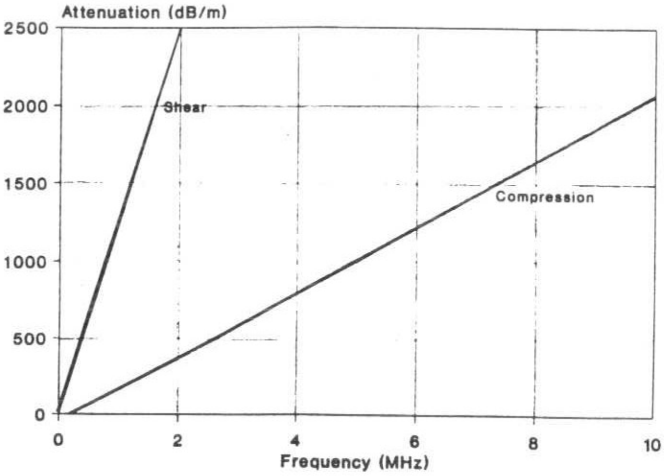

Fig.1 Attenuation of ultrasound through polyethylene (from (9)).

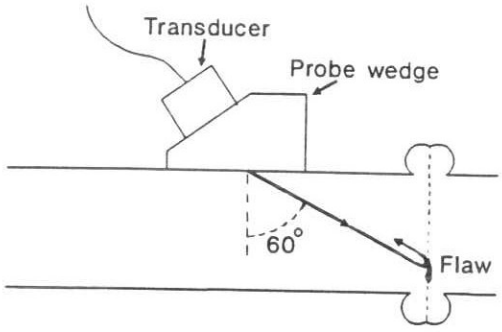

Fig.2 Probe configuration for pulse–echo compression wave techniques.

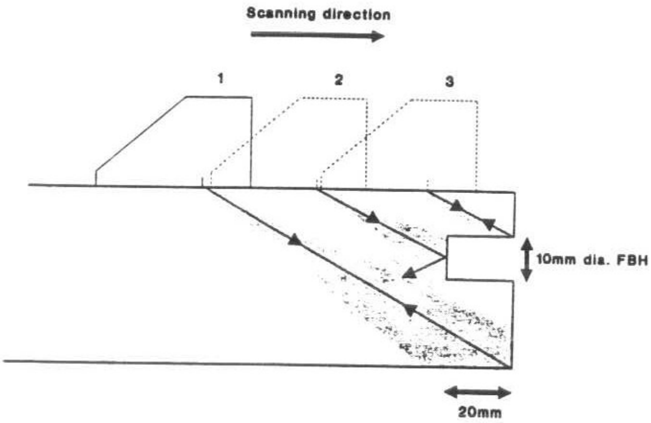

Fig.3 Pulse–echo detection of 10mm diameter flat bottomed hole.

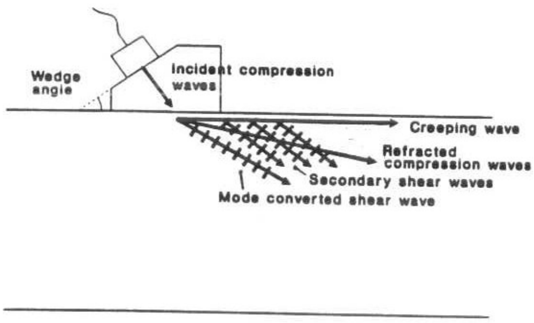

Fig.4 Ultrasonic creeping wave.

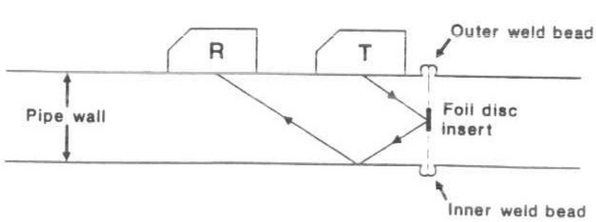

Fig.5 Probe configuration for tandem inspection.

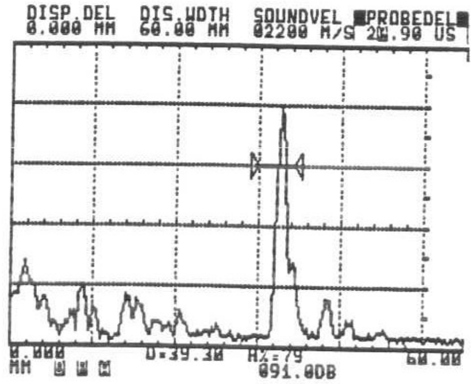

Fig.6 A–scan response from perpendicular reflector in a polyethylene pipe, inspected using the tandem technique.

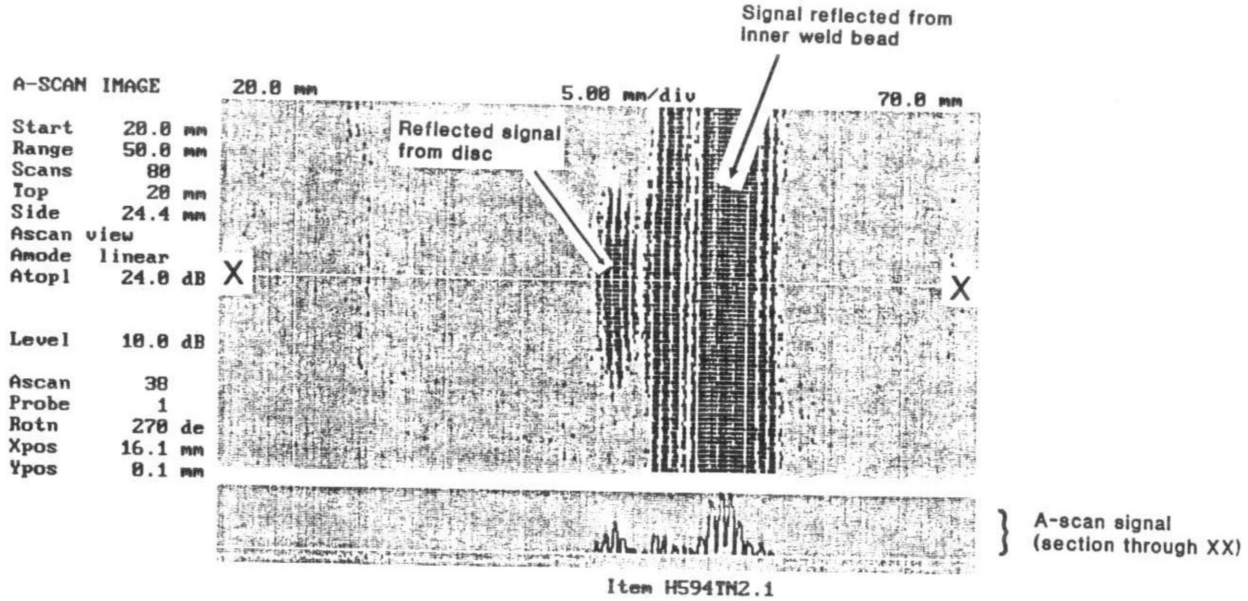

Fig.7 Composite A-scan image of 2mm diameter foil insert (scanned using the tandem technique).

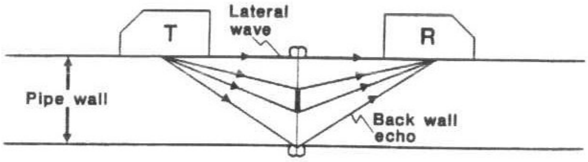

Fig.8 Probe configuration for time-of-flight diffraction (TOFD) inspection.

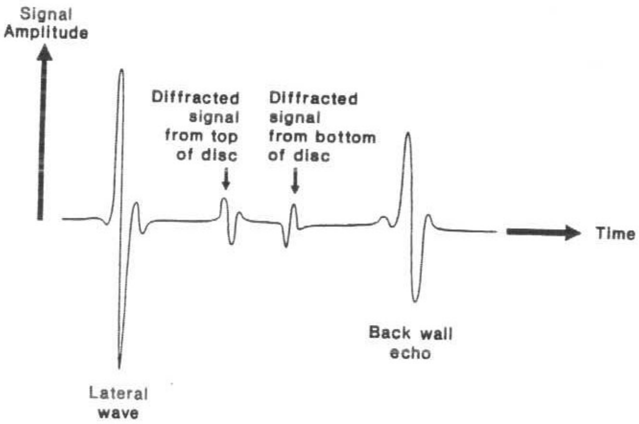

Fig.9 Typical A-scan response from perpendicular flaw inspected using TOFD technique.

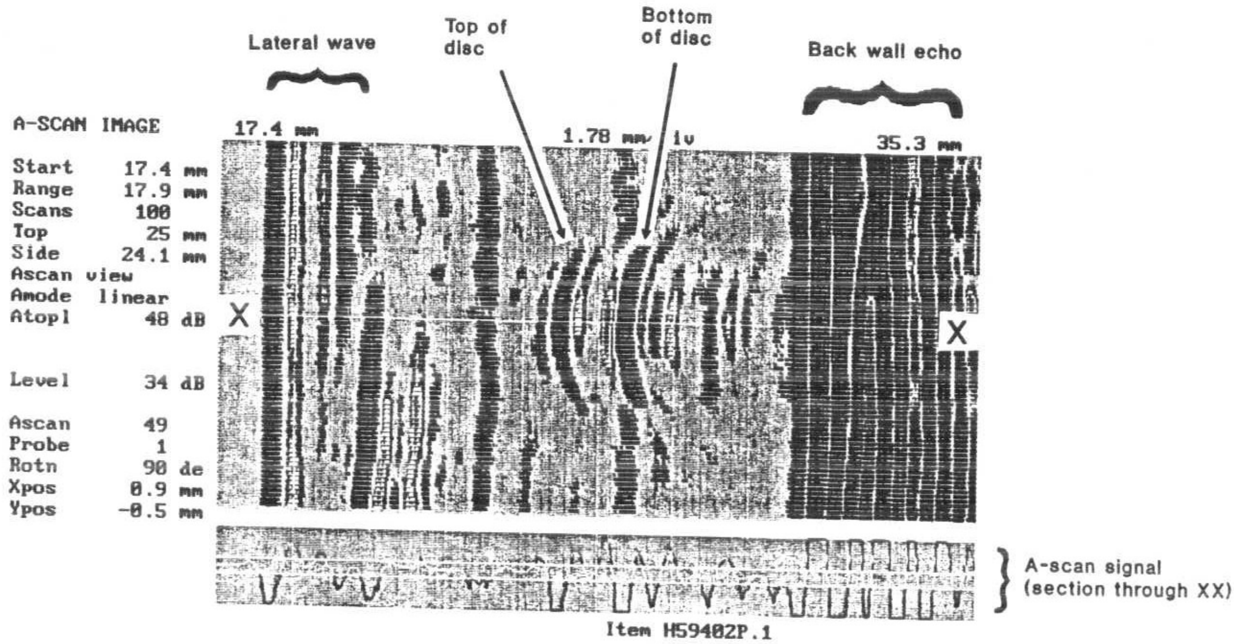

Fig.10 TOFD image of 2mm diameter foil insert.

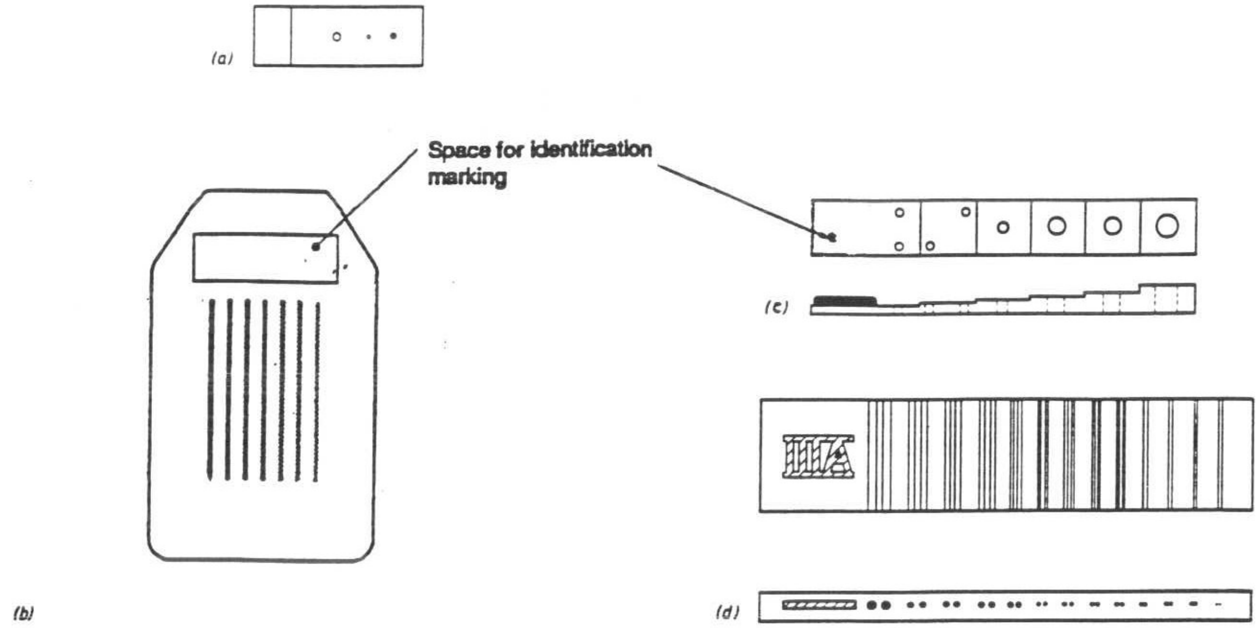

Fig.11 Various image quality indicators in common use:

a) ASME plaques with holes (ASME (V), Article 22 1989);

b) European wire type (BS EN 462-1 1994);

c) European step wedge with holes (BS EN 462-2 1994);

d) European duplex wire type (BS EN 462-5: To be published).

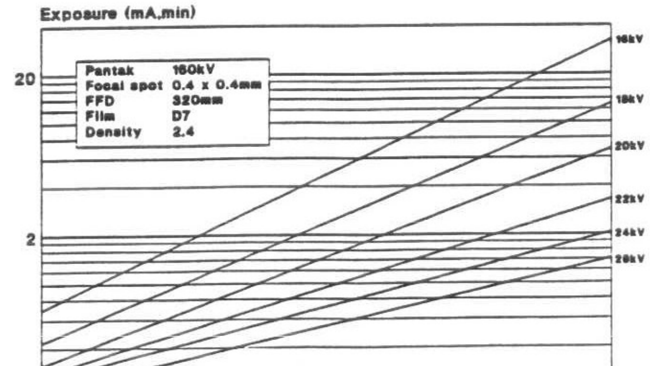

Fig.12 Exposure chart for polyethylene materials; Finathene 3802, Finathene 3802Y, Eltex TUB125.

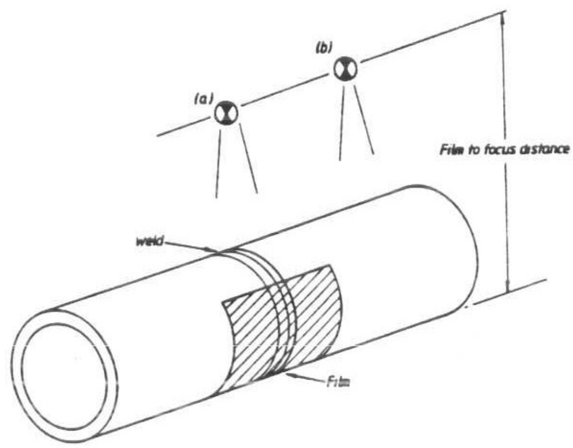

Fig.13 Arrangement for the radiographic testing of polyethylene pipes:

a) Straight technique;

b) Throwing technique.