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Non-Destructive Inspection of Components with Irregular Surfaces using a Conformable Ultrasonic Phased Array

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ABSTRACT

A conformable phased array device is being developed that allows reliable ultrasonic inspection of components with irregular surfaces. The device uses a standard linear phased array transducer, which is coupled to the surface under test by a water path, encapsulated by a low loss, synthetic rubber membrane. A comparison of results obtained using conventional ultrasonic techniques and the conformable phased array device is given. These results demonstrate a number of potential improvements that are achievable when using the conformable phased array device.

INTRODUCTION

When using conventional ultrasonic NDE techniques it is not always possible to achieve 100% test coverage of welded pipe-work without the removal of the weld cap. Weld cap removal is an expensive, time-consuming task that can compromise the integrity of safety critical pipe-work. If the weld cap is left in place then any mismatch between the surface profile under test and the base of the solid wedge, used to refract the ultrasonic beam into the test piece, will produce an irregular coupling layer resulting in a loss of inspection performance. A cost effective solution that we have chosen [1] is to couple a standard phased array to the surface under test via a water path which is made more convenient by encapsulating the fluid with a conformable synthetic rubber membrane. A single device is used for surface profile measurement (required for updating of delay laws) and inspection, allowing rapid scanning of components with irregular surfaces without the need for multiple angled probes and time consuming mechanical scanning.

PROTOTYPE MEMBRANE COUPLED PHASED ARRAY DEVICE

Figure 1 shows a photograph of the membrane device that incorporates a standard linear 2 MHz, 80 element, 1.25mm pitch phased array probe from Imasonic France [2]. The phased array was angled at 12º (for 65º longitudinal waves in stainless steel). The original design [1] used a constant volume of fluid whereas the latest design allows a constant pressure configuration with the use of a header tank, where a head of 100mm to 150mm of water proves adequate for the membrane to conform over the irregular surfaces of interest such as weld caps. The number of faces that require a watertight seal has been minimised by machining the device body out of one block of material.

The membrane material used is a low loss castable polyurethane rubber, with an acoustic impedance similar to water, which has been developed with the help of Rolls-Royce, Derby, UK. Future membrane designs will utilise the rubber castability to assist the application of couplant between the membrane and surface under test. The device housing has been designed to allow the membrane to be changed within five minutes should this prove necessary.

When testing above an irregular surface profile the use of delay laws computed for a plane surface may lead to beam splitting and loss of the original focal point [3]. The inspection performance can be recovered with the application of updated delay laws requiring knowledge of the surface profile under test. This could be measured prior to testing by some mechanical technique. We have chosen a more convenient method where the phased array incorporated in the membrane device is utilised to scan and measure the surface profile at each test location.

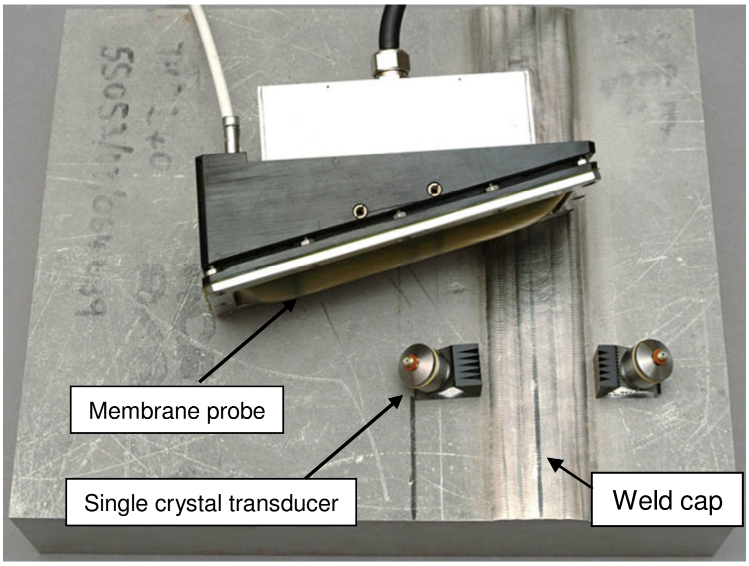

Figure 1 - Photograph of membrane coupled conformable phased array device seen along with conventional single crystal transducers and stainless steel test piece.

TARGET APPLICATION FOR THE MEMBRANE COUPLED DEVICE

An investigation into the performance of the membrane probe was completed by developing an inspection of a specific section of stainless steel pipe-work. The pipe-work consists of an elbow section with variable radius of curvature welded to a straight piece of pipe. The inspection must be capable of detecting small defects with through-wall dimension of less than twice the wavelength of the inspection centre frequency. The pipe-work has a wall thickness of greater than 50mm, and defects can occur anywhere within the weld and Heat Affected Zone (HAZ) of the pipe-work; this limits the maximum inspection frequency. The variable radius of curvature in the elbow section prevents inspection from this side of the weld using conventional rigid transducer technology. The inspection must be completed on the straight section of pipe from the outside only. Due to these access constraints thorough inspection of the pipe-work is challenging.

All experimental testing has been completed on flat plate non-welded test-pieces that replicate the target application. A schematic of a test piece is shown in Figure 2. On the top surface of the test piece a series of welds were laid so as to produce a real weld cap profile. The presence of defects in the weld material was simulated by spark eroded slots 4mm deep by 8mm wide. The inspections described in this paper were carried out on the defects shown in Figure 2.

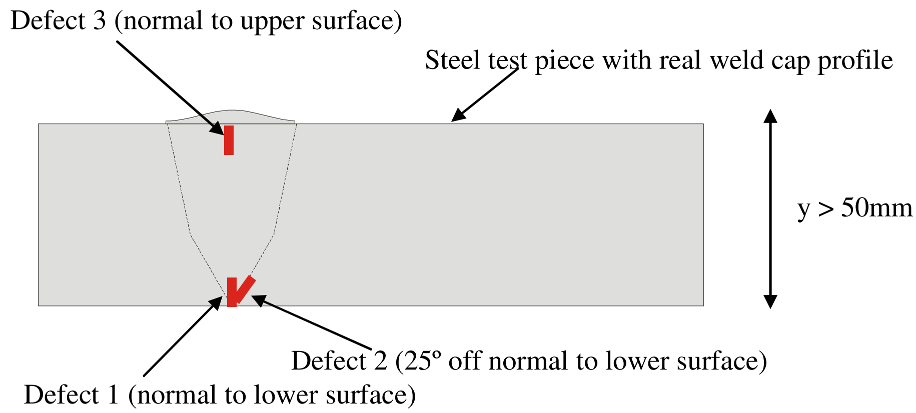

Figure 2 - Steel test piece showing defect locations and real weld cap surface profile

Defect 1 simulates a lack of root fusion defect; this type of defect can occur on the inner diameter of the target application pipe-work. The artificial defect is positioned normal to the back-wall of the test-piece at the centre of the simulated weld. This defect was generated as a slot machined into the test-piece from the back-wall. This type of defect is typically inspected using the corner echo effect [4].

Defect 2 simulates a surface breaking lack of sidewall fusion defect on the inner diameter of the target application pipe-work. The artificial defect is positioned at 25º to the back-wall normal of the test-piece at the centre of the simulated weld. The defect is a machined slot that was generated from the test-piece back-wall. The primary detection technique selected to detect this defect was a Transverse-Longitudinal (TL) mode conversion technique in pulse echo arrangement. The test-piece does not contain a weld, therefore any detection techniques that traverse a significant distance of weld material have not been considered in this investigation. The maximum defect response using this TL technique occurs when the mode converted longitudinal wave travels perpendicularly to the orientation of the defect.

Defect 3 simulates a planar defect that could occur along the weld centre line at the top surface of the target application component. The artificial defect was positioned normal to the test-piece outer surface and was produced by machining a slot into the test-piece prior to the addition of the weld cap. This type of defect is very challenging to inspect using conventional ultrasonic techniques because of the position of the weld cap. The weld cap must be removed in order to complete this type of inspection using conventional transducer technology.

EXPERIMENTAL PROCEDURE

In order to quantify the benefits of the membrane probe and demonstrate potential inspection improvements when using this type of device, benchmark testing was undertaken. The test-pieces were inspected using conventional single crystal and wedge coupled phased array techniques to provide an inspection baseline. Conventional single crystal results and modelling of these inspections have been reported [5]. The inspection was then completed using the membrane probe and a comparison of the findings made. The three experiments described in this paper were designed to:

1. Compare the inspection performance of the membrane coupled phased array device with inspections completed using a single crystal transducer and solid wedge coupled phased array transducer when inspecting Defect 1. The experimental set-ups for single crystal and membrane coupled phased array inspection are shown in Figure 3 and Figure 4 respectively. The inspection setup for the wedge coupled phased array was similar to Figure 4. Direct 45º shear waves in a pulse echo arrangement were used to inspect a region in the root of the weld.
2. Demonstrate that updating of delay laws retains the inspection performance of the membrane device when inspecting above an irregular surface profile. Investigation would compare the inspection performance of single crystal and membrane coupled phased array device when inspecting Defect 2. Inspection with a wedge coupled phased array would not be possible due to the presence of the weld cap. The technique used mode converted 67º longitudinal waves to inspect for a lack of sidewall fusion near the root of the weld. The experimental set-ups for the single crystal transducer and membrane device are shown in Figure 5 and Figure 6 respectively.
3. Demonstrate the capability of the membrane device to perform near surface inspection in the region of a weld cap that would otherwise prove very challenging to inspect using conventional ultrasonic techniques. Inspections would be undertaken on Defect 3. The experimental set-ups for single crystal and membrane device inspection are shown in Figure 7 and Figure 8 respectively. For inspection using a single crystal transducer the inspection technique used mode-converted 67º longitudinal waves in pitch catch arrangement. The placement of the receiving transducer is not ideal due to the presence of the weld cap. The conformability of the membrane device allows a simplified approach where the device was placed on the weld cap and direct shear waves were used for the inspection.

The application of single crystal and phased array transducers was achieved by interfacing to a Focus Scan controller supplied by Technology Design [6]. Images of the defect region were generated by B-scans for all inspection techniques. Phased array data was collected in Full Matrix Capture mode

[7] and post processed using software written for the task by Imperial since the controller does not currently allow real time updating of delay laws. For phased array inspection the ultrasonic beam was focused at the mid point of the defect and an electronic scan of a given defect region in the test block was made using a suitable transducer aperture (number of elements employed for each increment of the scan). For solid wedge coupled phased array inspection a standard linear 2 MHz, 48 element, 1.25mm pitch probe from Imasonic France [2] was used coupled to a 21.3° solid wedge.

The single crystal transducer used for these inspections was a Krautkramer 2.25 MHz, 15mm diameter probe coupled to a wedge angled at 31.7° and 21.8° for inspection of Defect 1 and Defect2/Defect 3 respectively.

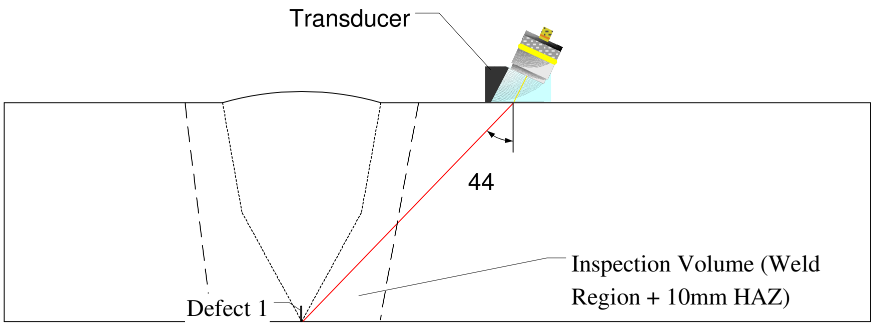

Figure 3 - Schematic of pulse echo shear wave inspection technique of Defect 1 (lack of root fusion) using a single crystal transducer.

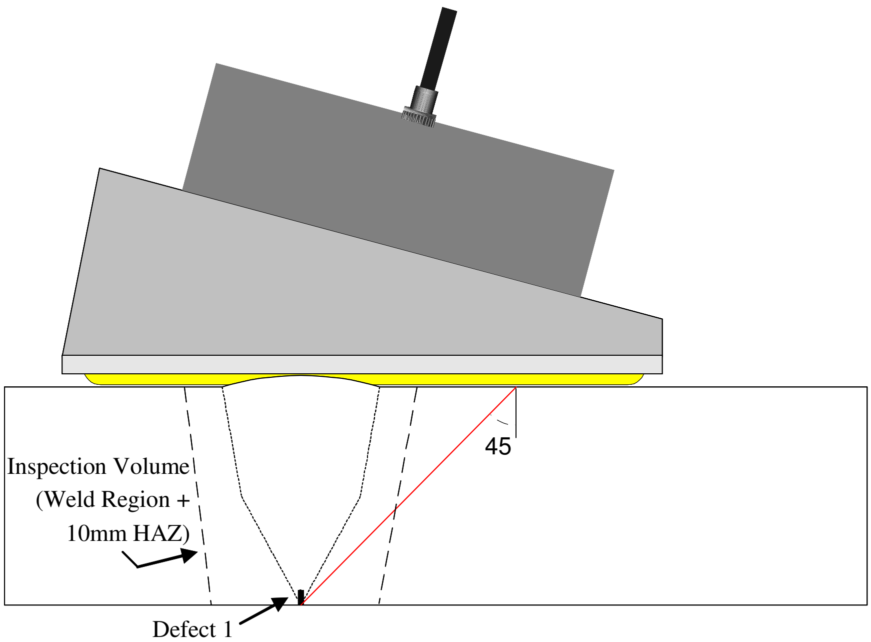

Figure 4 - Schematic of pulse-echo shear wave inspection technique of Defect 1 using the membrane coupled phased array device.

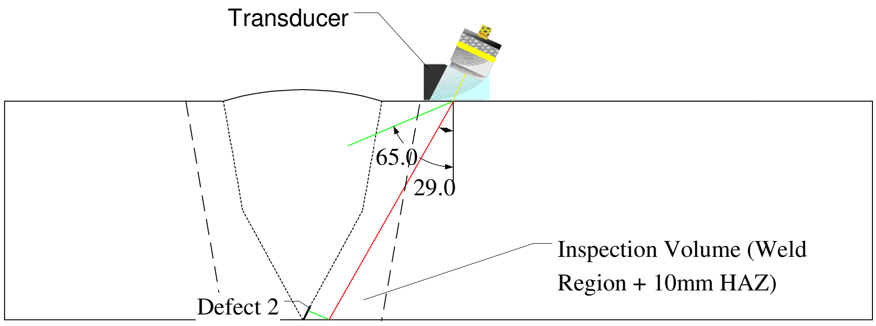

Figure 5 - Schematic of pulse-echo Transverse-Longitudinal mode conversion inspection of Defect 2 (lack of fusion in side wall) using a single crystal transducer.

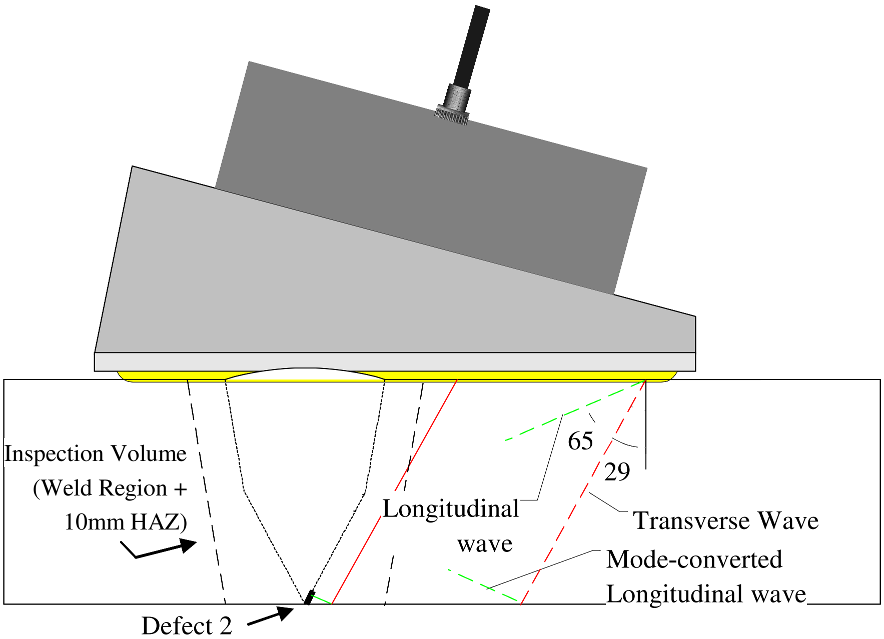

Figure 6 - Schematic of pulse echo Transverse-Longitudinal mode conversion inspection of Defect 2 using the membrane coupled phased array device.

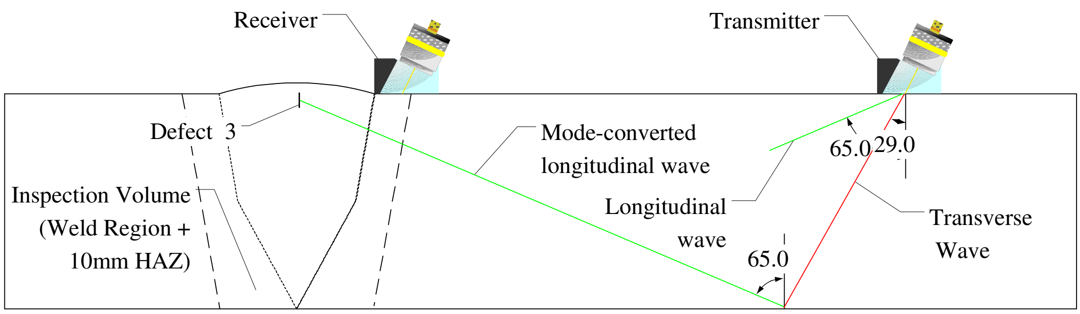

Figure 7 - Schematic of the Transverse-Longitudinal-Longitudinal mode conversion inspection of Defect 3 using pitch catch arrangement of single crystal transducers.

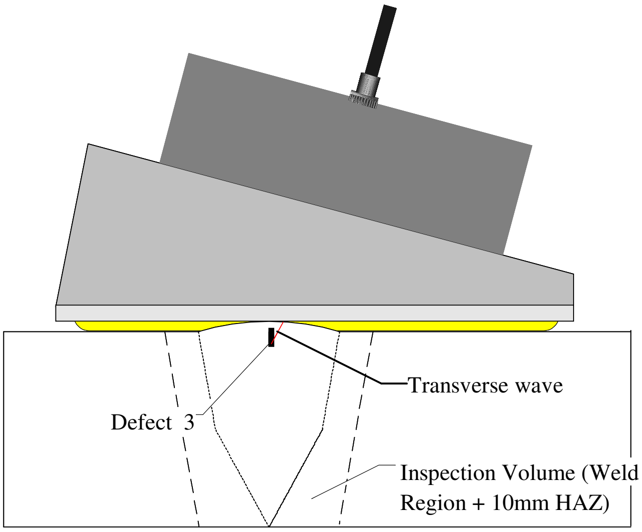

Figure 8 - Experimental set-up to demonstrate the capability for near surface inspection in region of a weld cap using the membrane coupled phased array device.

EXPERIMENTAL RESULTS

The experimental results for inspection of Defect 1 when inspecting with the membrane phased array device, wedge coupled phased array and single crystal transducer are shown in Figures 9, 10 and 11 respectively. Phased array results are displayed using the Imperial software whereas single crystal results are displayed using GUIDE [8]. For phased array inspection the electronic scan of the defect region was obtained using a transducer aperture width of 20 elements. The inspection using the single crystal transducer was achieved using a line scan with a 1mm step size which took 20 seconds (length of phased array probe = 100mm, single crystal travels 5mm/s). The advantage of phased array inspection over single crystal is observed to be two fold; by taking advantage of the ability to focus the ultrasonic beam the phased array results show improved localisation of the defect image and no axial scanning is required. Results confirm that the performance of the membrane device is comparable to the wedge coupled phased array, though for this inspection there is no advantage in using the membrane device since updating of delay laws was not required.

Figure 12a and Figure 12b show the membrane device experimental results that demonstrate how the inspection performance varies with the application of plane surface and updated delay laws respectively. A transducer aperture width of 25 elements was used. When plane surface delay laws are applied the B-scan image shown in Figure 12a suggests a number of possible defects are present that might indicate lack of sidewall fusion in the root region. If the delay laws are updated with respect to the measured profile of the surface under test, then the inspection performance is retained, as shown in Figure 12b, where Defect 2 is clearly identified in the B-scan image. For inspection of Defect 2 the results obtained using the single crystal transducer are shown in Figure 13. The GUIDE software only allows results to be displayed as direct waves such that the TL response coincides with the direct longitudinal reflection off the corner of the test piece.

The experimental results that demonstrate the capability of the membrane device to perform near surface inspection in region of weld cap are shown in Figure 14 where the B-scan shows the crack tip diffraction from the lower part of Defect 3. The electronic scan of the defect region was obtained using direct shear waves angled at 27° with a transducer aperture width of 12 elements. The results gate out the dominant reflection off the upper surface of the block such that an image of the crack tip diffraction off the upper part of Defect 3 is not observable. Figure 15 shows the experimental results for inspection of Defect 3 using the single crystal transducer. Inspection coverage of the defect cannot be achieved because of the location of the weld cap, any signal obtained is well below the noise level of the scan. The TLL technique is not ideal resulting in low signal to noise levels so that it is not possible to identify the reflection off the defect.

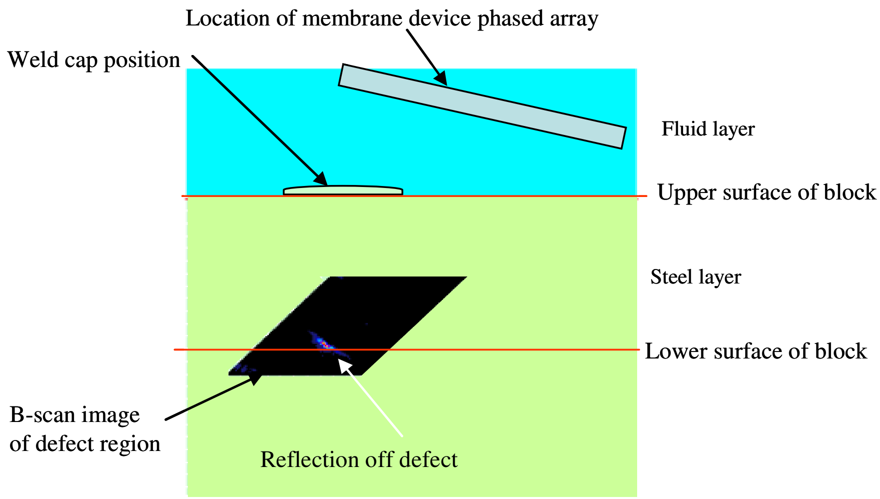

Figure 9 - Experimental results obtained using membrane device showing B-scan image of Defect 1 using a 20 element transducer aperture.

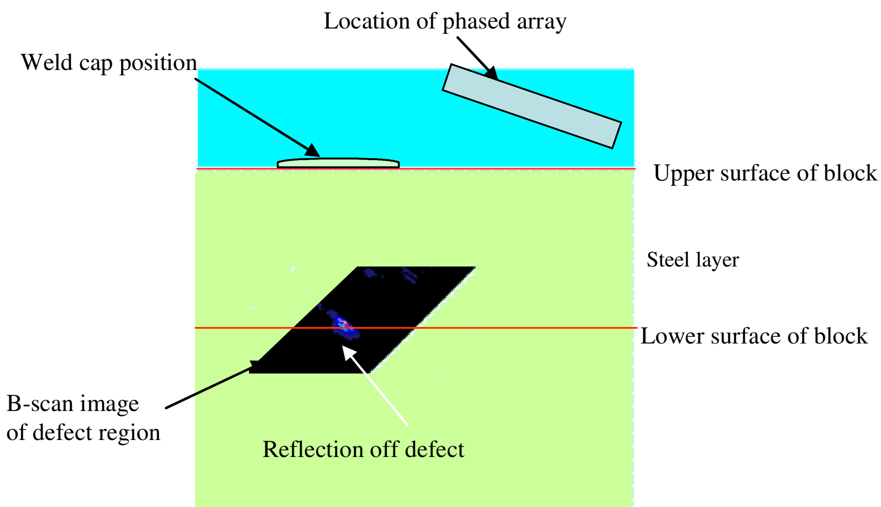

Figure 10 - Experimental results obtained for inspection of Defect 1 with a wedge coupled phased array using a 20 element transducer aperture.

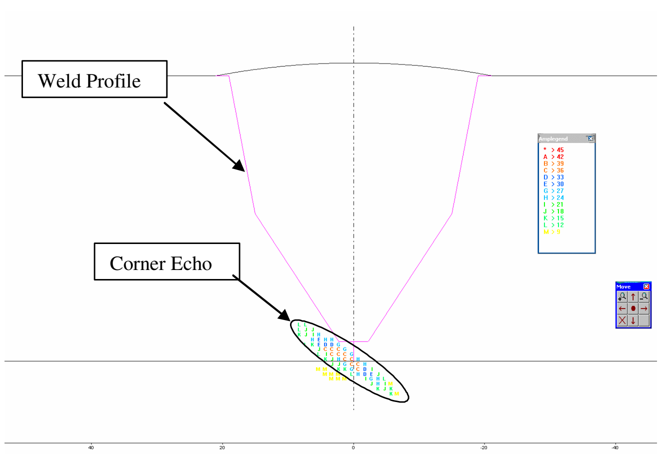

Figure 11 - Experimental results for inspection of Defect 1 with a single crystal transducer.

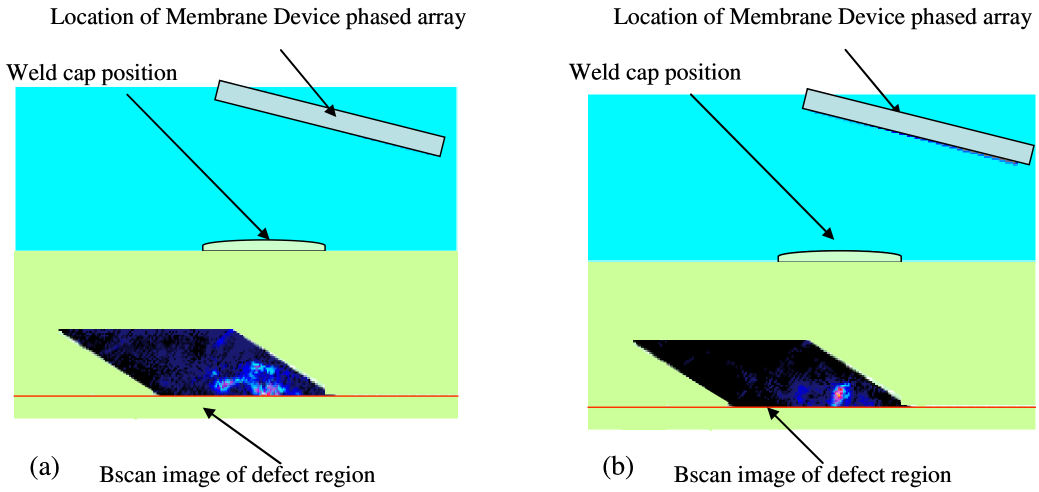

Figure 12 - Experimental results for inspection of Defect 2 (lack of sidewall fusion in root region) using membrane device in pulse echo mode using shear waves mode-converted at block lower surface. (a) plane surface delay laws applied; (b) updated delay laws applied.

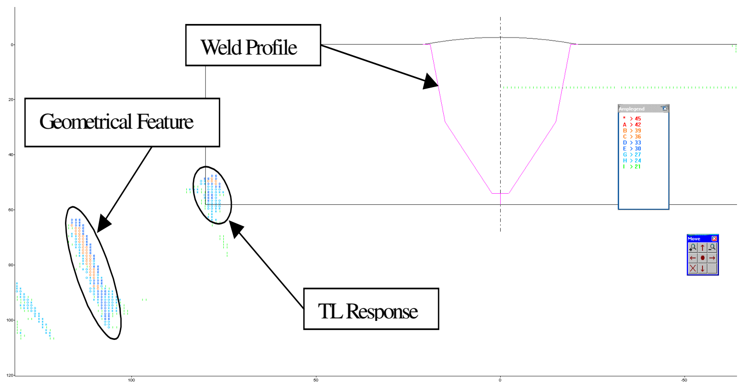

Figure 13 - Experimental results for inspection of Defect 2 with a single crystal transducer.

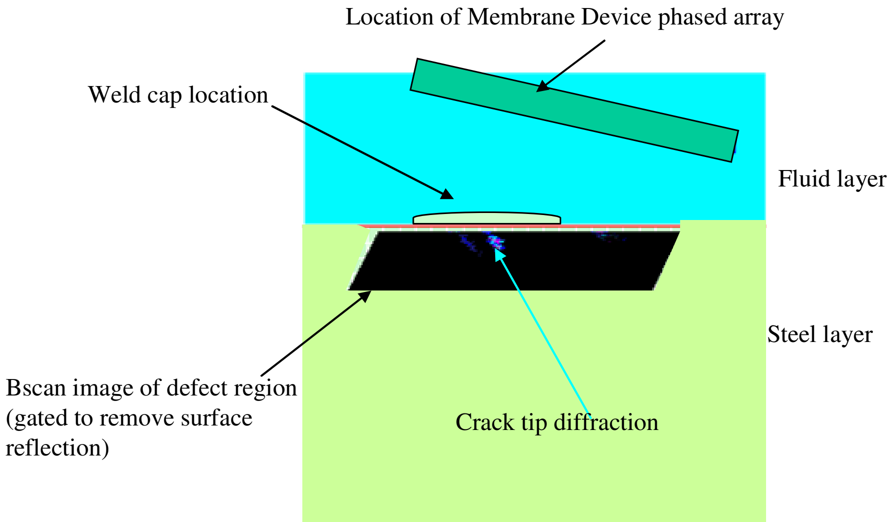

Figure 14 0 Experimental results using membrane device showing B-scan image of Defect 3 obtained using a 15 element transducer aperture.

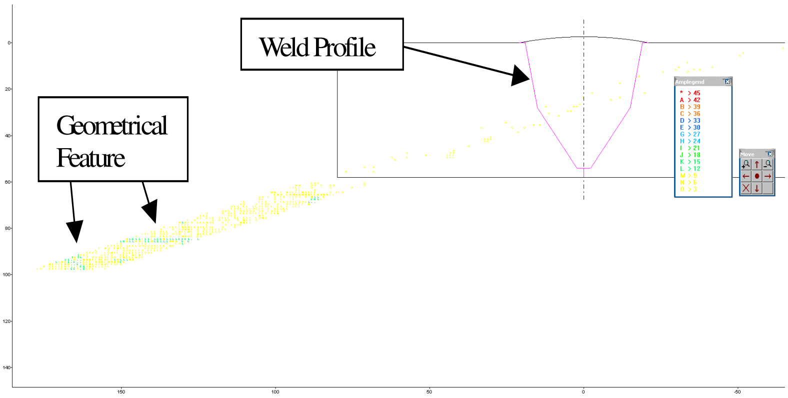

Figure 15 - Experimental results obtained for inspection of Defect 3 with a single crystal transducer.

CONCLUSION

A membrane coupled phased array device is being developed that allows inspection of components with irregular surface profiles. Experimental results have been obtained that successfully demonstrate the inspection capability of membrane device. The device can be used to replace a conventional wedge coupled phased array where irregular surfaces interfere with transducer placement, it is capable of near surface inspections and the application of updated delay laws retains the inspection performance, allowing control of the focused beam transmitted through irregular surfaces. Phased array inspection has the advantage of allowing rapid scanning of components with irregular surfaces without the need for multiple angled probes and time consuming mechanical scanning.

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