Manual ultrasonic inspection of thin metal welds

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Abstract

BS EN ISO 17640 contains standard ultrasonic inspection techniques for ferritic steel welds. The techniques in general include scans with different angles from either side of the weld.

The minimum thickness noted in this standard is 8mm. However there are an increasing number of applications involving smaller thicknesses (e.g., containments) and these cannot strictly be inspected by these methods.

This paper describes a series of experiments of conventional ultrasonic and phased array testing on thin butt welded sections with simulated flaws using the procedures described in BS EN ISO 17640 and BS EN 13588 but allowing the use of high frequency and small probes easily available in the market. The results show that the procedures of BS EN ISO 17640 can be adapted in this way for detection scanning and sizing for thicknesses down to 4mm.

1. Introduction

Thin walled vessels and pipes are increasingly required to be tested non-destructively when they are used to contain substances that can damage a local environment. Examples include some designs of nuclear waste storage vessels, nuclear processing plant, low pressure oil pipes and other fuel systems. Different welding methods for stainless and duplex steel are also under investigation for these areas. Equally there is a need to determine the actual size of a remaining ligament as this has a significant effect on fracture mechanics analyses.

Conventional ultrasonic testing (according to BS EN ISO 17640) (1) limits thicknesses that can be examined to less than 8mm. Similarly, the draft phased array standard BS EN 13588 (2) goes down to 6mm. Smaller thicknesses are frequently inspected by radiography, this cannot normally give the through thickness information required for fracture mechanics analyses. There is a requirement for non-destructive test methods in the smaller thickness ranges. Bird (3) reported an experiment comparing manual UT and phased array with thicknesses down to 6mm with good results for good operators using both techniques. New or different technologies, such as eddy current arrays or high frequency ultrasonic phased arrays may be needed for smaller thicknesses. A special case where ultrasonic methods have been developed for a thin wall has been given by Bird et al.[4] Some work on eddy currents is reported in this conference [5]. However, from the manufacturers' point of view it is convenient to refer to a standard when requesting items to be made, and to know what the actual limitations are of the current UT methods.

The main purpose of this paper is therefore to examine whether the normal manual ultrasonics procedures used in the standard can be applied with minimum modification to inspect arc welds in thin sections and whether phased array techniques can improve on this. The reason that the 8mm limit applies in most cases is that it is not possible with thinner sections to apply standard UT probes because they cannot approach the weld close enough nor can the beam be easily defined. The modification to the standard procedure adopted is to allow the use of high frequency 10MHz angled beam probes.

Phased array technology for weld inspection is becoming mature, with a draft standard for weld inspection BS EN 13588[6], and this standard and technique were also adopted.

2. Test Samples

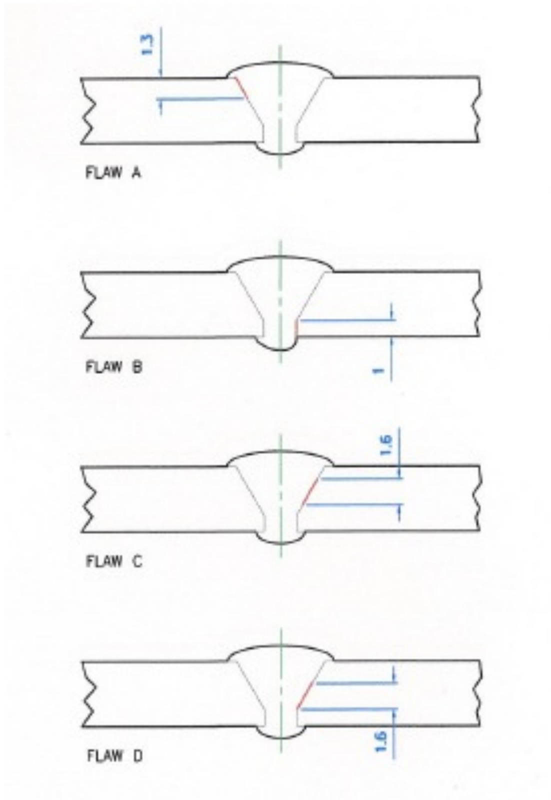
The test samples specified consisted of plates 3, 4 and 5mm thick in ferritic and stainless steel, each containing 4 flaws. Figure 1 shows the position of these in the 4mm plate, the others were similar. The weld has a 60° preparation and there are three embedded lack of fusion flaws at the weld cap and one root lack of fusion flaw in each plate.

The flaws have been made with intended dimensions and those supplied by the manufacturer, and these are used in the analysis. However, it should be noted that manufacture and measurement of such flaws has some uncertainties so the results obtained must be viewed with this in mind.

A radiographic inspection of these welds was performed in order to verify the length of these flaws (Table1). As expected, the radiography was not able to reliably detect lack of side wall fusion.

Table 1. Results of radiographic inspection of welds

Carbon steel	3mm plate				4mm plate				5mm plate			
Flaws	A	B	C	D	A	B	C	D	A	B	C	D
Detected?	N	Y	N	N	N	Y	N	Y	N	Y	Y	N
Length	\	12	\	\	\	12		3	\	12	15	\
Stainless steel	3mm plate				4mm plate				5mm plate			
Flaws	A	B	C	D	A	B	C	D	A	B	C	D
Detected?	Y	Y	N	N	N	Y	N	N	N	Y	N	Y
Length	7	12	\	\	\	12	\	\	\	12	\	15



Length: 10mm

Length: 10mm

Length: 5mm

Length: 15mm

Figure 1 Position of the simulated flaws in the welds

3. Manual UT

3.1. Standard Requirements

The international standard for the manual ultrasonic testing of fusion-welded joints in metallic material BS EN 1714 has been withdrawn in 2010 and replaced by BS EN ISO 17640:2010. This standard is specified to be applied for the testing of fusion welded joints in metallic material of thickness greater than or equal to 8mm and where both the welded parent material are ferritic.

The probe frequency specified in this standard are to be within the range 2 and 5MHz. However, the standard allows the use of higher frequency for improving range resolution if necessary for acceptance criteria based on characterisation of indications. It is also required that at least one angle beam shall be normal or nearly normal to the weld fusion face.

The testing volume is to include the weld body and at least 10mm on each side of the weld to cover the heat affected zone (HAZ).

The standard is open to several techniques to set the sensitivity. One of the techniques specified in the standard allows the use of reference from a distance-amplitude curve (DAC) for side-drilled holes of diameter 3mm. Reference can also be made on notches of 1mm wide with a depth of 1mm only for the thickness range between 8 and 15mm and for angle beam angles larger than 70°.

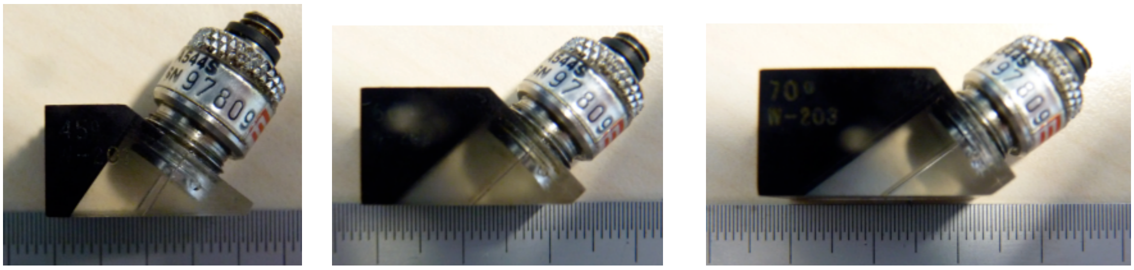
BS EN 17640:2010 refers to BS IS 11666:2010 for the definition of the evaluation level above which an indication will be investigated. For an acceptance level 2, which corresponds to the most common quality level, the level of evaluation is set at -14dB below reference level.

3.2. Equipment and Procedure

The equipment used to carry out the manual testing was a Sonatest Masterscan 380M with 10MHz transducers 45, 60 and 70°, 6.35mm crystal diameter. The transducers used for the testing are shown in Figure 2. The footprints of these transducers were between 20 to 30mm and enabled the probe index point to be close to the weld cap and hence reduce the number of ultrasonic skips on the back wall.

As has been mentioned above the procedures of BS17604 together with an allowance for the use of high frequency probes has been used. DAC was used relative to a 3mm SDHs.

No attempt was made to have blind trials in this case. The operator had some knowledge of the flaw location and was seeking to identify and use the indication.



a) b) c)

Figure 2 Pictures of ultrasonic transducer Parametrics A544S 10 by 0.25
a) 45° wedge
b) 60° wedge
c) 70° wedge

4. Phased Array UT

4.1. Standard Requirements

The use of (semi-)automated phased array technology for the inspection of welds is covered by the draft international standard BS EN ISO 13588 which is currently open to public comments. This standard specifies the application of the phased array technology for fusion welded joints in metallic materials equal to and above 6mm thickness.

This standard is open to the use of linear scan (E-scan) and sector scan (S-scan) at a fixed distance to the weld to generate multi angle beam from a single position of the transducer. In addition, this standard specifies the use of scanning mechanism that allows data collection with a scanning increment of no more than 1mm for component thicknesses up to 10mm.

It is also required to perform prior testing sensitivity setting for each beam and focal point generated by the phased array probe. The use of angle corrected gain (ACG) and time corrected gain (TCG) shall be used to display the signals for all beam angles and all distances with the same amplitude. The standard provides recommendation on the type, size and positions of reference reflector to be used for the sensitivity settings. For a thickness between 6 and 25mm, a notch of 1mm deep or a 2.5mm diameter SDH can be used.

In addition, there is no specification in this standard regarding a set level for assessment of indication. This is based in accordance with specified acceptance level and acceptance level applied.

4.2. Techniques

The samples were inspected with ultrasonic phased array using the off the shelve transducer 10L16 SA00 N60S manufactured by Olympus as shown in Figure 3. This transducer generates shear waves at 10MHz using 16 elements. This transducer is traditionally used for aerospace applications and presents the advantages to have a relatively foot print (21mm) which allow to come close to the weld cap.

The weld root and fusion face were inspected using a sector scan generating ultrasonic beams from 45 to 75° with an angular resolution of 0.3° and three linear scans at 45, 60 and 70°. The same delay laws were used for 5, 4 and 3mm thick plates. The ultrasonic beams were focussed at different depths in order to take into account the multiple skipping on the back wall for different beam angles and plate thickness.

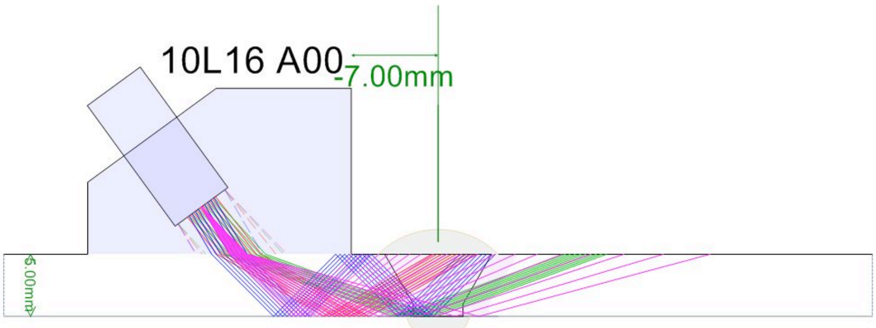
The welds were examined from both sides and at two index offsets from the centre of the weld in order to cover the weld fusion face at different angle of incidence. The index offsets were different for each thickness. Figure 4 shows the ray tracing of the beams generated by the sector and linear scans for a weld 5mm thick and at the two index position from the weld centre. The aim was to choose the right index offset in order to ensure that the weld fusion face, cap and root were covered by at least two different angles.

As required in most codes and standards for phased array testing, the wedge attenuation and delay compensation was carried out using the 25mm radius of the V2 calibration block in both carbon and stainless steel. For each delay law, an ACG was set based on 3mm SDH at a depth of 10mm in both carbon and stainless steel.

A TCG was applied on each delay law in order to compensate the attenuation loss throughout the range of the sound path. The TCG curves were generated using a series of 3mm diameter SDH at a depth of 5, 10 and 20mm. The plates were then scanned using a sensitivity set at TCG + 6dB and TCG +12dB. The sensitivity level was also checked on notch with a depth equal to 10% of the thickness of the plate tested for the welds in stainless steel. It was noted that the sensitivity on the notches was equivalent to the sensitivity set on the SDHs within 10% FSH.

Data were recorded using the Omniscan MX with a string encoder at a scanning resolution of 0.5mm.

Figure 3 Picture of phased array transducer 10L16 SA00 N60S manufactured by Olympus and used in the study,



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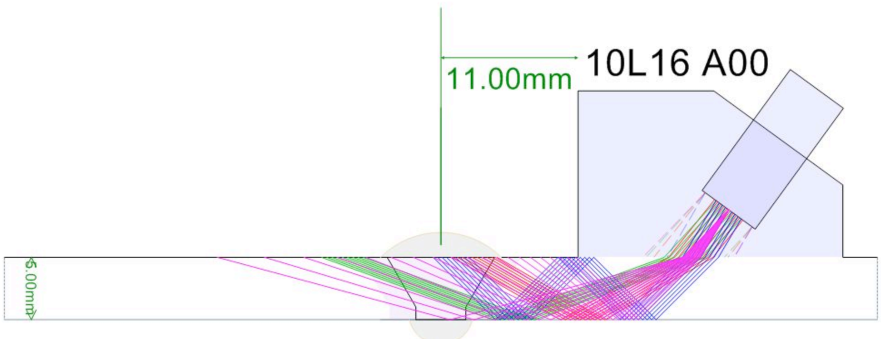


b)

Figure 4 Scan plan for the inspection of the 5mm thick plate (green lines = 70° beam, red lines = 60°, blue line = 45°, pink line = sector scan)

a) Index offset at 7mm

b) Index offset at 11mm

5. Modelling

In order to evaluate the length sizing resolution or lateral resolution of the inspection and compare beam profile between the conventional and phased array testing, the ultrasonic beams generated were modelled using the modelling platform CIVA v10.1.

The ultrasonic beam size was extracted from the cross section of the ultrasonic beam sound pressure at a depth corresponding to the range where the weld is examined. Figure 5a shows the model configuration for a beam generated by the phased array transducer at 45° focussed at 7.5mm in depth and the ultrasonic beam modelled in 3D. The ultrasonic beam profile was also displayed along three cross section planes (X;Y), (Y;Z) and (X;Z) as shown in Figure 5b,5c and 5d. The maximum energy is displayed in blue. The projected 6dB beam width along the Y and X axis was exacted to evaluate the lateral resolution of the inspections and compare the performance of the techniques for through wall sizing.

Table 2 summarises the beam width along the Y axis of the ultrasonic beams at 45, 60 and 70° generated by the phased array techniques using sector and linear scans and by the conventional method at the range for which the welds in the 3, 4 5mm plate are examined. For the phased array techniques the beam size predicted was averaged for the stand-offs at 7 and 11mm.

Along the 45° beam, and for the three thicknesses, the sector scan generates a smaller beam of about 1mm smaller compared with the linear scan in the conventional method. Along the 60° beam, the sector and linear scans are equivalent but there is a slight increase within 1mm of the beam width for the conventional method. Along the 70° beam, the phased array using the linear technique generates a smaller beam in comparison with the sectorial technique and the conventional method. In overall, the linear techniques and conventional method provide a more regular beam width over the three angle beams. The lateral resolution with a beam generated with the sectorial technique is better for the small angle beam but increase significantly at higher angle.

Overall, the length sizing resolution generated with the methods used in this study is anticipated to be in average equal to 3mm.

Table 2 Prediction of the 6dB ultrasonic beam width along the Y axis generated by phased array (PA) and conventional techniques at 45, 60 and 70 angle beams:

Plate thickness	Techniques	45deg	60deg	70deg
5mm	PA Secto	2.3	2.8	4.3
	PA Linear	3.3	2.8	3.3
	Conv.	3.4	3.7	3.8
4mm	PA Secto	2.1	2.1	4
	PA Linear	3.2	2.8	2.1
	Conv.	3.4	3.7	3.8
3mm	PA Secto	1.8	1.8	4
	PA Linear	3.1	2	2.1
	Conv	3.4	3.7	3.8

Table 3 summarises the beam width along the X axis of ultrasonic beams at 45, 60 and 70° generated by the phased array techniques using sectorial scan and linear scan and by the conventional method at the range for which the welds in the 3, 4 and 5mm plates are examined. For the phased array techniques, the beam size predicted was averaged for the stand-off at 7 and 11mm. Through wall sizing resolution is predicted by evaluating the beam dimension in the X/Z plane. The beam width given in Table 3 with modelling is the projected dimension of the beam width along the X axis. The projection of the beam width along X axis was compared for all inspection techniques in order to evaluate the sizing capability.

For the weld in the 5mm plate, the through wall resolution are equivalent for the three techniques. As expected, the beam width increases with the angle of propagation.

For the welds in the 4mm and 3mm plates, beam width for through wall resolution are equivalent along the 45° beam for the three techniques. Along the 60° beam, there is a significant difference in the beam width between the sectorial scan and the linear scan with the sectorial scan generating a smaller beam. The conventional testing provides equivalent performance as the linear scans. Along the 70°, there is a significant increase in the beam width for the three techniques. The largest increase and the largest beam width are generated by the sectorial scan.

In conclusion, the sectorial scan provides a better beam characteristic at low angle compare with the linear and conventional methods. However the performance with the sector scan decreased significantly and become less beneficial than the linear and conventional methods at high angle.

Table 3 Prediction of the 6dB ultrasonic beam width along the X axis generated by phased array (PA) and conventional (Conv.) techniques at 45, 60 and 70 angle beams:

Plate thickness	Technique	45deg	60deg	70deg
5mm	PA Secto	2.7	3.9	7.8
	PA Linear	3.2	3.8	5.8
	Conv.	3.2	4.4	7.1
4mm	PA Secto	2.6	2.6	9.3
	PA Linear	3.3	4	6.1
	Conv.	3.2	4.4	7.1
3mm	PA Secto	2.6	2.6	9.3
	PA Linear	3.4	4.2	6.1
	Conv	3.2	4.4	7.1

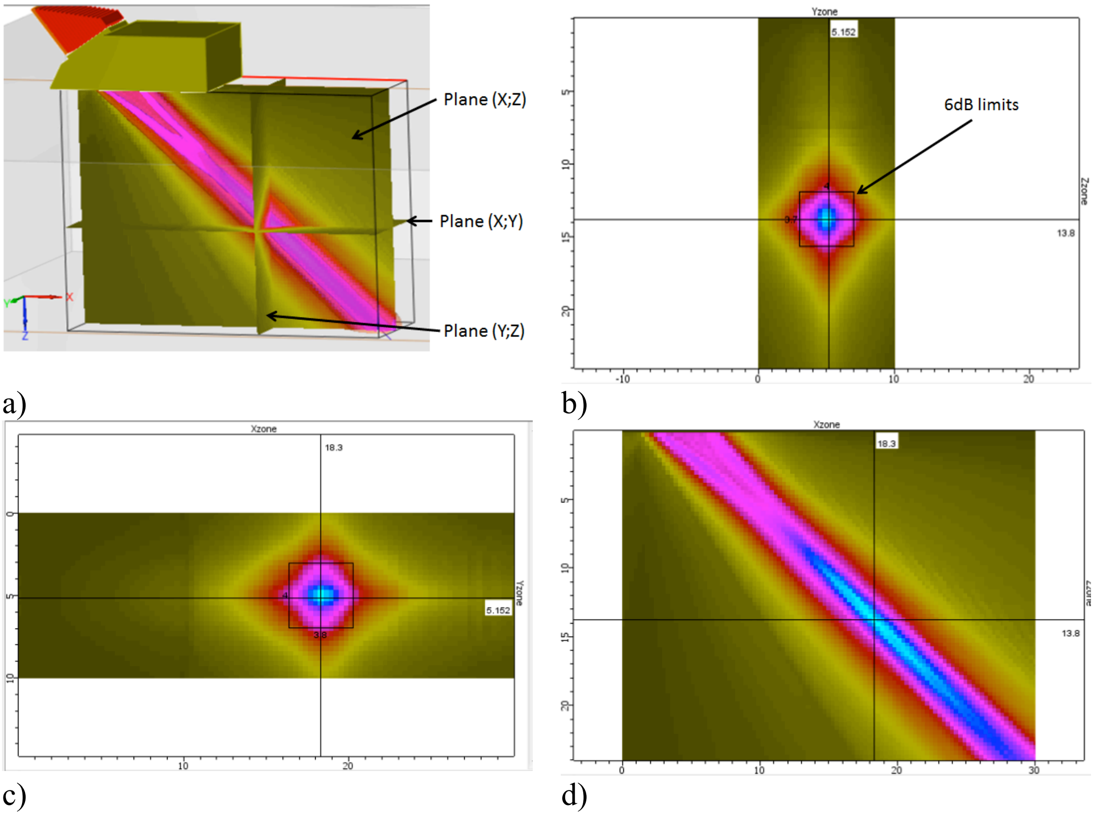


Figure 5 Prediction of the ultrasonic beam profile generated at 45° with the phased array transducer

a) 3D modelling
b) Beam cross section along (Y;Z) plane
c) Beam cross section along (X;Y) plane
d) Beam cross section along (X;Z) plane

6. Results

6.1. Manual UT

Tables 4 and 5 summarise the inspection results of the conventional ultrasonic testing on the weld sample for carbon steel and stainless steel respectively. Some of the flaws were not detected either because no signal has been discriminated from the noise or because the signal amplitude was below the -14dB evaluation level but identified from the noise. The latest case is identified in the tables when the amplitude is <14.

Most of the flaws in the 5 and 4mm thick plates were detected. Not all the flaws in the 3mm welds were detected. It can be noted that the level of detection of flaws in carbon steel and stainless steel are equivalent. For these small thicknesses, the anisotropic and attenuative property of the stainless steel does not seem to have a particular effect on the performance of the ultrasonic testing.

It was not possible to measure the through wall size of the flaws. The operator was not able to identify the edge of the flaw either with the 6dB drop technique or max amplitude. The spatial and temporal resolution was not good enough for through wall sizing.

Table 4 Inspection results for the conventional ultrasonic testing of welds in carbon steel:

	3mm plate				4mm plate				5mm plate			
Flaws	A	B	C	D	A	B	C	D	A	B	C	D
Detected?	Y	Y	N	N	Y	Y	N	Y	N	Y	Y	Y
Beam angle	70	70	70	/	45	45	70	60	45	70	45	45
dB from DAC	-12	-14	<14	/	-4	-12	<14	-8	<14	-5	-8	-7
Ligament	/	/	/	/	/	/	/	/	/	/	/	/
Through wall	/	/	/	/	/	/	/	/	/	/	/	/
Length	4	5	/	/	6	18	/	3	/	16	6	16

Table 5 Inspection result for the conventional ultrasonic testing of welds in stainless steel

	3mm plate				4mm plate				5mm plate			
Flaws	A	B	C	D	A	B	C	D	A	B	C	D
Detected?	N	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y
Beam angle	/	45	/	60	60	70	/	45	70	60	60	70
dB from DAC	/	-14	/	-7	-2	-11	/	1.5	0.5	-5	4	4
Ligament	/	/	/	/	/	/	/	/	/	/	/	/
Through wall	/	/	/	/	/	/	/	/	/	/	/	/
Length	/	3	/	6	11	5	/	5	12	8	7	7

6.2. Phased Array

Tables 6 and 7 summarise the inspection results of the phased array testing on the weld samples for respectively carbon steel and stainless steel.

Figures 6 to 8 show some example of the plane view (C-scan) of the data collected with the phased array from both side of the weld (skew 270° and 90°). The blue axis provides the position and length of the flaws. On the green axis the position of the flaws with regard to the weld centreline (at zero) is shown.

The phased array inspection provided a good detection for the welds 5 and 4 mm thick. From the plane view, in the 5mm thick weld in carbon steel and in the 4mm thick weld in stainless steel, the four flaws were clearly identified from the data. The data on the stainless steel was fairly clear and did not show a strong signal from the root as shown in Figure 7.

In the 3mm thick weld in carbon steel and stainless steel (Figure 8), strong indications are noted along the weld coming from multi-reflection from the cap and the root which mask the reflection from the flaws. In addition, signals from the flaws in the welds 3mm thick are not expected to be high amplitude. Gain was then increased which made the inspection on the stainless steel worst as the noise level from the weld were higher than the flaws signals.

Figure 9 shows the data from the flaw B in the 5mm thick weld in stainless steel. The flaw B is intended to be vertical lying at the weld root. The data shows effectively an indication from the corner and the tip of the flaws from which the flaw through wall height was measured.

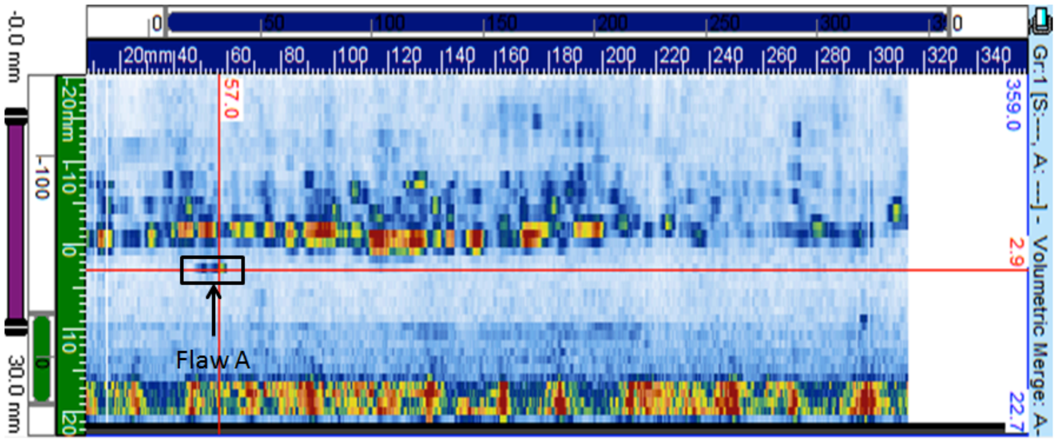
Flaw C shown in Figure 10 for the 5mm thick weld in stainless steel is lying along the weld fusion face, specular to the ultrasonic beam. Assuming that the flaw was bigger than the beam width, the through wall sizing was possible using 6dB drop on either side of the flaw edge.

Table 6 Inspection result for the phased array testing of welds in carbon steel

	3mm plate				4mm plate				5mm plate			
Flaws	A	B	C	D	A	B	C	D	A	B	C	D
Detected ?	Y	N	N	N	Y	N	Y	Y	Y	Y	Y	Y
Technique	Sector	/	/	/	Sector	/	Sector	Linear	Linear	Linear	Linear	Linear
Beam angle	48	/	/	/	48	/	60	60	45	70	45	45
Amplitude	30%	/	/	/	80%	/	84% (3dB)	52%	76%	75%	>100 %	>100 %
Ligament	0	/	/	/	-0.6	/	-2.5	-2.2	-0.3	-3.3	-1.8	-1
Through wall	0.6	/	/	/	1.6	/	2.0	2.0	1.2	1.7	0.3	2.8
Length	9	/	/	/	11.5	/	5	6	11.5	13.5	6	15

Table 7 Inspection result for the phased array testing of welds in stainless steel:

	3mm plate				4mm plate				5mm plate			
Flaws	A	B	C	D	A	B	C	D	A	B	C	D
Detected ?	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
Technique	/	/	/	Sector	Sector	Sector	Sector	Sector	Sector	Sector	Sector	Sector
Beam angle	/	/	/	65	51	76	50	70	49	53	52	52
Amplitude	/	/	/	>100 %	55%	70%	100%	55% (3dB)	80% (3dB)	41%	>100 %	>100 %
Ligament	/	/	/	1.4	-1	-2.9	-1.7	-1.1	-0.3	-3.2	-1.5	-3.1
Through wall	/	/	/	1.4	1.6	1.1	1.7	2.8	1.7	0.8	2.8	3.0
Length	/	/	/	19	4	8.5	8.5	8	11	10	10	17



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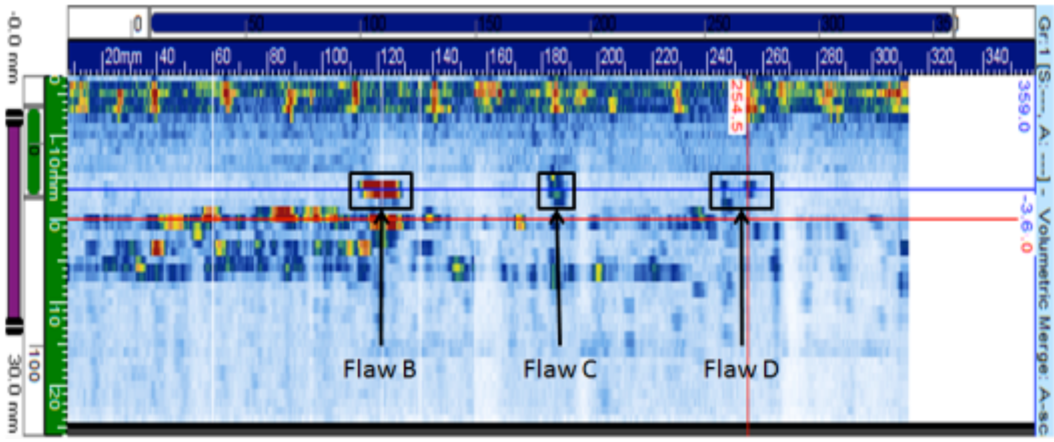

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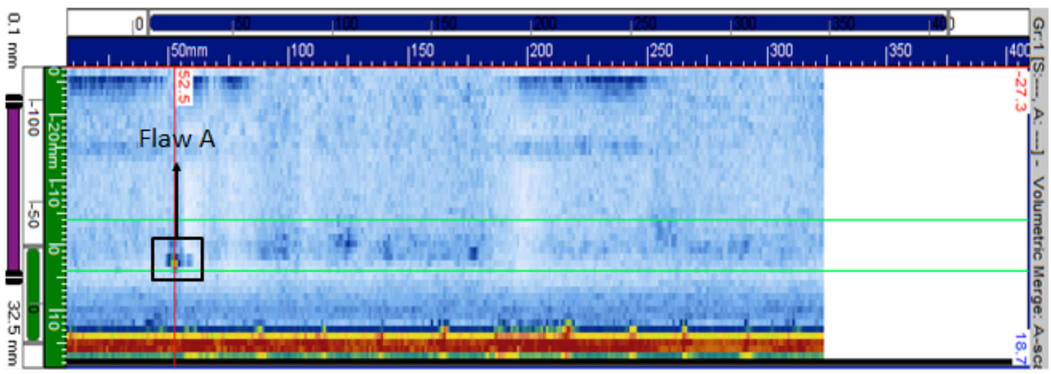
Figure 6 Plane view of the data collected with phased array on the 5mm plate in carbon steel at sensitivity TCG +12dB from

a) sector scan at 11mm stand off at skew 270°

b) sector scan at 7mm stand off at skew 90°



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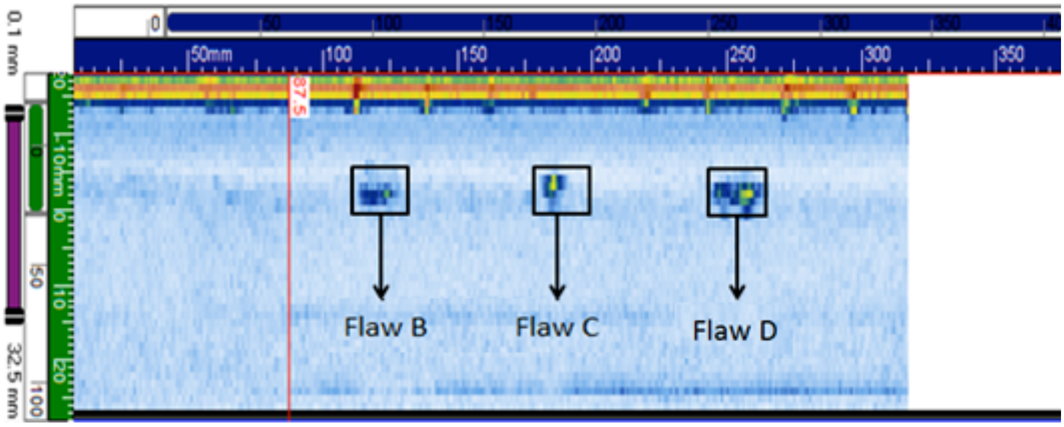
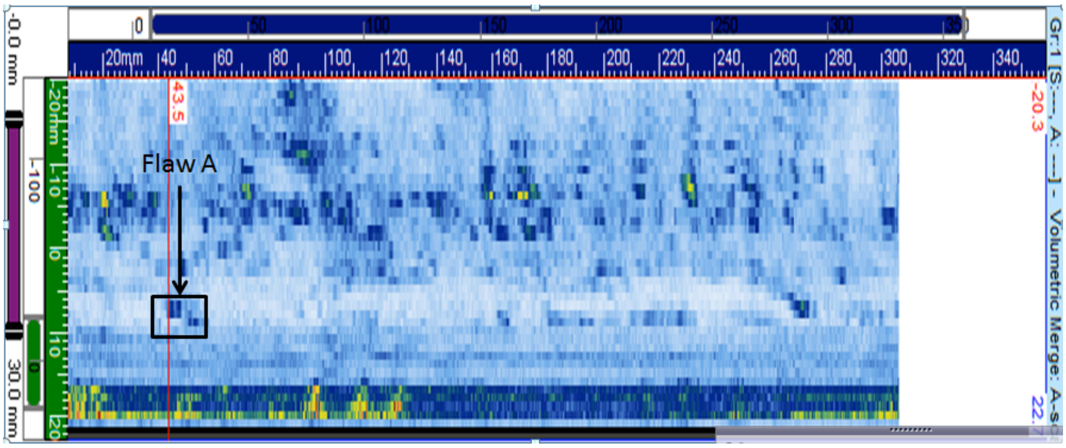


b)

Figure 7 Plane view of the data collected with phased array on the 4mm plate in stainless steel at sensitivity from

a) sector scan at 7mm stand off, TCG +3dB, at skew 270°

b) sector scan at 7mm stand off, TCG +6dB, at skew 90°



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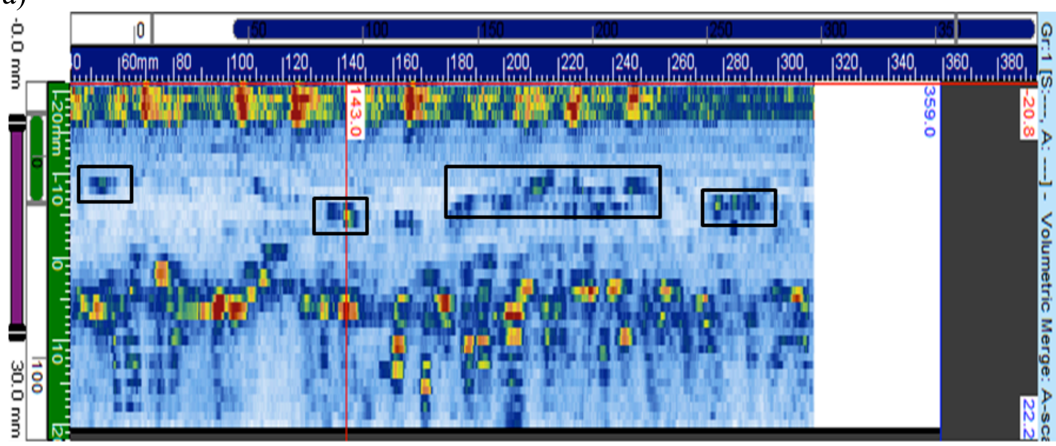
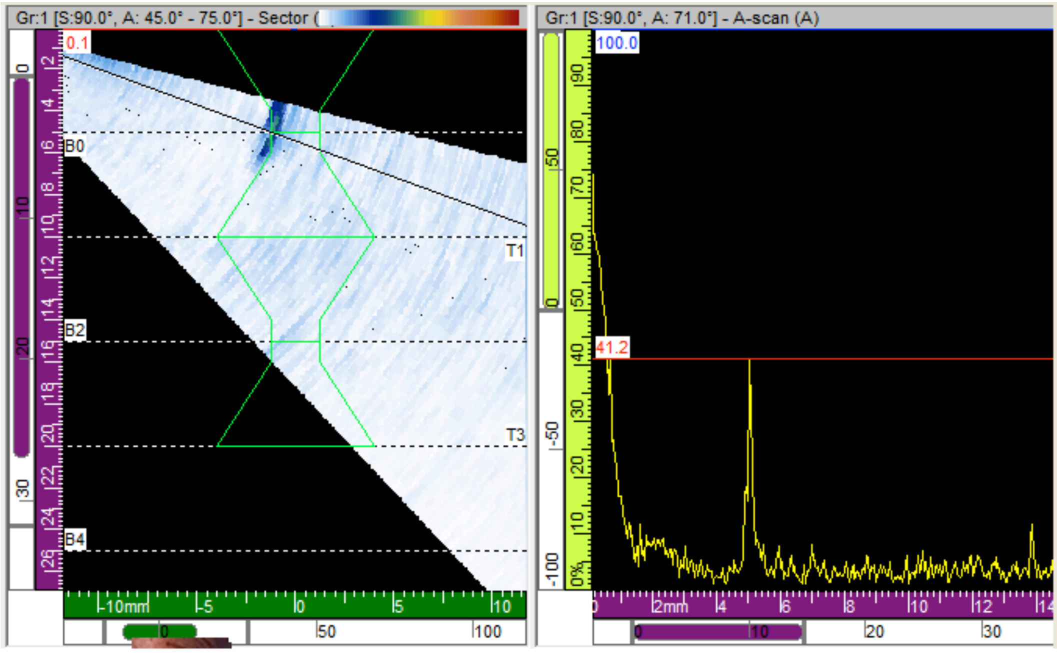


b)

Figure 8 Plane view of the data collected with phased array on the 3mm plate in carbon steel at sensitivity from

a) sector scan at 11mm stand off, TCG +12dB, at skew 270°

b) sector scan at 11mm stand off, TCG +12dB, at skew 90°



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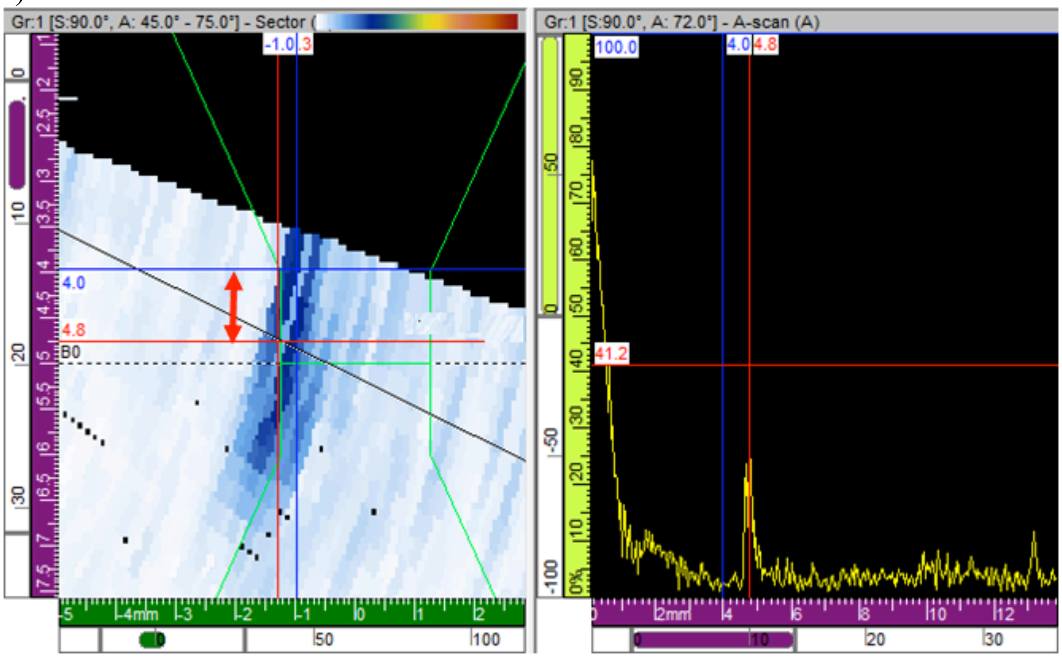

b)

Figure 9 Flaw B phased array data on sample 5mm in stainless steel

a) sector scan, stand-off 7mm, 6dB, skew 90°

b) detail of Flaw B, sector scan, stand-off 7mm, 6dB, skew 90°

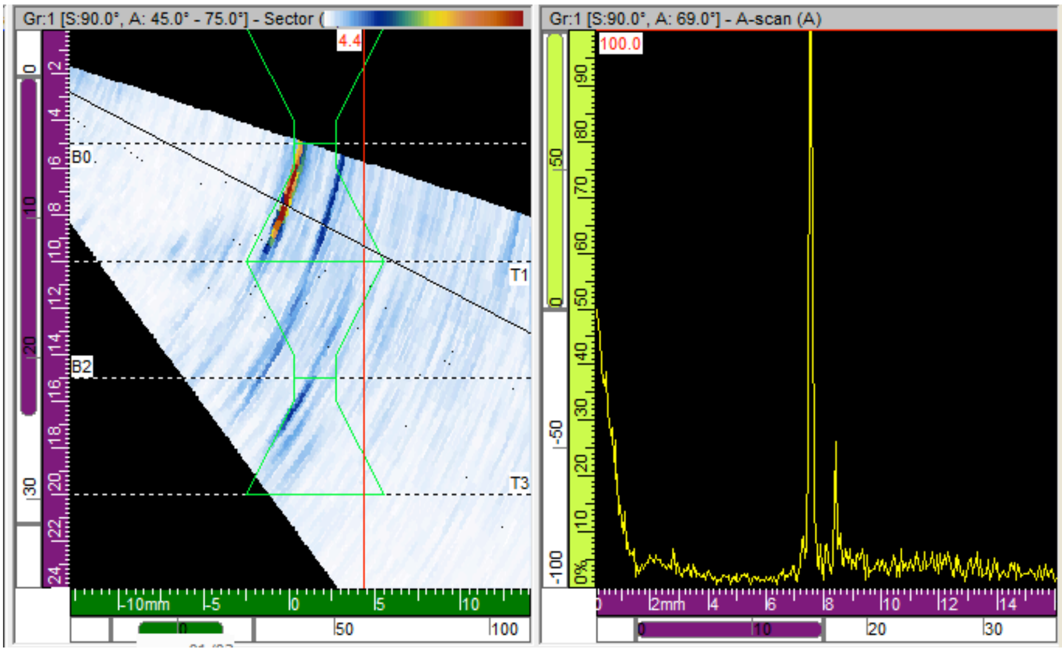

Figure 10 Flaw C phased array data on sample 5mm in stainless steel , sector scan, stand-off 11mm, 3dB, skew 90°

7. Discussion

It can be noted that the level of detection between the conventional method and phased array techniques is similar for the plate 4 and 5mm. For the 3mm plate, the conventional method gives detection of more flaws. This could be because in conventional testing the operator can skew the probe and hence discriminate the signal from a flaw to other geometry features such the root and geometry which are very close together in time for weld in small thickness.

Phased array testing provides, by displaying the data in plane and cross section views, the advantage to ease the interpretation of the signals and hence allows in some cases through wall sizing using tip diffraction for vertical flaw and specular reflection for flaw such as LOF. In addition, length sizing seems to be closer with phased array to the intended flaw size and also the result from the radiography.

8. Conclusions

1. BS EN standards for the use of conventional ultrasonic and phased array testing for welds is today limited for the examination of thickness larger than 8mm for the conventional method and 6mm for the phased array. From this study, it has been shown that this standard could be extended to weld larger than 4mm thick in the condition that a small foot print and high frequency transducer is used (higher than 10MHz) and the sensitivity settings is set on reference target representative to the size of flaws to be found in small thickness ie use of small diameter SDHs or notches.

2. The phased array method has the advantage of a display which gives easier interpretation of signals and hence better sizing and characterisation of flaws. However, at the smallest thickness, it has been shown that allowing the probe to be moved freely in all direction along the weld as used with the conventional testing helped detection of flaws in comparison with the rigid scan from a fixed distance from the weld used with phased array. Therefore, for this thickness below 4mm, a free manual scan using phased array techniques could be recommended for the detection of flaws. This could then be followed by encoded scans in the area presented indications to be investigated.

Acknowledgements

The work was funded by TWI's Core Research Programme. Full reports are available to member companies of TWI.

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