

MATERIALS FOR ENERGY

Phased Array Ultrasonic Inspection of Dissimilar Metal Joints

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Guidelines for generating array ultrasonic procedures for the inspection of dissimilar/austenitic welded components

General

The following guidelines for designing and implementing ultrasonic inspection of austenitic dissimilar welds draw together the findings of the Technology Strategy Board funded research project DISSIMILAR and previously established best practice knowledge.

1. The design and fabrication of a joint containing an austenitic weld, in terms of geometry and selection of welding processes, should be undertaken with due regard to the capabilities of ultrasonic inspection techniques.
2. Ultrasonic technique development should be performed on a representative sample containing the weld to be inspected, fabricated using identical welding procedures. Ideally, artificially implanted flaws simulating the expected flaws should be used but, if not possible, then side drilled hole (SDH) targets should be used in the appropriate positions in the reference weld.
3. The velocity of ultrasound is dependent on propagation direction within an austenitic weld and the degree of variation depends on the weld. Hence, it is important to get a handle on this variation in any given weld through basic measurements, for example by extracting cubic coupons from within the reference weld through sectioning and establishing the variation in longitudinal (and/or shear) velocities.

Quantifying the weld microstructure using Electron Back Scatter Diffraction (EBSD)

4. To be able to design advanced ultrasonic techniques using arrays, the structure of the weld must first be quantified. EBSD offers a route (when used in conjunction with models) with sufficient resolution to capture the beam distortion evident when sound is propagated through an austenitic weld. This then provides a potential tool for compensating for or overcoming the microstructural barriers.
5. EBSD is costly (in equipment and time) and the subsequent processing steps required add further complexity. Specific metallurgical and ultrasonic expertise is required: in particular the knowledge of the elastic stiffness values (see 47).
6. In order to (1) reduce costs and (2) capture sufficient information to model ultrasonics, both the scanning resolution and the mapping must be subject to the minimum scatterer criterion (see Section 3).
7. To make use of the raw EBSD data for application in a semi-analytical model (such as CIVA) a processing method termed orientation unification must be used, which results in a map with closed regions containing a limited number of grain orientations and well defined boundaries. However, use of finite element models may not require this step.
8. An implicit assumption in sampling several weld cross sections is that the microstructure does not vary significantly along the welding direction. This assumption can be tested

ultrasonically using a target which runs the length of the weld, monitoring the target at the beam angles to be used (travelling through the weld), and quantifying changes in received amplitude and plotted position. The degree of variation will be indicative of any severe changes in lengthwise uniformity.

Probes

9. The selection of the type of probes will be dictated by the techniques used for inspection. To achieve the required inspection range, probe frequency must be selected such that the Rayleigh model can be assumed for the attenuation in the weld, ie the wavelength must be much larger than the average size of grains in the path of the sound beam (see also 39).
10. If focusing is to be used, then in the case of single element probes the focal range should be approximately equal to the required inspection range; more specifically, the inspection range should generally lie within the 6dB drop zone either side of the focus point. Additionally, the efficiency of coupling through the probe footprint (ie the surface through which the sound is transmitted into the component) must be considered. In the case of arrays, the near zone range due to the aperture must be greater (by at least 10%) than the maximum required inspection range. Note: the aperture is here taken to be the size of the actual radiating area due to the number of elements chosen for operation.
11. An iterative approach to the selection of probes is likely to be needed to ensure that the sound field characteristics at all required inspection regions is sufficient for the task - detection and/or sizing as appropriate (see 12).
12. Sizing capability is determined by both temporal resolution (ie the pulse length) and the spatial resolution (ie the beam size at the inspection range). Both of these must be small enough to achieve the required sizing accuracy. The minimum measurable flaw size will also depend on these parameters.
13. In the manufacturing specification of the probe, the key parameters to consider for application to austenitic weld inspection are: (1) pulse length, (2) bandwidth, (3) cross talk, (4) parasitic echoes, and (5) spatial resolution.
14. Modelling tools are strongly recommended for investigation of the probe capabilities before manufacture. The use of models (1) reduces likelihood of mistakes in the probe specifications, (2) allows optimisation of parameters based on given ultrasonic or geometric constraints, and (3) increases confidence in the resulting techniques, thus contributing to the technique justification during inspection qualification.

Techniques

15. The technique here refers to the ultrasonic method (covering probes, instrumentation, physical positioning, encoded / manual scanning, calibration method and setting sensitivities) that is proposed to satisfy the inspection requirement; see 39 – 50 for detailed treatment of the component parameters of the ultrasonic technique.

16. Note that it may not be possible to satisfy the complete inspection requirement with a single ultrasonic technique and, hence, several different techniques (including other disciplines such as eddy current) may be required to satisfy the inspection requirement.
17. To be able to design the technique well, expected flaw positions, orientations, dimensions and characteristics should be known. Techniques should be designed to meet specific inspection objectives.
18. For inspection of thick section (>25mm) austenitic welds, in particular where the sound is required to traverse the weld, the use of phased array transmit-receive longitudinal (TRL) probes is recommended. TRL probes have been shown to provide an improvement in signal-to-noise (in comparison to conventional dual element probes which operate on similar principles), along with the versatility to cover a much larger inspection volume (in comparison to conventional dual element probes which are limited to a small inspection volume). The achievable inspection volume can be explored through modelling and probe parameters can then be optimised to achieve the required capabilities.
19. Two-dimensional (2D) array configurations can be used to achieve full three dimensional (3D) control of the sound field (note that phased array TRL probes can also achieve 3D control but are generally much limited in comparison to dedicated 2D arrays). 2D probes are useful in that they can electronically 'skew' the sound beam and hence increase sensitivity to flaws that do not lie in a plane perpendicular to a non-skewed beam.
20. The 2D probes are particularly attractive for the inspection of flaws that lie close to the transverse plane to the welding direction, especially in cases where the weld cap remains in place. Again, to optimise and verify the capability of a particular technique using 2D probes skewing the beams, modelling must be undertaken to establish feasibility, optimise parameters and demonstrate capability (through simulation).
21. Techniques based on the full matrix capture (FMC) of data, where each transmit-receive pair on the array is executed individually, leading to a matrix of data which can then be post-processed, could also be generated, provided the inspection frequency is well matched to the material's attenuation characteristics. Post-processing methods applied to the matrix of data assume that the sound wave fronts travel uniformly in the medium and in a geometric straight line (which is not usually the case in austenitic welds). This is likely to lead to distorted imaging, leading to a similar degradation in inspection quality as experienced by other ultrasonic techniques.

The adapted delay law (ADL) technique

22. Given that an array probe is able to manipulate the sound field and the austenitic microstructure influences the sound propagation, the concept of adapted delay laws (ADLs) is based on the idea that array ultrasonics can be used to overcome the barrier presented by the microstructure. The method makes use of temporal phasing, ie the act of delaying the firing time of each element of the array relative to the others; frequency phasing is not used.
23. ADLs can be generated through two potential routes: (1) modelling and (2) experimentally. The modelling route requires the microstructure of the weld to be mapped (using EBSD or other quantification methods), whereas the experimental route

can be limited by excessive attenuation in the weld metal and hence the inspection parameters must be well matched to the material attenuation.

24. When generating ADLs through modelling, time reversal concepts are used. The delay law is built such that the wavelets emanating from each element arrive at the target region at the same time and phase for constructive interference to take place. First, the model is used to evaluate the actual time of flight to the target point from each element, because the actual energy locus is often not a geometric straight line in anisotropic inhomogeneous materials, such as dissimilar welds. Secondly, the delay law is built such that the wavelets from all the elements arrive to constructively phase. In essence, whereas in isotropic media the delay laws can be calculated geometrically, in the anisotropic media the delay laws have to be generated using the model.
25. Theoretically, ADLs are only applicable to the point for which they were generated through modelling. Hence to execute inspection of a large volume in a joint, it is necessary to build a large library of ADLs, which are then used by the array controller according to the position of the target. The generation of ADLs for this library can be time consuming (see 26) and hence this adds a significant layer of complexity and cost compared to standard phased array methods. The cost will be in addition to that for quantifying the weld microstructure, eg by EBSD.
26. Various modelling packages can be used, subject to validation. At the time of writing, no known models have been specifically validated for the purpose of generating ADLs. A range of models exist (eg the semi-analytical CIVA and the finite element codes of ABAQUS and PZ Flex) that are able to propagate sound in complex media but some models are better than others in terms of computation times (for similar resources).
27. Experimentally, ADLs can also be generated subject to the caveat in 28. To achieve this, firstly targets (eg SDHs) must be introduced at the inspection sites. Then each element of the array can be fired individually and the arrival time of the echo from the target can be recorded. Then the ADLs can be generated as before by considering that all the wavelets must arrive at the target region concurrently. The experimental data collection method is a subset of full matrix capture of data (see 21) because only the pulse-echo signal from each element is required.
28. An assumption in deriving the ADL experimentally is that the echo from the target can be clearly identified and is distinct from other echoes. Since there is likely to be significant back scattered noise, identification of the relevant echo will not always be straightforward. Additionally, the size of elements in typical array probes may not be well suited to penetrate to any significant distance within the weld and hence no signal may be received at the required ranges. In general, for thick section austenitic welds, the experimental route for generating ADLs may not be physically well conditioned and selection of this route must be subject to stringent qualification evidence.

Personnel and training

29. Personnel who undertake the inspection of the components must be qualified to at least Level 2 through a certification scheme governed by EN 473. Additionally, the operators should undergo component-specific training (through the use of representative mock-ups – see 31) using the probes, techniques and procedures specified for use in the inspection. The component-specific training must be suitably monitored and the

performance of the personnel must be assessed to ensure they meet minimum requirements.

30. The minimum requirements required of the inspection personnel must be developed by a Level 3 holder (compliant with EN 473), subject to a review of the inspection requirements as stated in the procedures. The assessment of the inspection personnel must be witnessed by the Level 3 and approval authorised independently.
31. Representative specimens (using identical materials, welding procedures and ideally of identical geometries and sizes) must be generated containing representative flaws. These mock-ups must be used for the qualification of techniques and for the training of the inspection personnel.
32. The inspection personnel must be made aware of the issues involved in the inspection of inhomogeneous coarse grained anisotropic materials through relevant literature and practical demonstrations. Their performance in the component-specific training (see 29) must be assessed in terms of not just the detection of flaws but also the errors in positioning, sizing and characterisation (where applicable).
33. The personnel who develop the techniques (including the selection of conventional or specialist ultrasonic technology) must be overseen by a Level 3. Tasks involving EBSD and the development of ADLs may involve personnel who are not qualified in ultrasonic inspection. Hence, the aim of the guidance provided by the Level 3 is to ensure that the decisions taken during the development process are considered within their proper context.

Validation and qualification

34. The techniques and procedures developed should ideally be subject to stringent qualification. The qualification methods should be subject to standards specified by either the European Network for Inspection Qualification (ENIQ) (see 35) or the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XI or Section V, as appropriate (see 36). Open trials for procedure qualification may be performed on the mock-ups generated for the specific training (see 31). However, it may be appropriate to also involve other qualification specimens, eg if blind trials are required (see also 35 and 36).
35. The ENIQ route to qualification requires the definition of inspection objectives. The concepts being proposed in the inspection should be subject to technical justification, which may involve the use of simulations (subject to the caveats in 37) and experiments. The technical justification is designed to provide reasonable evidence that the techniques being proposed will meet the inspection objectives. ASME V Article 14 contains similar requirements.
36. The ASME XI route to qualification calls for the use of performance demonstration test pieces containing representative flaws. The component should be representative (as in 31) and the flaws used should be appropriately positioned in regions of the weld where damage could be critical to the operation of the component.
37. Models used for inspection simulations should be independently validated. Scenarios used in the validation efforts must correspond to the inspection scenario as closely as

possible but need not be identical; the requirement is to establish a scientific judgment of relevance between the simulation to be performed and the scenarios used in the validation. The validation evidence should ideally include comparisons with experiment, but may also include comparisons with previously validated models. The limits to the validity of the models should be clearly established and the accuracy of the models should be quantified and clearly documented.

38. The use of EBSD and ADLs are considered special cases and their use will need to be subject to stringent evidence also. These technologies for use in ultrasonic inspections require special care as they lead to significant complications if implemented incorrectly.

Key parameters for technique design

39. Selecting the sound frequency is dependent on two primary considerations. Firstly, the frequency must be well conditioned with respect to grain size (see 9), as scattering of the sound waves at the grain boundaries is the dominant component of attenuation (absorption being the other). Secondly, the resolution of the technique to detect small flaws is dependent on the wavelength (hence frequency) and so the frequency must be high enough to be sensitive to the minimum flaw size that must be detected.
40. Considerable past evidence has shown that the longitudinal wave mode is often better suited to inspection of coarse grained anisotropic materials than the shear mode (for the same inspection frequency), as the wavelength is larger in comparison to the shear mode since the sound velocity is faster. Additionally, the angular difference between group velocity and phase velocity due to anisotropy are larger for the vertically polarised shear wave than for the longitudinal wave or the horizontally polarised shear wave. Where the coarse grained volume is not significant (eg the root) it may be possible to use the shear wave modes; in particular, the horizontally polarised shear wave has been shown to be a feasible mode for inspection.
41. The beam angle(s), measured with respect to the vertical at the point of entry – ie the index point – into the component, should be chosen to firstly detect the flaws and secondly to size them (assuming sizing is required). The reflectivity (including signals generated from diffraction effects) of flaws is dependent on the incident beam angle and on many other geometric conditions, such as whether the flaw is void-like, crack-like and whether it is close to material boundaries such as a component surface etc. In general, the beam angle should be selected to maximise the amplitude of the reflected echo. Models can be used to aid in technique design to select beam angle(s) to achieve the goals of detection and/or sizing.
42. The scanning extent should be sufficient to cover 100% of the volume (weld or otherwise) where flaws that threaten the integrity of the component or structure could develop either during service or post-fabrication. The required inspection volume should be covered by either the physical movement of the transducers using scanners or electronic manipulation of the sound field, or a combination of both.
43. The approach to the calibration of the system (ie the time base) will depend on the severity of distortion induced by the medium. In a medium where changes in velocity due to the anisotropy are significant, average values of the sound velocity should be used for plotting and data presentation. This route will lead to errors in positioning echoes and the

resulting inaccuracies in sizing should be quantified during any qualification of the sizing techniques (using representative specimens).

44. Sensitivity for the inspection should be set using calibration targets (typically SDHs) placed in the representative specimen in locations where the flaws are expected. The diameter of the SDHs will be similar to the minimum size of flaw requiring detection, and will usually lie in the range 2 to 5mm. A specimen containing a representative weld shall be used so that the attenuation effects of the weld material are adequately captured in the sensitivity setting for the inspection.
45. Techniques may make use of wedges to generate beam angles inside the component using the law of refraction. The wedge material may be solid (eg Perspex or Rexolite) or liquid (eg water). A water wedge has the advantage of tolerating inspection surface roughness (see 46) better than a solid shaped wedge. Solid wedges also require the use of couplant material (eg Ultragel II) between the wedge and the inspection surface. The distribution (thickness) of couplant should be consistently maintained during calibration, sensitivity setting and the actual inspection.
46. The surface roughness shall be less than or equal to $6\mu\text{m Ra}$; where this level is not achieved, it is recommended that the surface is adequately prepared before inspection takes place. The use of the longitudinal wave mode (see 40) may lead to mode conversions on reflection and refraction at boundaries, which could complicate the inspection. Hence, techniques using the longitudinal wave mode may require the weld cap to be ground flush to allow access to 100% of the weld volume using direct incidence on flaws, ie without prior reflections (skipping) at component boundaries. If, however, the weld cap cannot be removed, then techniques that take due account of mode conversion effects and/or polarised shear wave modes may need to be considered.
47. The elastic stiffness constants are here considered to be a key parameter for effective technique design only when utilising the EBSD method to quantify the weld and generate ADLs. The austenitic weld demonstrates anisotropic properties which derive from the anisotropy of the face centred cubic (FCC) unit crystal, whose elastic stiffness constants can be evaluated using a single crystal of the alloy and measurements of ultrasonic velocity. This approach can incur significant costs. Alternative approaches to the evaluation of elastic stiffness constants include the use of values from the literature, where these have already been evaluated for alloys of similar composition.

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Executive summary

Background

This document was generated in the DISSIMILAR project (TSB project no. TP11/MFE/6//AA058J) and aims to outline the method developed in the project for ultrasonic inspection of textured coarse grained austenitic welds. This document is not a generic technical justification for inspection of these welds through the use of phased arrays; the limited data generated in the DISSIMILAR project is used to illustrate and propose best practice routes available for the inspection of such joints. In effect, this document outlines a set of options available to the ultrasonic inspector when faced with inspecting what is widely known to be a challenging class of fusion joints between metals.

This document will make reference to several earlier documents generated in various different organisations and forums. The use of evidence and recommendations from the reference documents will be selective and this use does not implicitly support all aspects/claims of those documents.

The DISSIMILAR project (www.dissimilarweld.co.uk) was initiated in July of 2008 and completed in December of 2010. The project Consortium was composed of a total of eight Partners. Three of the Partners - British Energy Generation Ltd, Shell UK and the Nuclear Installations Inspectorate of the Health & Safety Executive - formed the Project Steering Committee under whose guidance this document has been finalised. The bulk of the research and development focused on the inspection of a specific component and was undertaken by the Metallurgy and Materials department of the University of Birmingham and TWI Ltd. Development of ultrasonic transducers (probes) was undertaken by Alba Ultrasound, instrumentation was developed by Peak NDT and implementation of baseline scanning and performance trials was done by Applied Inspection.

The aim of the project was to:

1. Position and size flaws/accurately, compensating for the distortive effects of the anisotropic, inhomogeneous austenitic/ferritic weld.
2. Improve the overall inspection quality through the use of phased array technology such that the inspections provide vastly better signal-to-noise quality (compared to present probes), are faster (by orders of magnitude) and provide accurate, quantifiable and digitally recordable data.

The project was focused on a class of joints termed 'dissimilar' or 'transition' welds, which generally refer to the joint between two different types of materials. In the context of this project, the joint is between parent ferritic and parent stainless steels. The weld metal between the two parents is in the austenitic condition. It is widely known that inspection of austenitic welds is difficult in comparison to equivalent ferritic joints, but those involving the use of buttering layers have proven to be even more difficult to inspect.

Objective

The aim of this document is to provide guidance, based on the experience of the DISSIMILAR project, for the inspection of austenitic / dissimilar welds and disseminate the generated data, results, methods and findings.

The industrial case

The DISSIMILAR project was focused on the energy sectors in the UK to meet the low carbon vision of the future outlined by the Government of the United Kingdom. The ability to design the new components for a high stress, high temperature environment through Engineering Critical Assessment (ECA) methods depends directly on the ability of the inspection techniques to detect and accurately size the flaws.

In the thermal energy sectors (ie oil & gas and nuclear) the use of dissimilar welds in critical joints has initiated the drive to improve the capabilities of the non-destructive testing (NDT) methods, in particular the application of ultrasonics. Line pipes used to transport the products extracted from within the Earth increasingly need to be clad with a corrosion resistant alloy (CRA) to survive chemical attack by the products. The joint between these clad pipe sections (the girth welds) often require the use of weld fillers such as Inconel 625, 316 and super duplex 2209. Depending on the weld metal volume, bevel geometry, thickness and the filler grade, the inspection of clad line pipe girth welds vary in difficulty from possible to severely limited possibilities.

Those critical dissimilar joints which make use of buttering layers between the carbon (ferritic) and the weld are known to be even more difficult to inspect as the ultrasound finds it difficult to traverse the buttering layer. In the oil & gas industry a key example of such a weld can be found on the sea bed where flow lines are collected at a junction termed the subsea hub before being despatched upwards to storage facilities. The use of dissimilar joints involving buttering has been known to cause problems (TWI Member's Report 962/2010) at the buttering layer with the need to detect very small flaws induced by hydrogen embrittlement. The detection and characterisation of such small flaws (sub one millimetre) is a significant challenge for ultrasonic NDT and the development work undertaken as part of the DISSIMILAR project goes some way to address the issues.

Within the nuclear industry there are a number of joints close to the reactor pressure vessel (RPV) and within the primary cooling circuit that are classed to be critical for containment of radiation. The joint which connects the CRA clad reactor pressure vessel to the stainless steel pipe work is a classic thick sectioned dissimilar joint including buttering. The specimen generated for the developmental work in the DISSIMILAR weld made use of the welding consumables and procedure to replicate the surge nozzle safe end transition weld. However, the DISSIMILAR specimen was twice as thick as the joint system in actual use so that the effects of the weld on the sound propagation could be better explored.

In addition to dealing with the configurations that are currently in service, the project was also aimed at pushing the boundaries of ultrasonic capabilities for application to inspecting the future configurations in the European Pressurised Reactor and the AP1000 designs, as well as for the ITER fusion reactor. The need to improve efficiency requires operation at higher temperatures which places increased mechanical stresses on the joints, which in turn requires the evaluation of the joint integrity to be improved. The presence of any cracks (both post-manufacture and those that may develop in-service) will be deemed a serious threat to the integrity of the nuclear components by the regulatory bodies, given the increased potential for its growth leading to catastrophic failure in the increased stress environment. Hence the aim of the ultrasonic inspection programme will be to first detect the presence of (primarily) crack-like flaws and then accurately characterise them (ie evaluate dimensions and orientations), such that their threat to the integrity of the components can be evaluated with greater confidence.

Ultrasonic phased array technology

Ultrasonic technology has been widely used from the earliest days for the inspection of austenitic materials. A key advantage of ultrasonics, in comparison to radiography, is the ability to better characterise crack-like flaws as the interpretation is based on signal amplitudes, orientations and distances (based on times of flight); whereas in radiography the interpretation is based on absorption (which can be severe) and the ability to evaluate crack-like flaws is limited. In comparison to techniques such as eddy currents or magnetic particle inspection, ultrasonic techniques are not limited to flaws which exist at or very near the surface. However, it is important to note that all techniques have their place and, for example, eddy currents are far more suited to the detection of surface breaking cracks (eg toe cracks) than ultrasonics and so should be used to complement wherever possible.

Phased array ultrasonic technology is a sophistication of the conventional ultrasonic technology and the key difference is in the probes. Conventional probes are designed to generate a sound beam along a certain angle when placed on the component. The sound beam may or may not be designed to concentrate the acoustic pressure at a certain point (termed focusing). Using array probes, however, the sound can be 'steered' to a range of angles within the component and can also be 'focused' to concentrate the energy to a desired region. Hence, firstly, the array probe offers greater versatility in that one probe can replace several conventional probes. Array probes can also be used in other configurations, including electronic scanning and full matrix capture of the data, which allow for the possibility to achieve a more sophisticated ultrasonic inspection in comparison to the use of conventional single beam angle probes.

The key drivers for adoption of the technology for inspection of critical components derive from demonstrated ability to reduce inspection times, hence direct costs and those due to lost operation time. Reducing the inspection time has an additional advantage in the nuclear sector as radiation dosage legislation in Europe is getting stringent and there is a drive to minimise human exposure to radiation in all activities. Mechanically, the ability to build systems which need not carry a large number of probes reduces the chances of creating debris within containment areas.

Phased array technology is, however, still expensive to implement. The cost lies in procuring the probes (which are orders of magnitude more expensive than conventional probes) and the instrumentation (termed array controllers) which are also several orders more expensive than standard conventional probe instrumentation. Additionally, there are significant costs in training personnel to use the technology, especially in the field of data interpretation. Very often the data collectors and the data interpreters are different personnel and there is a requirement to establish the working mechanisms.

Finally, the development of inspection procedures using phased array techniques is critical for the inspection to be successful. Procedure development incorporates the selection of the array probe ensuring that the sound field characteristics are sufficient and unwanted energy distributions (termed side energy lobes) do not degrade inspection quality. Very often mode conversion phenomenon can adversely affect the interpretation if not clearly understood and accounted for in the procedure. The use of modelling tools to evaluate the inspection capabilities is much more important when developing phased array techniques in comparison to conventional ultrasonic techniques. The course of the DISSIMILAR project, which follows, is an illustration of the stages required to implement a phased array solution.

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DISSIMILAR

1 Introduction

Ultrasonic inspection techniques are widely used for the non-destructive testing (NDT) of welds composed of austenitic material. The weld is defined as a fusion joint of two materials which is created by the deposition of a pool of a melted alloy which subsequently solidifies to form a metallic bond between the two materials being joined. The use of austenitic materials is dictated by the mechanical and environmental (high temperature / corrosive) conditions of nuclear power plants and products of the oil & gas (O&G) industries. However, the propagation of the ultrasonic wave through the austenitic material is complicated by its inhomogeneous and anisotropic nature. The primary obstacles to the uniform propagation of the sound wave front are the large (coarse) grains that develop during solidification of the weld and the differential texture (anisotropy) that exists across the grain boundaries.

'Austenitic' refers to a phase state of the element iron in which it takes the face-centred cubic (FCC) unit crystal atomic structure. Iron exists in its austenitic (or γ -phase) at a range of temperatures in the region of 1000°C; the addition of the key alloying element nickel retains this phase on cooling to room temperatures. The thermal cooling rates and channels give rise to what is termed dendritic epitaxial grain growth over successive weld deposits leading to the coarse elongated grain structure characteristic of austenitic welds. The solidified weld with the FCC structure exhibits strong anisotropy, ie it exhibits differing elastic properties depending on the direction in which it is stressed.

An ultrasonic wave propagates by the mechanical vibration of the atoms in the medium in its path such that the energy exists in a kinetic form. The mechanical motion of the atoms is dictated by the elastic stiffness between them, ie the elastic modulus. In the austenitic material of the weld, the propagating sound wave experiences changing elastic modulus along its path, leading to the three well known consequences for their ultrasonic inspection (in comparison to inspection of typical ferritic steel materials):

1. Increased backscattered energy, primarily from the grain boundaries which exhibit significant differences in texture across them; this energy increases the 'noise' in the received ultrasonic signals.
2. Increased attenuation of the propagating sound wave, limiting the range of inspection. Attenuation is composed of absorption of the energy in the wave by the material and losses due to scattering. In austenitic material, it is the increased backscatter of energy which is the primary contributor to increased attenuation.
3. Increased distortion of the sound wave, including what is termed 'beam skewing'. In essence, whereas in isotropic ferritic material the wave front would propagate uniformly, in the anisotropic austenitic material this is no longer the case.

In summary, the inspection of austenitic welds, in particular thick section welds with thicknesses in excess of 25mm can be difficult. The welding processes and conditions have a strong influence on the microstructure that develops in the weld upon solidification, and the microstructure then dictates the values of key parameters of the ultrasonic system. Appendix A contains a case study which illustrates the phenomenon described above.

It is noted as a key recommendation that, ideally, a holistic design of an austenitic joint - selection of geometries and welding processes - should take into account the ultrasonic inspection capabilities and this document aims to highlight those key aspects that will be of interest to inspection personnel, joint designers and welding fabricators.

A good treatise on the subject of ultrasonic inspection of austenitic welds is given in the Handbook by the International Institute of Welding [1], covering aspects of the material, issues, techniques and guidelines. In many ways this document complements the Handbook [1] by illustrating the design of an inspection technique for an austenitic weld. However, since this document is based on the specific case tackled in the DISSIMILAR project, the reader is referred to the Handbook [1] for a much wider discussion of the topic.

The primary aim of this document is to provide guidelines. The essential components of the ultrasonic inspection system are covered in their own sections and the recommendations are collated in Section 9. The secondary aim of this document to disseminate the data, results, methods and findings is also done through these sections.

The particular welded component considered in the DISSIMILAR project is described in Section 2, followed by its microstructural analysis in Section 3 using Electron Back Scatter Diffraction (EBSD). The use of EBSD was pioneered for application to the task of ultrasonic inspection development in the DISSIMILAR project and it now allows the possibility to quantify the complex structure of an austenitic weld.

Sections 4 and 5 consider the physical hardware requirements for the inspection, ie the probes and instrumentation, which are borne out of the microstructural analysis of the welded component. The necessary performance characteristics (bandwidth and sensitivity) required of the piezocomposite array probes is discussed in Section 4. The electronic capabilities required of the array controller are outlined in Section 5.

The techniques are then described and developed in Section 6. Several existing techniques were used in the DISSIMILAR project (as baselines) and an original technique (termed adapted delay laws) based on time reversal concepts was developed as part of the project. This was made possible by (1) ability (through EBSD) to quantify a weld, (2) through a model (called CIVA, developed by Commissariat à l'Énergie Atomique) to simulate the propagation of sound through that weld and (3) by array ultrasonic probes, which all together allow the possibility to manipulate the sound propagation to overcome the distortion induced by the weld.

Section 7 contains the experimental data generated in the project and contains an analysis of the performance of all the baseline techniques individually and in comparison to each other. Section 7 also discusses the performance of the adapted delay law technique with regard to its ability to deal with the distortion and improve the inspection quality.

Finally, Section 10 provides a discussion of future directions for efforts in this topic, consolidating the work done in the DISSIMILAR project to outline areas where further work is required.

This document is envisaged as a full account of the course of the DISSIMILAR project and aims to disseminate the knowledge to a wider audience to recreate, critically analyse and improve upon. The inspection of austenitic welds remains a challenge but, undoubtedly, the ever continuing improvements in the various technological fields considered in this document will eventually overcome the many obstacles.

It is hoped that, the guidelines and findings presented in this document will aid the future design of austenitic welded joints and improve confidence in their ultrasonic inspection.

2 Welded component

2.1 Joints with austenitic deposits

There are several key joint configurations used in both the nuclear and O&G industries that contain weld deposits which are in the austenitic state at operating temperatures. These include:

1. The safe-end welds, which connect the nuclear pressure vessel to its primary cooling circuit.
2. Subsea joints on hubs/manifolds, the use of which is rapidly increasing with the need to access oil/gas fields in deep waters.
3. Corrosion resistant alloy (CRA) clad flow lines which require the use of austenitic weld fillers in their girth welds due to metallurgical reasons.

There will be numerous other joints which contain austenitic weld deposits and hence many of the issues illustrated in Appendix A. Additionally, the content of this document will be of interest to the ultrasonic inspection of castings which develop large epitaxial grains and electrosag welds for similar reasons.

The term dissimilar metal welds (DMWs) is in common use within both the nuclear and O&G industries and refers to cases where the joint is between a low-alloy ferritic steel and an austenitic stainless steel (such as the specimen studied in Appendix A). Both the safe-end and subsea joints fall within this class of joints. A particular feature of some DMWs is the use of buttering between the ferritic component and the weld deposit which is deposited before the weld and often from a different welding position. It is known that the presence of buttering layers can lead to further inspection challenges in addition to those presented by homogenous austenitic welds.

Clad flow lines (line pipes) are not considered to be in the category of DMWs but have very specific inspection requirements which are complicated by the difficulties of inspecting austenitic material. In this document the specific case of line pipes is not discussed but the reader will be able to gain some insight into designing their ultrasonic inspection effectively.

2.2 Joint configuration of the DISSIMILAR project

The joint elected for use in the DISSIMILAR project is representative of a DMW used in the nozzle safe-end transition. However, the specimen fabricated for investigation in the project was thicker (around 85mm) than the dissimilar weld in-service, which is only 41mm thick (see specimen in Appendix A). The welding procedures aimed to accurately recreate the original fabrication and thus simulate the conditions present in the actual weld which is presently in-service. The specimen was manufactured as a plate with artificially implanted flaws for the purposes of:

- Simulating typical weld flaws
- Exploring the capabilities and limitations of ultrasonic inspection
- Studying the microstructure of the weld and its properties (Section 3)
- Developing techniques to inspect the joint
- Evaluating the performance of the techniques (Section 7)

Once manufactured the specimen was halved into what is termed Half-A and Half-B for ease of handling and a reference piece near the middle of the specimen was extracted.

The methods used to implant flaws were developed by Sonaspection (UK) and will not be discussed in this document. It is recommended that artificial flaws of typical weld flaws such as lack of fusion, root flaws and rough faceted cracks be implanted at expected positions in a representative weld for technique development. At the very least, technique development should make use of a reference piece with side drilled hole (SDH) targets in a representative weld fabricated using the actual welding procedure used for the fabrication of the weld to be inspected. This is necessary as the effects of the weld microstructure (as illustrated in Appendix A) can be quite severe and are very sensitive to welding procedures.

Figure 1 shows the weld preparation of the DISSIMILAR specimen. The joint is between a 50D carbon steel plate and a 316L stainless steel plate. Deposition of cladding, buttering and weld was all done to ASME III guidelines. The V-prep butt weld had a 30° included angle and was deposited in the flat 1G position.

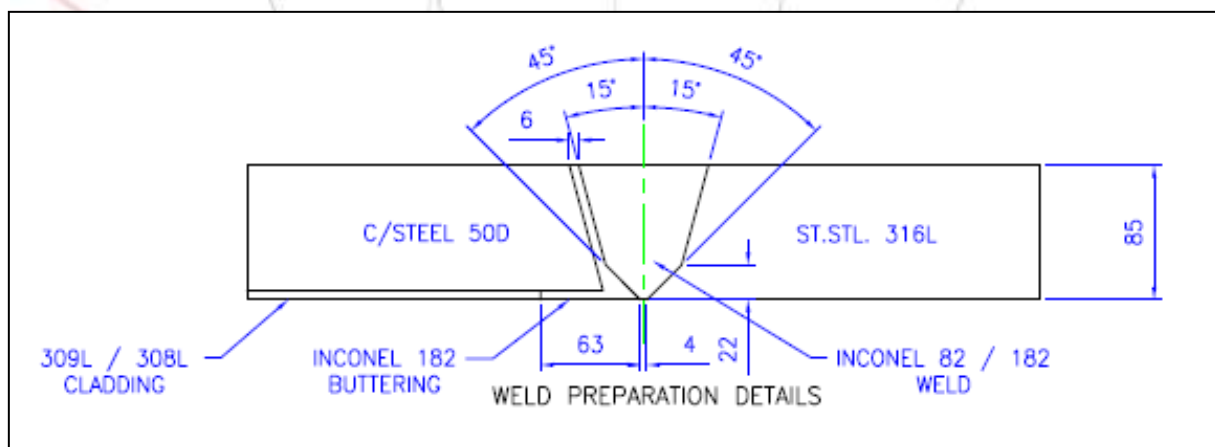


Figure 1 Weld preparation of the DISSIMILAR specimen.

The deposition procedures follow and are representative of fabrication techniques used for typical DMWs used in both the nuclear and O&G industries.

Cladding procedure

- Process GTAW.
- Horizontal 2G (to ASME III).
- Consumables:
 - Sandvik 24.13 LHF (Type 309L) 1.2mm dia. wire
 - Sandvik 19.9L (Type 308L) 1.2mm dia. wire
- Pre-heat: 150°C min, interpass 150 min - 232°C max.
- Heat treatment: 593-621°C.

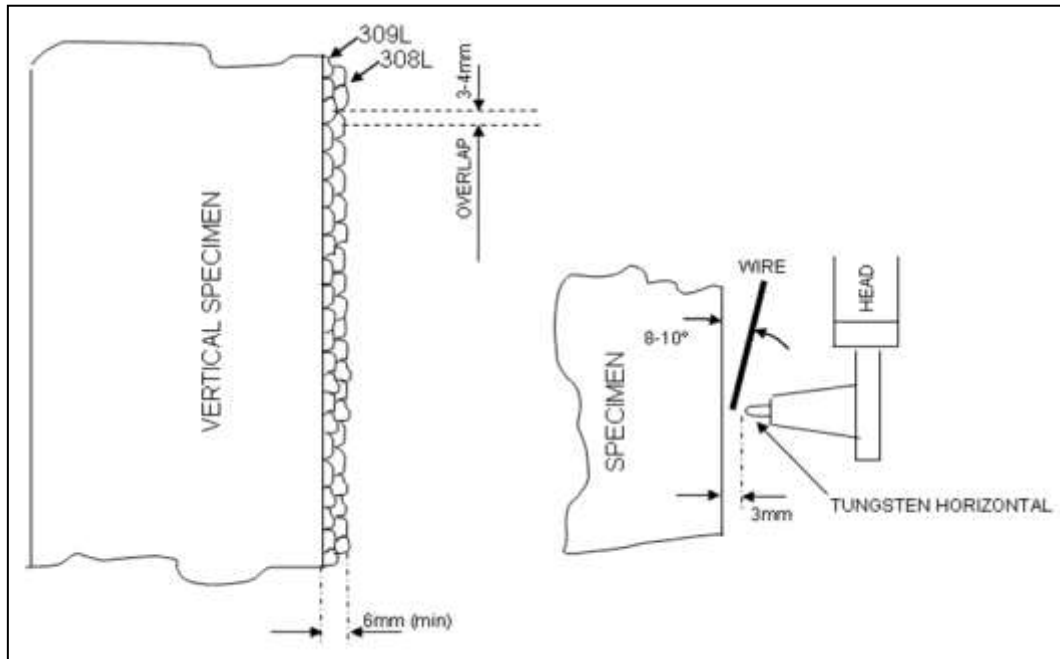


Figure 2 Details of the procedure for cladding the 50D plate.

Buttering procedure

- Process SMAW.
- Flat 1G (to ASME III).
- Consumables:
Inconel 182 electrodes (E Ni.Cr.Fe.3).
- Pre-heat: 150°C min, interpass 150 min - 232°C max.
- Heat treatment: 593-621°C.

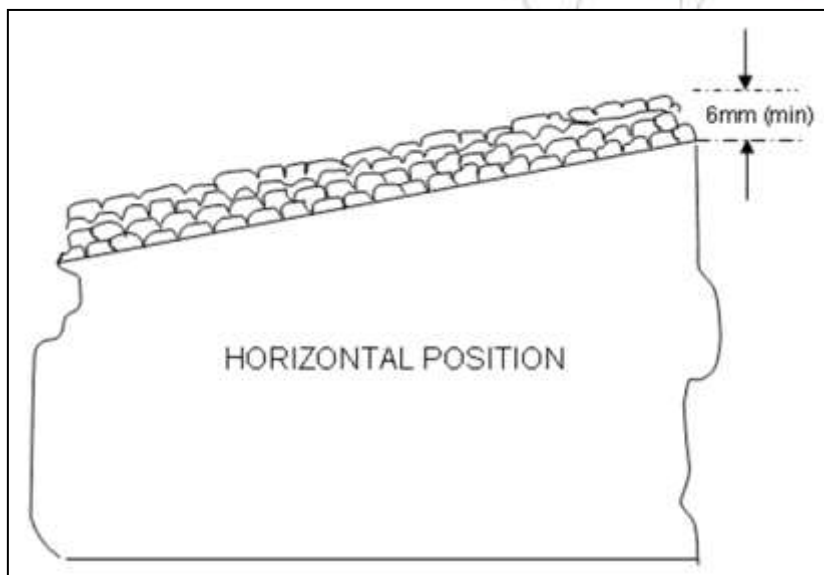


Figure 3 Details of the procedure for buttering the 50D bevel face.

Welding procedure

- Process GTAW and SMAW.
- Flat 1G (to ASME III).
- Consumables:
 - Inconel 82, 2.4 dia. wire (ER Ni.Cr.3).
 - Inconel 182 electrodes (E Ni.Cr.Fe.3).
- Pre-heat: 5°C min, interpass 232° max.
- Heat treatment: None.
- Cap and root will be dressed flush.

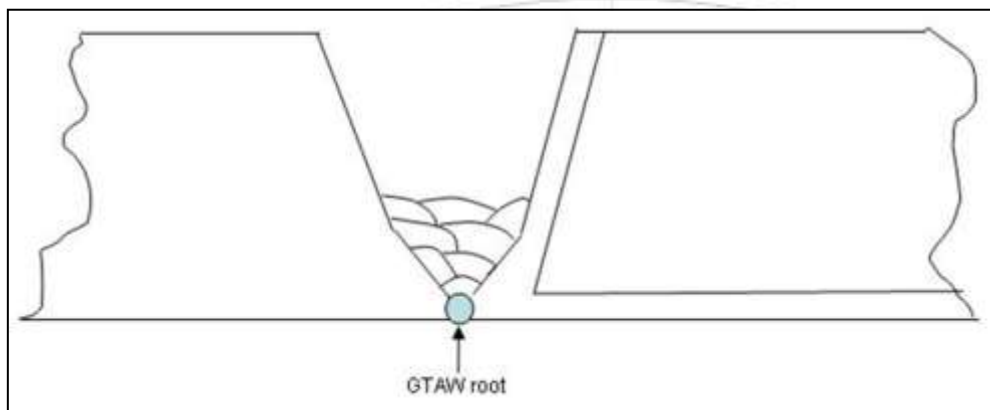


Figure 4 Details of the procedure for filling the weld.

A total of eight flaws were artificially introduced into the specimen. The lengths and positions of all eight flaws when looked at from above the weld are shown in Figure 5. Flaw 1 is an electrical discharge machined (EDM) notch designed for the study of the microstructure ultrasonically (Section 3). Flaws 2, 3, 4, 5 and 6 are lack of fusion (LOF) type flaws on the different fusion boundaries. Flaw 7 was designed to be a rough (multi-faceted) crack along the centreline of the weld and Flaw 8 is a surface breaking vertical (EDM) flaw at the root.

It is important to note that the insertion of the flaws will be affected by the welding, and their presence can also affect the welding and the resultant microstructure as they would modify the heat extraction flows.

Each of the flaws above was introduced with the aim to study the inspection capabilities. Figures 6 to 13 provide through thickness positions, sizes and orientations of all eight flaws. Note that Figures 6 to 13 show the *intended* position of the flaws; the *actual* position of the flaws (determined through sectioning) is presented in Section 7 as part of the performance analysis.

Figure 14 shows the as-received specimen post-fabrication.

The key parameters of interest to ultrasonic inspection of the component are (1) thickness, (2) materials and (3) bevel geometry. These parameters have to be determined primarily through the mechanical stress conditions the component is required to withstand and metallurgical considerations. However, if sufficient thought is given to the inspection requirements as well during the early design stage of the joint then the subsequent inspection techniques and procedures are likely to be much better configured to assess the condition of the joint throughout its lifetime.

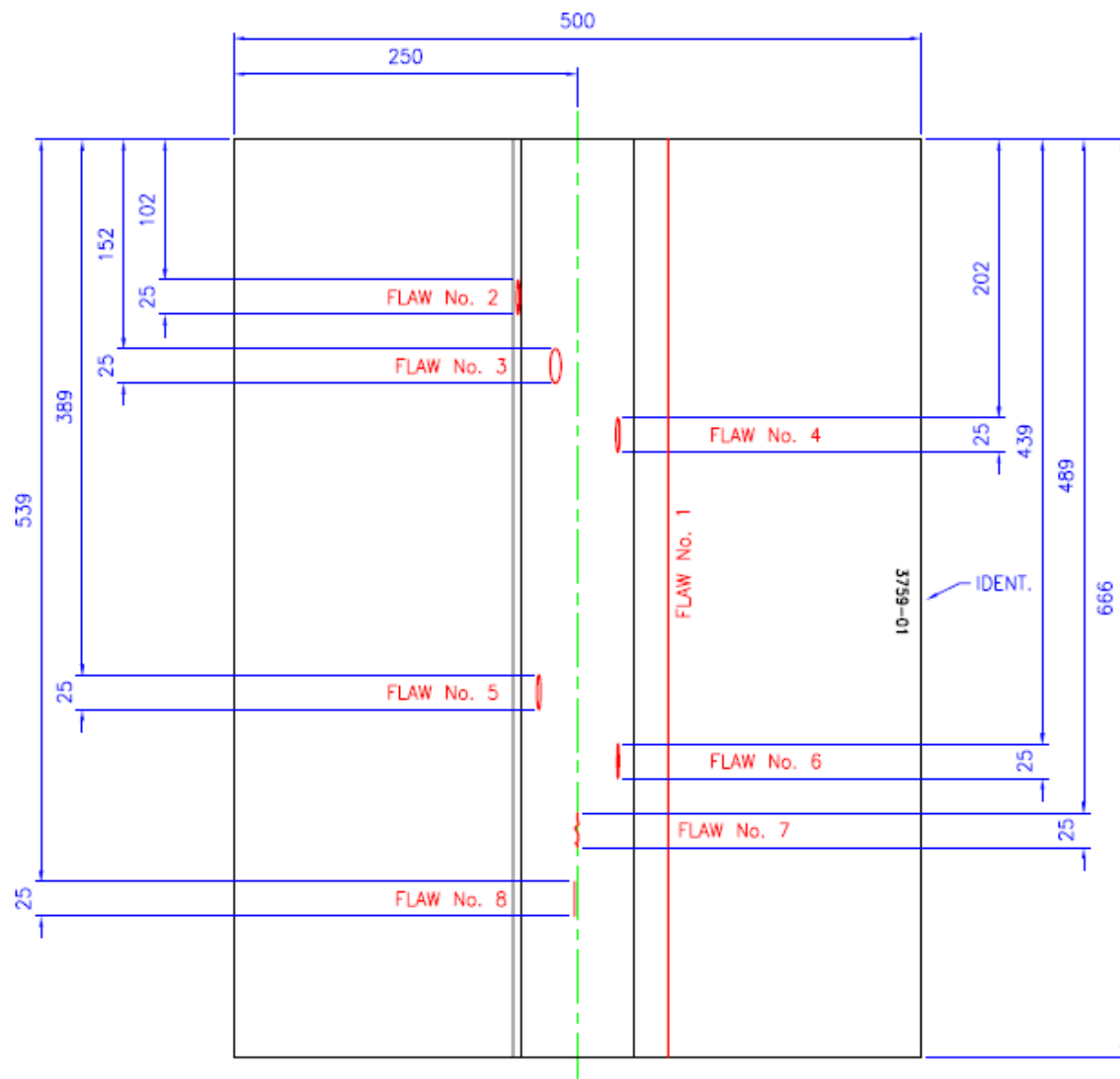


Figure 5 Specimen dimensions and flaw positions; Flaw 1 was as long as the specimen whereas all other flaws were 25mm long.

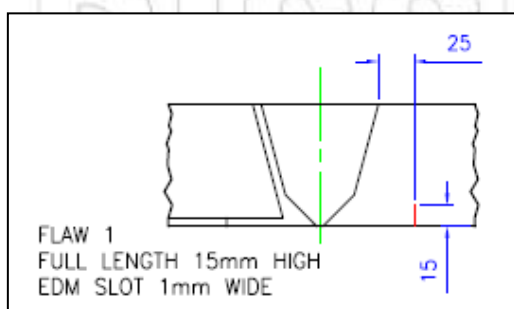


Figure 6 Flaw 1, EDM slot in the stainless steel parent material.

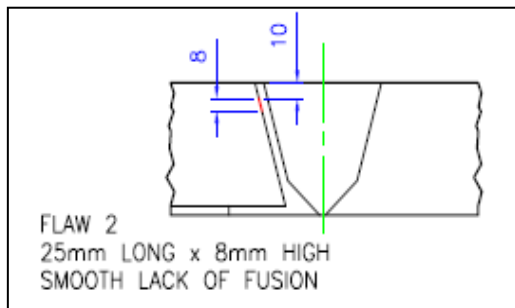


Figure 7 Flaw 2, smooth LOF on the external buttering fusion face (carbon steel/buttering).

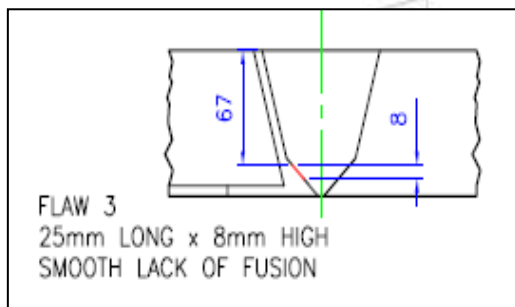


Figure 8 Flaw 3, smooth LOF on the internal buttering fusion face (buttering/weld).

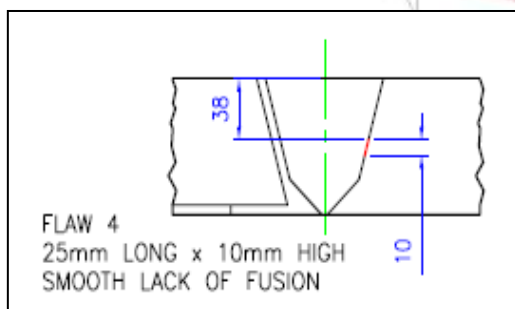


Figure 9 Flaw 4, smooth LOF on the weld/stainless steel fusion face.

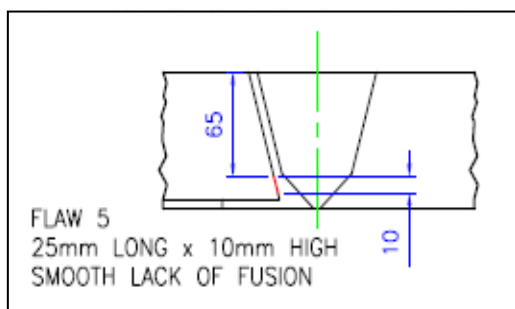


Figure 10 Flaw 5, smooth LOF on the external buttering fusion face (carbon steel/buttering).

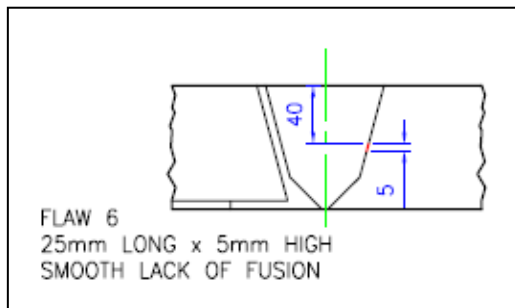


Figure 11 Flaw 6, smooth LOF on the weld/stainless steel fusion face.

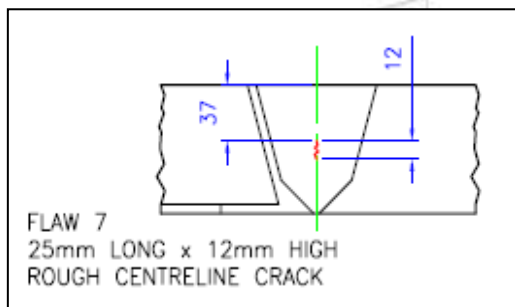


Figure 12 Flaw 7, rough fatigue crack like flaw along the weld centre line.

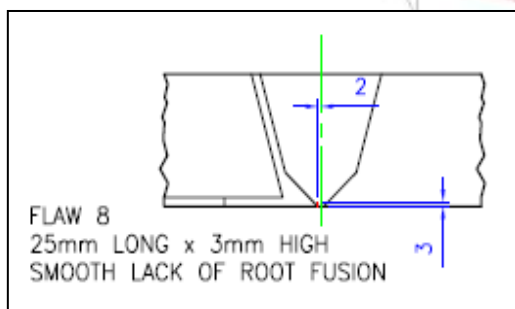


Figure 13 Flaw 8, smooth lack of root fusion.

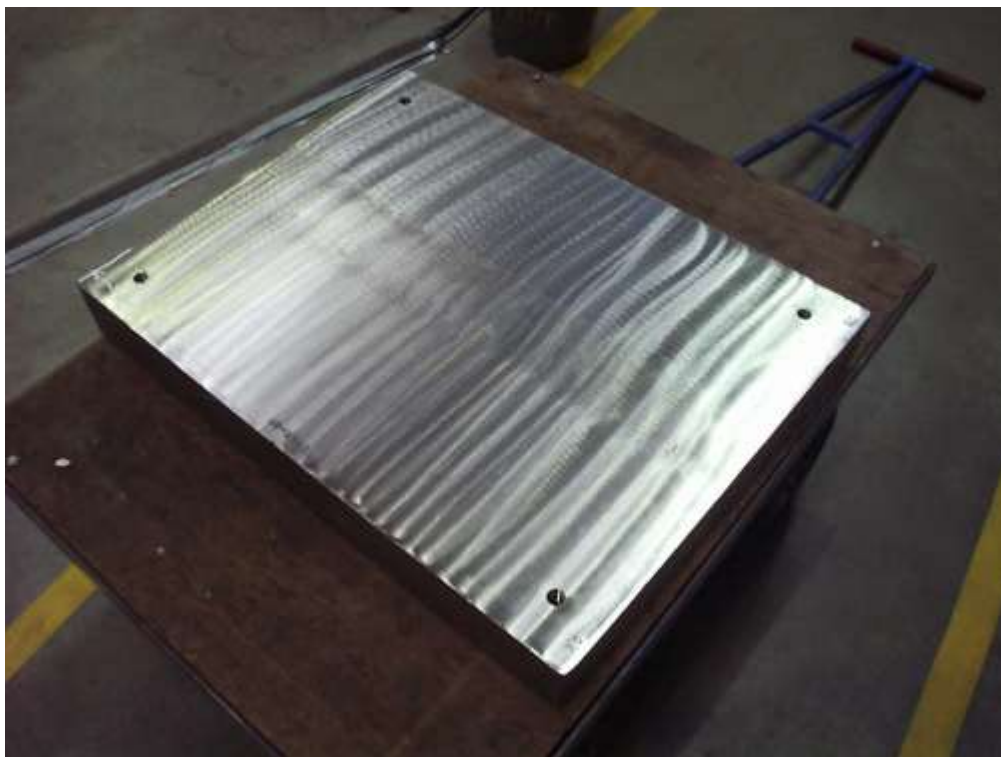


Figure 14 Image of the as-received DISSIMILAR test specimen.

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3 Microstructural analysis

3.1 Introductory comments

Ultrasonic velocity (both shear and longitudinal) are functions of the material properties elasticity (bulk / shear), density and Poisson's ratio [2]. Changes in velocity along different directions imply changes in material properties along those directions. Assuming that bulk density and Poisson's ratio remain unchanged, then the changes in velocity are due to the changes in elasticity. Figure 15 shows a 13mm thick cross section of a K-prep DMW along with the dimensions.

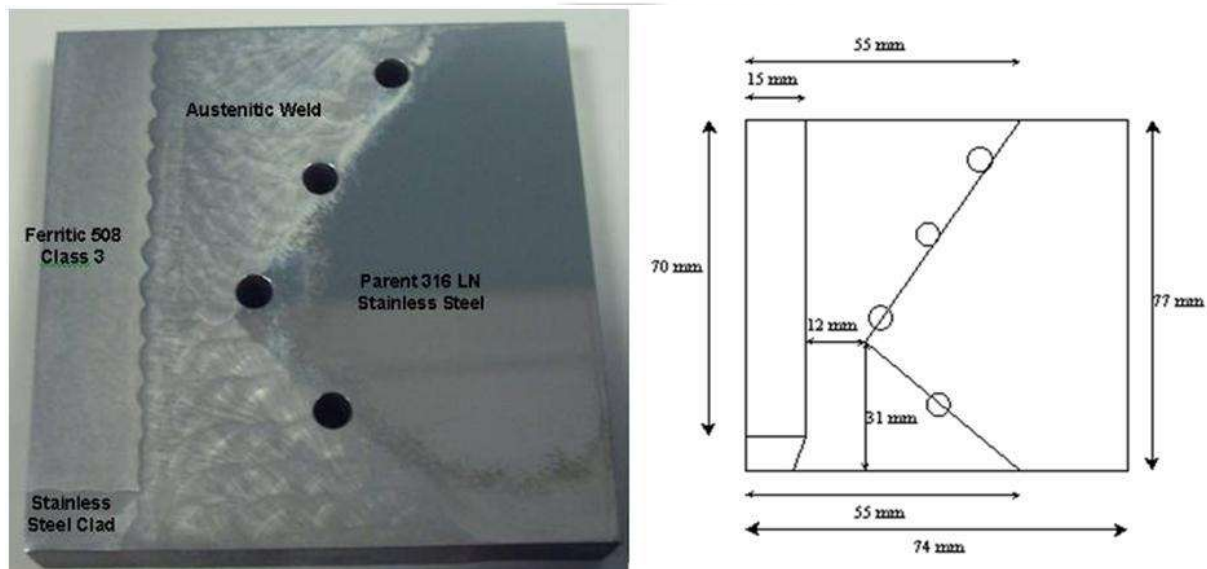


Figure 15 A 13mm thick section of a K-prep weld used in a nuclear power plant.

Considered separately the different components of the DMW will exhibit different longitudinal velocities; typical measured values are given below:

- Ferritic nozzle - 5892m/s
- Inconel buttering and weld metal - 5890m/s
- Austenitic safe-end stainless steel - 5740m/s

The weld shown in Figure 15 was then divided into 13 accurately machined cubes (ie the cubes are weld metal), as illustrated in Figure 16. The longitudinal velocity of along the three possible directions through the cube was then measured in immersion using the second and third back wall echoes.

The mean of the velocities measured through all sides and through all the cubes was evaluated to be 5910m/s, which is consistent with the longitudinal velocity in steel. However, Figure 17 shows the variation in velocity through each side of all the cubes expressed as a difference from this mean velocity. The extent of the variation is dependent on many factors and will be different between different welds. However, the existence of the variation is well known: for instance lesser variation from 5500 - 6100m/s was reported for another austenitic weld [2]. Conventional ultrasonic techniques assume that the velocity of the sound, once introduced into the material, remains constant. Out of this assumption the tasks of plotting the position of echoes (indications) can be effectively carried out. Clearly, in an austenitic

weld, the isotropic assumption of constant velocity is no longer valid and will lead to errors in geometrical plotting.

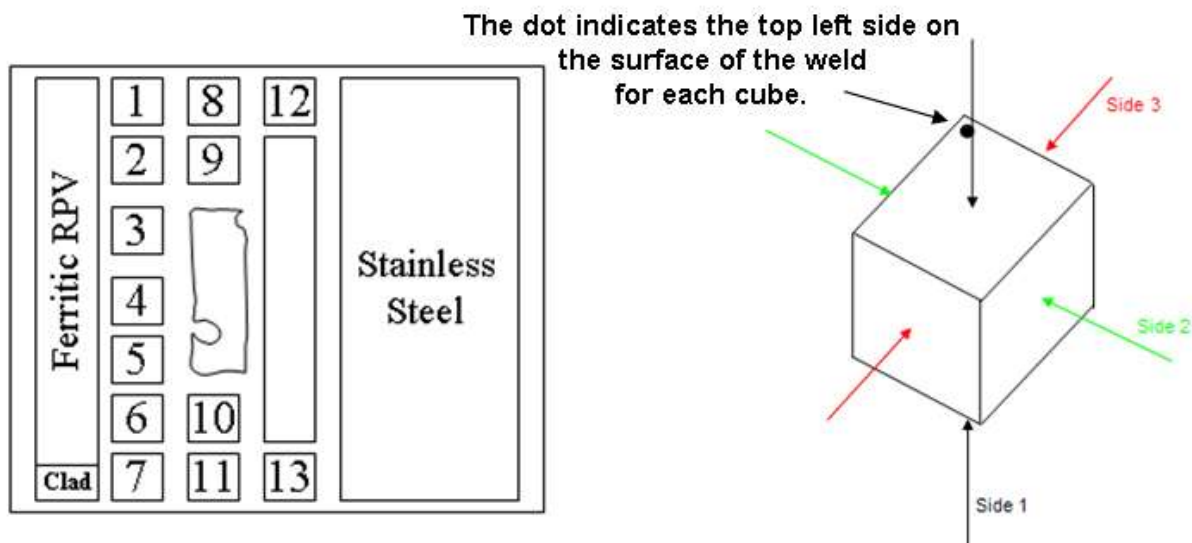


Figure 16 Division of weld into cubic specimens to evaluate the variation in velocity.

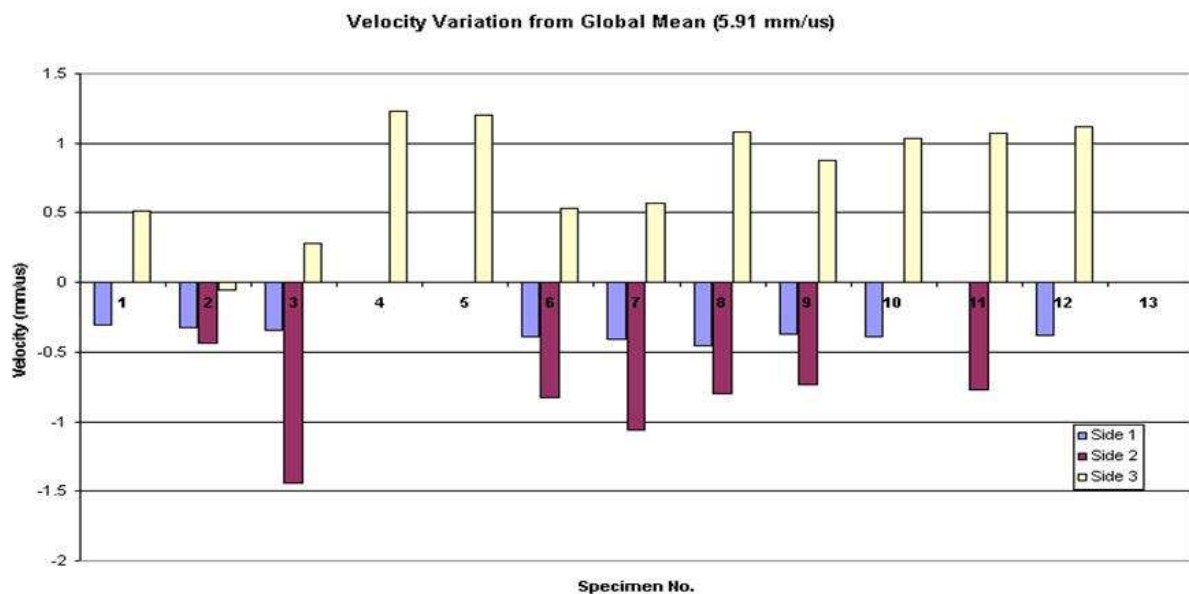


Figure 17 Variation in velocity through the sides of the 13 weld cubes with respect to the mean.

From early on it has been known that austenitic stainless steel welds develop a columnar grain structure during solidification [3, 4]. These dendritic grains grow along the directions of maximum heat loss during cooling. The elongated and oriented grains can grow typically up to several millimetres in length. X-ray diffraction technique has been applied to obtain the texture of the austenitic welds, and it was found that the long axis of the columnar grains corresponds to the 100 crystallographic direction [3]. To establish the true propagation directions of the sound it is necessary to know the elastic stiffness encountered by the wave.

To understand how the ultrasonic wave is affected by the microstructure of the weld, models can be used but they need a quantified description of the weld. Since it is the sound velocity that is of interest, then the elastic stiffness variation in the weld needs to be quantified. The large dendritic grains can be observed using optical microscopes but the optical microscope is unable to provide quantified information. X-ray diffraction can also be used to quantify the weld to a limited extent, as large sampling volumes are required leading to a very low resolution description of the weld.

Recent advances in Scanning Electron Microscopes (SEM) has led to the development of Electron Back Scatter Diffraction (EBSD) techniques which are able to map the orientation of the crystallographic structure on the surface of a metallic specimen to very high resolutions. The data provided by the EBSD technique results in a map which is able to reveal the constituent grain morphology, boundaries and orientations [5]. With the high resolution map, the behaviour of the sound field can be studied better and array ultrasonic concepts (of steering and focusing sound energy) can be better tailored to the weld.

3.2 EBSD approach to quantifying the weld

From the DISSIMILAR specimen three cross sections of the weld was taken, two from the ends and one from the middle, as shown in Figure 18.

The two samples at the ends of the plate (Samples 1 and 3) were extracted at a distance greater than 25mm from the ends of the plate to avoid any end effects from the welding. Sample 1 is near Flaw 2 and Sample 3 is near Flaw 8. Sample 2, the middle sample, was taken between Flaws 4 and 5. EBSD maps were then created of all three samples.

The specimens were mechanically polished to a surface finish of $1\mu\text{m}$ and silica colloidal was used as the final polishing step to eliminate the surface deformation due to the mechanical polishing. The prepared specimens were then loaded into the SEM at an angle of 70° from the incident electron beam and facing a phosphor detector. The electron beam was then raster scanned across the sample in a grid pattern with data collected at a specified increment (the scanning resolution). When the electron beam strikes the tilted crystalline sample, the diffracted electrons (following the Bragg condition [5]) form a characteristic Kikuchi pattern on the florescent phosphor screen.

The Kikuchi pattern carries information of the crystal structure and orientation of the sample region from which it was generated. When the beam is scanned in a grid across the sample surface, crystal orientation will be measured at each sampling point. The crystal orientation is calculated from the Kikuchi band positions. The positions of the Kikuchi bands are found by using the Hough transform to convert the Kikuchi lines to points in Hough space. Using the calibrated system, the angles between the planes that produce the Kikuchi bands on the phosphor screen can be calculated, then the results will be compared with a list of inter-planar angles for the analysed crystal structure to allocate the correct Miller indices to each detected bands. This last step will allow calculation of the orientation of the crystal lattice in terms of Euler angles with respect to coordinates fixed in the sample [5]. With modern computing resources, the whole process for calculating the orientation data using the Kikuchi pattern takes less than a few milliseconds.

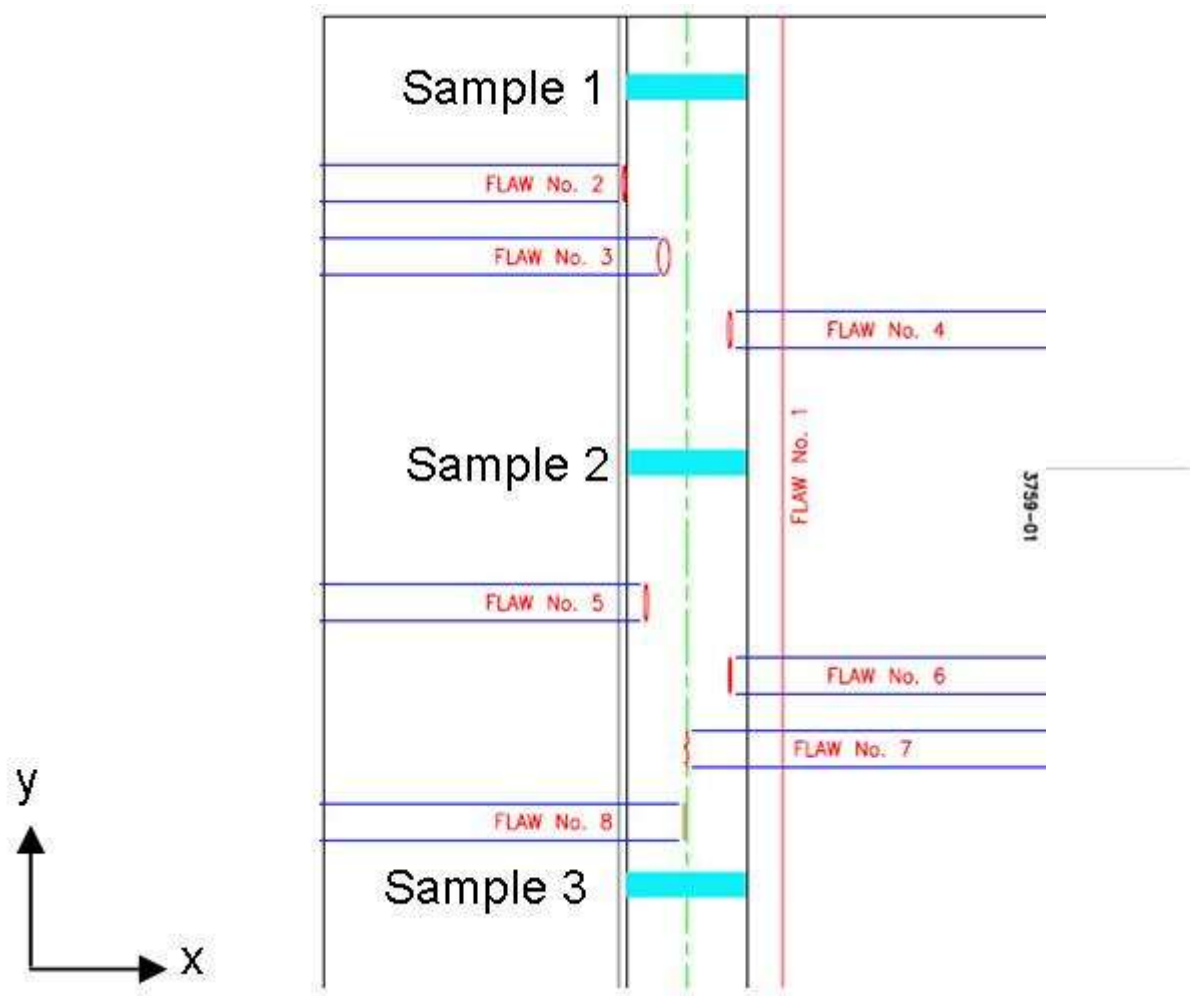


Figure 18 Position of the three samples, referred to as Sample 1, 2 and 3.

The raw data obtained is expressed in terms of the Euler angles notation (ϕ_1 , ϕ and ϕ_2) and the rotation sequence of the unit (FCC) crystal with respect to the sample reference is shown in Figure 19(a). However, the three angles (termed α , β and γ) to orient the crystal in the weld when input to the model (described in Section 6) describe a different sequence of rotation around the x, y and z axes, as shown in Figure 19(b). An algorithm written in MATLAB was used to convert the Euler angles to the required angles with respect to the specimen axes; the transformation matrix is given in Figure 20.

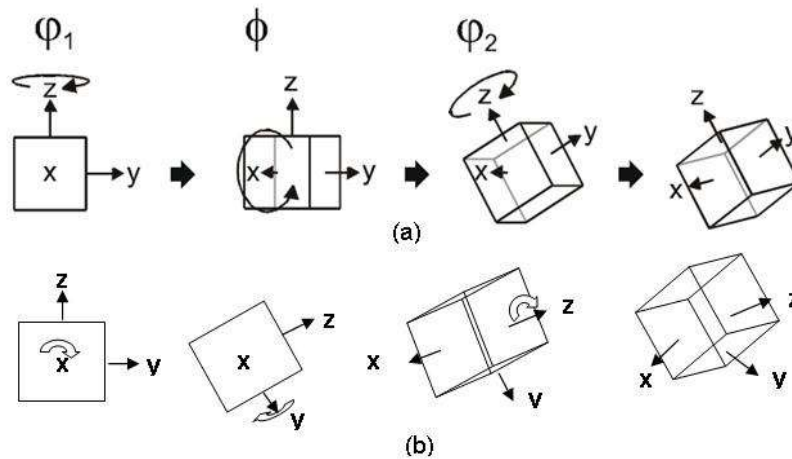


Figure 19 Description of the rotation sequence to orient the crystals using (a) Euler angles (ϕ_1 , ϕ and ϕ_2) and (b) around the specimen axes x , y and z (α , β and γ).

(a) Matrix of Euler angles notation:

$$g = \begin{pmatrix} \cos\phi_2 \cos\phi_1 - \sin\phi_2 \cos\Phi \sin\phi_1 & \cos\phi_2 \sin\phi_1 + \sin\phi_2 \cos\Phi \cos\phi_1 & \sin\phi_2 \sin\Phi \\ -\sin\phi_2 \cos\phi_1 - \cos\phi_2 \cos\Phi \sin\phi_1 & -\sin\phi_2 \sin\phi_1 + \cos\phi_2 \cos\Phi \cos\phi_1 & \cos\phi_2 \sin\Phi \\ \sin\Phi \sin\phi_1 & -\sin\Phi \cos\phi_1 & \cos\Phi \end{pmatrix}$$

(b) Matrix of rotation sequence about x , y and z axis:

$$g = \begin{pmatrix} \cos\gamma \cos\beta & \sin\gamma \cos\alpha - \cos\gamma \sin\beta \sin\alpha & \sin\gamma \sin\alpha + \cos\gamma \sin\beta \cos\alpha \\ -\sin\gamma \cos\beta & \cos\gamma \cos\alpha + \sin\gamma \sin\beta \sin\alpha & \cos\gamma \sin\alpha - \sin\gamma \sin\beta \cos\alpha \\ -\sin\beta & -\cos\beta \sin\alpha & \cos\beta \cos\alpha \end{pmatrix}$$

Figure 20 The transformation matrix g , is used to derive the specimen related angles (b) given the Euler angles (a) output by the EBSD technique.

3.3 Optimisation of EBSD scanning parameters

A primary parameter of concern is the step size or scanning resolution, which impacts on the efficiency and cost of implementing the EBSD approach to weld quantification. The aim is to select the scanning resolution such that sufficient crystallographic information is collected in the shortest possible time. Optical and SEM analysis show that the grains in the weld range from a few micrometres to millimetres. Additionally, it is known that the propagation of the ultrasound is sensitive to the 'mean' grain size distribution of the material. In particular, attenuation is known to have a strong relationship to grain size and the frequency (ie wavelength) of the ultrasound [6]. Hence it is important to establish the 'significant' grain size and the grain boundaries which affect the propagation of the sound and capture this for input to the model.

3.3.1 The minimum scatterer criterion

The attenuation in the material can be classified to fit three possible models and which of these three models that fit a particular inspection case depends on the ratio of wavelength to mean grain size [6]. The first of these models is termed the Rayleigh regime in which the wavelength of the sound is much larger than the mean grain size. The second is termed the stochastic regime where the wavelength is similar to the mean grain size and the third is termed the geometric regime where the wavelength is much smaller than the grain size. If the inspection system is in the stochastic or geometric regime, then the attenuation is excessive and useful inspection will not be possible. Hence, ideally, it is required to choose a sound frequency that places the system in the Rayleigh regime, ie the wavelength being larger than the mean grain size. Equation [3.1] describes the Rayleigh model of attenuation.

$$\alpha(D, f) = a_R D^3 f^4 \quad [3.1]$$

Where α is the attenuation coefficient (dB/mm), D is the grain size (mm), f is frequency (MHz) and a_R is a function of the material anisotropy (dimensionless coefficient).

As the sound wave propagates in the metal, grains become scatterers of the energy (the strongest component of attenuation in austenitic materials) when they become larger than a one tenth of the wavelength λ ; that is when $D \geq \lambda/10$ [2]. Experimental methods can be used, under certain assumptions, to show the size of the grains that fit the model given in equation [3.1].

Figure 21 shows a cuboid extracted from within an austenitic weld, with typical compositions to those used in the nuclear primary coolant circuit. All the dimensions of the cuboid are very accurately machined and the two large sides are polished to a very smooth finish. Through transmission techniques were then used to measure the attenuation through the weld metal coupon; Figure 22 shows the experimental setup within an immersion tank.

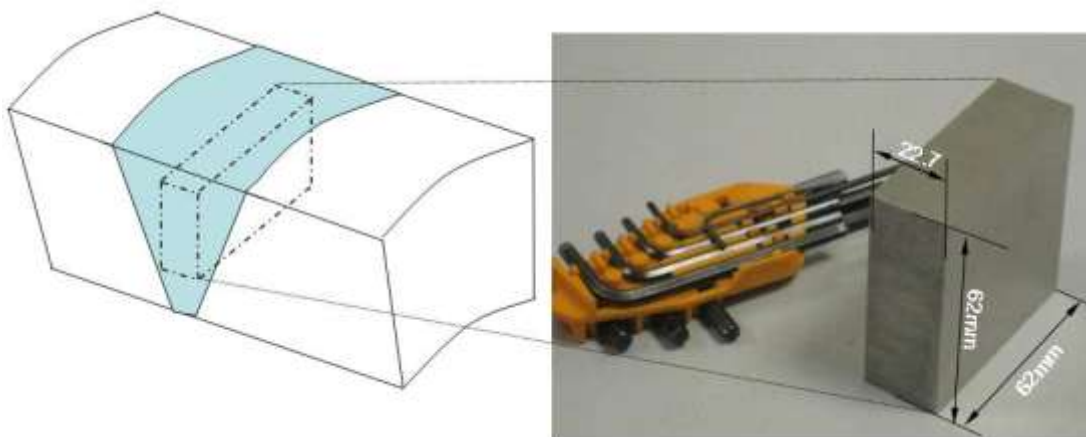


Figure 21 Extraction of an accurately machined and polished coupon from the weld.

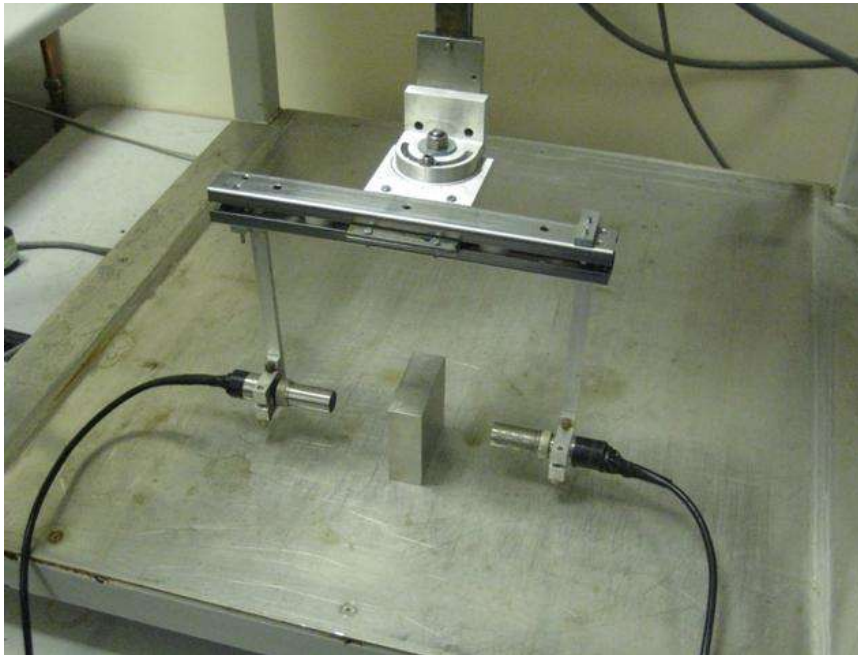


Figure 22 Through transmission experimental setup to measure the attenuation.

The attenuation is measured in the cuboid block at several frequencies. The thickness of the block (in the direction of attenuation measurement) is then decreased by a small step (eg 5mm) and the attenuation at several frequencies is measured again, such that such measurements can be taken at a minimum of 5 step sizes. Figure 23 shows the through transmission data, determining the difference in gain required to place the transmitted signal at the same amplitude as the incident signal.

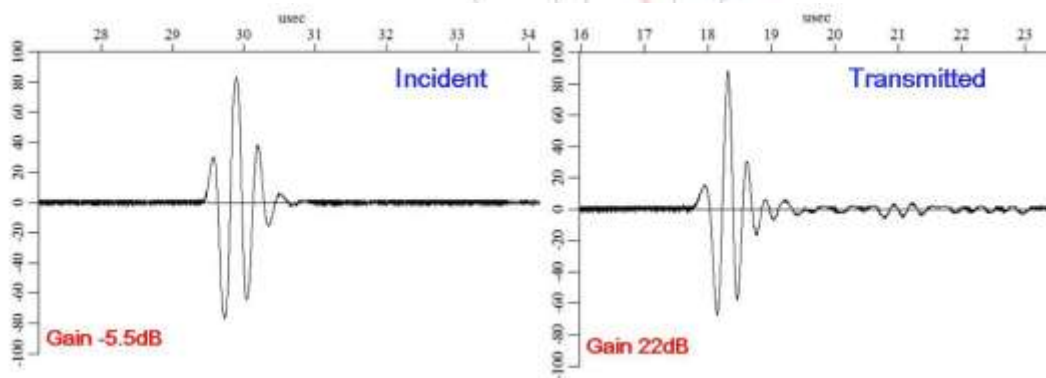


Figure 23 Through transmission data to evaluate the attenuation through the coupon.

A minimum of three frequencies (ie the centre frequency of the transmitting probe) should be selected around the frequency at which the inspection is to be designed. The data presented here was taken at frequencies of 1, 2.25 and 3.5MHz using well characterised immersion probes. Figure 24 shows the attenuation vs. thickness graphs for the dataset at the three frequencies. Assuming a linear relationship, a line of best fit is generated whose gradient is equal to the attenuation coefficient α at that frequency.

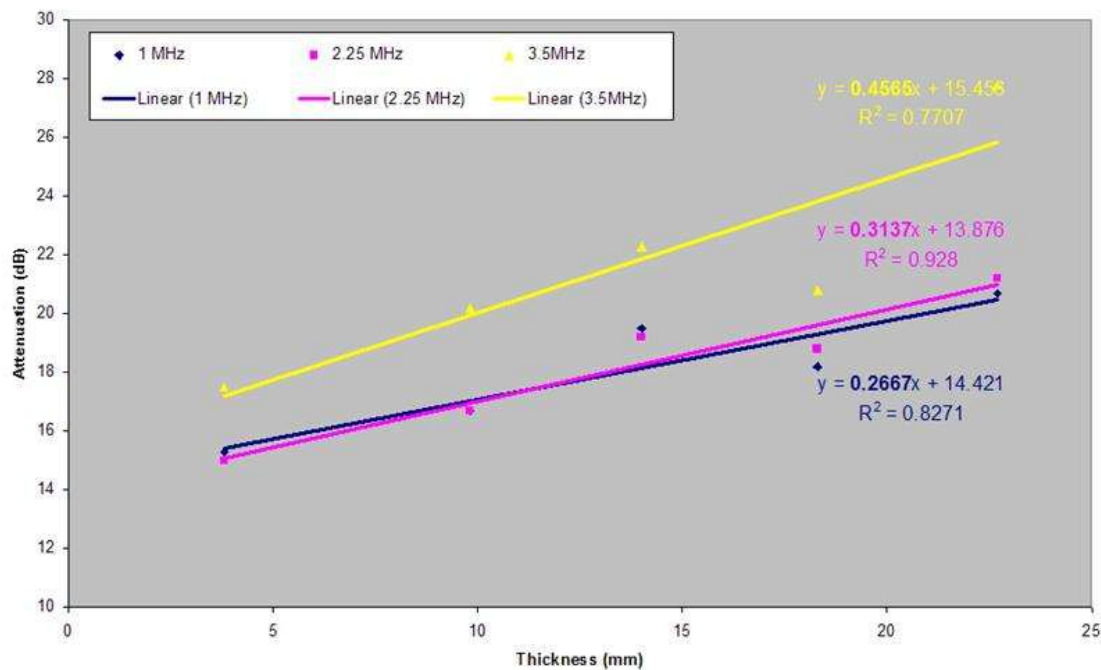


Figure 24 Attenuation vs. the thickness at the three frequencies, showing lines of best fit.

Subsequently the graph of the attenuation coefficient vs. the frequency can be generated (Figure 25) which shows the expected exponential increase in attenuation with increasing frequency. However, note that the curve of best fit is a polynomial of order 2 and the use of only three frequencies limits exploration of any higher order relationships.

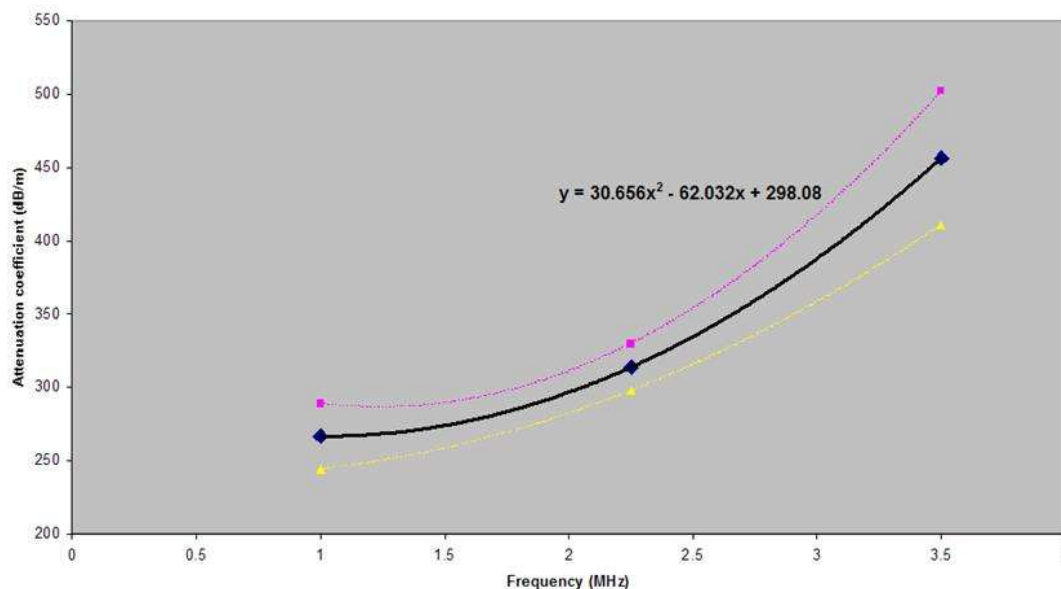


Figure 25 Attenuation coefficient (α) vs. the thickness showing the curves of best fit.

A plot of the attenuation coefficient vs. frequency to the power of 4 (ie to f^4) then allows assessment of whether the measured attenuation fits the assumed Rayleigh model. Figure

26 shows that the minimum three data points (at the three values of f) fit a linear relationship assumed by equation [3.1].

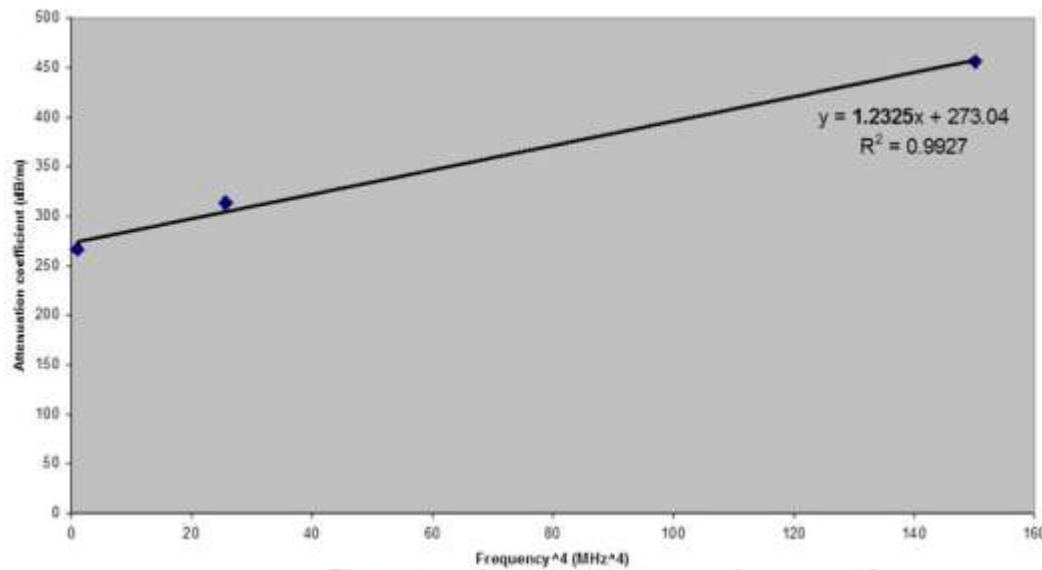


Figure 26 Plot showing the fit of the data to the assumed Rayleigh model.

The gradient of the line of best fit in Figure 26 is then equal to the product of the parameter a_R and the grain size D^3 , according to equation [3.1]. The parameter a_R is proportional to another parameter Δ^2 , which is a function of the stiffness constants. The austenitic material is known to be anisotropic and the stiffness constants of a material with a similar composition were measured using a single crystal [7]. In a single crystal, all the lattice structure is organised to align with the three major crystal axes of the unit crystal. Using ultrasonic velocity the three basic elastic stiffness constants can be measured. Hence the constants are $C_{11}=203.6\text{GPa}$, $C_{12}=133.5\text{GPa}$ and $C_{44}=129.8\text{GPa}$ [7]. A discussion regarding the elastic constants is presented in Section 3.7. Given that,

$$\Delta = \frac{2C_{44}}{C_{11} - C_{12}} - 1$$

, and the required constant is,

$a_R \propto \Delta^2 = 7.3077$. Now assuming the constant of proportionality to be equal to 1, we get the relation: $\Delta^2 D^3 = 1.2325$.

This then gives a value of 0.55mm for the grain size. If the frequency of inspection is chosen to be 1.5MHz, then the wavelength of the longitudinal wave would be ~3.8mm, which is about 7 times greater than D ; alternatively, $D \sim 1/7^{\text{th}}$ of the wavelength.

In summary, the experimental data supports the view that grains become significant scatterers of the sound energy when they approach a size approximately $1/10^{\text{th}}$ of the wavelength [2]. This implies that the description of the weld inside the model must sufficiently capture significant scatterers, but can neglect detail that is smaller (which would lead to needless inefficiencies and increased cost). This is termed the **minimum scatterer criterion** and is then used to set the scanning resolution for the EBSD scans.

3.3.2 Empirical study of scanning resolutions

Several trials were undertaken to optimise the scanning resolution (step size), electron beam current, the video gain and the integration time of the EBSD camera. The aim of the studies was to optimise parameters that maximise acquisition rates and reduce the overall cost of scanning the entire weld sections. As stated earlier, a primary goal is to select sufficient resolution for the model to effectively predict the sound propagation. Figure 27 shows the orientation maps of an area 2.5mm x 2.5mm when using different scanning step sizes. The best resolution showing well defined boundaries was given by the smallest step size of 5 μ m as shown in Figure 27(d). However the acquisition time at a 5 μ m resolution is 60 times longer than the scan with a step size of 40 μ m; considering that the area shown here is only 6.25mm², the required scanning time for a full weld cross section will be excessively costly. However, for the required purposes, the resolution of 40 μ m is deemed sufficient as it captures the boundaries between the regions sufficiently well. Note that at a frequency of 1.5MHz the longitudinal wavelength is ~3.8mm with the minimum scatterer being 0.38mm. Hence a 40 μ m step size fits ~10 sampling points within the width of the scatterer, which is sufficient to capture the significant regions within the weld map. Hence based on the minimum scatterer criterion a step size of 40 μ m was selected.

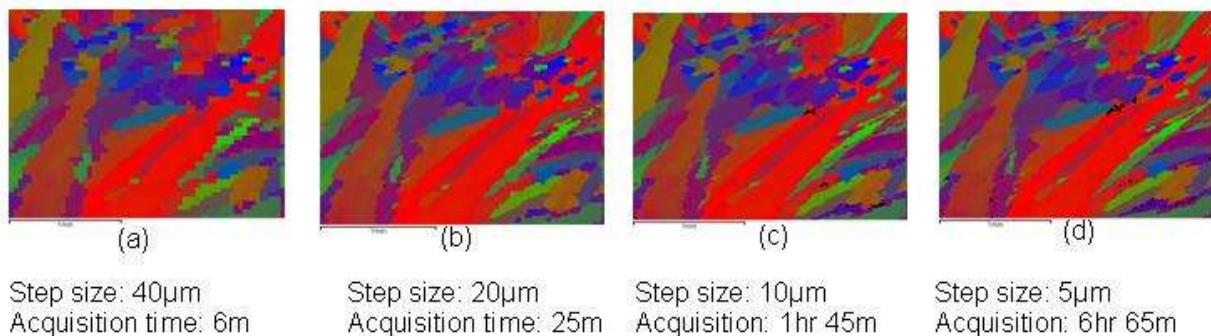


Figure 27 Scans at several step sizes and the corresponding time to completion.

3.4 Processing the EBSD data

Processing is necessary to convert a data set containing 3.8million sampling points covering an 80mm by 86mm weld cross section into a simpler orientation map for input to the modelling platform (Section 7). Determining the grain boundaries is dependent on the level of misorientation allowed within a region deemed to be a grain, ie how much orientation difference between areas was required to assign them as different grains. Allowing the misorientation range to increase effectively coarsens the grains. Figure 28(a) and 28(b) show the complexity of the orientation map when the allowed misorientation within a region defined to be a grain is small. The number of grains reduces significantly when the misorientation range rises to 20°, as shown in Figure 28(c).

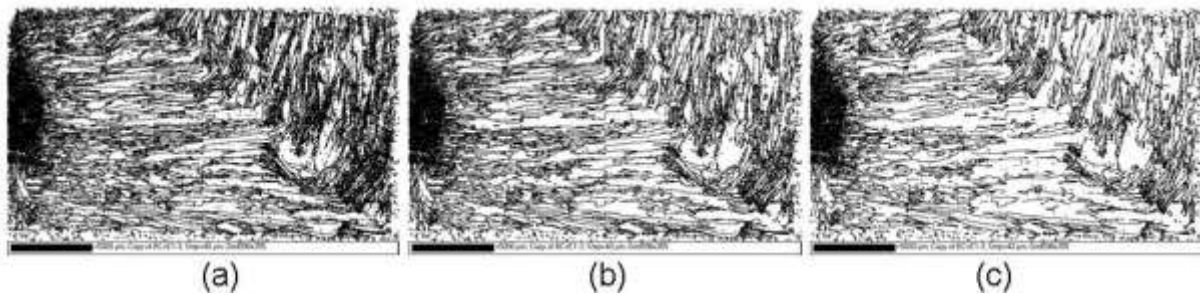


Figure 28 Grain orientation map when the misorientation range is (a) 5°, (b) 10° and (c) 20°. The area represented is about 20mm by 20mm at the clad, weld, buttering interface.

The misorientation within a grain or across grain boundaries can be quantified using the EBSD data, as shown in Figure 29. The raw map makes use of colour gradient to represent the misorientation within a grain. The insets in Figure 29 are the misorientation profiles over the lines indicated by the arrows. However, the concept of misorientation within grains cannot be transferred to the model. For the model, well defined regions (ie within closed boundaries) and with each closed region assigned one particular orientation is required. This gave rise to the development of a processing step termed **orientation unification**.

The aim of the orientation unification method, like the scanning resolution, is to satisfy the minimum scatterer criterion. Firstly, select a misorientation range such that the smallest grains approach the size of the minimum scatterer; this misorientation range for the DISSIMILAR weld specimen was evaluated to be 20°. Secondly, statistical analysis over the entire weld map was performed to select a small number of key (major) orientations around which the misorientation range was placed. Hence, the weld map is now composed of regions which are one of these major orientations and each major orientation is assigned its own distinct colour.

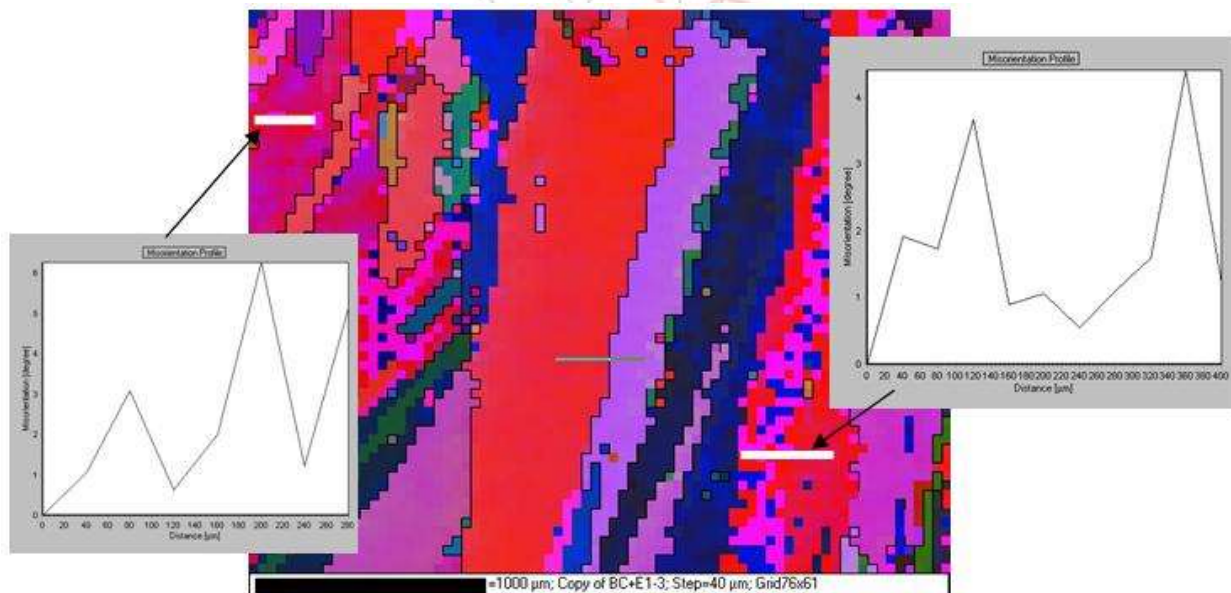


Figure 29 Misorientation profiles along two lines, with the insets showing the misorientation along the lines which is represented on the 2D map as a colour gradient.

Table 3.1 shows the eleven major orientations identified in the buttering and weld regions in terms of the Euler angles. Table 3.2 shows the eleven major orientations in terms of the three angles with respect to the specimen axes, converted using the transformation given in Figure 20. Hence the entire weld can now be described in a map which makes use of a number of major orientations to describe closed regions which satisfy the minimum scatterer criterion.

Table 3.1 Euler angles of the eleven major orientations in the DISSIMILAR weld specimen.

Colour	$\phi 1$ (°) (rotation about z)	ϕ (°) (rotation about x)	$\phi 2$ (°) (rotation about z)
Red 	0	0	0
Lime Green 	103.8	15.9	68
Yellow 	190.1	28.9	66.9
Blue 	265.1	43.9	9
Fuchsia 	310.9	7.9	11.1
Cyan 	68.1	45	85.6
Maroon 	44	23.9	14.5
Purple 	322	39.3	0.6
Gray 	231.8	32.29	29.93
Green 	330.6	40	16.8
White 	250.5	42.7	56.3

Table 3.2 The eleven major orientations expressed with respect to the specimen axes.

Colour	α (°) (rotation about x)	β (°) (rotation about y)	γ (°) (rotation about z)
Red 	0	0	0
Lime Green 	176.1	195.4	352.3
Yellow 	331.5	4.9	255.8
Blue 	355.3	43.7	272.2
Fuchsia 	5.1	6.0	322.3
Cyan 	200.5	221	326
Maroon 	197.7	196.3	235.8
Purple 	32.8	23.0	329.4
Gray 	338.6	24.8	257.0
Green 	36.4	18.5	353.5
White 	342.9	40	300.6

3.5 Analysis of the microstructure and texture of the austenitic weld

The V-prep weld section generated from the EBSD scanning and post-processing is shown in Figure 30. In the weld, the dendritic grains display epitaxial growth, starting from the earlier weld deposits growing upwards through subsequent deposits. The orientation of the dendrites follows the heat flow directions. Note that the grains in the buttering region are near horizontal and there is a clear difference between the orientations of the weld and the buttering, as indicated by the colours. The major orientations in the weld are coded red, lime

green and blue, with orientations $(001)[100]$, $(011)[100]$ and $(013)[100]$, respectively; note that orientation component expressed in the form $(hkl)[y]$, $[uvw]/z$. The weld metal exhibits a strong $[100]$ fibre with the $[100]$ direction oriented along the z-axis, as shown in Figure 30. This is consistent with the observed solidification growth in cubic crystalline materials. The grains have sizes in excess of 2 to 4mm and are tilted from the z-axis by up to 35° .

The grains on either side of the austenitic weld have fibrous orientation which is near $[-3-10]/z$ or $[-210]/z$, as shown in Figure 30(d) and (f). The grains in the buttering are perpendicular to the z-axis, ie they have a 90° rotation about the y-axis when compared to the orientation in the weld region. The major orientations in the buttering are yellow $(101)[010]$ and red $(001)[100]$. Figure 31 shows a schematic of the 3D crystal orientations of the eleven major orientations to allow visualisation of how the crystals exist in the different regions of the weld.

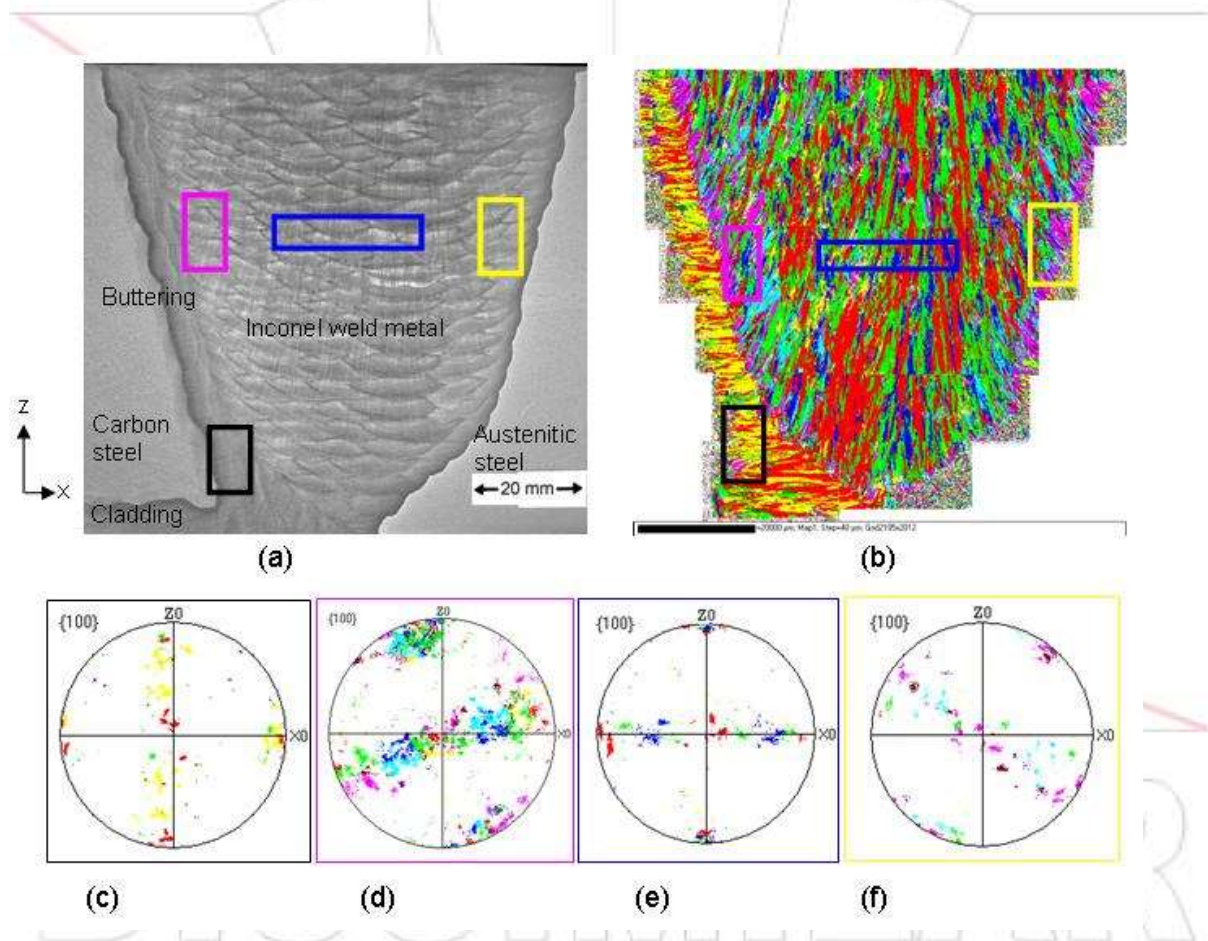


Figure 30 The optical and EBSD processed weld maps along with a texture analysis of different regions of the weld.

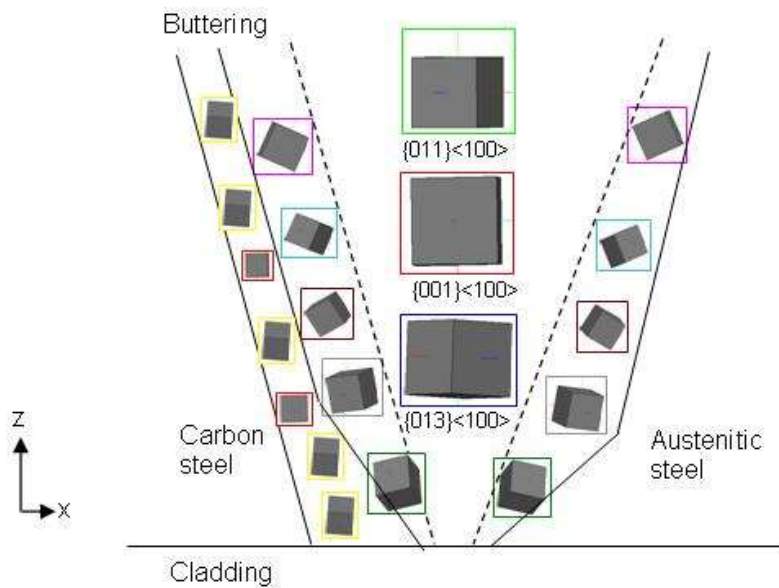


Figure 31 A schematic showing the orientations of the cubic unit crystal in the different regions of the weld.

Figure 32 shows the three weld sections extracted from the DISSIMILAR specimen (as shown previously in Figure 18) and they show that (1) they are well described by the same major orientations and (2) the volume fraction of those major orientations is similar.

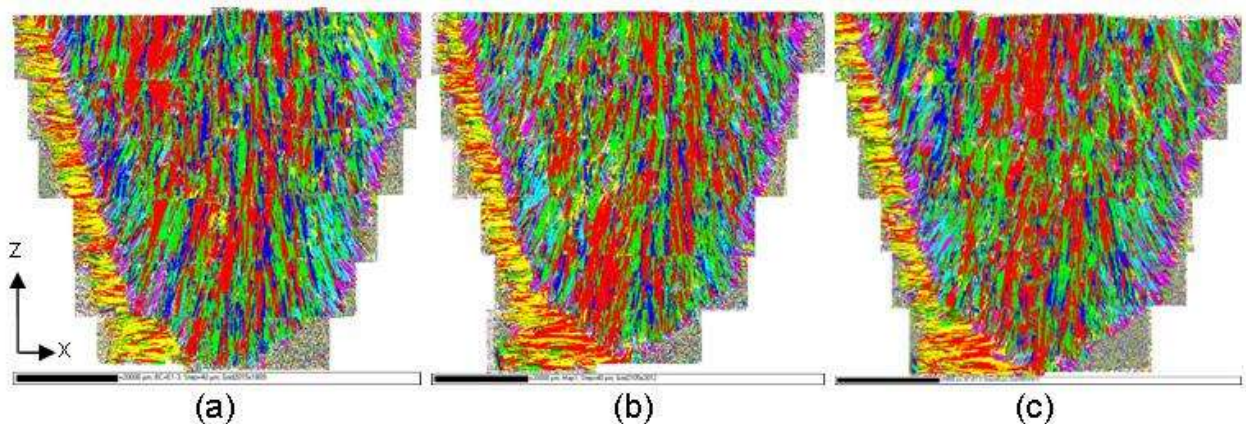


Figure 32 The orientation maps showing the eleven assigned orientations (see Table 3.1) of (a) Sample 1 near Flaw 2, (b) Sample 2 in the middle and (c) Sample 3 near Flaw 8.

The key texture direction parallel to [100] (in red) found in all three weld sections is shown in Figure 33. Samples 1 and 3 (ie those near the ends of the DISSIMILAR plate) exhibit similar distribution of the [100] fibre, with the largest concentration in the middle of the V-prep weld. However, in Sample 2 the distribution of the [100] fibre is pushed towards the stainless steel parent. Hence, although the volume fraction of [100] fibre is similar in near the ends of the plate and the middle, the distribution appears to be varying.

The distribution is determined by the process conditions (ie the heat flow directions) but this can have an effect on the ultrasonic propagation. This then requires consideration of how the

weld microstructure varies parallel to the welding direction, ie in a direction perpendicular to the cross sections shown in Figures 32 and 33.

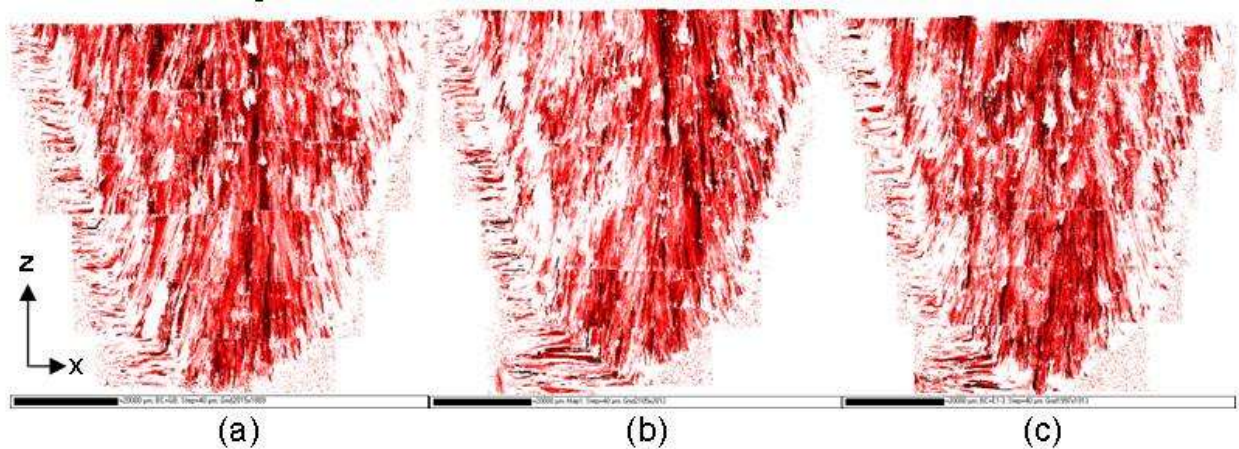


Figure 33 The distribution of the [001] fibre in three weld cross sections samples; (a) Sample 1 near Flaw 2, (b) Sample 2 in the middle and (c) Sample 3 near Flaw 8.

3.6 Lengthwise uniformity

The study of the weld microstructure variation parallel to the welding line, what is now termed the **lengthwise uniformity**, was undertaken using both EBSD analysis and an ultrasonic technique using Flaw 1.

3.6.1 Analysis of lengthwise uniformity using EBSD

Four specimens were extracted from the weld as indicated in Figure 34. Specimens L2 and L4 were scanned by EBSD while specimens L1 and L3 were examined using optical microscopy. Each specimen was 25mm by 15mm by 4mm thick and the large side (ie 15mm x 25mm) contains the microstructure which develops parallel to the welding direction, ie along the y-axis; EBSD was then used to scan the surface.

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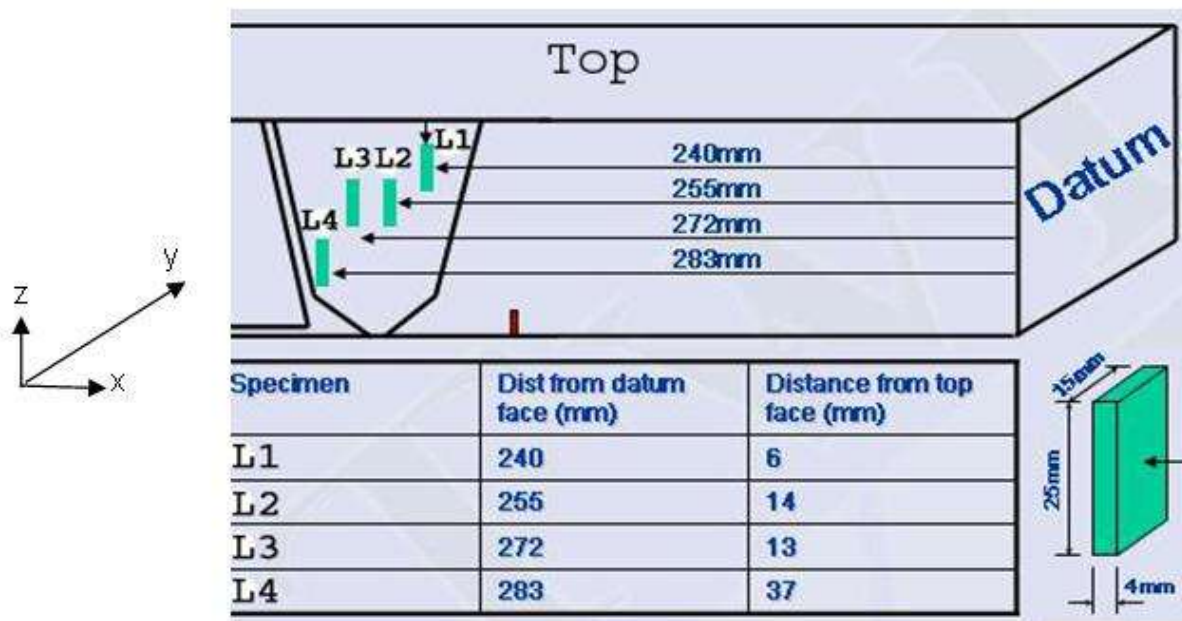


Figure 34 Positions and dimensions of specimens extracted from the weld for lengthwise uniformity analysis along the y-axis.

Specimen L2 was cut near the centre of the weld and Figure 35 shows the orientation map using the major orientations (Tables 3.1 and 3.2). Hence, as in the cross section maps shown in Figure 32, the major orientations of Table 3.1 are sufficient to fully map the scanned y-z plane. The dendritic grains take the orientations red (001)[100], lime green (011)[100] and blue (013)[100]. The smaller grains take the orientations near $[-3-10]//z$ or $[-210]//z$. The width of the columnar grains takes an average value of $650\mu\text{m}$ (with a scatter of $200\mu\text{m}$) and the lengths greater than 10mm, which is consistent with the observations in the x-z plane (ie the weld cross section maps).

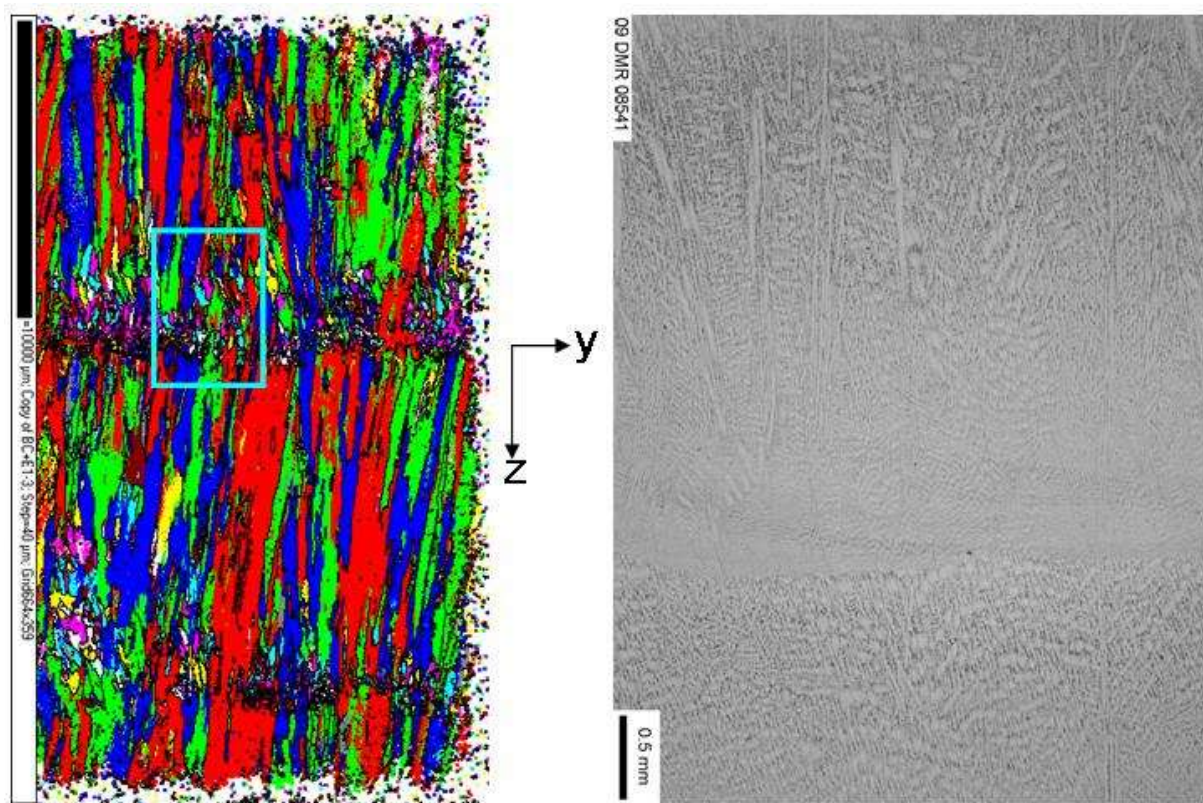


Figure 35 Processed orientation map of specimen L2 using the major orientations given in Table 3.1 and an optical image of specimen L1 close to the same region, identifying the inter-run boundary shown in cyan box.

Specimen L4 was close to the bottom of the weld near the buttering region, ie close to the edge of the weld. As shown in Figure 36, the grains at the top of the specimen are dendritic with major orientations of blue (013)[100] (see corresponding region in Figure 32(a)), whereas those grains near the bottom are smaller with average dimensions of 40 μ m (width) by 100 μ m (length). The lower region on specimen L4 has the same orientations as the buttering region identified in Figure 32, which are mainly yellow (101)[010] and red (001)[100]; the grains in this region are equiaxed.

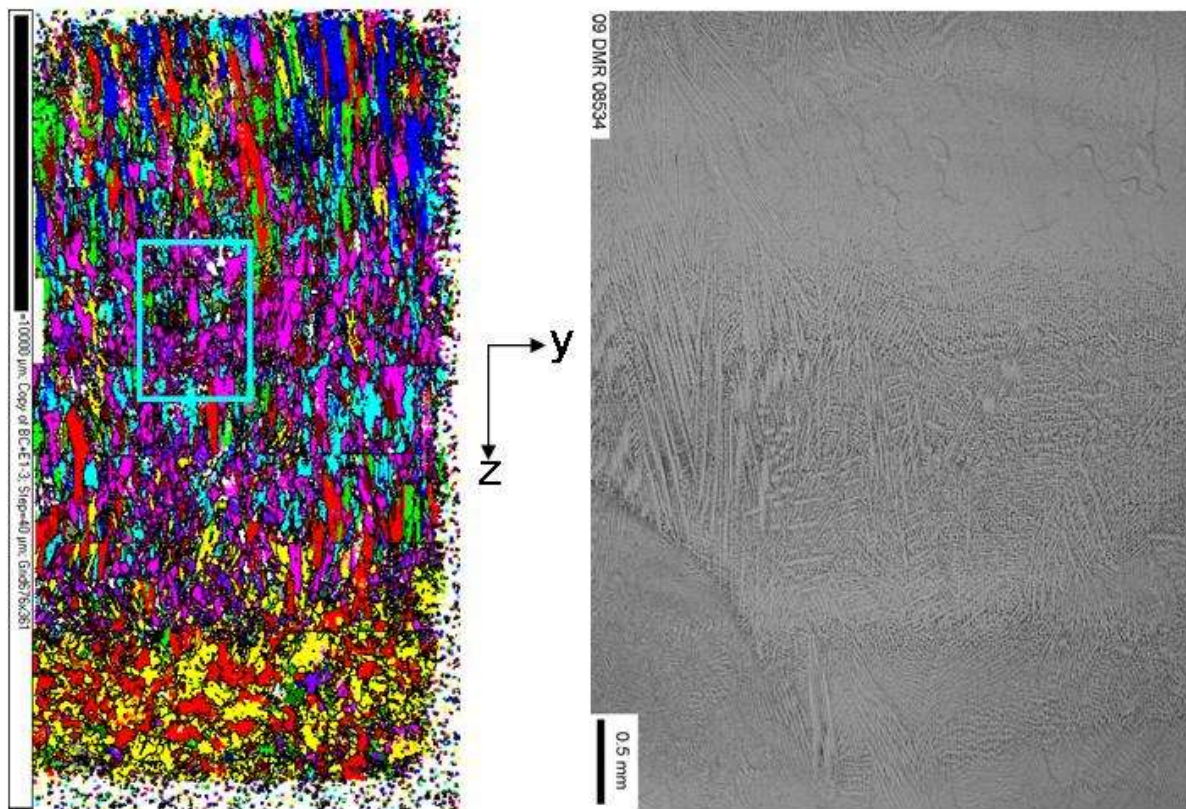


Figure 36 Processed orientation map of specimen L4 using the major orientations given in Table 3.1 and an optical image of specimen L3 close to the same region showing the inter-run boundary shown in cyan box.

Using the orientation maps of the samples and specimens extracted in the x-z and y-z planes, the average grain size of the different regions has been evaluated and given in Table 3.3. Despite the large scatter in the data, the shape of the grains can be approximately described as rods. The grains away from the edge of the weld are generally large and long, whilst those near the weld edges are small, short and tilted. A schematic of the grain shapes in the different regions is shown in Figure 37.

Table 3.3 Average grains sizes of the dendrites in different regions of the weld.

	x-z plane (data taken from the Sample 1 in the regions close to specimens L2 and L4).		y-z plane	
	W (μm)	L (μm)	W(μm)	L(μm)
Buttering	Width of the butter	780 ± 300	700 ± 300	650 ± 300
Large grains	900 ± 300	10000 to 20000	648 ± 200	10000 to 20000
Small grains	62 ± 30	150 ± 50	40 ± 30	100 ± 50

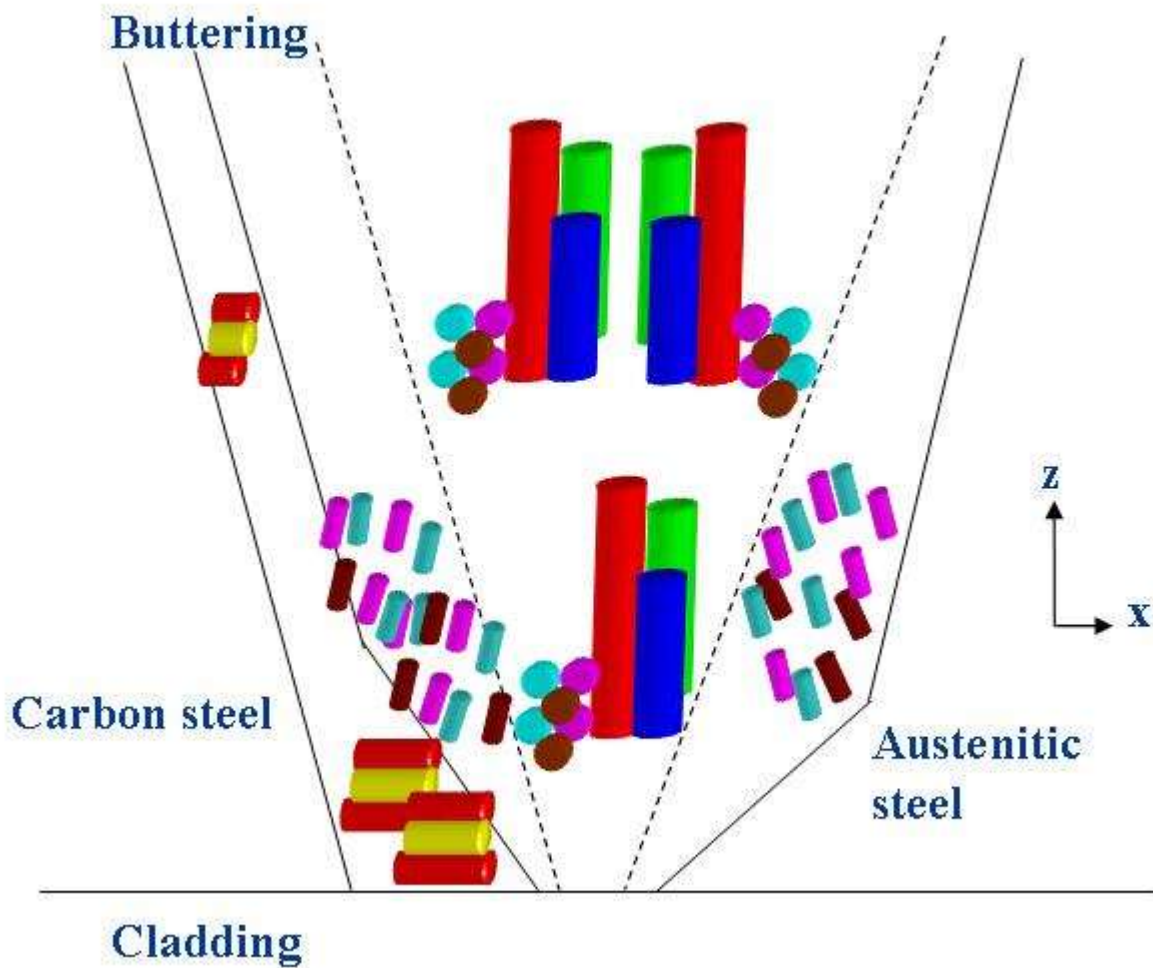


Figure 37 Schematic showing the rod like grains and their orientations in the different regions of the weld.

3.6.2 Analysis of lengthwise uniformity using ultrasonics

Flaw 1 (Figure 6) was introduced into the DISSIMILAR specimen for the purpose of ultrasonically studying the uniformity of the weld microstructure along the welding direction. Several experiments were undertaken during the ultrasonic baseline scans (Section 7) and the results were then analysed. Figure 38 shows the plan view of the inspection showing the probe which travels parallel to the weld centreline at a fixed standoff while the signal from the corner and tip of surface breaking slot Flaw 1 was monitored.

Figure 39 shows the inspection in side view and the data sets from the automated baseline inspection that was used for the uniformity analysis. The automated baseline was chosen as it contains encoded data with well-defined stand-off distances with respect to the datum. Additionally the frequency of the probe was 1MHz and the beam angles chosen were 45, 60 and 65°. The data from the austenitic side did not require the sound beam to traverse the weld; hence it is the reference data set.

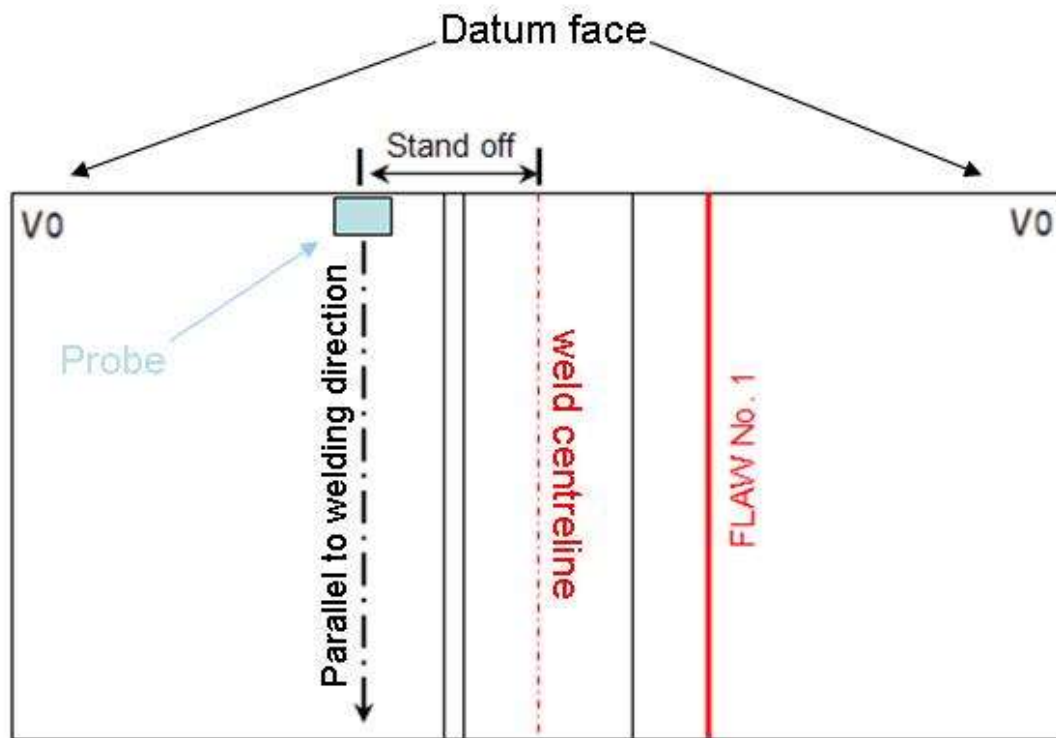


Figure 38 Plan view of the lengthwise uniformity experimental setup.

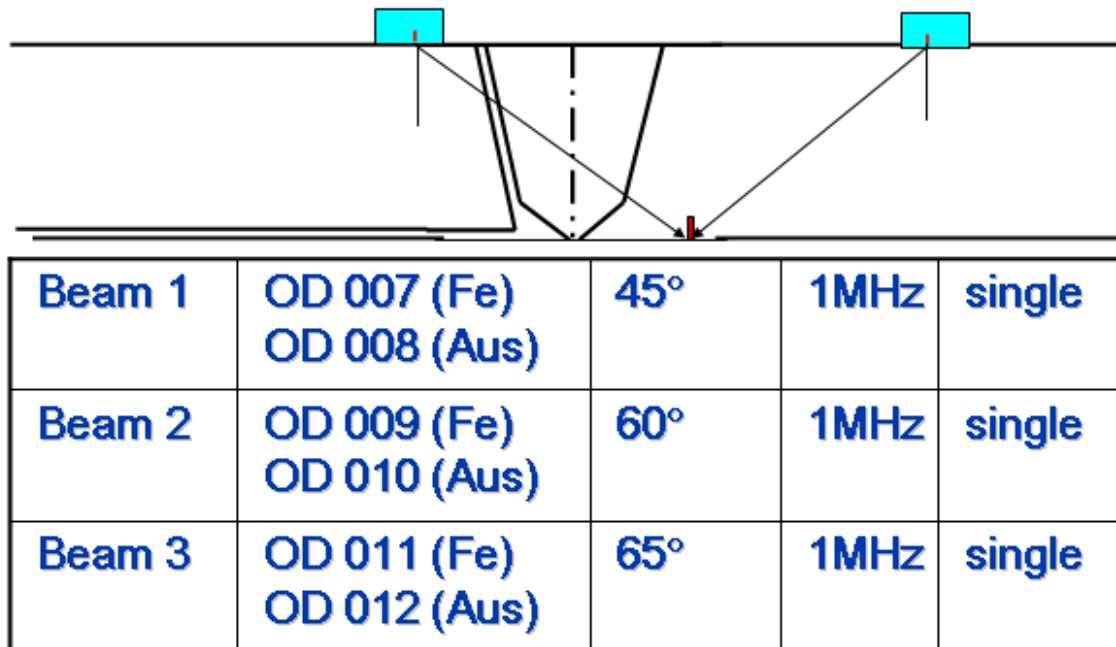


Figure 39 Side view of the lengthwise uniformity experimental setup, probes used and the data sets from the automated baseline scans.

Figure 40 shows the data from the reference scans performed from the austenitic side. The position of the artificially introduced flaws (Figures 5 - 13) is shown along the y-axis direction

in Figure 40 (and the following figures) to aid the analysis of the data. Figure 40 shows that the variation in amplitude of the slot corner over the length of the weld does not change by more than ~2dB for the two beam angles. Note that the vertical dashed line in Figure 40 at a y-axis position of 290mm represents the point where the as-received DISSIMILAR specimen (Figure 14) was halved to take the middle section for EBSD mapping.

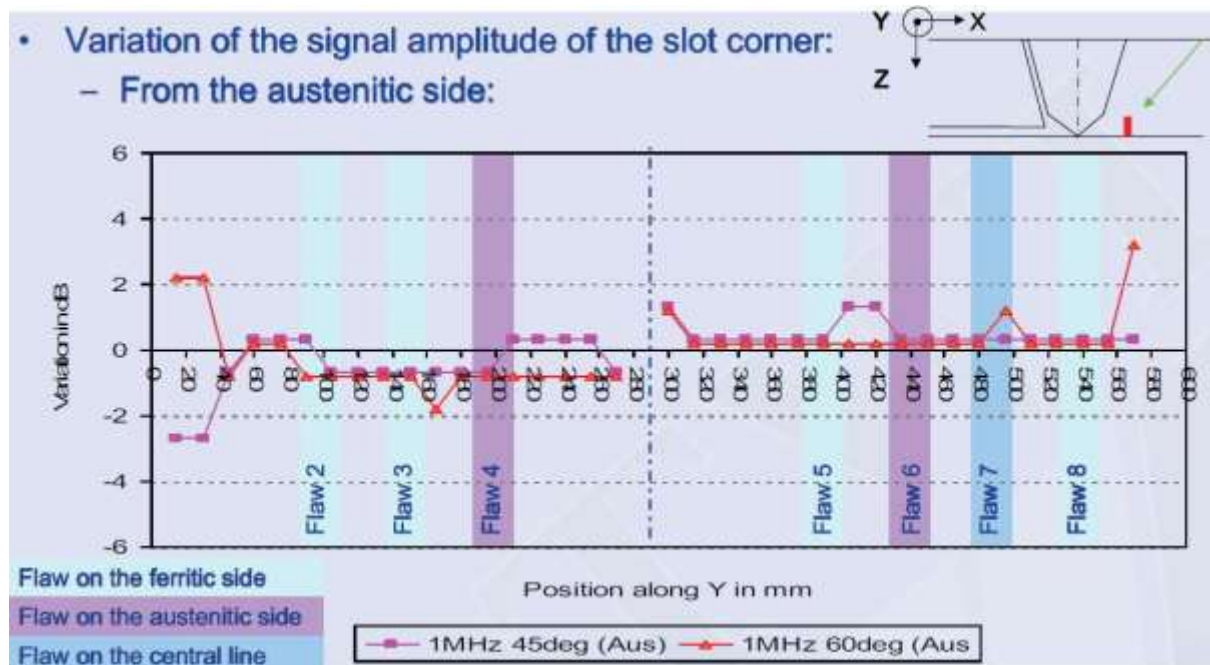


Figure 40 Variation in the signal amplitude from the slot corner measured from the austenitic side (reference scan).

Figure 41 shows the variation in the horizontal position of the slot corner measured from the austenitic side. In this dataset the effects due to the ends of the plate are more pronounced with variation in excess of 4mm near $y=0$ mm and $y=290$ mm. Figure 42 shows the variation in the vertical position of the slot corner measured from the austenitic side.

With the probe positioned on the ferritic side, the sound beam has to travel through the weld to approach the slot. Hence the sound wave will be subject to the distortive effects of the weld. Figures 43 to 45 show the data collected with the sound travelling through the weld. Figure 43 shows variation in the amplitude of the slot corner, Figure 44 shows the variation in horizontal position of the corner echo and Figure 45 shows variation in the vertical position of the corner echo.

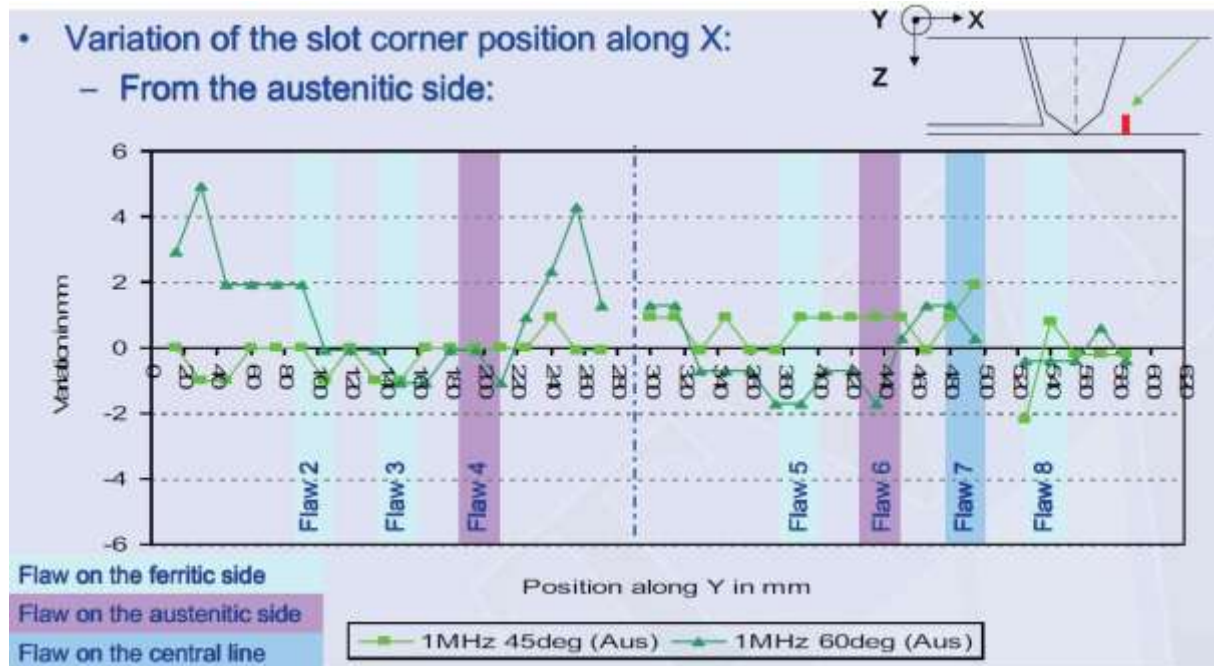


Figure 41 Variation in the horizontal position of the slot corner measured from the austenitic side (reference scan).

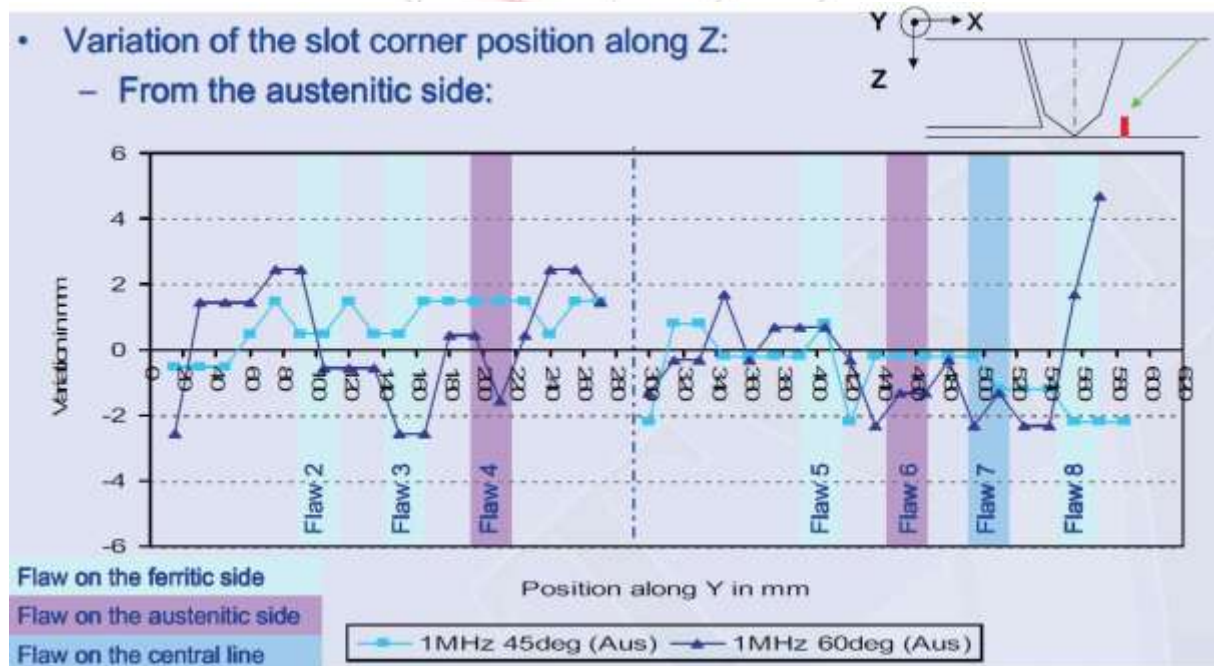


Figure 42 Variation in the vertical position of the slot corner measured from the austenitic side (reference scan).

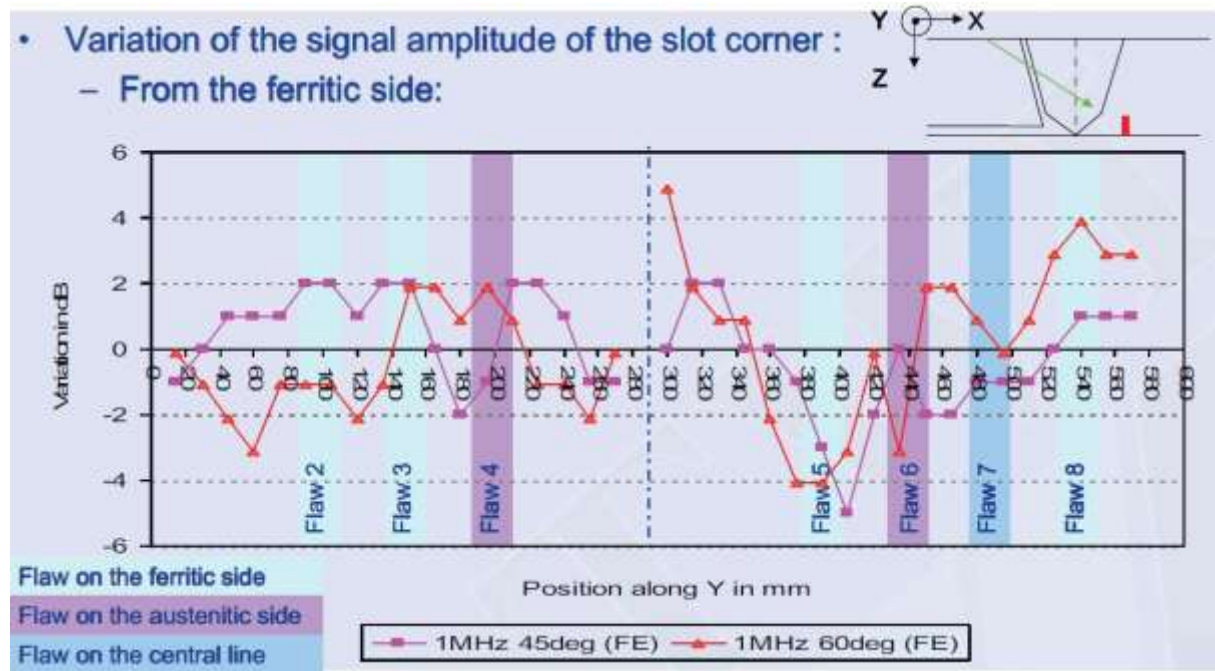


Figure 43 Variation in the signal amplitude of the slot corner measured from the ferritic side.

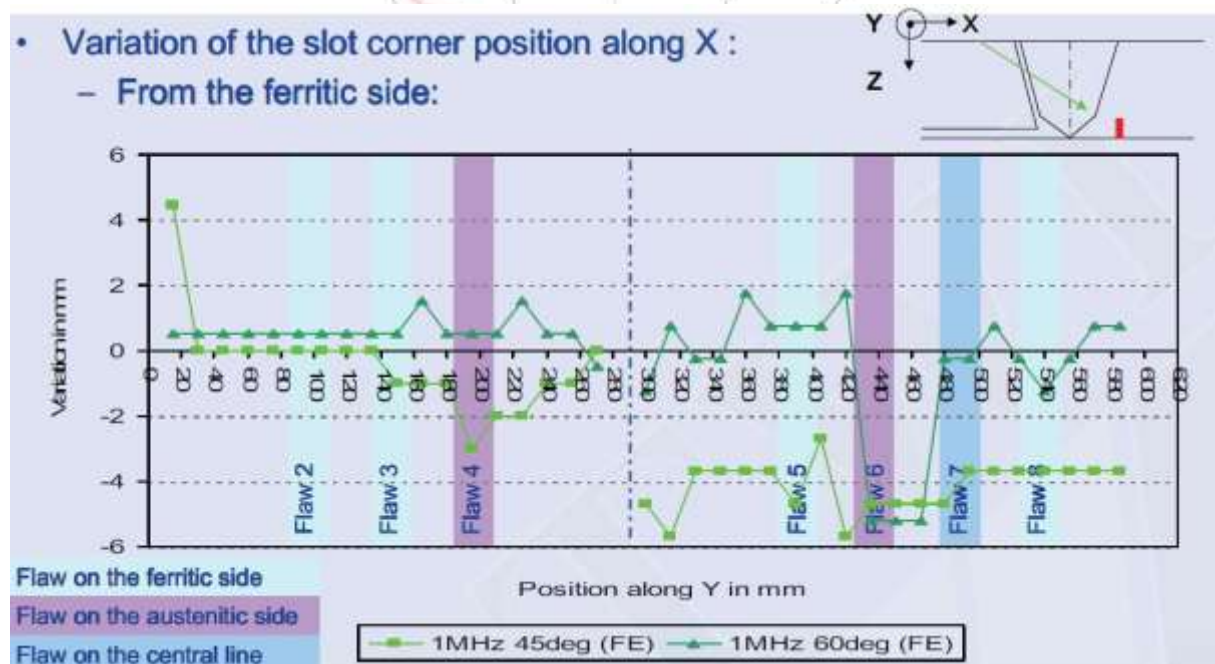


Figure 44 Variation in the horizontal position of the slot corner measured from the ferritic side.

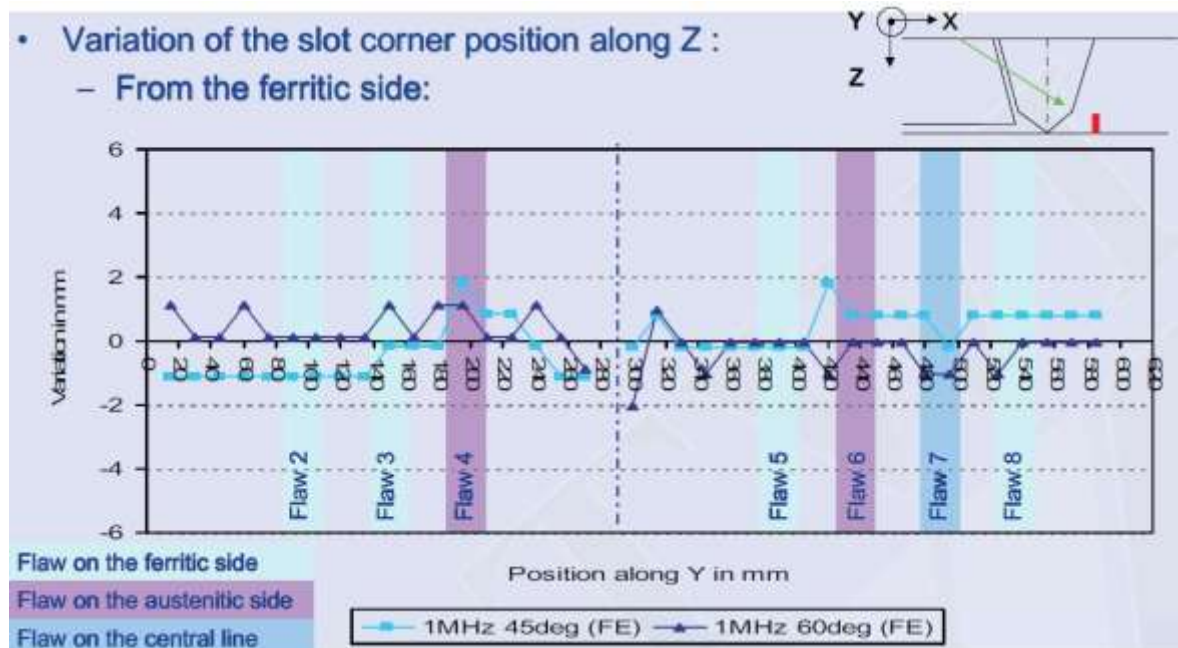


Figure 45 Variation in the vertical position of the slot corner measured from the ferritic side.

Note in Figure 44 that the data from the 1MHz 45° beam for $y > 290$ mm is significantly offset in comparison to the other datasets. The reason for this discrepancy is not known, however the variation to itself is similar to the other datasets.

For each flaw, the error between the measured through-wall positioning of top and bottom edges of the flaws (when using the conventional automated technique described in Section 6.3.2 and reported in Tables 3 to 9 of Appendix E) and the nominal values (confirmed through sectioning for Flaws 2, 3 and 4) is presented in Figure 46. This data indicates changes in the measurement error along the length of the weld, which could potentially be related to changes in the microstructural condition.

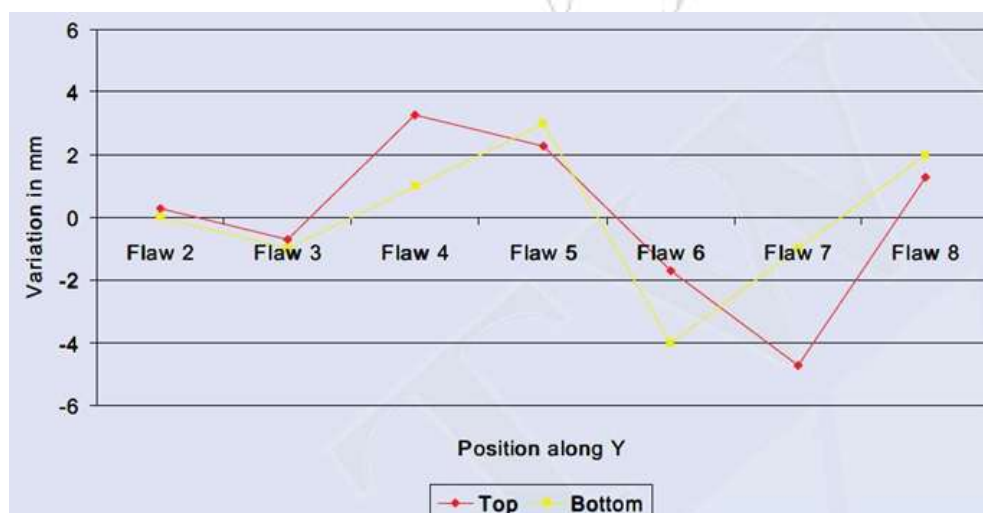


Figure 46 Error in the through-wall position of flaw edges using the conventional automated technique (see Section 6.3.2) compared to nominal values.

3.6.3 Summary of lengthwise uniformity analysis

- The analysis using EBSD shows that, over the 15mm studied, the microstructure is fairly uniform in the lengthwise direction.
- The ultrasonic analysis shows that the overall variation in positional changes is within 2mm, with the maximum variation being 5mm.
- The greatest effect of the weld anisotropy appears to be on signal amplitude, which is nevertheless within 2dB.

The uniformity study was aimed at determining whether sampling the weld microstructure (by taking several cross sections) for mapping is valid. In conclusion, the measured uniformity of the microstructure along the welding direction appeared to suggest that this weld was relatively uniform and hence the sampling approach was likely to be valid for the purposes of sufficiently quantifying the weld within the models.

3.7 Evaluation of the stiffness constants

To be able to model the sound propagation in the austenitic weld, the stiffness constants of the cubic crystalline system must be evaluated as accurately as possible. A popular method of doing so experimentally is the use of single crystals of that alloy and measuring the ultrasonic velocity of longitudinal and the two polarized shear wave modes [7, 8]. The velocities of the different sound wave modes are related to the three independent stiffness coefficients (C_{11} , C_{12} and C_{44}) of the cubic system, which can then be derived.

In the DISSIMILAR project an attempt was made to grow a single crystal using consumables of the Inconel 182 specified for the Manual Metal Arc (or SMAW) process specified for the specimen. Casting methods were used in the attempt to grow the crystal, however subsequent SEM analysis showed sufficient uniformity was not achieved.

Nickel super alloys are now widely used for aerospace applications (in particular for single crystal turbine blades) and extensive information regarding these super alloys (eg CMSX486, CM186LC, Rene N4) is available in the public domain [8, 9, and 10]. In the case of aerospace materials, researchers have noted that there is little impact on the composition of alloys on the measured stiffness coefficients [8, 9]. Based on this assumption, the values of the stiffness coefficients measured earlier [7] on an austenitic alloy with similar composition to the alloy used in the weld of the DISSIMILAR specimen was used to map the weld and input to the model for studying the propagation of sound waves.

It is noted that since the exact values of the stiffness in the DISSIMILAR weld was not determined, the subsequent work on adapted delay laws (Section 6) will have a degree of error. This error will be manifest in the experimental validation data and will be considered in the performance analysis of the techniques (Section 7).

The general recommendation for future effort is to, where the intention is to make use of advanced techniques such as adapted delay laws (Section 6), undertake the growth of a single crystal of the alloy to be used in the weld. Growth of single crystals is not easy and several different methods to grow the crystals may need to be investigated before success. However, establishing the actual stiffness coefficients will allow for better technique design.

3.8 Summary of EBSD analysis

- The EBSD analysis showed that crystalline growth during the solidification of the weld led to a macroscopic texture containing epitaxially grown dendrites along the preferred fibre direction of (001)//z.
- The scanning parameters, in particular the resolution, must be set according to the minimum scatterer criterion in order to minimise costs.
- Processing using the orientation unification concept has allowed preparation of the EBSD data for input to the model, with closed regions (using boundaries) that are assigned a major orientation containing the range of allowed misorientation.
- Analysis of the lengthwise microstructure shows good uniformity along the welding direction.
- Results from the x-z and y-z planes suggest that the grains are rod like in shape, consistent with previous experience which found dendritic growth.

It is possible that the sound wave may not be overly sensitive to some of the major orientations, which were selected statistically. Validation efforts to investigate the influence of particular orientations with respect to a propagating sound wave may allow for further simplifications when mapping the weld. However, such refinement work was not undertaken in the DISSIMILAR project and remains a task for future efforts.

3.9 Financial costs of implementing EBSD

EBSD scanning is implemented using a special detector attached to a Scanning Electron Microscope (SEM). EDAX (www.edax.com) and Oxford Instruments (www.oxinst.com) are leading suppliers of SEM and EBSD instrumentation. At the time of writing this document, the estimated cost of a standard SEM and EBSD system is £300,000. In addition specialist training will be required of the operator who will require a firm basis in metallurgy and knowledge of operating the SEM system.

For an organisation interested in acquiring the capability to implement EBSD analysis in-house, the primary cost will be the acquisition of the equipment and personnel costs. Additionally there will be costs associated with regular calibrations, possible costs for repairs to the systems, machining costs, chemicals for specimen preparation and overheads. An alternative to maintaining the capabilities in-house would be to subcontract the EBSD scanning and analysis to third parties. Such third parties are likely to be institutions (such as TWI who possess SEM/EBSD facilities) or universities (such as the University of Birmingham who undertook the microstructural development work in the DISSIMILAR project).

Regardless of which method is chosen, quantification of the weld microstructure using the EBSD technique involves considerable expense. In the DISSIMILAR project three sections were extracted and fully scanned at a cost to the project of £113,000. Future attempts may require the scanning of more sections, different materials (involving further investigations into specimen preparation), changes in parameters (resolution, misorientation) and further exploration of implementation methods, which may lead to additional costs. Choosing to explore the methods and techniques developed in the DISSIMILAR project is therefore not an easy option. Therefore this approach is only likely to be viable for industries (such as the power and oil & gas) where extremely critical components are present, where the consequences of failure would adequately justify such costs to mitigate.

4 Probes

4.1 Introductory comments

Ultrasonic transducers or probes make use of the piezoelectric effect to both generate and detect ultrasonic energy [2]. The aim of the DISSIMILAR project was to make use of advanced materials and methods available at the time to manufacture and then investigate the implementation of array probes for the inspection of the DISSIMILAR DMW. The transducer technology was provided by Alba Ultrasound of Glasgow, UK.

Two types of arrays were specified and manufactured for the DISSIMILAR project and their performance was compared with other probe types used in three different baseline inspections (Section 7). In this section, the methods and models used to specify the two DISSIMILAR array probes is presented. The approach to specification illustrated in Sections 4.2, 4.3 and 4.4 provides information on the typical steps involved in undertaking specification of an ultrasonic array for the inspection of austenitic welds.

4.2 Requirements

The difficulties of inspecting austenitic welds have been outlined earlier. In general, for thick section (ie >25mm) welds several key requirements are known:

1. Longitudinal wave mode must be used
2. Input power (ie pulsing voltage) applied to probe must be sufficient
3. The ultrasonic pulse generated must contain a broad frequency content
4. Low frequency is required to reduce the levels of attenuation

Additional requirements for effective implementation of array techniques involving focusing of the sound energy include ensuring that the radiating area of the probe is large enough for the near zone length to be greater than the range at which focusing is required.

The use of longitudinal waves is recommended from experience when the full volume of the weld needs to be inspected. Supplemental techniques involving the use of shear waves skipping (reflecting) on the back wall of the specimens maybe used for detection of flaw such as lack of side wall fusion (ie not requiring the sound to enter the weld), but such techniques will not be discussed in this document. Similarly, experience shows that the instrumentation must be able to provide sufficient power for the sound wave to be able to penetrate sufficient distance within the weld, ie the pulsing voltage must be greater than 200V (Section 5).

The bandwidth, ie the frequency content in the sound wave, is required to be as broad as possible, such that the sensitivity to a wide range of discontinuities is increased. In contrast, the requirement for low frequency is a balance between required inspection range and attenuation. As discussed in Section 3, the wavelength is required to be much larger than the mean grain size along the propagation path to place the system in the Rayleigh regime of attenuation. If the welded component was in existence then the first task would be to trial several frequencies to establish sufficient penetration vs. attenuation. However, in the case of the DISSIMILAR project the specimen was not in existence when the probe specification effort started and hence a decision on frequency (ie based on experience) had to be taken. The chosen frequency was 1.5MHz which is known to be well optimised for inspection of the welds fabricated using the procedures used for the DISSIMILAR specimen previously.

4.3 Specification approach

Specification of ultrasonic probes through modelling is inherently an iterative process that may take several iterations to arrive at the final values of key parameters. In this document, the process undertaken and the results of specifying the two arrays are presented.

The first level specification pertains to ensuring that the probe will have the required ultrasonic characteristics, ie sufficiently configured beam size at the required position to allow for sizing, along with sufficient focusing to enhance probability of detection with good signal-to-noise (S/N) characteristics. The second level specification regards the manufacture of the array, ensuring that the materials are chosen and configured sufficiently well to output the specified performance of the first level specification. The first level specification was undertaken using a model termed SimulUS developed by Peak NDT of Derby [11, 12] and a model termed CIVA [13] developed by the Commissariat à l'Énergie Atomique (CEA) of France. The second level manufacturing specification was undertaken using a model termed PZ Flex developed by Weidlinger Associates Inc. of USA. The engines of the three models explored in the DISSIMILAR project are very different:

1. SimulUS uses Huygens' Principle to plot the sound field ahead of a radiator.
2. CIVA uses semi-analytical methods to plot the sound field and evaluate interaction of the field with discontinuities (ie flaws) in the medium.
3. PZ Flex is a finite element model with a well refined engine based on fundamental wave propagation equations and is focused on modelling the piezoelectric effect.

All three models have been validated for the particular task they were used for in this specification effort and examples of using all three models will be presented in this section.

4.4 Specification of the TRL-1 array

The final specification of the TRL-1 array is given in Appendix B. SimulUS and CIVA were used for the first level specification and PZ Flex was used for the second level specification.

4.4.1 First level specification (CIVA and SimulUS)

4.4.1.1 Approach

Aim is to select values for parameters in order to provide the best possible performance for the detection of flaws and sizing them in wall thicknesses up to 85mm. In specifying the probes the assumption is that the material is isotropic, ie the effects of the austenitic weld structure are not taken into account; the impact of the austenitic weld will be accounted for in the design of the technique, making use of the ability of arrays to manipulate the sound field ahead of them. However, it is important to ensure that the probe characteristics are optimised for effective control of the sound beam within the volume of the weld.

The TRL-1 probe has a specific configuration known as Transmit-Receive Longitudinal (TRL), where the transmitting and receiving arrays are separated such that the setup is essentially in a pitch-catch configuration. The array is further configured to generate the longitudinal wave mode. In order to avoid mode conversions when reflecting on boundaries (such as the back wall), all inspection techniques will be assumed to be in half skip mode (ie direct incidence). A TRL probe is made of transmission (Tx) and reception (Rx) parts as shown in Figure 47.

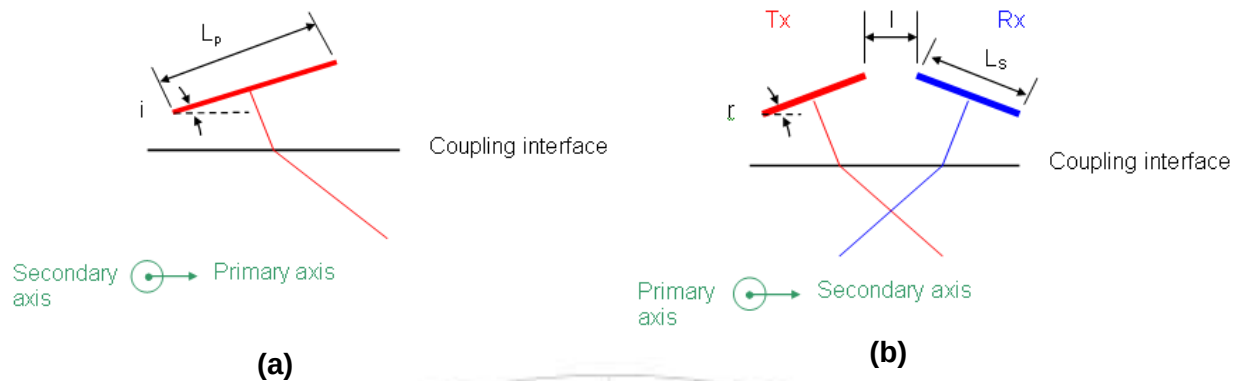


Figure 47 TRL profile along the (a) primary and (b) secondary axes.

In Figure 47 parameter L_p is the aperture of the array along the primary axis, equal to the number of elements along the primary axis (n_p) $\times$ the element pitch (p_p) and parameter L_s is the aperture of the array along the secondary axis, equal to the number of elements along the secondary axis (n_s) $\times$ the element pitch (p_s). Separating transmit and receive paths leads to the better S/N performance when applied to austenitic welds [14]. Key advantages given by the TRL configuration are:

- Elimination of the probe to steel interface echo.
- Providing a diverse beam path through the material providing some grain structure noise averaging.
- Eliminates the beam dead zone enabling the near surface material to be examined.

Table 4.1 is a summary of the parameters which are part of the optimisation effort.

Table 4.1 Probe parameters which are chosen and those that need to be optimised.

Parameter	Part of optimisation?	Initial value @ Iteration 1
Probe type	NO	TRL
Wave mode	NO	Longitudinal
Array type	YES	2D
Inspection type	NO	Direct / half skip
No. of elements on primary axis (n_p)	YES	16
Primary axis pitch (p_p)	YES	5mm
No. of elements on the secondary axis (n_s)	YES	4
Secondary axis pitch (p_s)	YES	5mm
Frequency	NO	1.5MHz
Coupling material	NO	Water (immersion)
Inclination / wedge angle (i)	YES	11.2°
Roof angle (r)	YES	5°
Inter array space (l)	YES	6mm
Coupling path distance	YES	15.6mm

The primary route to specifying the probe is to consider the sound field or sound beam generated by the probe, in particular the shape and energy in the beam. Modelling allows the evaluation of main beam characteristics at different steering angles and focus depths, and the amplitude of unwanted echoes around this main beam. To quantitatively compare the

simulated beams the -6dB cross beam size at the focus range is used. In order to achieve the best sizing resolution, the -6dB cross beam size must be minimised which also increases the intensity of the sound (ie focusing). Additionally, the optimisation will aim to eliminate side energy lobes which can lead to increases in the energy. The optimisation was required to provide good beam characteristics from a depth of 5 to 85mm. The optimisation effort underwent four iterations in total, which are presented and analysed in this document.

4.4.1.2 Iteration 1

The starting parameters values are given in Table 4.1. Figure 48 shows the beam cross section and side views along the primary and secondary axes as computed using CIVA.

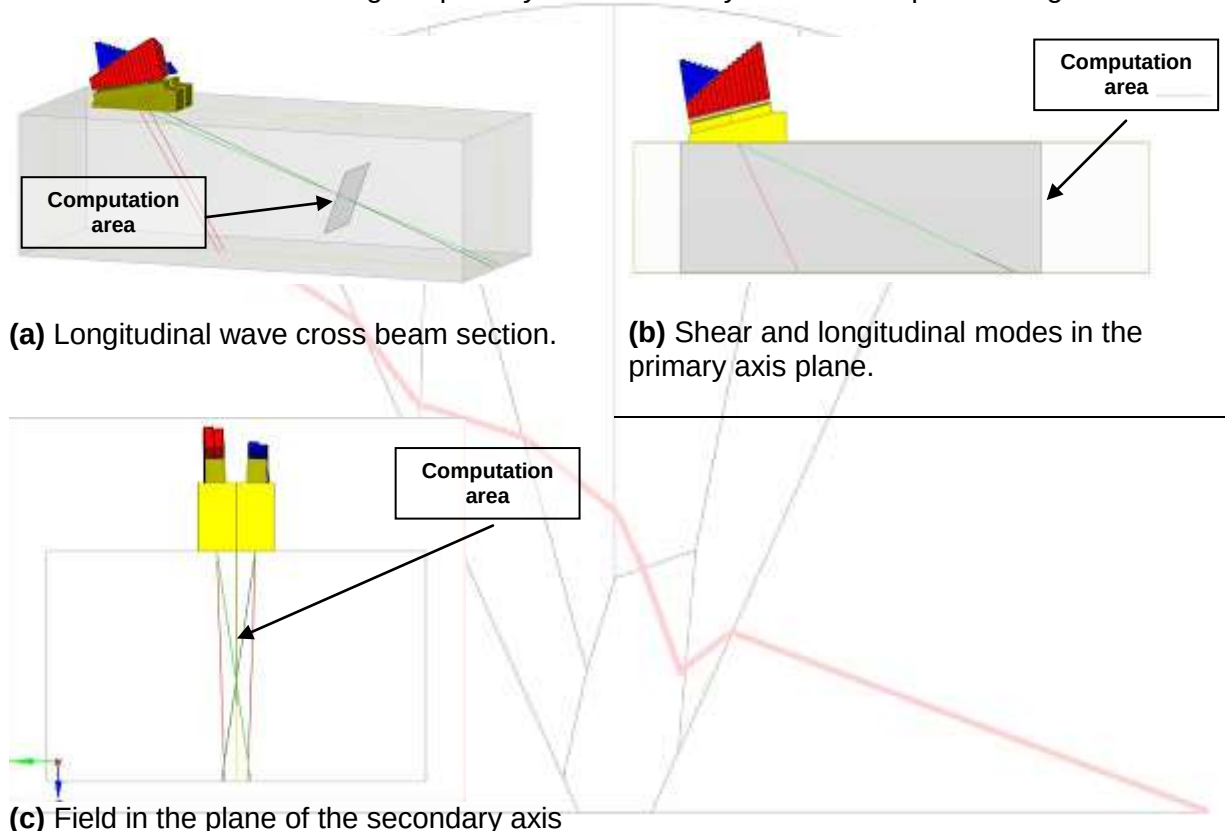


Figure 48 Configuration of views generated in CIVA.

Four cases were investigated as part of the optimisation study:

1. Beam steered at 40° , focused at 5mm deep.
2. Beam steered at 40° , focused at 85mm deep.
3. Beam steered at 70° , focused at 5mm deep.
4. Beam steered at 70° , focused at 85mm deep.

The beam focused at 5mm was to ensure coverage of near surface and that at 85mm was aimed at finding flaws near the back wall. The steering range required was from 40° to 70° ; the sound field is required to maintain integrity at both extremes of this range.

Figures 49 to 52 show the results computed by the model for the longitudinal wave mode.

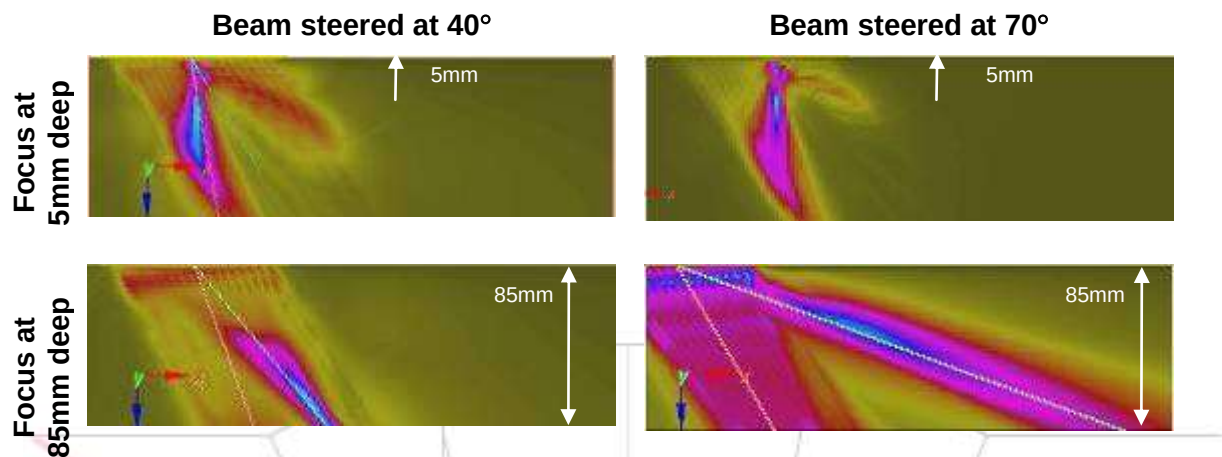


Figure 49 Plot of beams computed in the primary axis plane for 40 and 70° beams at focal depths of 5 and 85mm.

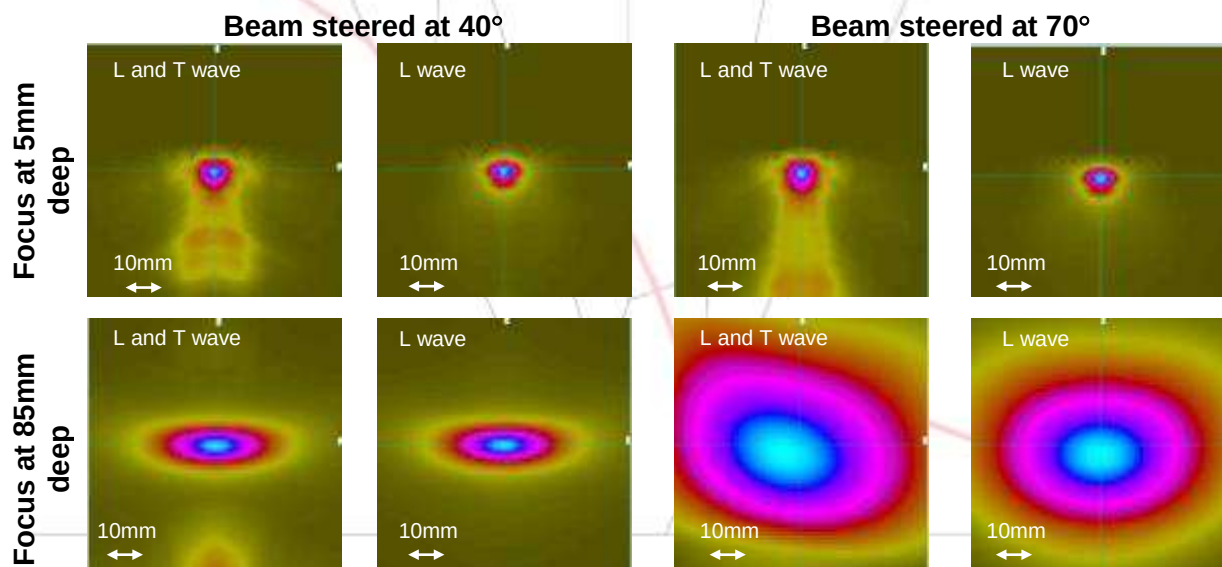


Figure 50 Results for cross beam section computation for 40 and 70° beams at focal depths of 5 and 85mm.

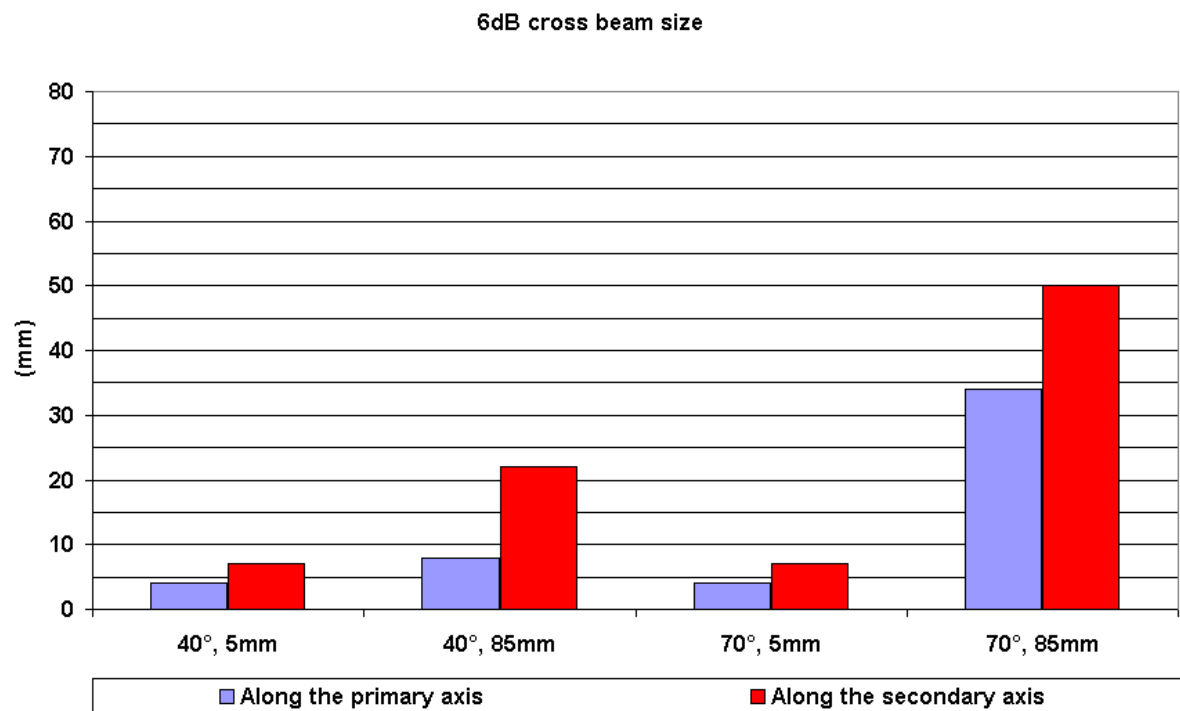


Figure 51 The -6dB beam size along the primary axis and the secondary axis for different beam steering angles and focal depths.

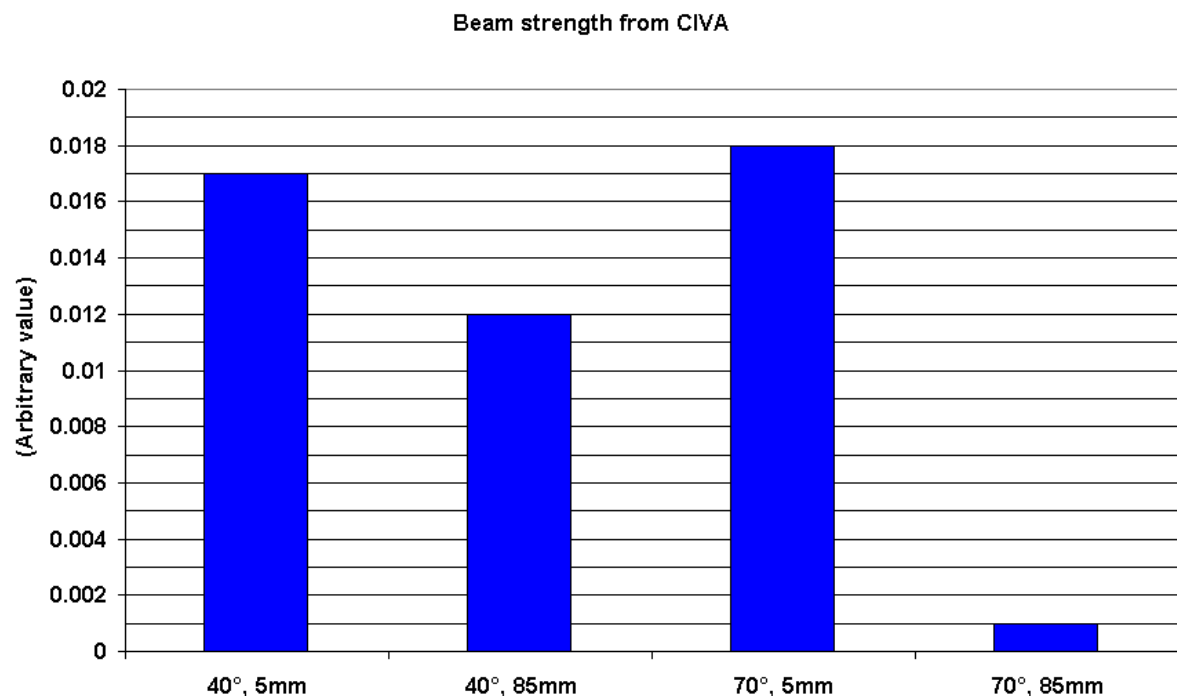


Figure 52 The beam strength for 40 and 70° beam angles at focal depth of 5 and 85mm.

At 70°, the beam is not able to focus at a range of 248.5mm (equivalent to 85mm deep) because the natural near zone range is 122mm and it is not possible to focus at a range greater than the natural near zone of the probe. In addition, the 70° beam width is greater than 50mm wide, with high sub-surface interference and a decrease of the beam strength by 25dB in comparison with a beam steering at 40° focused at 85mm.

Figure 53 shows the results of a computation to visualise the effect of reducing the width of the probe to a single row of elements 5mm wide (ie a linear array). Figure 53 shows the results for a linear array with 16 elements along the primary axis with 5mm wide elements. It was not possible to achieve good focusing capability to a depth of 85mm at 70° and consequently the size of the probe along the primary axis needed to be increased.

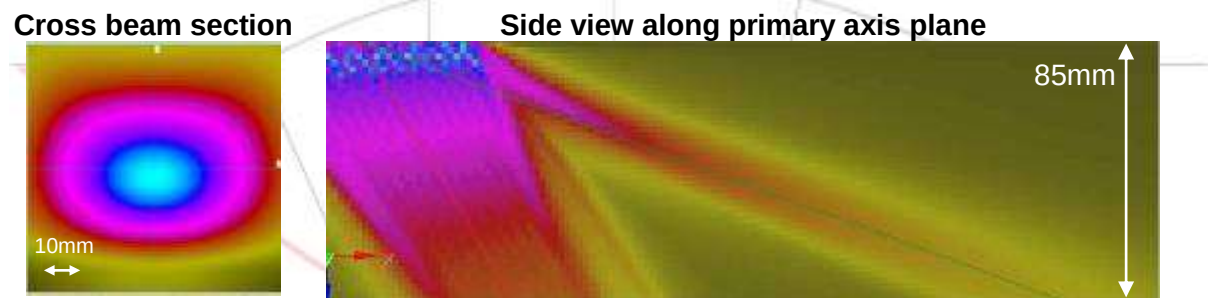


Figure 53 Plot of the computed beam cross section and beam side view along the primary axis for the equivalent linear probe (16 elements along the primary axis, element pitch 5mm and element width 5mm) steered at 70° and focused at 85mm deep.

In summary, after iteration 1, the conclusions were:

1. A small beam size was achieved at short range with a beam size less than 5mm along the primary beam axis and less than 10mm along the secondary axis.
2. A strong transverse wave occurs when the ultrasonic beam is focused near the scanning surface. Propagation of transverse waves into the material can lead to an increase in backscattered noise from the austenitic grain structure.
3. An aperture of 16 elements at 5mm pitch and 1.5MHz frequency cannot focus beyond the maximum range of 120mm at 70°.

4.4.1.3 Iteration 2

A new element configuration needed to be used in order to reduce the creation of shear wave modes, reduce interference near surface and, most importantly, improve the capacity to focus at the required range at high beam angle. In this iteration, the effect on the ultrasonic beam due to the change in the number of elements and the element pitch along the primary and the secondary axes was investigated.

For every case the beam is steered at 70° and focused at a depth of 85mm. Iteration 2 was undertaken using the SimulUS model. The key parameters kept fixed in Iteration 2 are given in Table 4.2. In the DISSIMILAR project the maximum number of channels available in the array controller (Section 5) was limited to 128. Hence transmit and receive halves had 64 elements each, and the aim of Iteration 2 was to find the optimum 2D configuration on each half and the cases considered are listed in Table 4.3.

Table 4.2 Parameters kept fixed during Iteration 2.

Parameter	Value
Probe type	TRL
Wave mode	Longitudinal
Array type	2D
Frequency	1.5MHz
Coupling material	Water
Inclination / water wedge angle	13.1°
Roof angle	2.5°
Inter array space	11mm
Coupling path	27mm

Table 4.3 List of cases considered in Iteration 2.

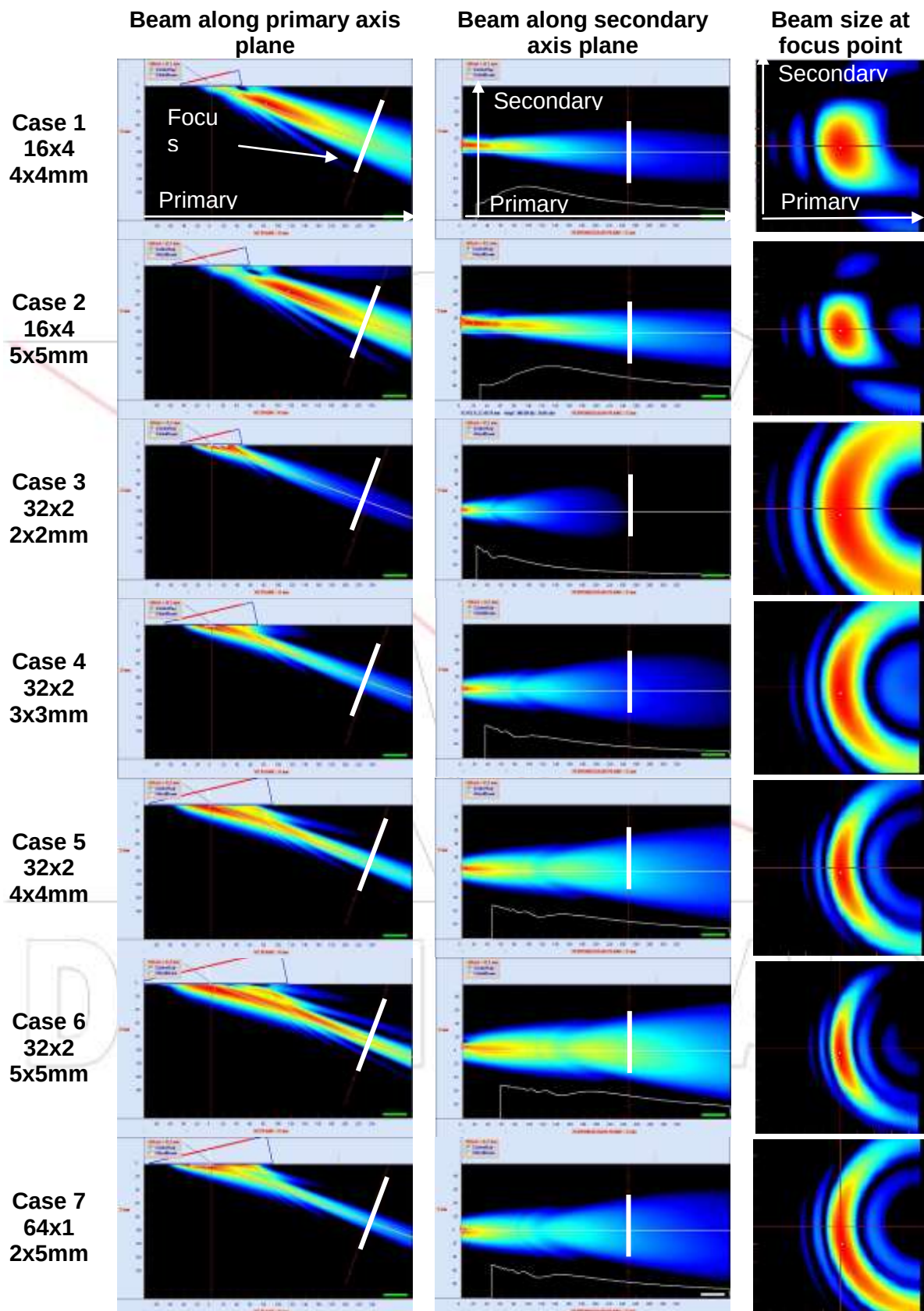
Case	Number of elements in the primary axis	Number of elements in the secondary axis	Element pitch in the primary axis	Element pitch in the secondary axis	Natural near zone length at 0° (mm)	Natural Near field length at 70° (mm)
1	16	4	4	4	251	78
2	16	4	5	5	392	122
3	32	2	2	2	254	75
4	32	2	3	3	571	169
5	32	2	4	4	1016	300
6	32	2	5	5	1587	469
7	64	1	2	5	1587	303
8	64	1	2	10	1012	299
9	64	1	3	3	2315	689
10	64	1	3	5	2307	685
11	64	1	3	10	2291	678
12	64	1	3	20	2267	673

An array is not able to focus beyond the natural near field zone. The natural near zone length is a function of the aperture (A) and the wavelength (λ) as given in Equation 4.1.

$$Nz = \frac{A^2}{4\lambda} \quad [4.1]$$

The maximum required range is equal to 248.5mm in the material when the beam is steered at 70° and focused at the backwall of the specimen (85mm). Hence aperture of the probe has been chosen to obtain a natural near zone length greater than 248.5mm (see relevant cases given in Table 4.3).

The results of all the cases in Table 4.3 is presented in Figure 54, showing the three views necessary to visualise the beam generated by the probe as illustrated in Figure 48: beams in the primary and secondary axes and the cross beam size in a plane at the range of the focal position (85mm deep). Figure 55 shows the predicted beam sizes for all the cases.



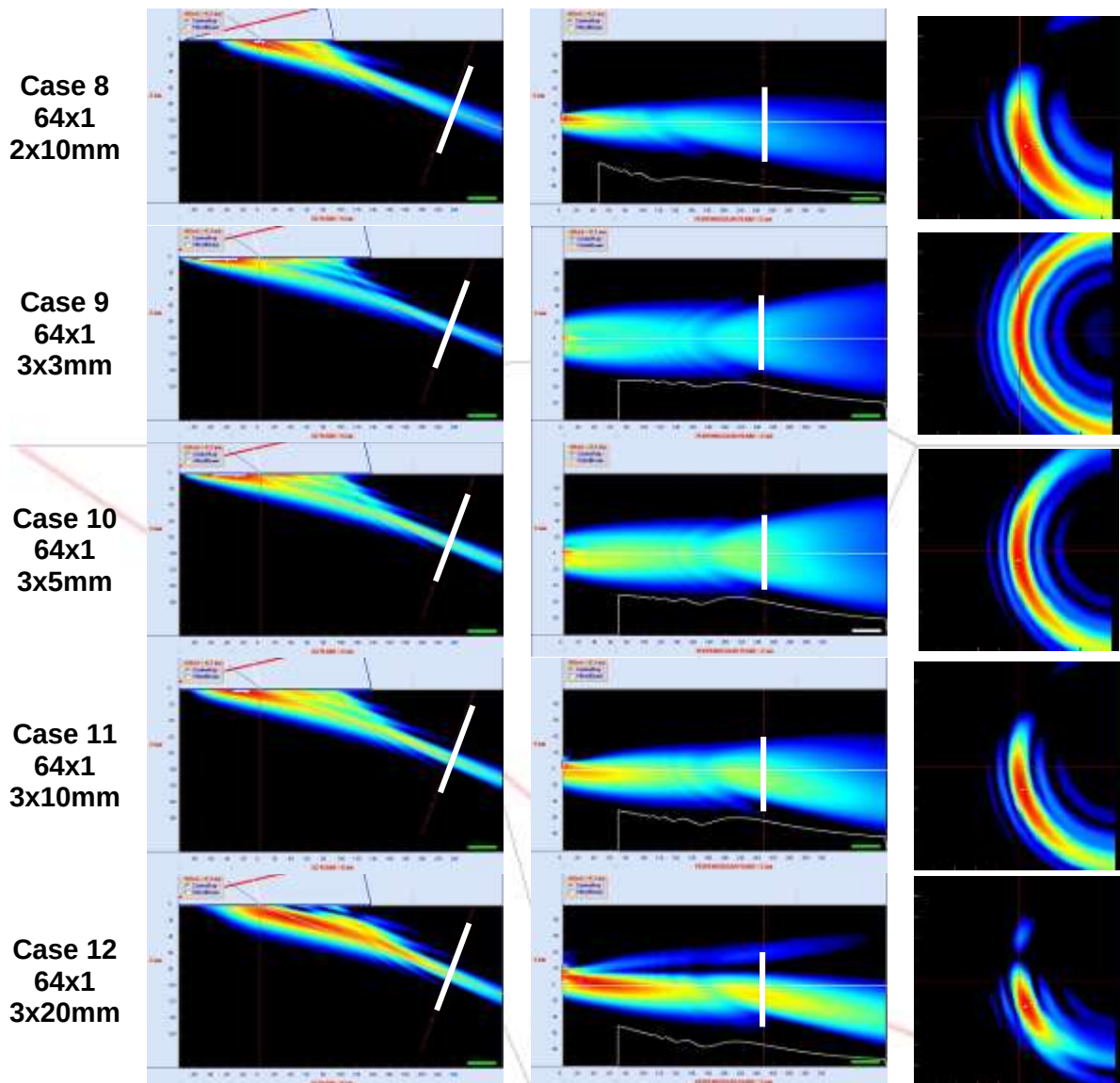


Figure 54 Modelling results from SimulUS (-20dB threshold applied) for different array configurations with a beam focused at 85mm deep and steered to 70°.



Figure 55 The -6dB cross beam measurement from the SimulUS models for all 12 cases.

In summary, after Iteration 2, the conclusions were:

1. In all cases, an increase in the aperture of the probe in primary or secondary axes leads to a decrease in the beam size and an increase in the intensity of the sound at the focus point. However, there can also be an increase in the side energy lobes around the main beam.
2. For the same aperture size, an increase in the number of elements allows better control of the beam and the energy along the beam axis has better distribution. Moreover, by increasing the number of elements, the generation of side energy lobes is reduced.
3. The use of several elements along the secondary axis allows the beam to be controlled better. Four elements can steer and focus the beam. Two elements allow the beam to be steered only. No control is possible with a single element. With the linear array 64x1 elements, the beam will be controlled only along the primary axis.

The recommendations from Iteration 2 are:

1. Use minimum of 32 elements along the primary axis.
2. Using 2 elements along the secondary axis limits the steering and focal capability but was deemed to be a satisfactory compromise in the particular case of the DISSIMILAR project. The ideal solution would be to increase the total number of channels available in the array controller.
3. Hence the array to be selected and taken into the next Iteration is the 32x2 configuration with a pitch of 5mm x 5mm.

4.4.1.4 Iteration 3

Iteration 3 is to assess the performances of the selected array (32x2 configuration, 5mmx5mm pitch) at the beam angles 40° and 70°, and at focusing ranges equivalent to depths of 10mm, 20mm and 85mm deep. Table 4.4 shows the parameters kept fixed during Iteration 3.

Table 4.4 Probe and inspection parameters kept fixed during Iteration 3.

Parameters	Value
Probe type	TRL
Wave mode	Longitudinal
Array type	2D
No. of elements on primary axis (np)	32
Primary axis pitch (pp)	5mm
No. of elements on secondary axis (ns)	2
Secondary axis pitch (pp)	5mm
Frequency	1.5MHz
Coupling material	Water
Inclination	13.1°
Roof angle	2.5°
Inter array space	11mm
Coupling path	27mm

In this iteration, an apodisation curve, shown in Figure 56 was applied to investigate the possibility of reducing the effects of side energy lobes. Apodisation is where the excitation energy (voltage) of each element is not uniform along the primary axis (rows) of the array with the maximum energy in the centre of the array. Figures 57 to 63 present the results generated using CIVA in Iteration 3.

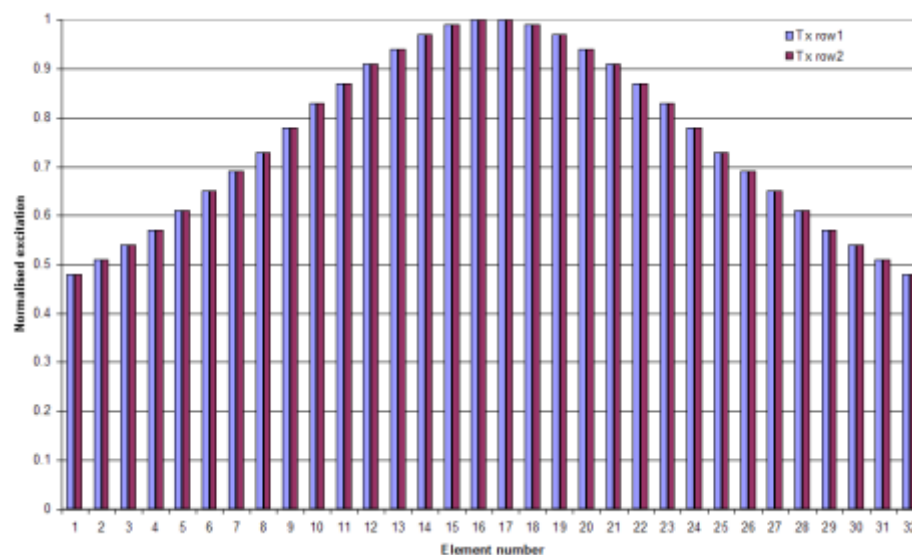


Figure 56 The apodisation curve applied to each of the 32 elements on transmit and receive rows.

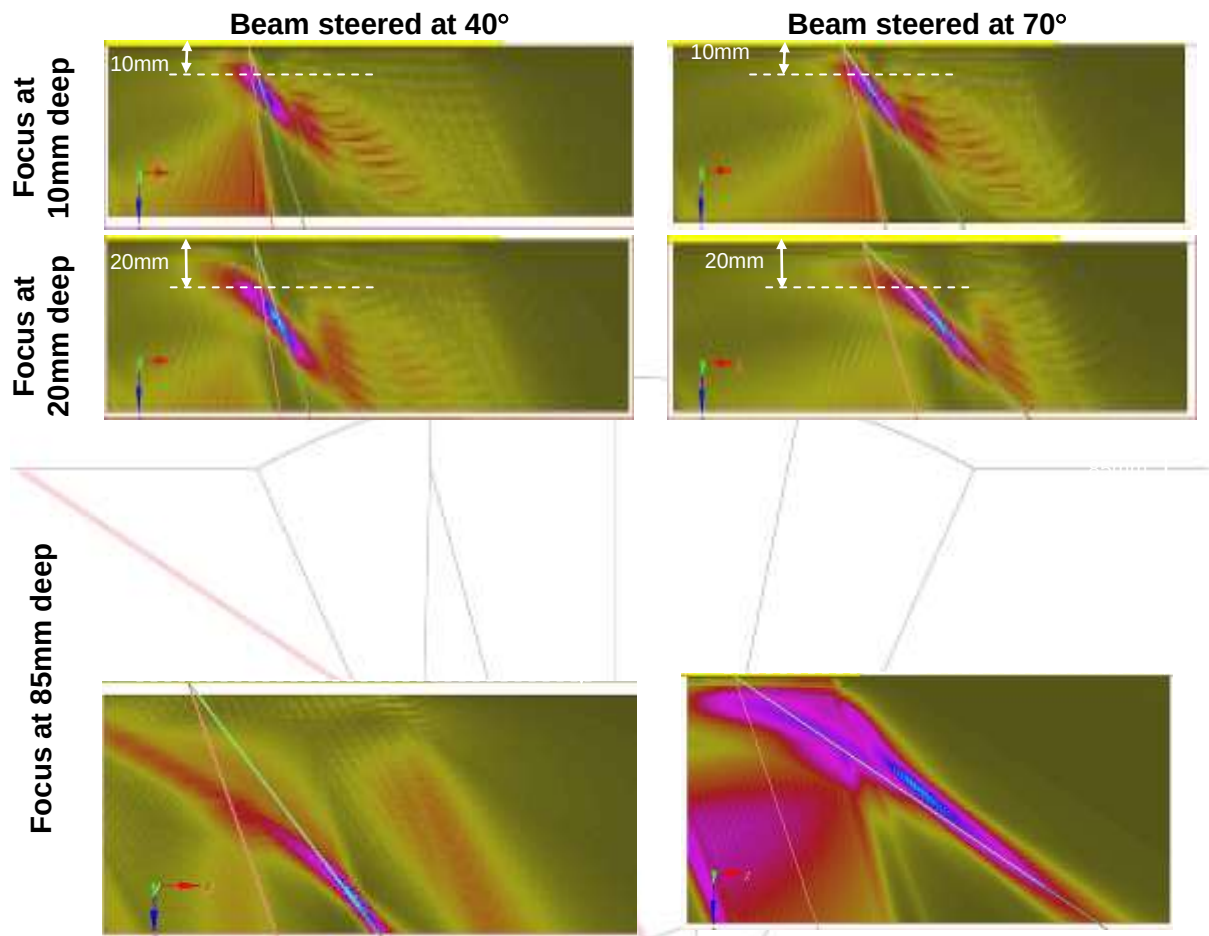


Figure 57 Beam computation results in the primary axis plane without apodisation.

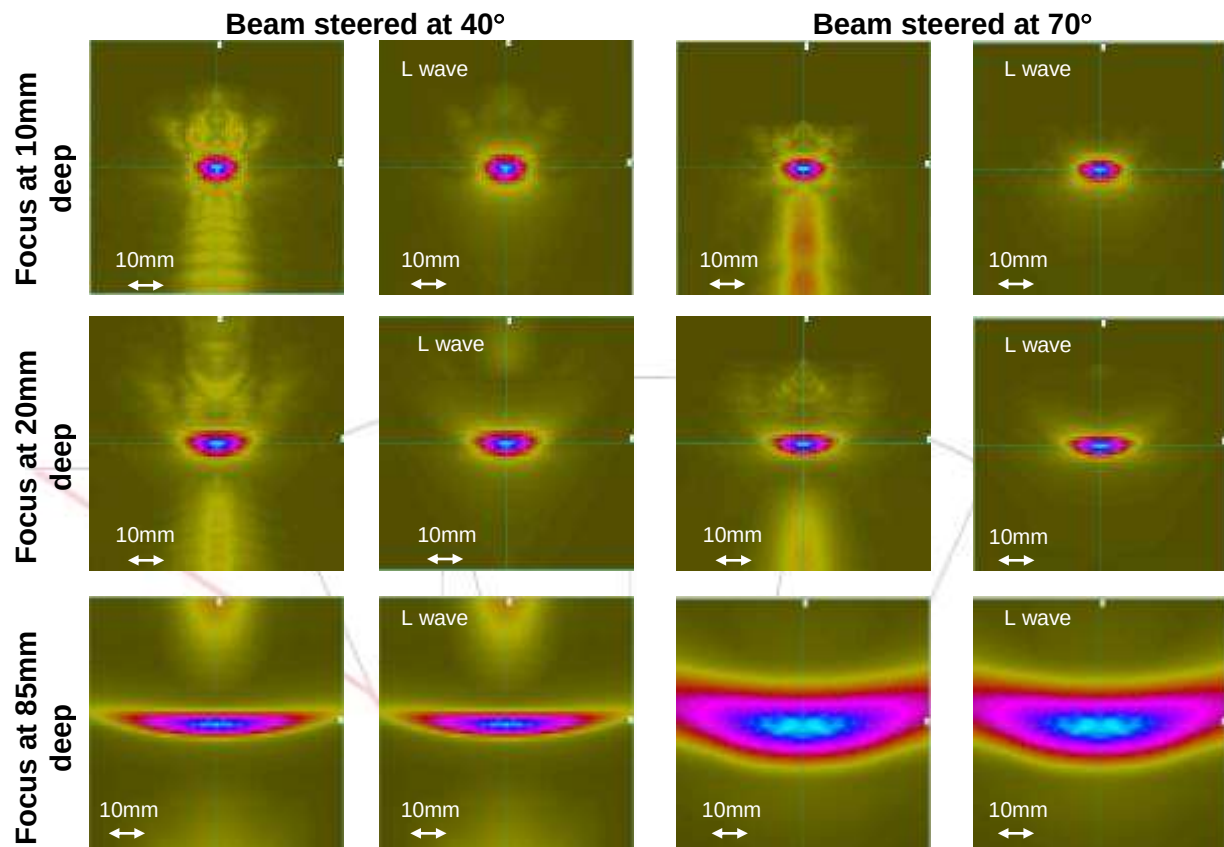


Figure 58 Results of the beam size at the focal positions without apodisation.

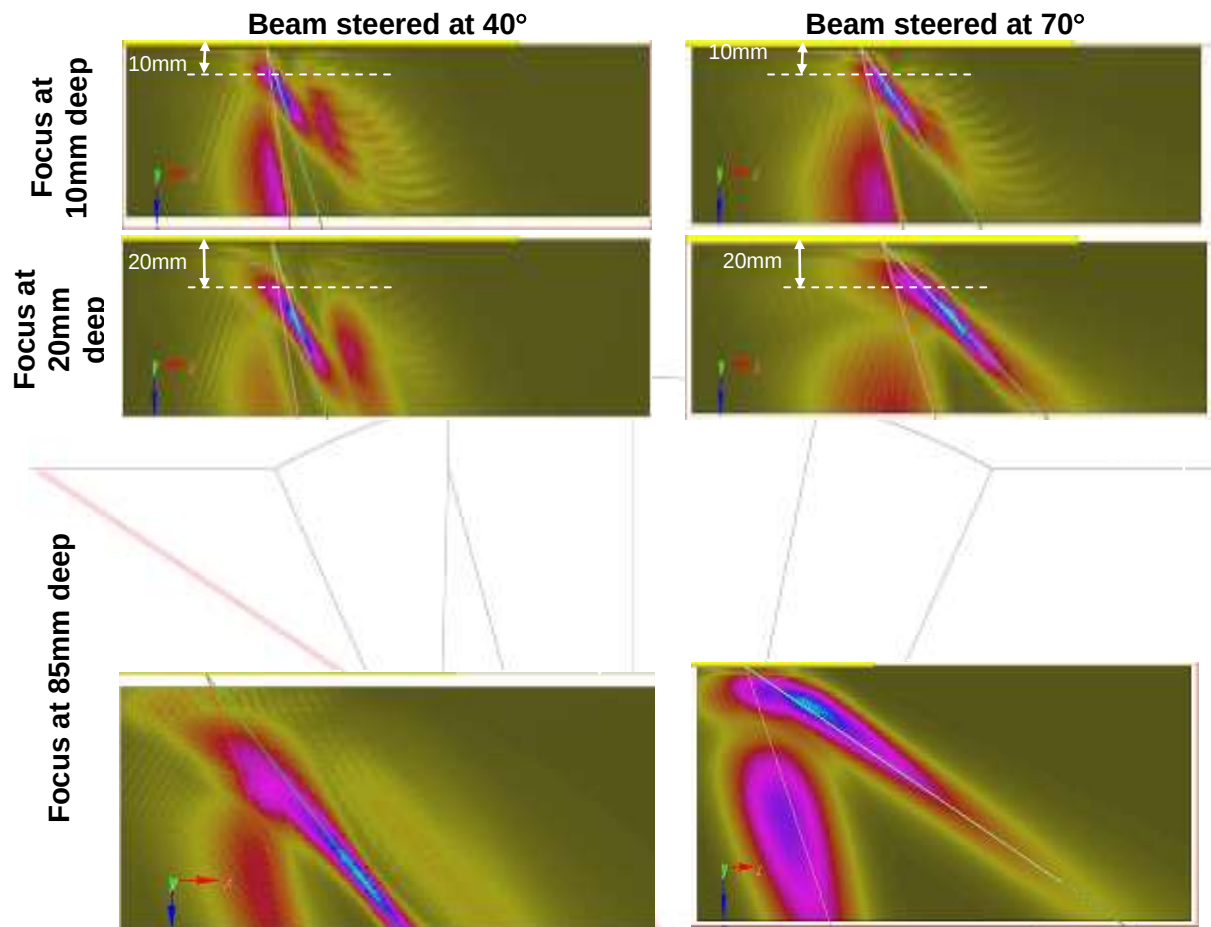


Figure 59 Beam computation results in the primary axis plane with apodisation.

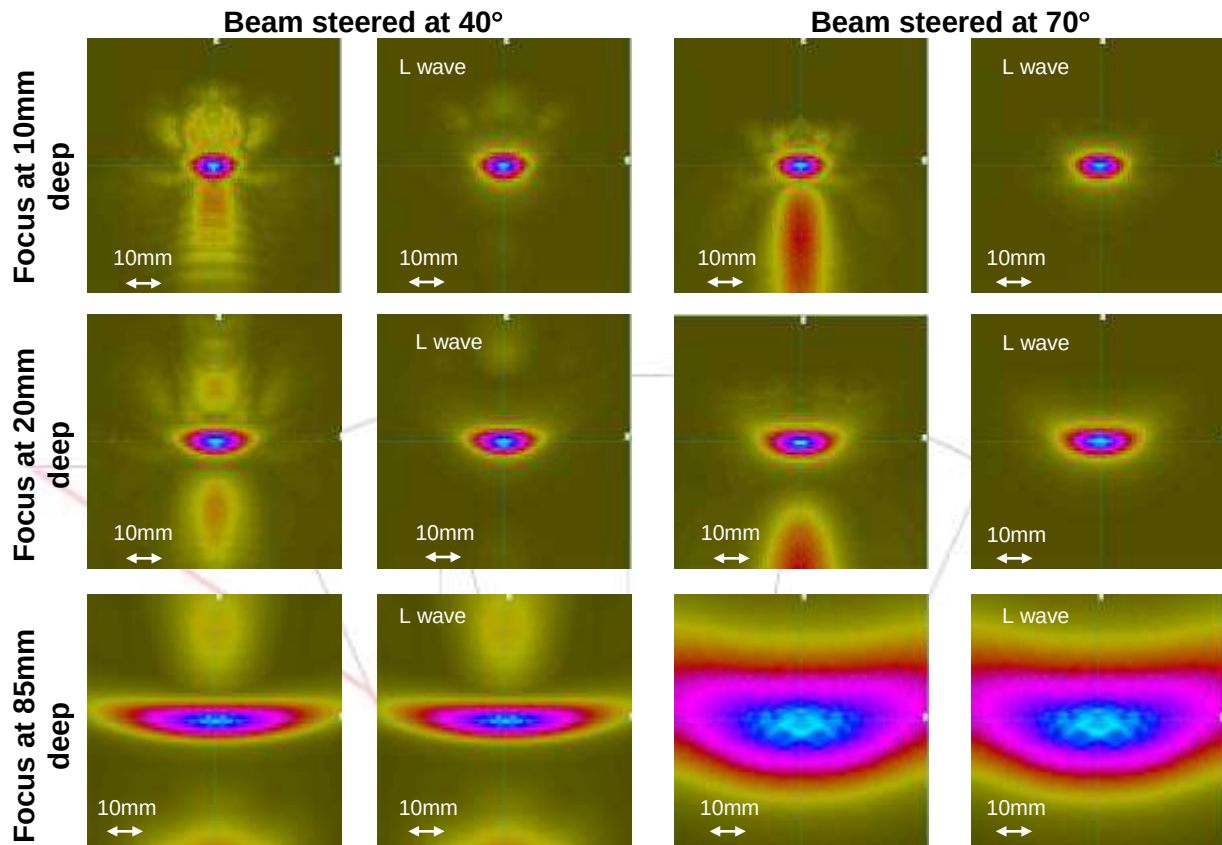


Figure 60 Results of the beam size at the focal positions with apodisation.

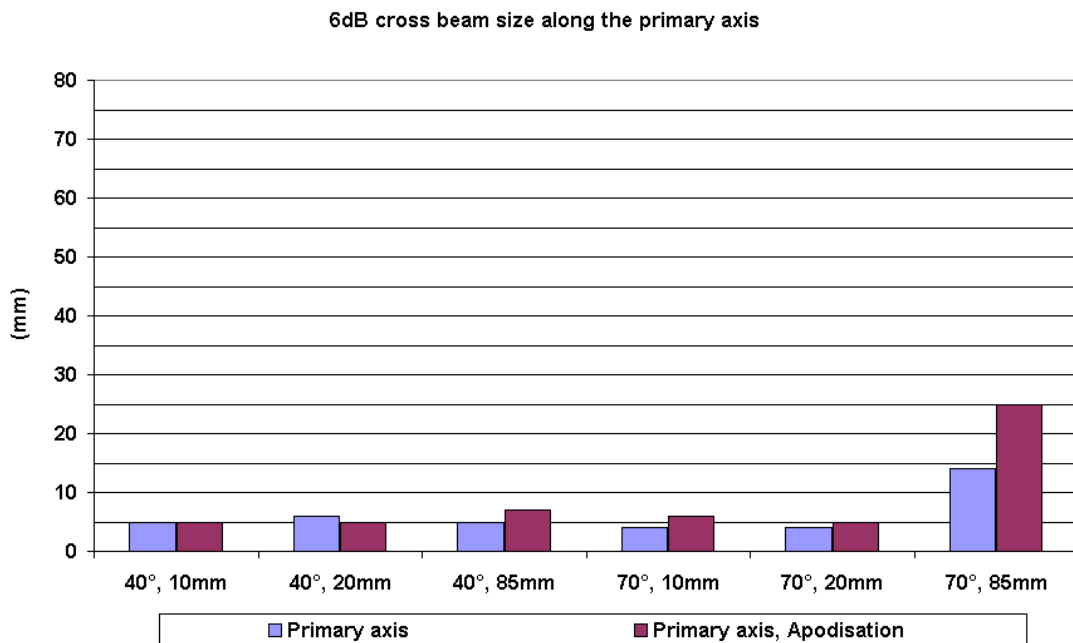


Figure 61 The -6dB beam size measurement from modelling along the primary axis with and without apodisation curve.

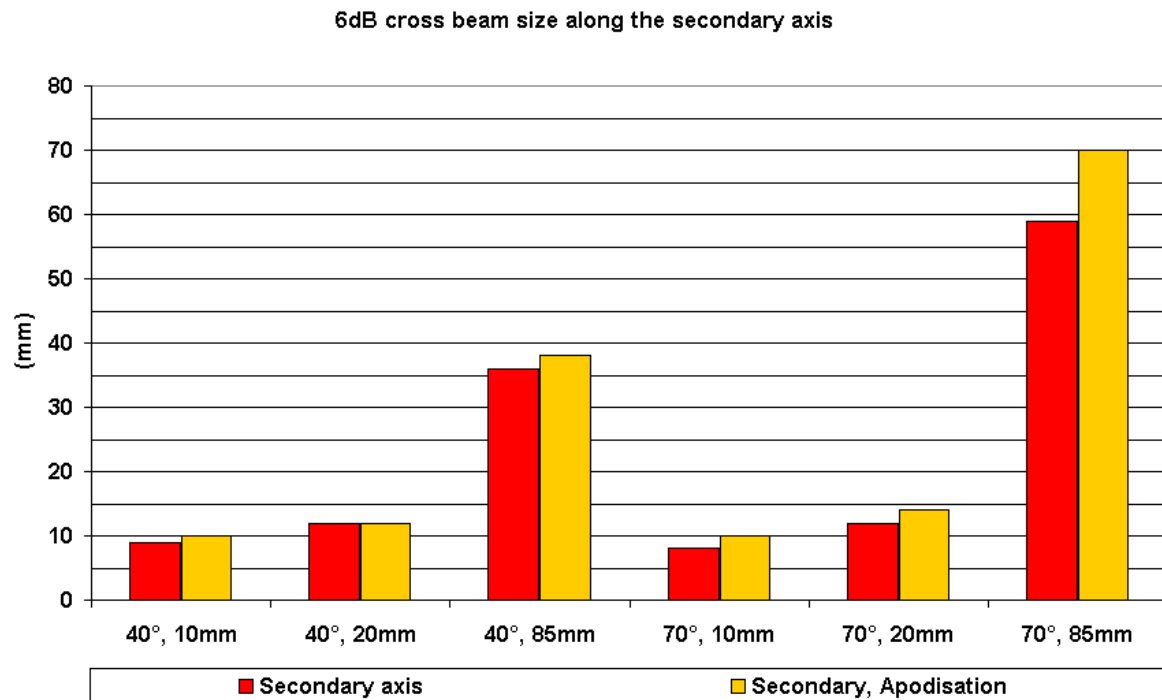


Figure 62 The -6dB beam size measurement from modelling along the secondary axis with and without apodisation curve.

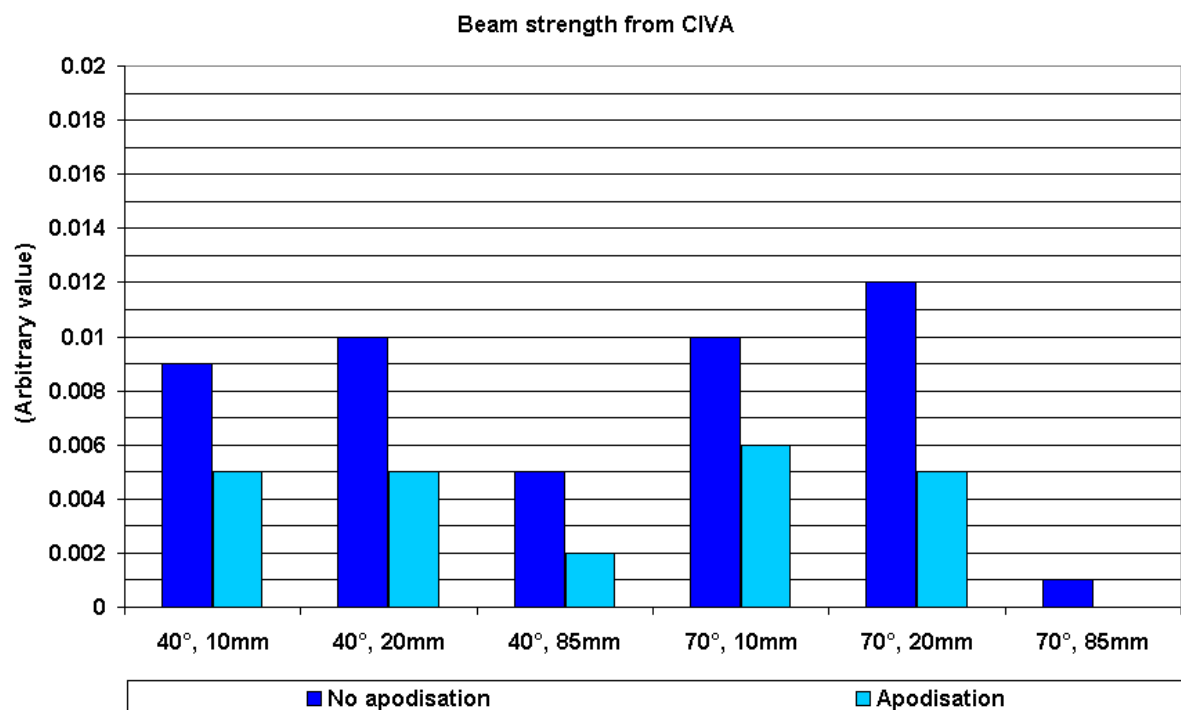


Figure 63 Beam strengths for different beam steering angles and focus depths with and without apodisation curve.

In summary, after Iteration 3, the conclusions were:

1. This probe configuration has eliminated the strong shear waves at short focal ranges.
2. The small focused beam size of 5mm along the primary axis and smaller than 10mm along the secondary axis is modelled to be theoretically possible.
3. The model has shown that by using this element configuration the high energy near the scanning surface has been reduced when the beam is focused at long range (equivalent to 85mm deep).
4. Some side energy lobes are still present around the main beam at short and long focusing ranges, and at both low and high steering angles.
5. At a focal depth of 85mm the beam size is now smaller than 5mm at 40°. At 70° the beam has been significantly reduced from 34mm to 14mm.
6. The reduction in beam size along the primary axis at long focusing range has been earned at the expense of beam size along the secondary axis: the beam size along the secondary axis has increased by 14mm.
7. Modelling has shown that apodisation provides advantages and disadvantages. In general, the beam shape is better with fewer side lobes but generates a stronger shear wave. Additionally, at the focus point, the beam size is increased and the beam strength is reduced.
8. Hence based on the evidence generated through modelling in Iteration 3, the use of apodisation is not recommended. The reasons are firstly it does not lead to any significant changes in beam sizes but it does lead to a significant reduction in beam strength.

4.4.1.5 Iteration 4

The array 32x2 elements, 4x5mm pitch and 32x2 elements, 4x6mm pitch at the beam angles 40° and 70° and focusing ranges 10mm and 80mm deep were investigated. Table 4.5 shows the parameters fixed in Iteration 4 and Figures 64 to 71 present the results.

Table 4.5 Probe and inspection parameters kept fixed during Iteration 4.

Parameters	Iteration 3a	Iteration 3b
Wave mode	Longitudinal	Longitudinal
Array type	2D	2D
No. of elements on primary axis (np)	32	32
Primary axis pitch (pp)	4mm	4mm
No. of elements on secondary axis (ns)	2	2
Secondary axis pitch (pp)	5mm	6mm
Frequency	1.5MHz	1.5MHz
Coupling material	Water	Water
Inclination	13.1°	13.1°
Roof angle	2.5°	2.5°
Inter array space	11mm	11mm
Coupling path	27mm	27mm

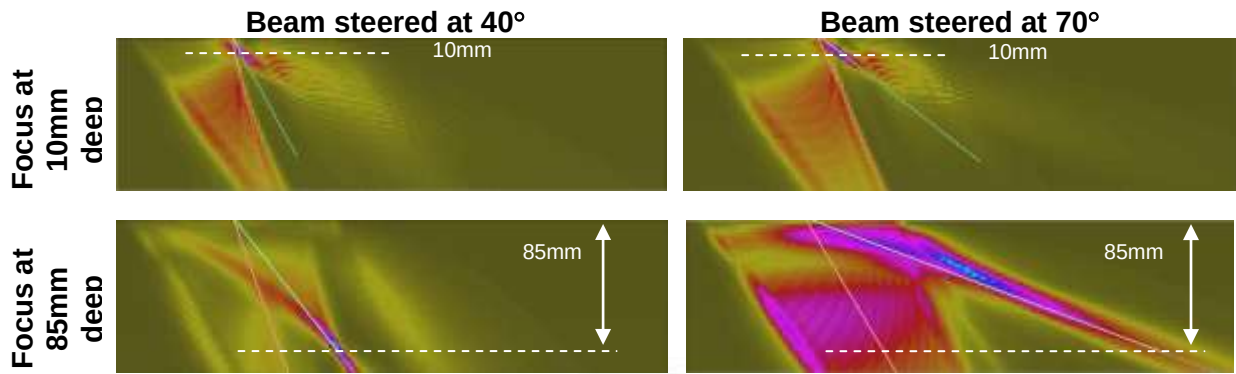


Figure 64 Beam computation in the primary axis plane for the array 32X2 4mmX5mm array.

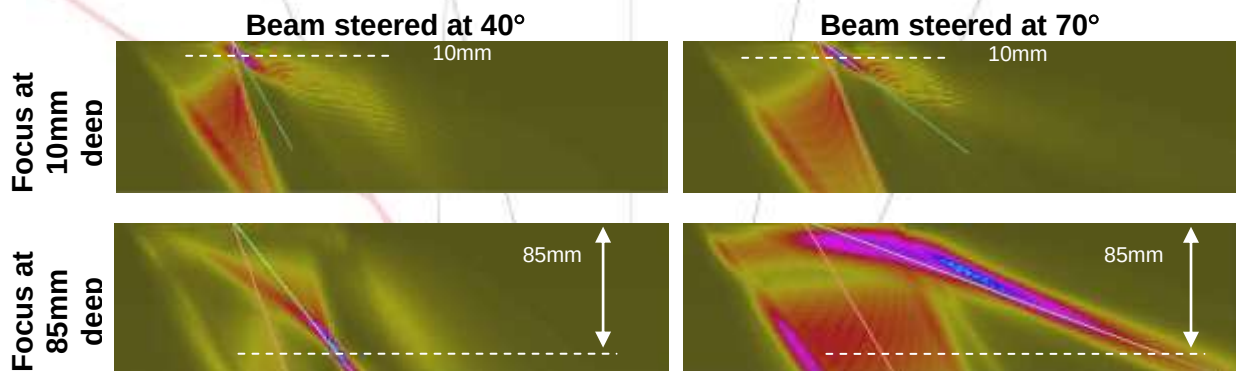


Figure 65 Beam computation in the primary axis plane for the array 32X2 4mmX6mm array.

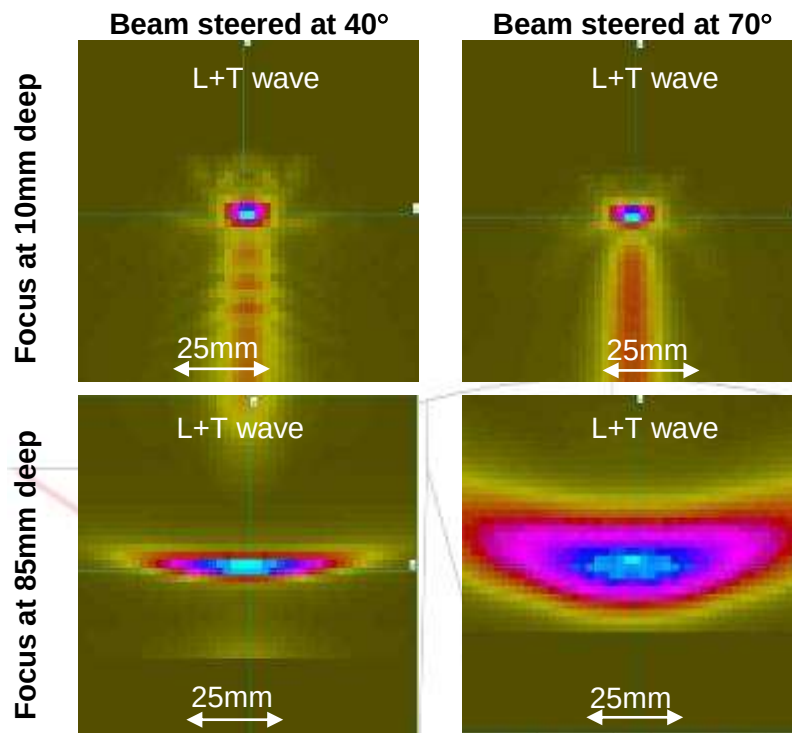


Figure 66 Results of the beam size at the focal positions for the 32x2 4mmx5mm array.

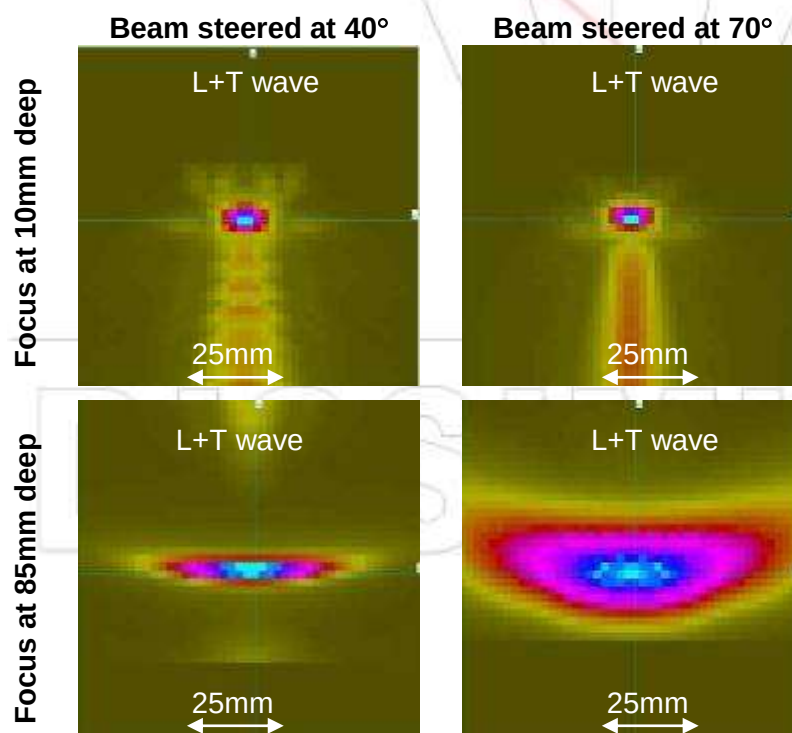


Figure 67 Results of the beam size at the focal positions for the 32x2 4mmx6mm array.

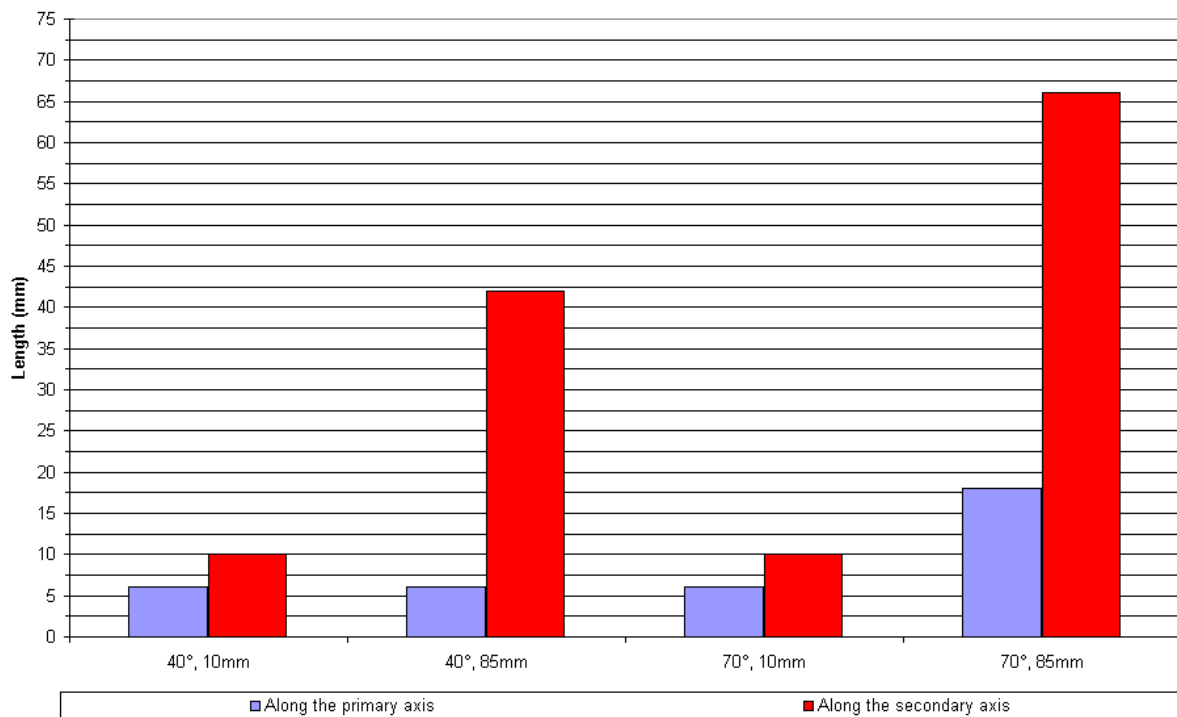


Figure 68 The -6dB beam size measurement from modelling along the primary and secondary axes for the 32x2 4mmx5mm array.

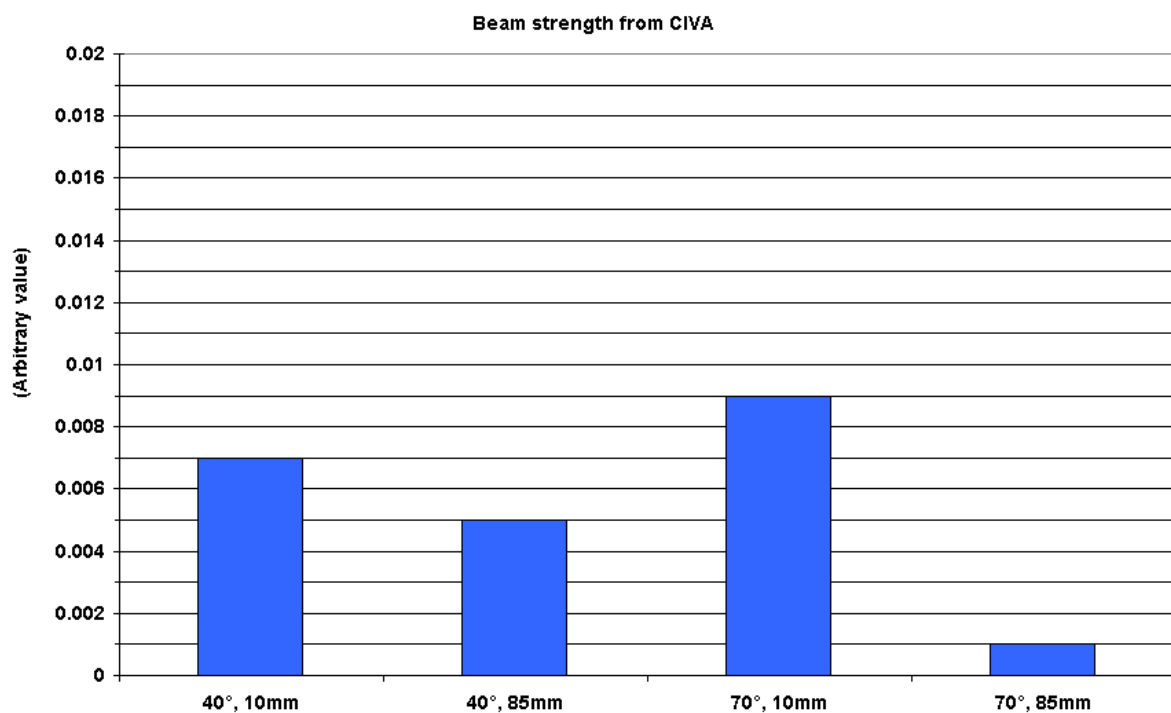


Figure 69 Beam strength for different beam steering angles and focus depths for the 32x2 4mmx5mm array.

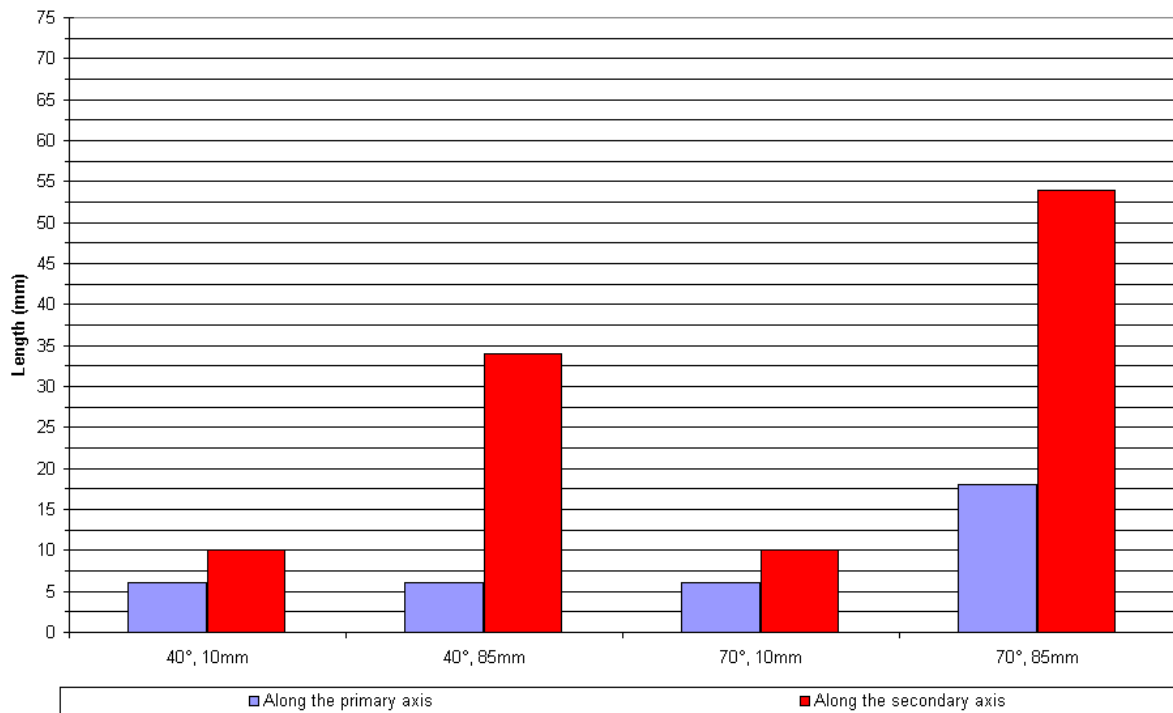


Figure 70 The -6dB beam size measurement from modelling along the primary and secondary axes for the 32x2 4mmx6mm array.

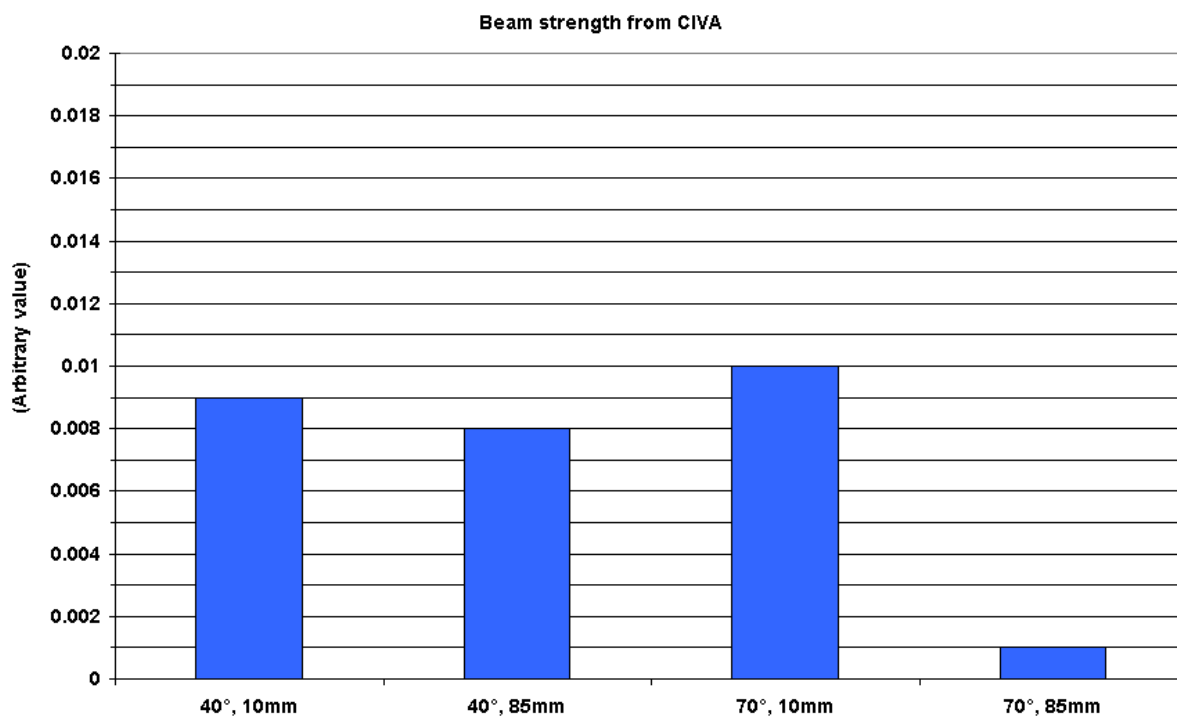


Figure 71 Beam strengths for different beam steering angles and focus depths for the array 32x2 4mmx6mm.

In summary, after Iteration 4, the conclusions were:

1. Both configurations (32x2, 4mmx5mm and 32x2, 4mmx6mm) appear to make possible a small focal beam size of 6mm along the primary axis and smaller than 10mm along the secondary axis.
2. Both configurations show a reduction of side energy lobes around the main beam at long focused range.
3. With 32x2 elements, 4mmx6mm pitch, the shear wave appears to be reduced at long range and at high beam.
4. With 32x2 elements, 4mmx6mm pitch, at a focal depth of 85mm the beam size along the primary axis is increased by 4mm at 70°. However the beam size is still smaller than 20mm in this direction. Along the secondary axis, by increasing the aperture the beam width is now reduced by 5mm.
5. The beam strength produced by the 32x2 configuration, 4mmx6mm pitch is greater by 4dB at 40° and at a focus point 85mm deep. At higher beam angle, this configuration appears to produce the same beam strength level as the previous configuration in Iteration 3 (32x2 5mmx5mm).

4.4.1.6 Discussion

Position and definition of computation area

The cross beam sections at the focal positions computed using CIVA and SimulUS were at the intersection point of transmit and the receive beams. In all models, only the contribution of the transmit beam is computed (free field). The beam computed at the intersection point from the transmitter is the one that will interact with flaws to generate echoes for the receiver. To completely model the pulse-echo system, the simulation of a target must be performed at the desired range using the modelled probe.

Manufacturing tolerance

The tolerance in the manufacture of the probe is critical especially with regard to the wedge and roof angles. These angles must be identical for both arrays in order to ensure the intersection of transmit and the receive beams at the focus point defined by the delay law. In particular an error of 0.1° in the wedge angle will generate a positional error of 1.8mm at 254mm range. Therefore the tolerance on each on tilt and roof angle needs to be better than 0.05° or a maximum difference between the two array halves of no more than 0.1°. The housing design for TRL-1 is presented in Section 4.3.3.

Apodisation

Apodisation is a capability available in the instrument (Section 5). The specification of the probe can be done without apodisation but it can be applied at a later date if needed.

After Iteration 4, the review indicated that the specification of the array arrived at was sufficient to perform the task of inspecting the DISSIMILAR DMW. Hence the specification document in Appendix B was produced and submitted for manufacture, which then initiated the second level specification, which considered the issued specification and aimed to select the materials and manufacturing processes to achieve the required performance.

4.4.2 Second level specification (PZ Flex)

The aim of the second level specification is to ensure that the ultrasonic performance demanded from the first level specification can be attained by the physically manufactured probe. Of primary concern is the choice of the active material, ie the generation and reception of ultrasonic energy. Secondary considerations include the generation of unwanted modes which travel laterally in between the elements of the array. The piezocomposite material, shown in Figure 72, is an advanced composite material which was used to manufacture the array. The advantages provided by the piezocomposite materials over traditional monolithic piezoceramics are:

1. Good suppression of parasitic resonances - ensure only the compression mode is transmitted into the medium.
2. Increased sensitivity and efficiency - increased S/N and penetration
3. Increased bandwidth - for higher resolution imaging
4. Reduced cross talk

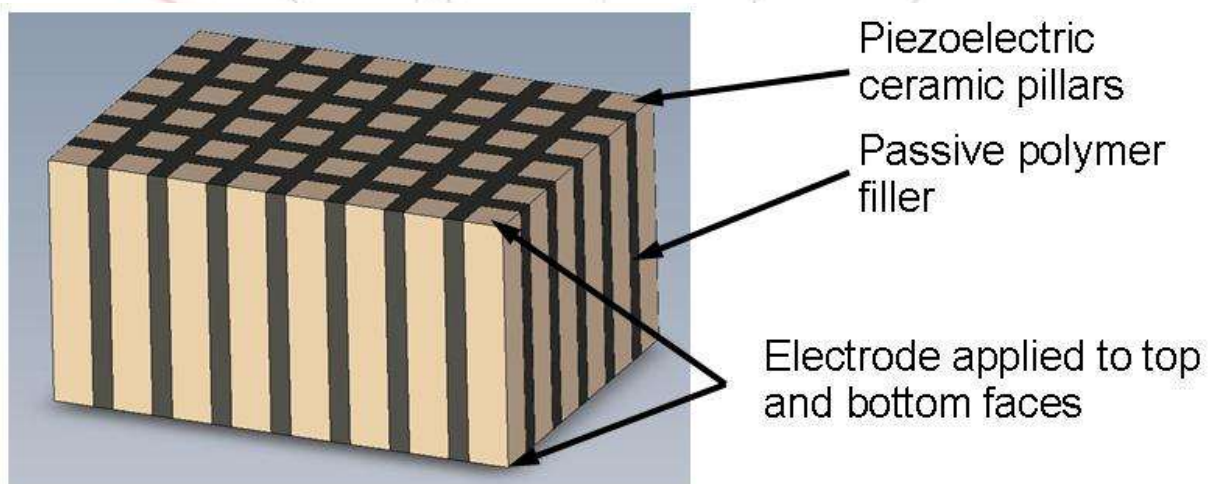


Figure 72 Structure of the 1-3 piezocomposite material, showing the active ceramic pillars embedded in a soft polymer matrix.

A number of lateral wave modes could be setup in the piezocomposite which could then interfere with the thickness mode (which is the one of interest); these different modes are illustrated in Figure 73. The aim of the specification is to ensure that either these modes are well separated from the frequency of interest or are damped out by careful choice of materials.

The second level specification procedure used was to (1) use the requirements specified in the first level specification (eg sensitivity, bandwidth, cross talk etc) and (2) use the finite element model PZ Flex to determine the microstructure (ie design out the lateral resonances and meeting the requirements of bandwidth, sensitivity etc).

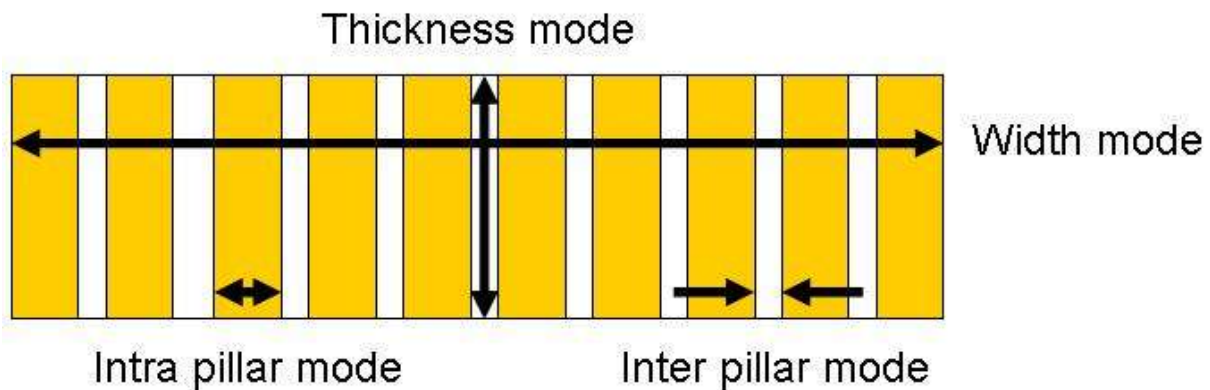


Figure 73 Unwanted lateral modes which could exist in the piezocomposite material.

PZ Flex is a specialist finite element analysis package for modelling piezoelectric devices. It uses an explicit time-domain based approach to solve large finite element problems quickly. Figure 74 shows two images of models of piezocomposite materials; on the left the material is in its undisturbed state whereas on the right the material is undergoing its transient response to an input voltage.

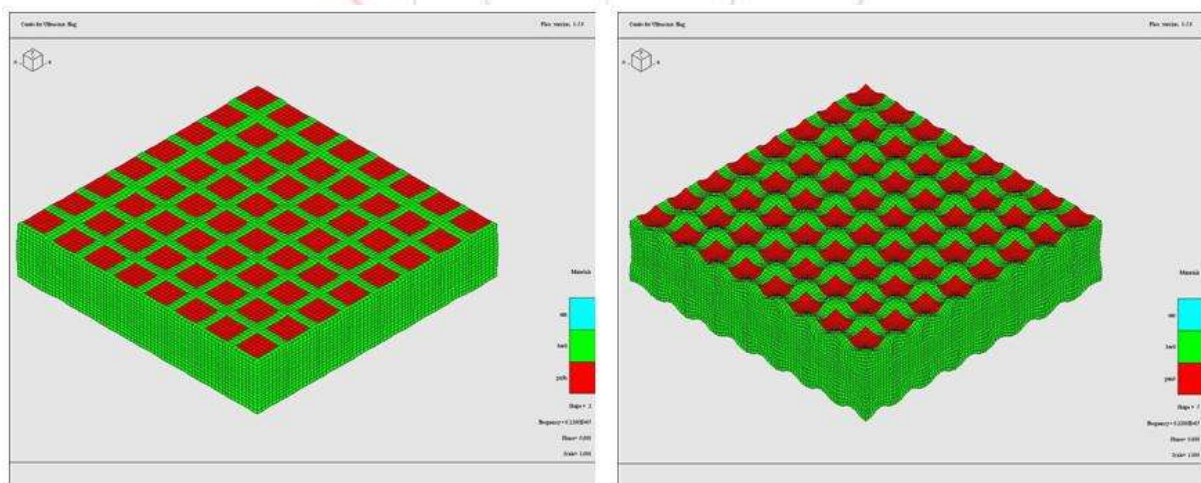


Figure 74 Model of the piezocomposite material in PZ Flex. The left image shows the material at rest and the right shows the material undergoing mechanical distortion on application of a voltage due to the piezoelectric property of the ceramic pillars.

An alternative active material considered in the DISSIMILAR project is piezoelectric single crystals, which are known to have higher electromechanical coupling coefficients and higher permittivity in comparison to piezoceramics. Figure 75 shows that the single crystal material (the trace in purple) has a smaller pulse-echo wave train hence temporal resolution and greater bandwidth than the piezocomposite material (the trace in black). In general, the use of single crystal material was thought to provide greater resolution, S/N performance and penetration. However, single crystal materials are more expensive than piezoceramics and hence a decision was made to not explore their use in the DISSIMILAR project.

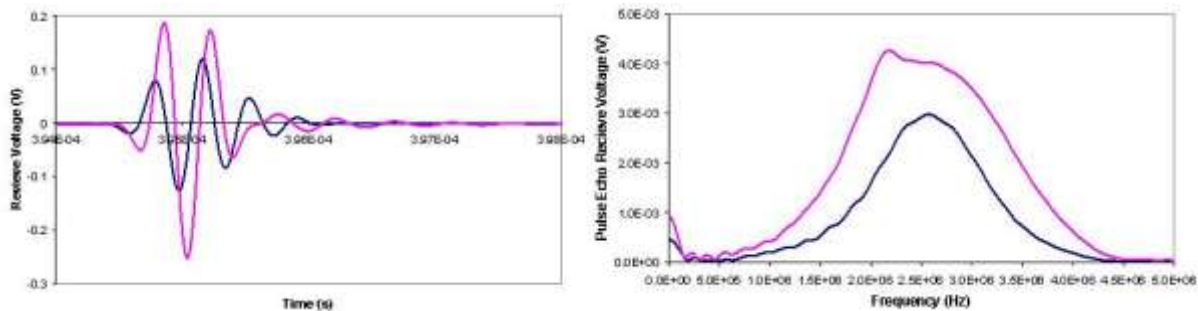


Figure 75 Pulse-echo and bandwidth performance of single crystal (purple) vs. piezoceramic material.

The primary characteristics of concern to the inspection of austenitic welds are (1) to decrease the number of cycles in the pulse in order to increase temporal resolution and (2) increase the bandwidth to increase penetration of attenuative materials by having appreciable low frequency content. In addition, a further requirement is to reduce 'cross talk', ie energy that leaks from one element to another. Simulation tools exist to predict these characteristics and optimise them by changing the array materials and geometry. The choice of the 'backing material' plays a crucial role in controlling the level of damping applied to the resonant active material.

The finer details of materials design and manufacture will not be presented in this document. In addition to selecting and configuring the active materials, second level specification tasks for array probes include design of interconnects, cabling and connectors as well as suitable backing materials/design. These aspects are considered the intellectual property of the probe manufacturer but it is important to be aware of issues surrounding the manufacture of array probes when designing the inspection of austenitic welds. The following is a list of key probe characteristics which must be well conditioned during the second level specification:

1. Element conductance: usually the array is required to be unimodal, ie each element must be identical to the other. The electrical conductance of each element is a good indicator of this uniformity as it is highly dependent on element construction (ie the piezocomposite) and the matching layer thickness.
2. Pulse length: this is specified in the first level specification and is measured to the 20dB drop value from the peak.
3. Bandwidth: this is related to pulse length and is also specified in the first level specification. The bandwidth is often measured using a Fast Fourier Transform of the time domain pulse length. The quoted value of bandwidth is calculated as:

$$[(\text{width @ 6dB drop from peak (in MHz)}) / \text{peak frequency (in MHz)}] \%$$

4. Cross talk: is specified in the first level specification and refers the signal level that leaks from one element to another directly.
5. Parasitic echoes: these refer to any internal echoes generated within the array which is unwanted.

At the end of the second level specification, the manufacture of the array can begin with confidence that the array will provide the performance stated in the first level specification.

4.4.3 The TRL-1 prototype for immersion coupled inspection

Figure 76 shows one half of the TRL-1 array manufactured for the DISSIMILAR project: 32x2 configuration, 4mmx6mm pitch and 1.5MHz central (peak) frequency.



Figure 76 A half of the TRL-1 array, as received after manufacture.

Post-manufacture the arrays must undergo a series of tests to (1) ensure array is functional and (2) meet the requirements of the first level specification. Standard tests include:

1. Element check: each element is checked to see if it is active, establish pulse length and bandwidth.
2. Calibration block check: standard calibration blocks with SDH targets are used to study the whole array when focusing and steering the sound field
3. Laser vibrometry: may be used to check the uniformity in displacement exhibited by each element on the array. Non-uniform vibration would indicate problems in the piezocomposite and/or electroding.

Figure 77 shows the electrical conductance and capacitance of all the elements on the array, showing uniformity within 5% of the mean (black line is mean, dashed red lines is +/- 5% of mean). This indicates that the elements are sufficiently uniform. Additionally the cross talk was measured to be <-44dB at 1.5MHz, where the specification required it be <40dB (see Appendix B); hence cross talk performance met the specification. Similarly the parasitic echoes were found to be within specification (<60dB).

Figure 78 shows results of the laser vibrometry measurements which indicate that the displacement (both magnitude and phase) of the element shown is uniform over its surface area, along with the profile across the two lines which similar show sufficient uniformity.

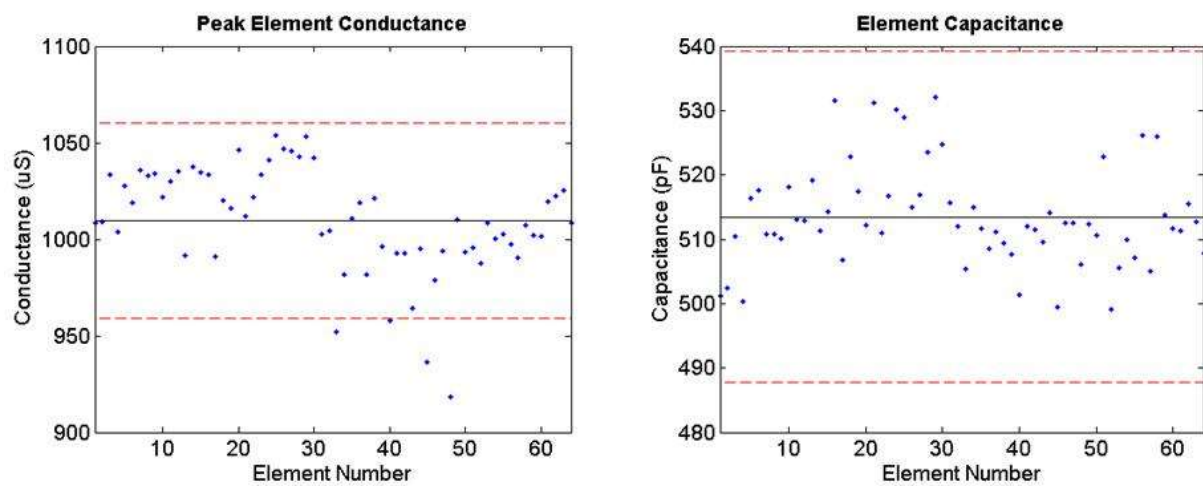


Figure 77 Electrical conductance and capacitance measurements on the TRL-1 array.

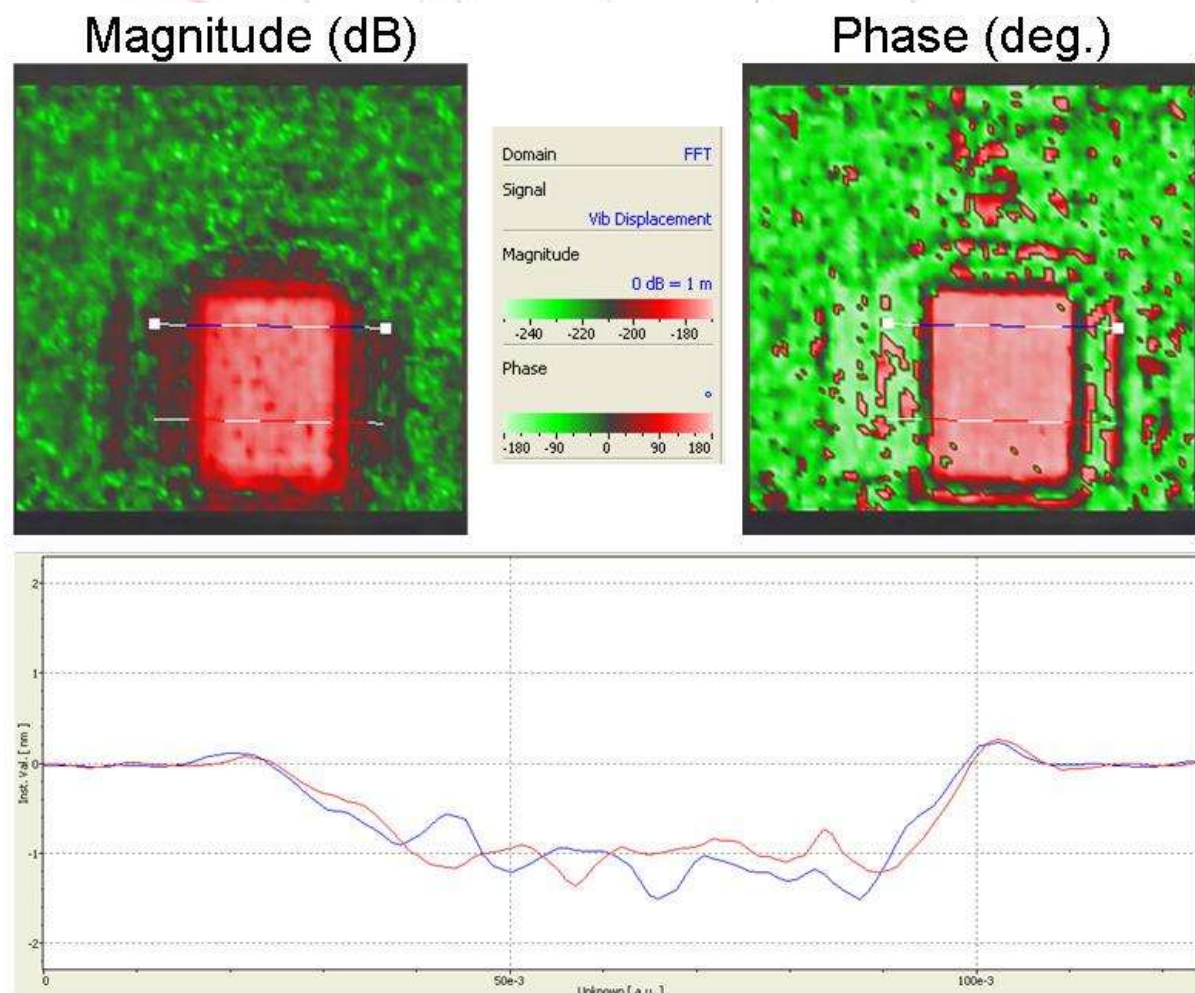


Figure 78 Laser vibrometry measurements showing the magnitude, phase and profile across the two white lines.

Figure 79 shows the pulse length and the bandwidth provided by the array (typical). The -20dB pulse length of the $1.51\mu\text{s}$ is well within specification (which required it to be $<1.69\mu\text{s}$). The bandwidth was measured to be 66%, which was below the 80% required. However, since the aim of the DISSIMILAR project was to push the manufacturing capabilities, the value of 66% was deemed higher than what is typically available in the market at the time, and the ideal goal of 80% remains to be achieved.

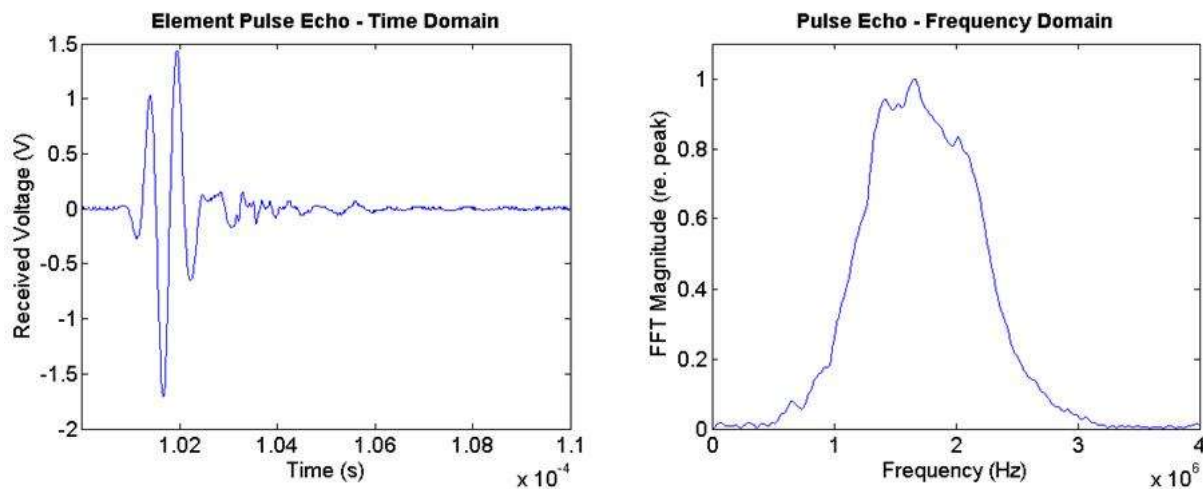


Figure 79 The pulse length and bandwidth measured on the TRL-1 array using pulse-echo.

Figure 80 shows the array half setup in immersion for a typical phased array inspection.

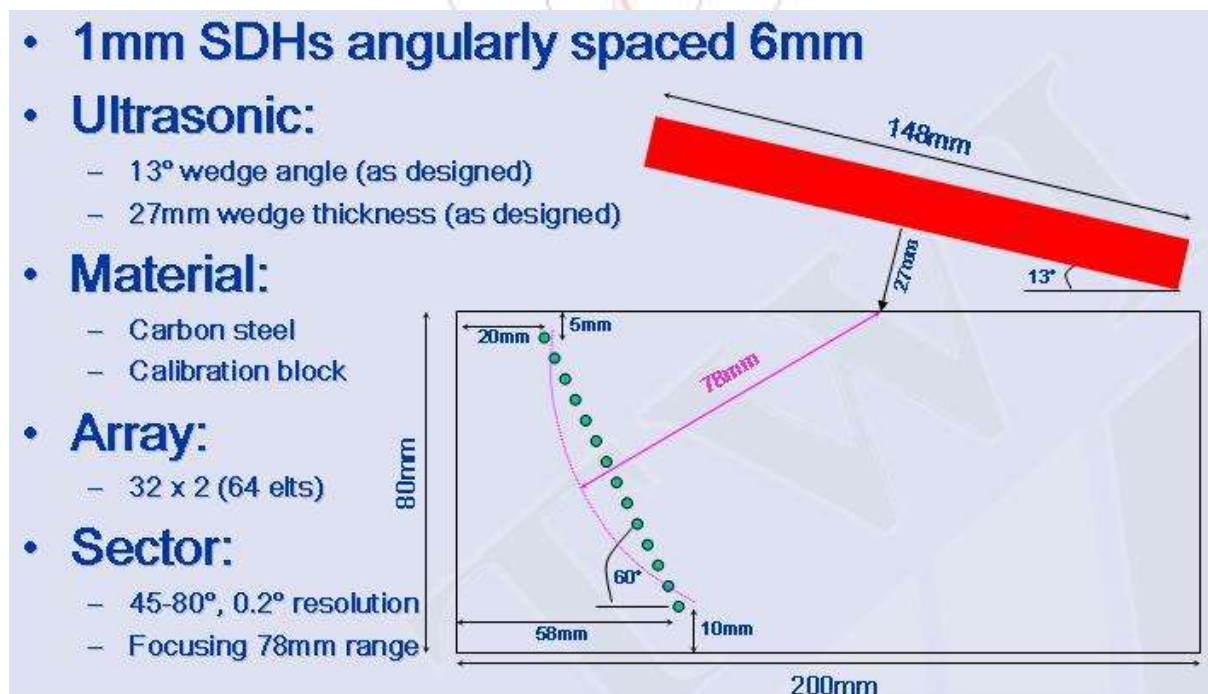


Figure 80 The 148mm long half of the TRL-1 array configured for a sector scan on a carbon steel calibration block containing 1mm SDHs.

The data is shown in Figure 81, with all the targets aligned as described in Figure 80. The target in the cursors (which are at an angle of 60°, depth of 38.5mm and horizontal stand off 68mm) is well resolved; however at the higher beam angles (>70°) the beam width is not sufficiently small to resolve the targets well. Note also the characteristic large dead zone near the surface due to the pulse-echo setup.

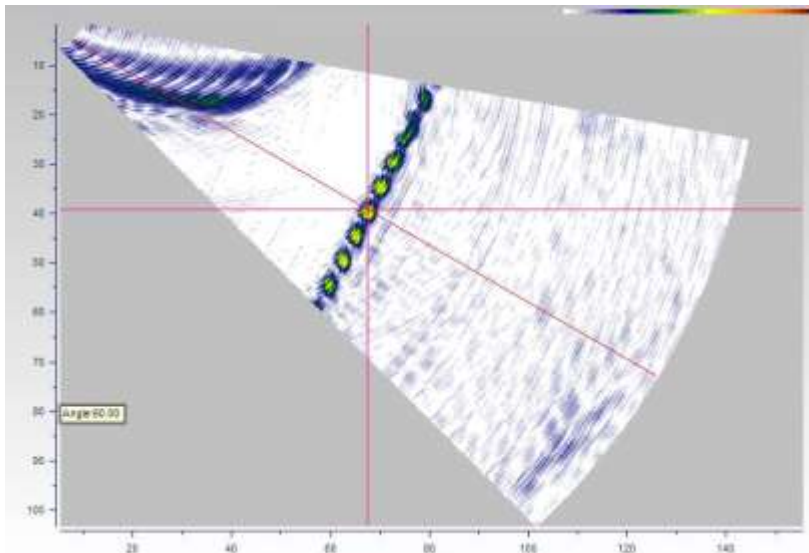


Figure 81 A sector scan data of the functional test described in Figure 80.

TRL-1 is an immersion coupled probe and the required roof / wedge angles were achieved using a mechanical housing frame, as shown in Figure 82 with all measured parameters.



Figure 82 The final configuration of the TRL-1 probe, ready to be used for inspection.

4.5 2D-1 array

The final specification of the 2D-1 array is given in Appendix C. SimulUS was used for the first level specification and PZ Flex was used for the second level specification. The methods used for arriving at the values for the various parameters of the 2D-1 array was similar to that described for the TRL-1 in Sections 4.3 and 4.4, and will not be presented in this document.

The 2D-1 array differs from the TRL-1 array in many respects but was constrained by the 128 maximum available channels. Hence the first level specification involved the study of several configurations:

1. 16x9 with 4 elements at each corner not active
2. 21x6 and 18x7, which only require 126 channels
3. 16x8
4. 21x12, which is termed a 1.5D array configuration

The 2D-1 array was a two-dimensional array (ie 2D), which coupled the sound into the component using Rexolite as a wedge (rather than using water as for TRL-1) and it was not implemented in transmit-receive mode, ie it was used in the pulse-echo mode. The 2D-1 array was designed to optimise both the steering and focusing performance required to cover the full weld of the DISSIMILAR specimen but also to implement skewing of the sound beam, which is to be able to steer the beam in the plane parallel to the secondary axis of the probe. The ability to skew the beam has been shown to provide further information on the orientation of a flaw and allow for full three dimensional manipulation of the sound field.

Figure 83 shows the 2D-1 array on its Rexolite wedge and the metallic mast, through which it can be attached to the scanning frames.



Figure 83 The 2D-1 array on its Rexolite wedge of 18.5° designed to generate longitudinal waves in the component.

4.6 Advanced array configurations for future exploration

Several different array configurations were considered in the DISSIMILAR project, but were not manufactured and used for inspection. These include annular/segmented arrays, spiral/fractal arrays, sparse arrays and 1.5D arrays.

The simulated and experimental results for the 2D matrix array demonstrated that it is possible to produce an array which can skew the beam up to 10° , without introducing artefacts into the image (see Section 7). Where larger skew angles are required, matrix arrays with periodic spacing are limited, due to the large number of elements required to achieve sufficient resolution without forming grating lobes. Even the large array controllers that are currently on the market with 256 and even 512 channels cannot support these dense matrix arrays, which in many cases would require upwards of 1,000 elements. Alba Ultrasound has been developing a series of fractal based array patterns, which overcome this problem through their aperiodic design. Grating lobes are eliminated, allowing full volumetric steering with much smaller arrays than could be previously considered. Alba Ultrasound has constructed a prototype device along a similar specification to the 2D-1 matrix array, which is capable of skewing its beam up to 60° outside the scan plane, using only 127 elements. For comparison, a 2D matrix design would require 540 elements to achieve this performance.

To illustrate the difference in capabilities between a standard configuration matrix arrays, ie the 2D-1 developed for the DISSIMILAR project, and a design based on a fractal configuration, trials were undertaken to skew the sound beam by up to -60° to $+60^\circ$. Figure 84 shows the result using the 2D-1 array where the sound field was skewed from -30° to 30° ; the presence of grating artefacts are noted. To compare, an array of the same frequency, similar number of elements (26 elements in 2D-1 and 27 elements in the fractal array) and coupled through the same Rexolite wedge was fabricated by Alba Ultrasound. Figure 85 shows the result using the fractal array where the sound field was skewed from -60° to 60° with the absence of diffracting artefacts.

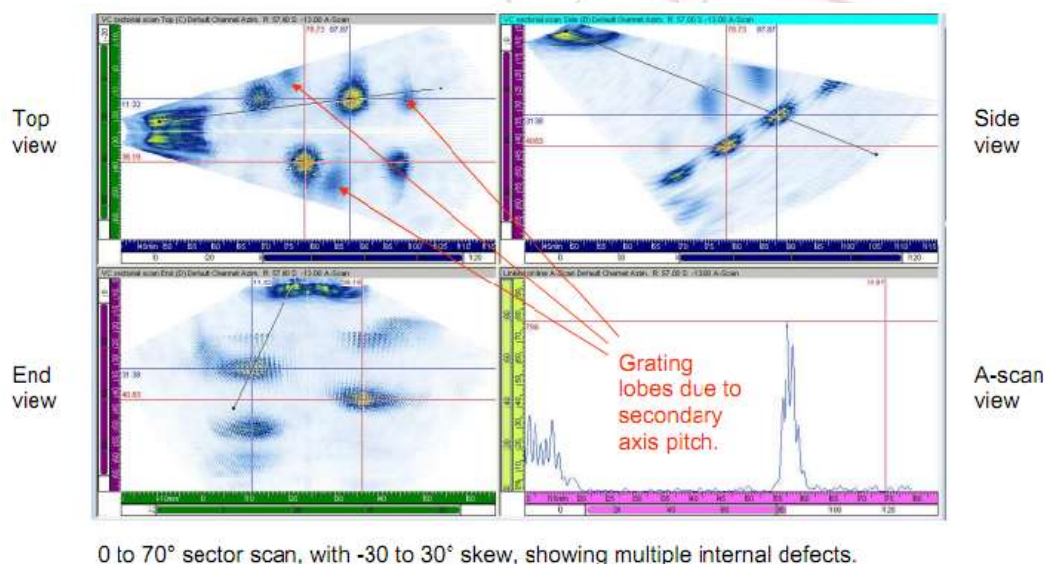
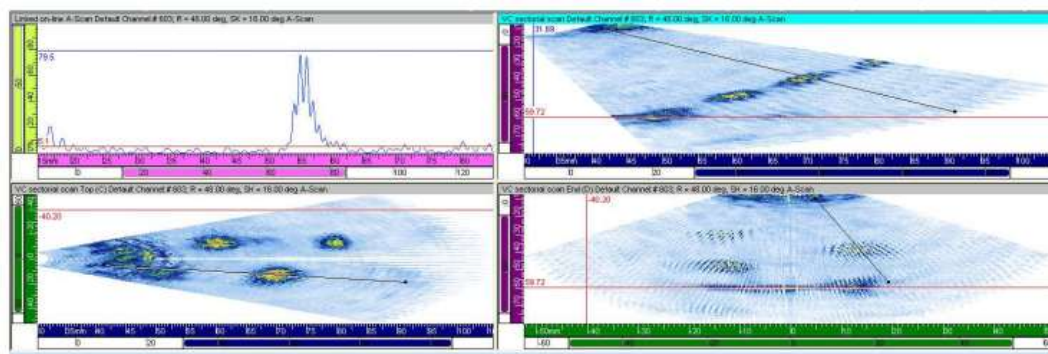


Figure 84 Result of skewing the sound beam using the 2D-1 array in-excess of 10° , leading the generation of grating lobes.



Multiple internal defects detected in volumetric scan, showing no grating lobes.

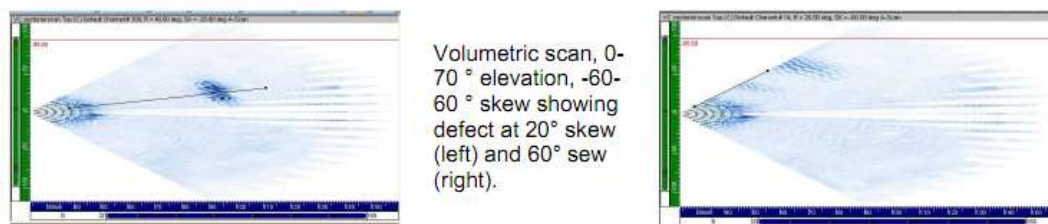


Figure 85 Result of skewing the sound beam using the fractal array designed by Alba Ultrasound by up to 60° without the generation of grating artefacts.

These results hold promise to be able to fabricate arrays with low element counts (hence reduce the associated instrumentation costs) which would allow for full 3D control of the sound field within the component being inspected, opening the possibilities for designing ultrasonic techniques with greater versatility.

4.7 Specification flow chart and standardisation of probes

The procedure to undertake a first level specification for phased array inspection can be generalised, independent of array configuration. Starting with the assumption that focusing will be required, then the near zone length must be greater than the maximum required focus range, and then the pitch must be suitable for steering range and so on. This procedure can be visualised in the specification flow chart shown in Figure 86 which captures the steps and criteria for selecting the key parameters for the TRL probe. The generic design of any phased array probe consists of iterative loops to optimise key inter-dependent parameters.

In conventional ultrasonic testing, the ability to standardise probes has greatly aided those who provide inspection services and the generation of industrial application standards. The use of phased array technology and in particular designing the technique through the use of flow charts to select the probe will inevitably lead to the generation of a wide variety of specifications. However, it may still be possible to select a group of probes which would be prescribed for the majority of inspection tasks. The prescribed probe set will be dictated by the task; for example, the inspection for (1) root flaws / (2) lack of fusion / (3) cap flaws of butt welds in carbon steel plates of thickness less than 25mm could be achieved through the use of a 4MHz linear array probe with 32 elements.

Standardisation efforts should ideally be coordinated by a body such as the British Standards Institution as part of efforts to generate standards for application of phased array inspection in industry [15, 16].

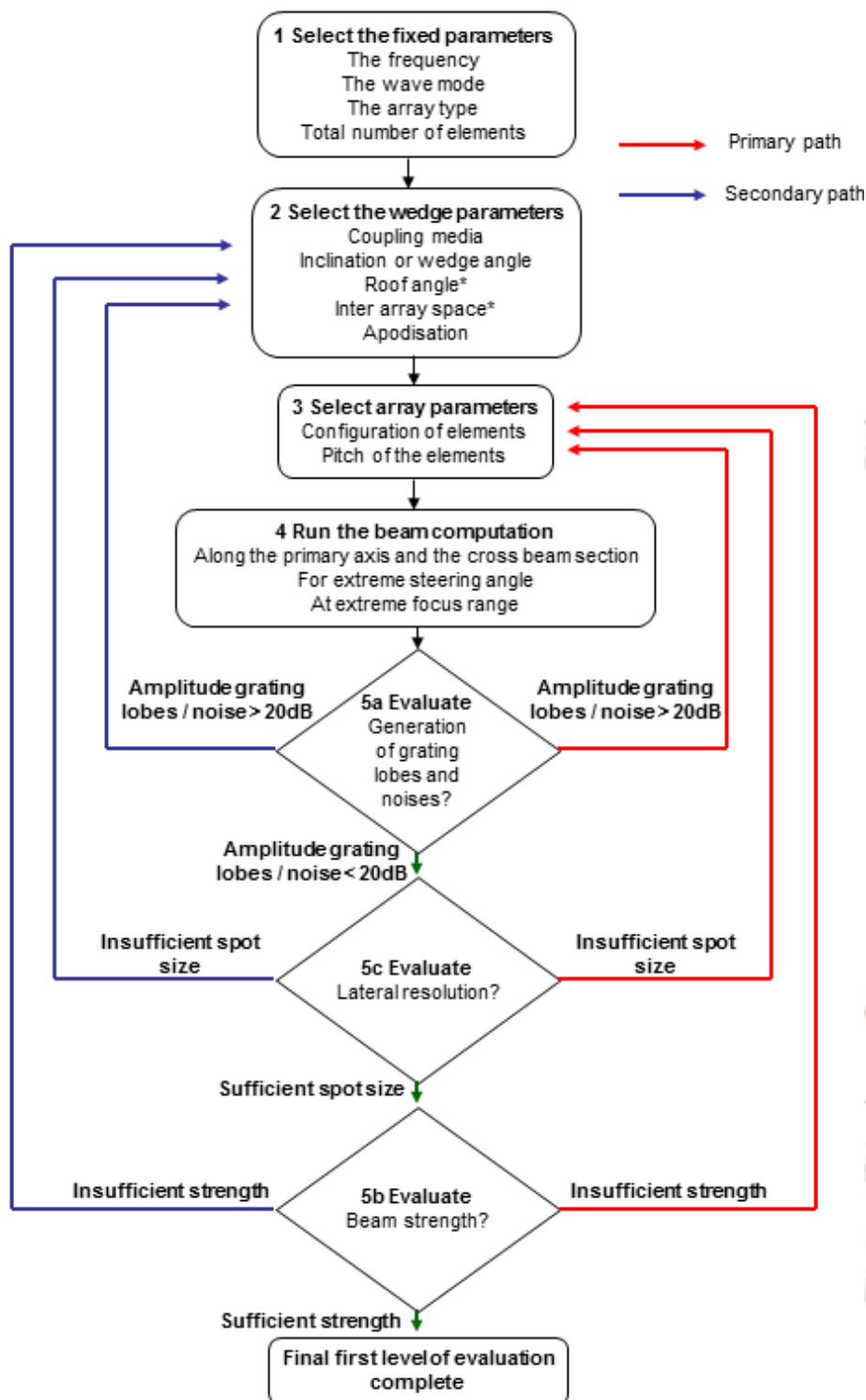


Figure 86 The iterative procedures to follow for setting the parameters of the TRL phased array probe through modelling the sound field.

5 Instrumentation

To implement phased array techniques a more sophisticated equivalent of the ultrasonic flaw detector is required. These instruments, often termed array controllers, are essentially composed of higher specification versions of the simple flaw detector unit, with the key difference that several independent pulser-receiver channels are required. This is because each element of an array is considered an independent transducer or probe and hence must be operated by its own transmitter-receiver electronics. The consequence is that, in general, array controllers are at least an order of magnitude more expensive than a standard flaw detector.

For application to the inspection of thick-section austenitic and dissimilar welds the bandwidth of the pulser-receiver electronics must be sufficiently low to cover the low frequency probes that would be required. The pulsing voltage should be 200V or higher to impart sufficient energy to penetrate the high attenuation weld material. For operation in metals the time delay resolution, ie the delay between the firing of elements on the arrays, must be 1ns. Additionally, capabilities such as apodisation (ie the ability to change the pulsing voltage to different elements) can be beneficial in certain scenarios.

Filters are often applied to the receive circuits of the array controller such that the signals can be actively processed on reception before storage or display. Band pass filters, ie filters which allow through frequency content between certain ranges, can often be used to limit the recorded noise levels. Further active processing can be applied within the electronics to, for instance, implement fast Fourier transforms (FFTs) to analyse the signals in the frequency domain rather than the time domain.

The number of independent pulser-receiver channels onboard an array controller impacts on the phased array techniques that can be developed by limiting the total number of elements on a probe that can be addressed and the number of elements that can be used to build focal (or delay) laws. For application to thick-section dissimilar welds, a minimum of 128 independent pulser-receiver channels will be required.

For implementation of full matrix capture techniques (see Section 10.2) the array architecture needs to be optimised for fast transfer of data from the array controller to the data storage unit (ie computer). Full matrix capture refers to the recording of data over all possible transmit-receive combinations of the array; the stored data is then processed by a computer before being displayed. Hence, for real-time imaging, the data capture and processing must take place rapidly and increasing the data throughput from the array controller to the computer to be processed is critical.

The DISSIMILAR project made use of the array controller termed MicroPulse 5PA containing 128 channels (or pulser-receiver units); the specifications of the MicroPulse, manufactured by Peak NDT of Derby, is given Appendix D. At the time of writing, Peak NDT have developed and started manufacture of the next generation of array controllers, termed MicroPulse FMC, which is specifically designed to advance and promote the use of full matrix capture techniques in industry.

Further detailed discussion of the array controller instrumentation is not included in this document as the electronic technology in this field is rapidly advancing to enable real-time imaging capabilities. The reader is referred to the many manufacturers on the market for detailed information regarding their products and capabilities.

6 Techniques

6.1 Introductory comments

The DISSIMILAR project was initiated as an attempt to overcome the considerable difficulties of inspecting austenitic welds. With the ever increasing development in the fields of modelling and array ultrasonics, coupled with the quantification method described in Section 3, it was thought that the tools had matured enough to address the fundamental problems of sound propagation in the inhomogeneous anisotropic austenitic materials. The aim in the DISSIMILAR project was then to develop a new kind of inspection technique and procedures tailored for application to the specific case of austenitic materials.

Two complementary routes were considered for (1) overcoming the distortion to improve sensitivity and (2) correct for the positioning errors. Only the route to improve the sensitivity was explored in the DISSIMILAR project.

Route 1: Translation tables

In this approach, the distortion induced by the anisotropic weld is first evaluated and then the **positioning** is corrected. The modification is specified in the interpretation procedure using translation tables or lookup tables. The steps required to implement this route are:

- Section a reference weld specimen
- Map the austenitic weld structure incorporating the crystallographic information
- Input the weld map into a model
- Perform simulated scans using point reflectors in all positions in the weld
- Correct for error in the **interpretation procedures**

The translation tables are generated using a point reflector introduced into the virtual weld and inspections are then simulated at the different beam angles used in the actual inspection; the plotting position of the target is then recorded in a table (assuming a nominal value for the velocity). The process is repeated with the point reflector in a different position until the full weld volume has been covered by the reflector at a suitable resolution. This approach is simulation intensive and is illustrated in Figure 87.

Route 2: Adapted delay laws

This approach is similar to that taken in Route 1 but, instead of using the knowledge of distortion in the interpretation procedure, it is used to adapt the focal laws used for the inspection. Note that this technique only improves the inspection **sensitivity** in its limited form of application explored in the DISSIMILAR project.

- Section a reference weld specimen
- Map the austenitic weld structure incorporating the crystallographic information
- Input the weld map into a model
- Generate adapted delay laws which compensate for distortion
- Specify in **scanning procedure** for inspection

Since the computation times involved in undertaking simulations can be long, only Route 2 was investigated as part of the DISSIMILAR project and the ideas of Route 1 was used to undertake a limited validation of the quantification method and modelling.

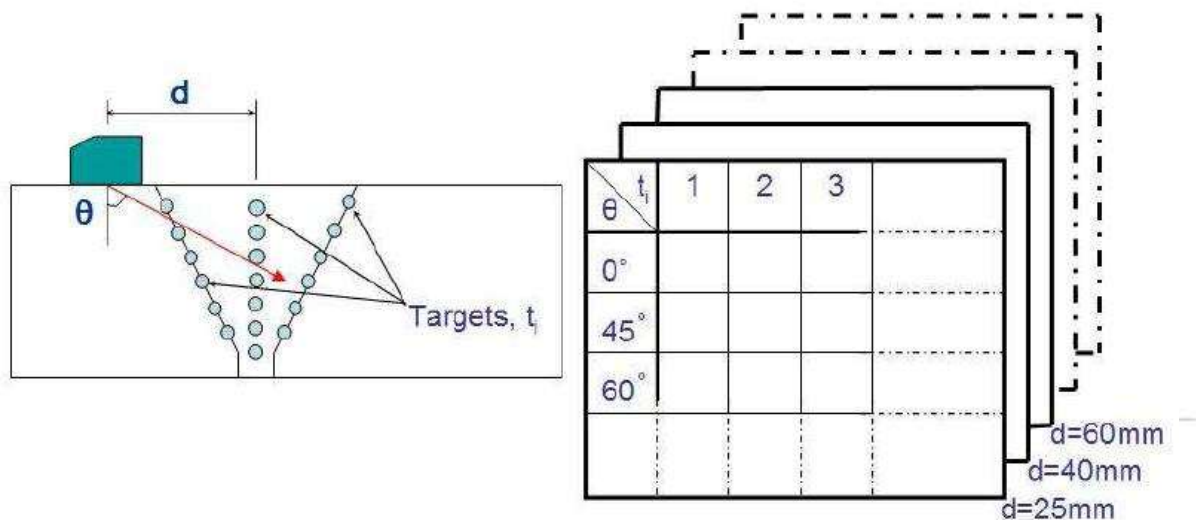


Figure 87 Generation of the translation tables through the simulation of the inspection for different beam angles, probe positions and target positions.

In this section, the Route 2 method (termed **adapted delay laws**) to generate a new technique is described along with the baseline techniques. The baseline techniques presented in this document are representative of the vast majority of ultrasonic techniques used for the inspection of austenitic welds. The DISSIMILAR specimen was inspected using all the baseline techniques and their performance is presented in Section 7 in comparison to each other and the sectioning results. The adapted delay laws technique was only applied for the inspection of Flaw 3 and Flaw 4, the results are again presented in Section 7. The timescales and complexities of development only allowed a limited investigation of this new technique in the DISSIMILAR project.

6.2 Adapted delay laws (ADL) technique

In this technique the quantified weld is input to the model, which is then used to generate the adapted delay laws (ADL). Delay laws refer to the firing times of the elements in an array, such that the subsequent sound field (or the propagating sound wave generated in the medium) behaves in the way required. In phased array techniques the two major reasons for wanting to control the sound field are (1) to direct the wave in a particular direction (ie beam angle) and (2) to focus the sound energy at a particular position in order to increase the returned echo amplitude from an indication at that position. Hence the aim of the delay laws is to ensure that the waves emanating from each element of the array arrive at the correct *time* at a position for constructive interference to take place. The delay laws can be computed from knowledge of the path that the sound will take from each element on the array, which is a straight line (obeying Snell's law at boundaries where there is a change in acoustic impedance). In an austenitic weld there are numerous boundaries (ie grain boundaries) and additionally the velocity of the sound changes across those boundaries, hence the simplistic geometric assumptions are no longer valid such that delay laws can no longer be calculated. In practice, when implementing phased array inspection (as in Section 6.2.3) the effect of the weld is ignored and delay laws are calculated, assuming it is a typical isotropic weld (such as a carbon steel weld). This then gives rise to the issues illustrated in Appendix A.

The ADL method implemented in the DISSIMILAR project is applied primarily with the aim of improving the sensitivity of the inspection. The material induced error in target position is corrected for implicitly in the forward transmission, but the software used to plot the returning echoes still assume a single velocity and straight line paths; hence the error due to incorrect plotting remains uncorrected when using the ADL technique. For a holistic solution that both improves sensitivity (overcoming the distortion on transmission) and reduces the error in positioning, both the ADL concept and the translation tables must be implemented together.

Before the ADL can be generated, the information provided by the weld quantification (Section 3) must be input to a model. A range of models exist which can be used, including semi-analytical models such as CIVA and finite element models such as PZ Flex. The work done in the DISSIMILAR project made use of the CIVA platform, primarily because it was designed exclusively for the purposes of simulating ultrasonic inspections, whereas PZ Flex and other models are more generic where it is difficult to simulate complex ultrasonic inspection scenarios (such as the use of phased arrays). In this section the steps to generate an adapted delay law is explained, along with the initial evidence showing its potential to improve inspection. Results of ADL being used for inspection of Flaw 3 and Flaw 4 are presented in Section 7 and were used to assess any benefits to be derived.

6.2.1 Inputting the quantified weld to the model

The weld map generated using the methods of Section 2 must be input to the CIVA model. Figure 88 shows the root region of an austenitic weld showing the buttering on the ferritic steel oriented horizontally. The important task in translating the weld map into the model is to identify closed regions with clear boundaries, which was done with a combination of digitisation and manually selecting the boundaries of interest. Subsequently, the weld map of Figure 88 was transformed to a weld map suitable for the model, as shown in Figure 89. There are 89 distinct regions and 1276 distinct boundaries in the model map of Figure 89.

The orientation values relevant to each region are then input explicitly to the model along with the cubic stiffness constants. The weld cross section is then extruded to create the three dimensional component, ie it assumes that the microstructure remains constant along the welding direction (Section 3.6).

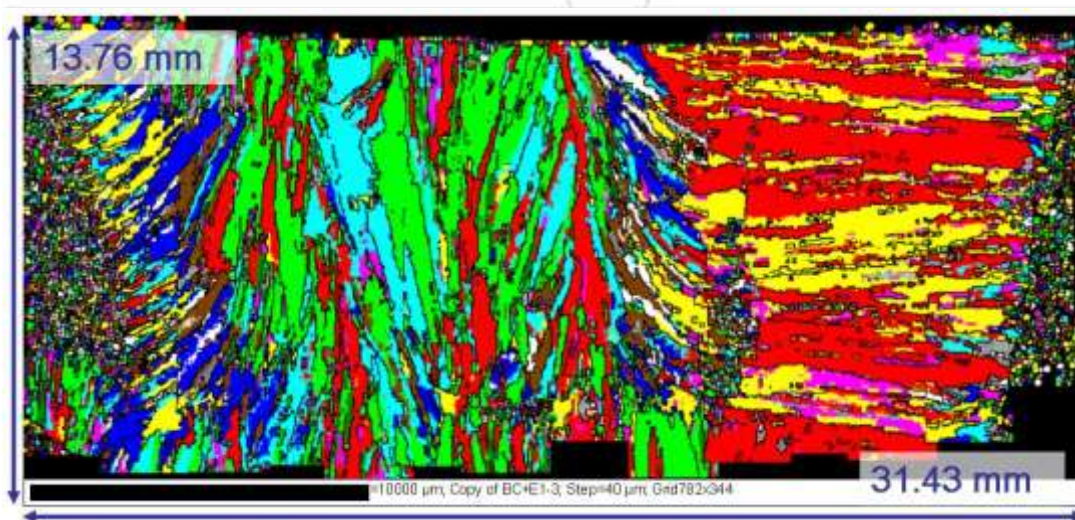


Figure 88 The root region of an austenitic weld showing the major regions in key colours.

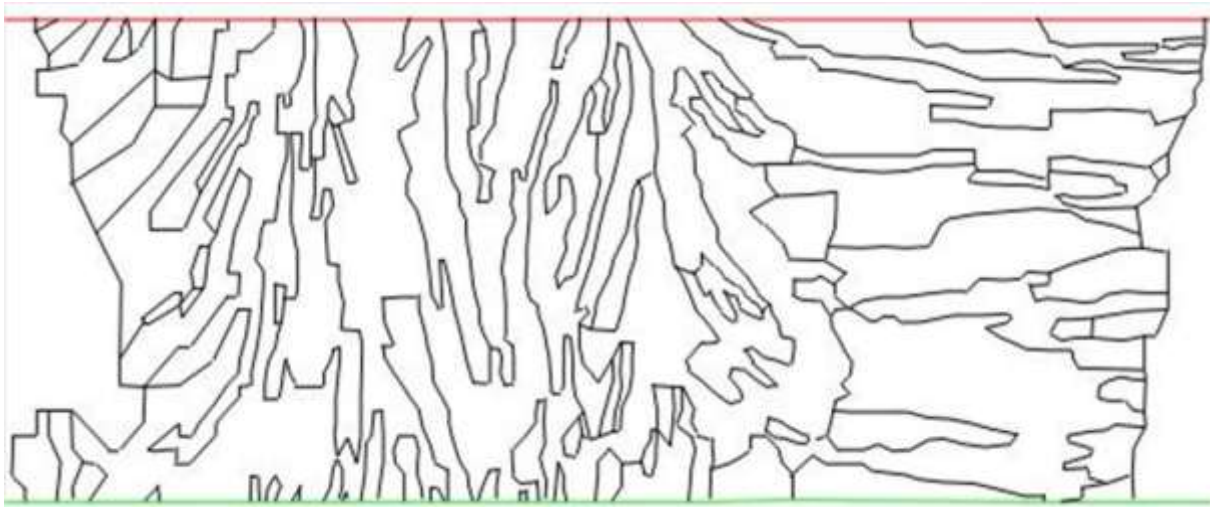


Figure 89 The EBSD weld map translated into a model map with closed regions.

6.2.2 Generating the ADL

Once the model of the weld is ready, simulated scanning can be undertaken in the CIVA platform. The generation of ADL is based on time reversal concepts, where the time taken for echoes to return from a target is converted into the delay laws. Essentially, ADL are not *calculated* (as in traditional delay laws using algorithms in the delay law calculator) but *generated* using simulation results.

Firstly, a point target (ie a SDH) is introduced at a position in the weld where the sound energy is to be maximised (ie focused). Then, each element is fired such that a widely divergent sound field (ie a point source) emanates from the element and enters the weld. In the weld the propagating wavefront will be distorted and upon incidence on the point target will return along the same path and the signal is received on the same element. Hence, the pulse-echo data from the element is collected. The time to arrival of that echo depends on the specific path that the wave travelled in the weld. The same process is then repeated for all the elements on the array.

When completed, the travel times to and back from the target is known for all elements on the array. Hence now, it is possible to fire all the elements such that the waves from all the elements will arrive at the position of the target at the *same time*, and in phase. This then is the generated ADL to maximise the incident energy (ie increase sensitivity) to a target at the position considered.

Generating the ADL does not require the introduction of SDHs in the actual component or in reference welds; the ability to quantify the weld using EBSD to such high resolutions and the use of models such as CIVA has allowed the possibility to undertake what would have been a very expensive route much more cost effectively through simulations.

6.2.3 Example of inspecting Flaw 3 using ADL

Figure 90 shows an inspection scenario where a 2MHz 32 element linear array is setup to inspect Flaw 3 in the DISSIMILAR weld; the beam angle incidence is specular on the flaw.



Figure 90 The inspection scenario for a specular incidence inspection of Flaw 3.

Figure 91 shows the linear array probe generating the 46.5° beam focused at the depth of Flaw 3 by using a delay lay calculated assuming that no weld exists.

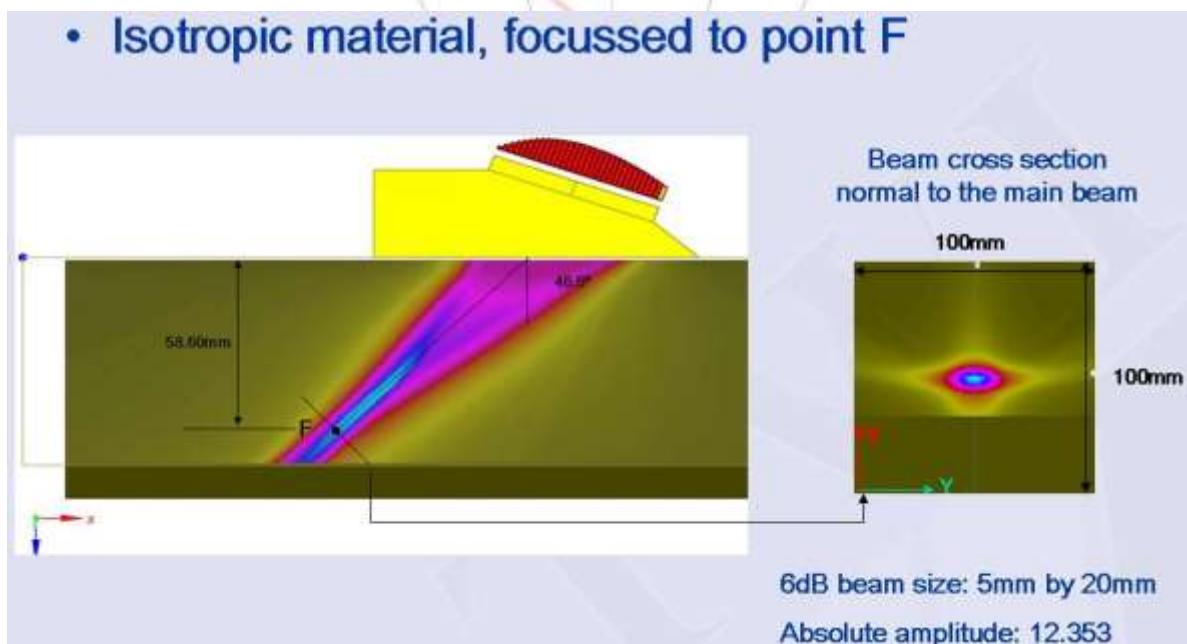


Figure 91 Integrity of the sound beam focused at the depth of the flaw with no weld.

Figure 92 shows the same delay law applied to generate the beam when the anisotropic weld is present and the distortion of the beam is clear. The loss in beam strength at the range of the flaw in comparison to the case when the weld was absent is greater than 20dB.

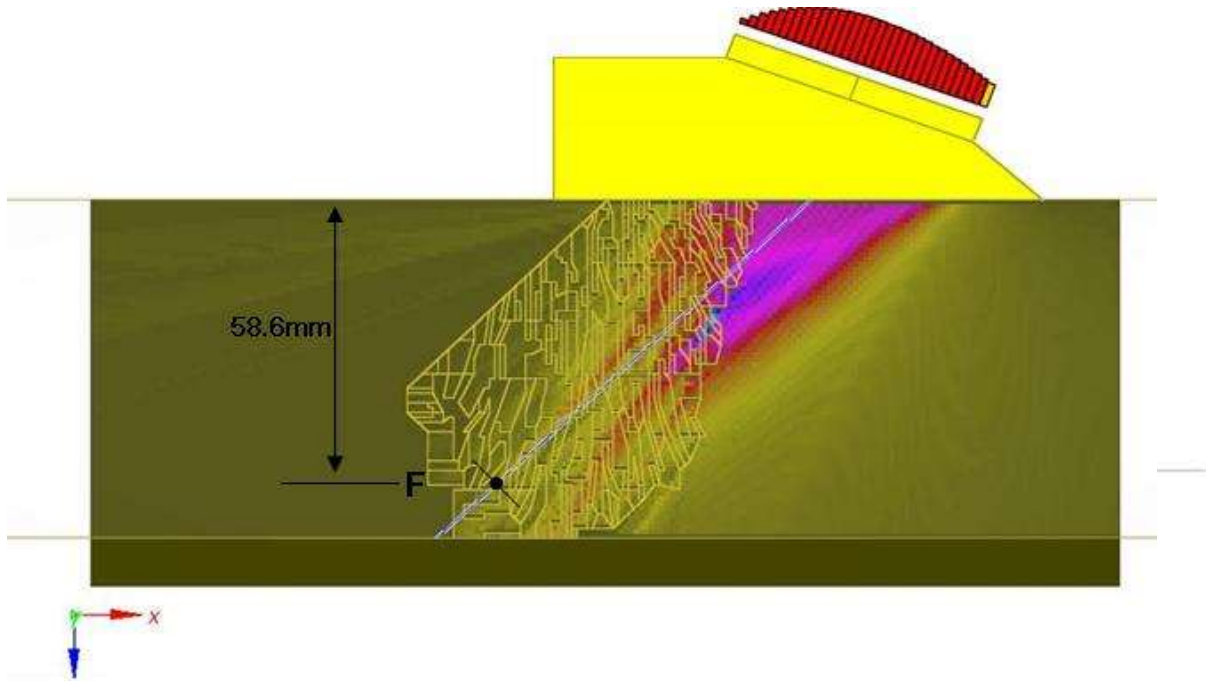


Figure 92 The distortion of the sound beam due to the weld when the isotropic delay law is applied.

Figure 92 illustrates the difficulties inherent to the inspection of austenitic welds in a similar way to Appendix A where experimental data was presented. Figure 93 shows the A-scan signal from Flaw 3 when using the calculated delay law and Figure 94 shows the signal when the generated ADL is used. The maximum amplitude is on the flaw centre when using the ADL and the absolute gain in signal strength in comparison to when the isotropic law was used (Figure 6.7) is around 2dB. This result indicates that, theoretically, it is possible to improve the inspection by being able to project energy better into the required inspection regions through the use of ADL. Note the shape of the ADL in Figure 94 in comparison to that of the calculated shape in Figure 93, which indicates that the path taken by the waves is not based on simple geometric relationships.

In the DISSIMILAR project, ADL were generated for the inspection of Flaw 3 using a linear phased array probe and for inspection of Flaw 4 using a half of the TRL-1 array. Flaw 3 was inspected with the beam arriving specular at the flaw through the weld such that the well validated Kirchhoff interaction method was used. However, the incident beam on Flaw 4 was not specular and the validity of the theory (Geometric Theory of Diffraction) used to evaluate the interaction has not been fully established. The performance of the ADL in comparison to experimental data and detailed information of the inspection setup is presented in Section 7. Additionally, the ADL for Flaw 3 was generated using version 9.2b of CIVA (32-bit) whereas the ADL for Flaw 4 was generated using version 10.0 (64-bit); the implications of the change in version will also be discussed in Section 7.

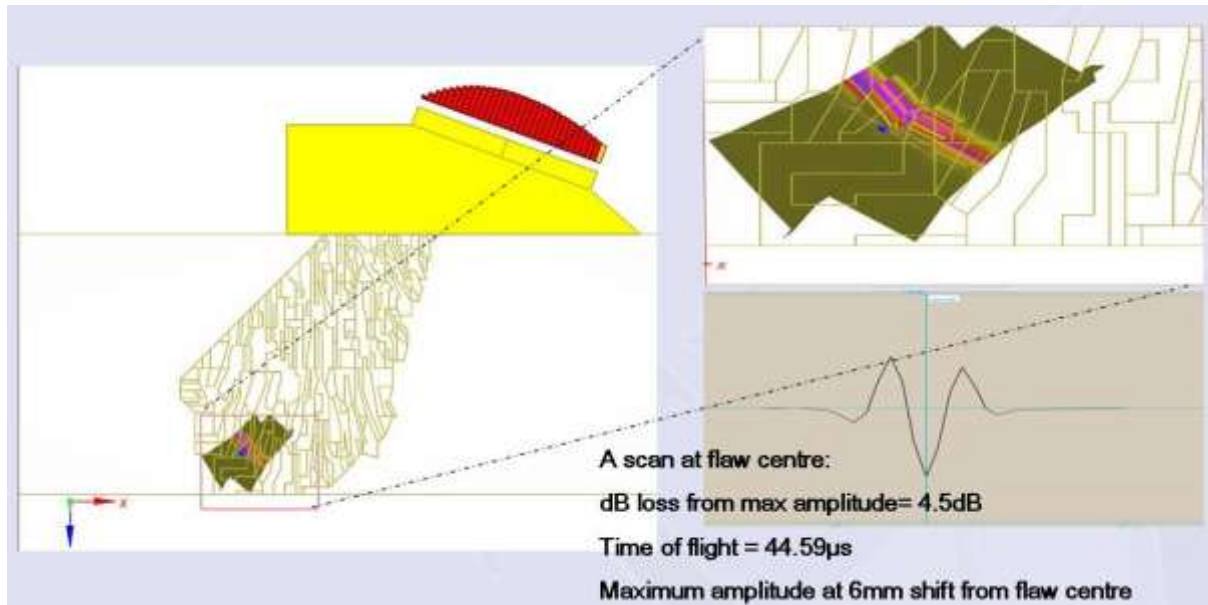


Figure 93 The A-scan signal from Flaw 3 when using the calculated isotropic delay law.

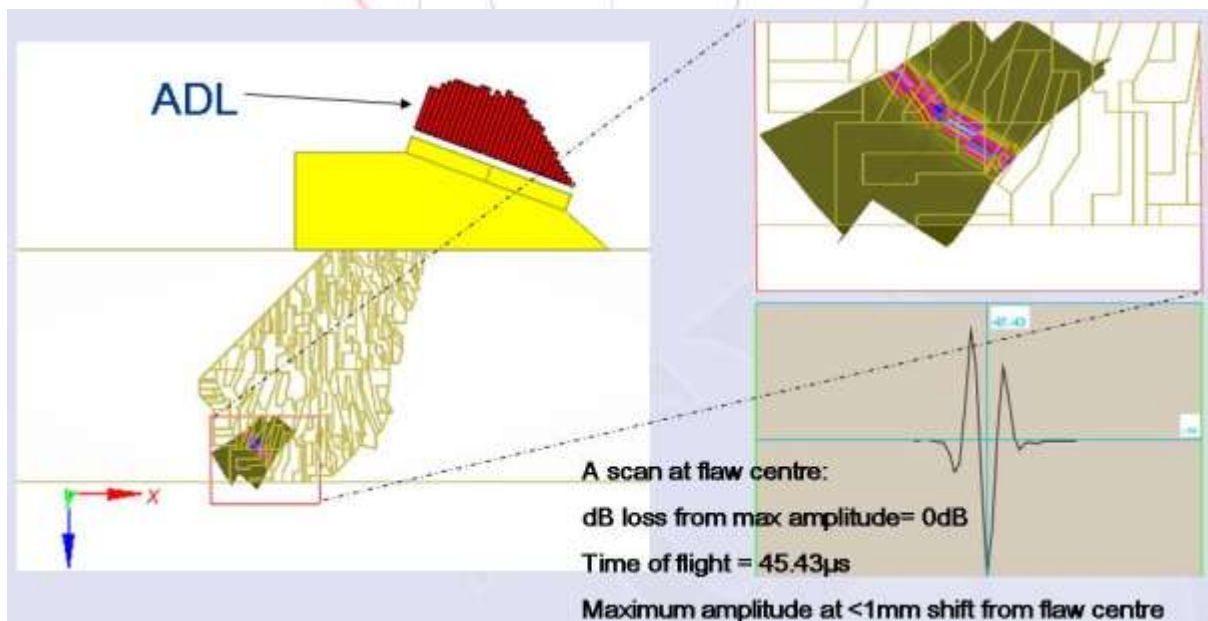


Figure 94 The A-scan signal from Flaw 3 when using the generated adapted delay law.

6.3 Baseline techniques

The aim of all the baseline techniques was to inspect 100% of the DISSIMILAR weld and report indications with (1) position, (2) orientation and (3) through-wall size. It was not an explicit requirement to characterise the indications into typical weld flaw types, however knowledge of their nature was implicitly required. There were five baseline inspections, two of which made use of the probes developed in the DISSIMILAR project: TRL-1 and 2D-1.

All scans were performed from both sides of the weld with the probes placed on the top surface (OD surface); in the case of the automated baseline (Section 6.3.2), the inspections

were performed from the bottom surface also, the ID surface. Note that the ID surface is where the root of the V-prep weld in the DISSIMILAR specimen has been deposited.

6.3.1 Manual conventional technique

The SONATEST Powerscan 400 flaw detector was used which provided a 400V pulser along with gain increments in 0.5dB. The probes used were conventional probes designed for inspection of austenitic welds:

1. 0° 2MHz twin-crystal 20mm diameter compression probe
2. 45° 2MHz twin-crystal angle compression probe (Krautkrämer type VRY)
3. 60° 2MHz twin-crystal angle compression probe (Krautkrämer type VRY)
4. 70° 2MHz twin-crystal angle compression probe (Krautkrämer type VRY)

Calibration of time base was performed in accordance with a draft standard for the inspection of austenitic welds [15]. There were several exceptions to the recommendations of the draft document [15] which are listed below:

1. A reference block (with targets in a representative weld) was not used for generation of the distance amplitude correction (DAC) curves
2. Sensitivity was based on 5-10% full screen height (FSH) grain interference (grass noise)
3. The 20dB beam spread was not established for all the beams as a reference block with the weld was not available
4. The max amplitude technique was used for sizing all indications

Inspection was performed by a Level III ultrasonic operator experienced in austenitic welds.

6.3.2 Automated (encoded) conventional technique

The automated technique was performed using the MIPS/GUIDE system developed by British Energy Generation Limited (BE). Details of the instruments, equipment and probes used in this baseline are available in the inspection report presented in Appendix D. This baseline represents the current best practice inspection being implemented in the nuclear power plants of the UK.

6.3.3 Linear phased array technique

This is the first of three phased array technique which made use of a 32 element 2MHz linear array probe with a pitch of 1.5mm and width 20mm. The MicroPulse (Section 5) was used with the software ArrayGen (version B1008) to collect, process and display the data; the data was displayed and interpretation was done in the sector scan format. The probe was mounted on a Perspex wedge of 20° with a wedge thickness (as defined in ArrayGen) of 16.5mm.

The technique was conducted in accordance, wherever possible, with the draft standard for inspection of austenitic welds [15] and with the draft standard for inspection using phased arrays [16]. As for the manual technique (Section 6.3.1) an exception was the absence of a DAC generated in a reference weld, which was not available. Time base calibration was performed for all the angles in the sector using a 304 stainless steel calibration block containing 3mm SDHs with a measured nominal velocity of 5750m/s. Sensitivity, as in the manual technique, was taken with reference to the grass noise level. However, sizing was

performed using tip diffracted echoes, whenever these could be established with some confidence.

The array was used to focus the sound energy to the depth of the target and each flaw was investigated individually over the beam angles available in the sector.

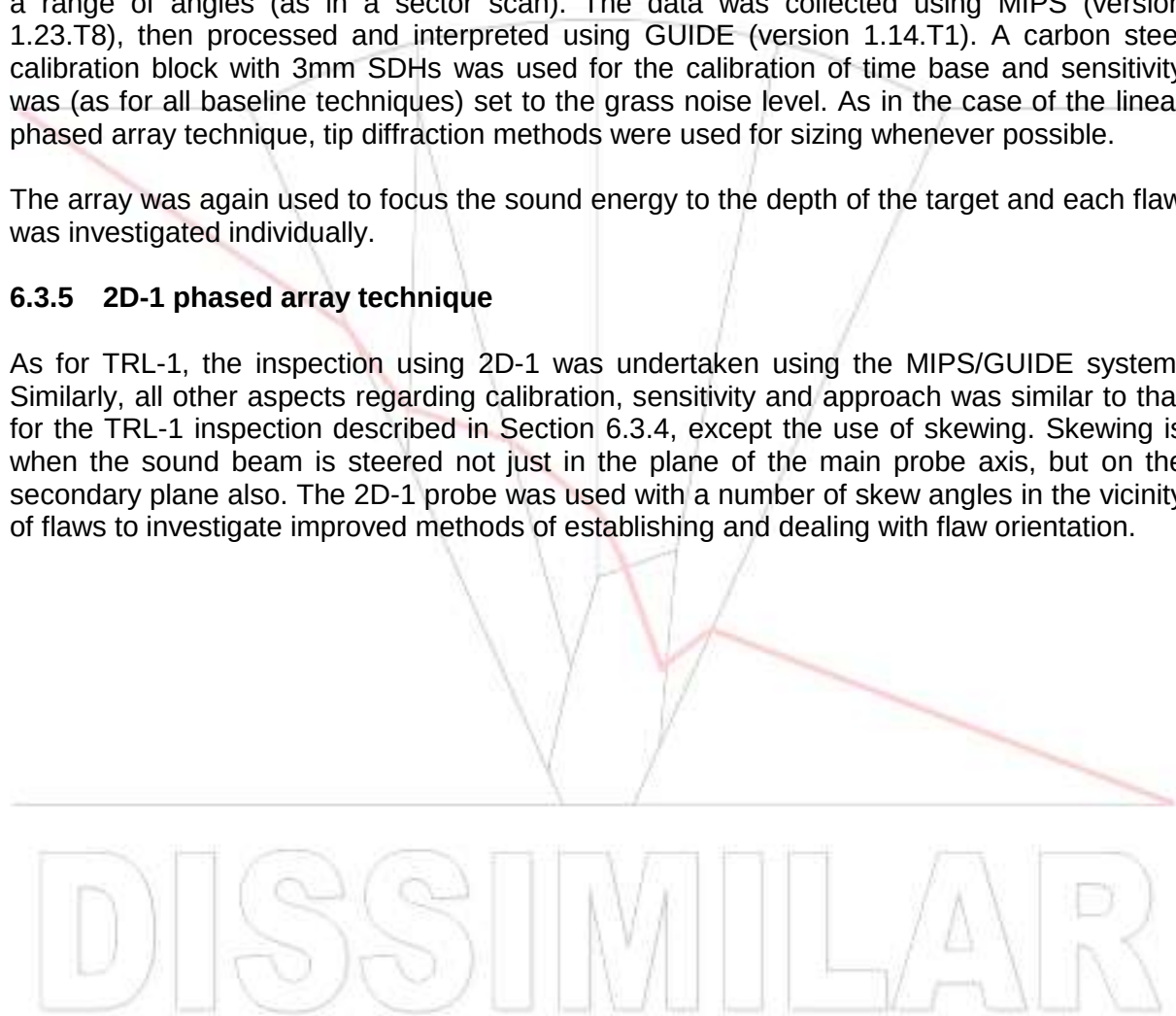
6.3.4 TRL-1 phased array technique

The inspection using TRL-1 was done using the BE MIPS/GUIDE system configured to implement phased array inspection. The array probe was programmed to generate beams at a range of angles (as in a sector scan). The data was collected using MIPS (version 1.23.T8), then processed and interpreted using GUIDE (version 1.14.T1). A carbon steel calibration block with 3mm SDHs was used for the calibration of time base and sensitivity was (as for all baseline techniques) set to the grass noise level. As in the case of the linear phased array technique, tip diffraction methods were used for sizing whenever possible.

The array was again used to focus the sound energy to the depth of the target and each flaw was investigated individually.

6.3.5 2D-1 phased array technique

As for TRL-1, the inspection using 2D-1 was undertaken using the MIPS/GUIDE system. Similarly, all other aspects regarding calibration, sensitivity and approach was similar to that for the TRL-1 inspection described in Section 6.3.4, except the use of skewing. Skewing is when the sound beam is steered not just in the plane of the main probe axis, but on the secondary plane also. The 2D-1 probe was used with a number of skew angles in the vicinity of flaws to investigate improved methods of establishing and dealing with flaw orientation.



7 Performance

7.1 Introductory comments

This section discusses the performance of all the techniques to detect and size the flaws that were introduced into the specimen. The performance of the baseline inspection techniques is discussed in Section 7.2, followed by the performance of the ADL technique explored in the project in Section 7.3 and efforts towards validation of the models in Section 7.4.

7.2 Baseline inspections

The primary aim of the project was to establish the positioning and sizing capabilities of phased array ultrasonic techniques against other established ultrasonic techniques; all the techniques explored in the project are described in Section 6.3. All the baseline techniques were used to inspect the DISSIMILAR specimen (see Figure 5) to detect, position and size the implanted flaws. Flaws 1, 2, 3 and 4 were then sectioned to confirm against the nominal positions and sizes; flaws 5, 6, 7 and 8 were retained for future experimental demonstrations and trials to compare against the work done in the DISSIMILAR project.

The general requirements of ultrasonic inspection are to establish:

1. The type of flaw
2. The position of an aspect (eg the top tip) of a crack from a reference (eg top surface)
3. Size; both through thickness and lateral

The operators who undertook the baseline inspections were not required to establish the flaw type; it was assumed that the range of flaws introduced could be quite readily characterised through the data obtained. The positions and sizes reported using the baseline inspection techniques were compared to the nominal sizes, which were checked through sectioning.

The performance of each technique for Flaws 2 to 8 is quantified in charts where the through-wall extent bars show the flaw height and measured distance from the top surface of the specimen to the top edge of the flaw, and the (lateral) flaw length bars give the start position and measured length of the flaw along the welding line. The inspection data from using the various techniques are presented in this section, except for those from the conventional automated scans which are given in Appendix E.

In the figures that follow showing the through-wall and length measurements provided by the different baseline techniques, the key to the data labels are as follows:

- Nominal: as implanted, confirmed by sectioning for Flaws 2, 3 and 4;
- PA 2D (AA): 2D-1 phased array technique (see Section 6.3.5) where AA is the side of the weld centreline where the probe was placed - either SS for stainless steel side or CS for carbon steel side;
- TRL (AA): TRL-1 phased array technique (see Section 6.3.4) where AA is the side of the weld centreline where the probe was placed - either SS for stainless steel side or CS for carbon steel side;
- PA (AA): linear phased array technique (see Section 6.3.3) where AA is the side of the weld centreline where the probe was placed - either SS for stainless steel side or CS for carbon steel side;
- Conv. Ma (XX): conventional manual technique (see Section 6.3.1) where XX is the beam angle of the probe used to collect the data;

- Conv. Au (BB AA): conventional automated technique (see Section 6.3.2 and Appendix E for full inspection report) where (1) BB indicates whether the scanning was done on the ID for inside diameter surface or OD for outside diameter surface and (2) AA is the side of the weld centreline where the probe was placed - either SS for stainless steel side or CS for carbon steel side;
- Conv. Au (All): indicates the closest measurement found from all the probes that were used in this baseline inspection.

Note that only the conventional automated technique was performed from both inspection surfaces, termed ID and OD, and all the other techniques were performed from the OD surface only, which is the top surface opposite to the weld root.

7.2.1 Flaw 2

Figure 95 shows the performance of all the techniques for Flaw 2. The greatest positional error through-wall was when using the TRL-1 technique, which positioned the top edge of the flaw 5mm below the surface (error of -5mm). The conventional automated technique overall had a lesser error in through-wall position (-1mm) but the greatest error in through-wall size (+3mm). None of the techniques were able to measure both the flaw position and size to within +/- 1mm.

Figure 96 shows the results of the conventional manual technique for plotting Flaw 2 when using the 45, 60 and 70° beams; the technique used the max amplitude sizing method. There were substantial changes in both the plotted position and evaluated through-wall size when using the three different beams.

Note that all three beams have positioned the flaw on the weld side of the buttering, whereas the sectioning (see Figure 97) shows that the flaw was introduced on the parent ferritic side of the buttering. However, there will have been some measurement error (estimated to be around 2mm) when measuring from the centreline and in addition changes in the actual beam angles / probe index points. The primary parameter which would have affected the plotted position of Flaw 2 would likely have been the assumed velocity (6042 or 5626m/s depending on whether inspection was from ferritic or stainless steel sides, respectively).

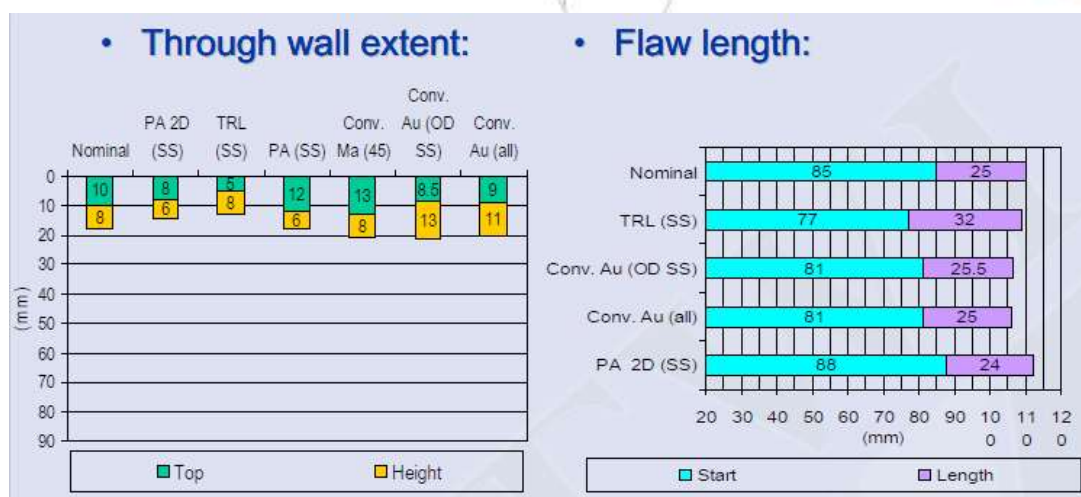


Figure 95 Graphs showing the comparison of the position, through-wall and length measurements made by the baseline techniques for Flaw 2. Refer to key on page 95.

In general, over all the other flaws also, the performance of the TRL-1 technique for lateral flaw sizing was found to be poorer than the other techniques. It is known that twin element probe configurations (such as the TRL probe developed in DISSIMILAR) have an optimum working volume which is constrained by geometric parameters, in particular the roof angle. The use of two dimensional arrays on each half of the twin probe allows for some control and widening of this working volume; however, each half of the TRL probe developed had a 32 x 2 configuration and it was not possible to greatly influence the working volume using only 2 elements along the lateral axis. Future designs of the TRL probe should increase the number of elements along the width of the array (hence also increase the total number of channels in the instrument) to improve the lateral sizing ability of the TRL-1 type techniques.

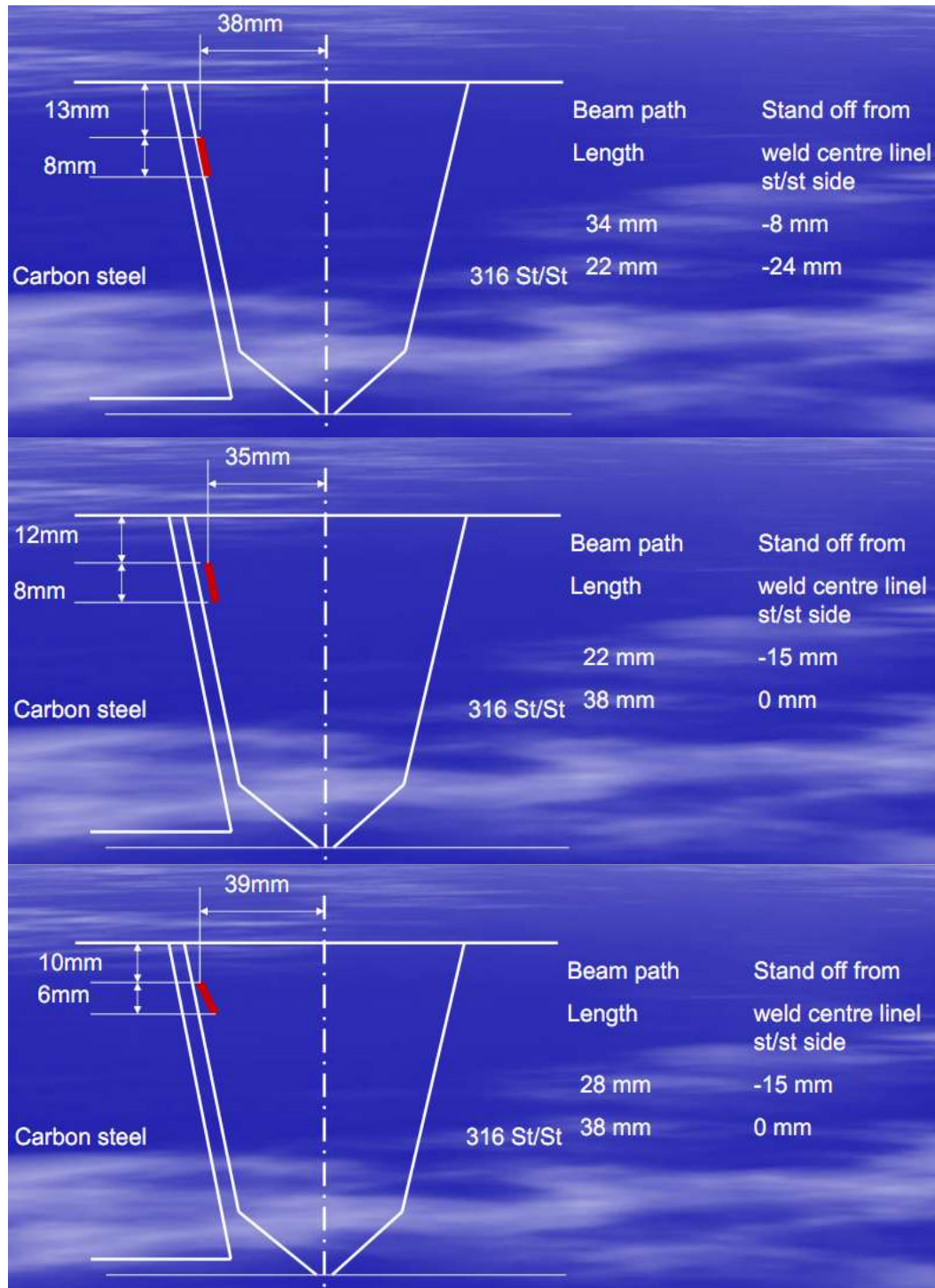


Figure 96 Plotting of Flaw 2 using the conventional manual technique; the 45° beam (top), the 60° beam (middle) and the 70° beam (bottom) were used in the technique.



Figure 97 Sectioned view of Flaw 2 through the central point along its length.

Inspection of Flaw 2 was accomplished most readily by all the techniques from the stainless steel side where the sound had to travel through the weld, rather than through the clean ferritic parent side. With the probe placed on the ferritic carbon steel the flaw was not oriented well for specular detection, which then had to be detected through tip diffraction signals. Figure 98 shows the detection and sizing of Flaw 2 using the linear phased array (PA) technique with the probe placed on the stainless steel side and Figure 99 shows the same flaw from the ferritic side. In both cases the flaw could be both detected and sized; however the S/N of the diffracted signals is weaker when the probe is placed on the ferritic side.

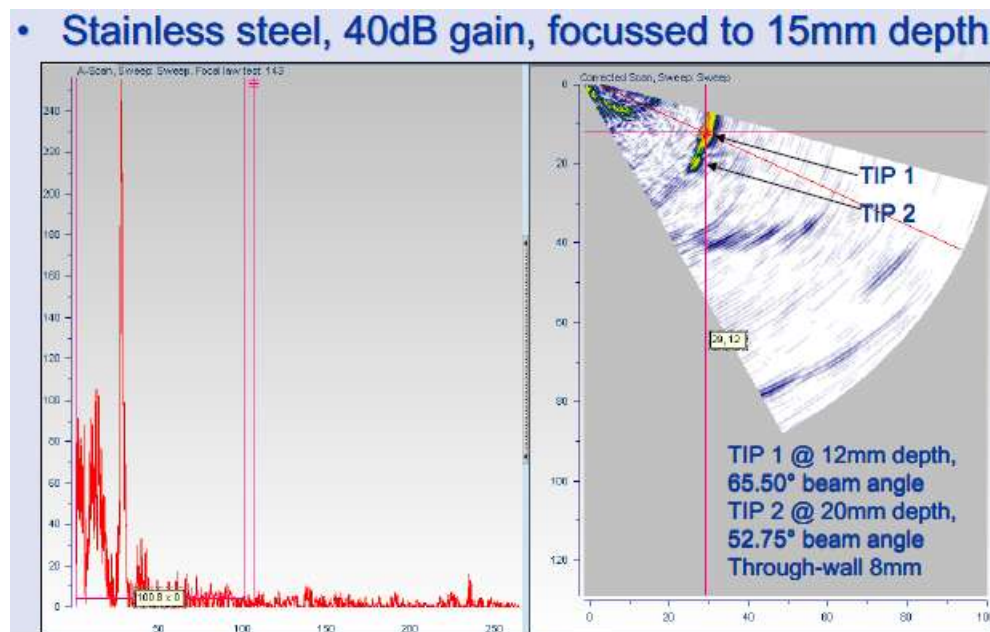


Figure 98 Detection and sizing of Flaw 2 using the linear phased array (PA) technique with the probe placed on the stainless steel side of the specimen.

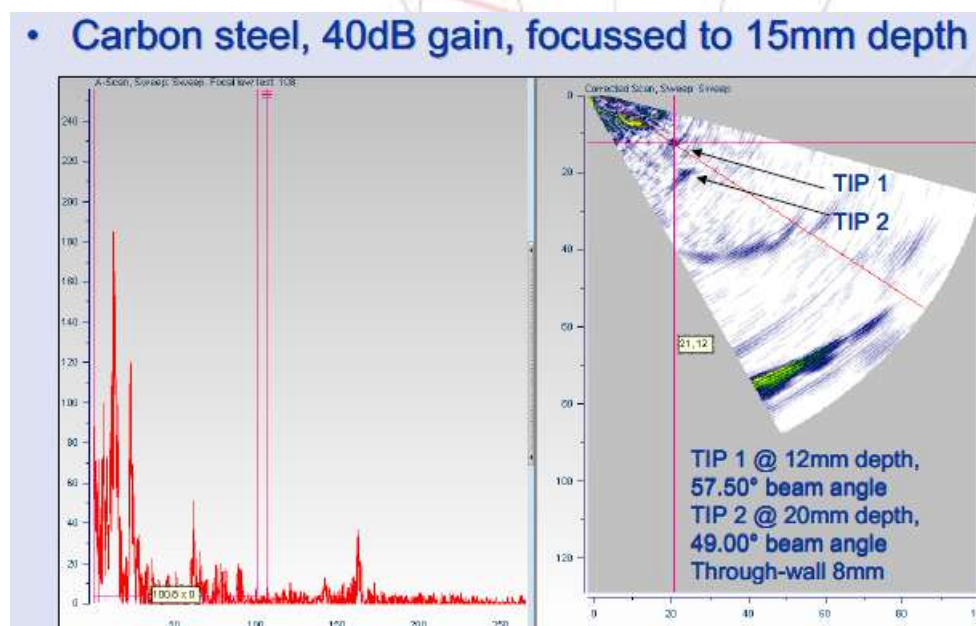


Figure 99 Detection and sizing of Flaw 2 using the linear phased array (PA) technique with the probe placed on the ferritic side of the specimen.

Figure 100 shows that there were differences in the measured orientation of Flaw 2 using inspections from either side of the weld centreline. The weld bevel angle to the vertical was designed to be 15° but was measured to be 20.6° from the stainless steel side (ie when sound travelled through the distortive weld metal) and was 14° from the carbon steel side. This implies that even though detection was easier through the weld metal due to favourable

orientation of the flaw, the actual measurement of orientation appears to be adversely influenced by the distortion.

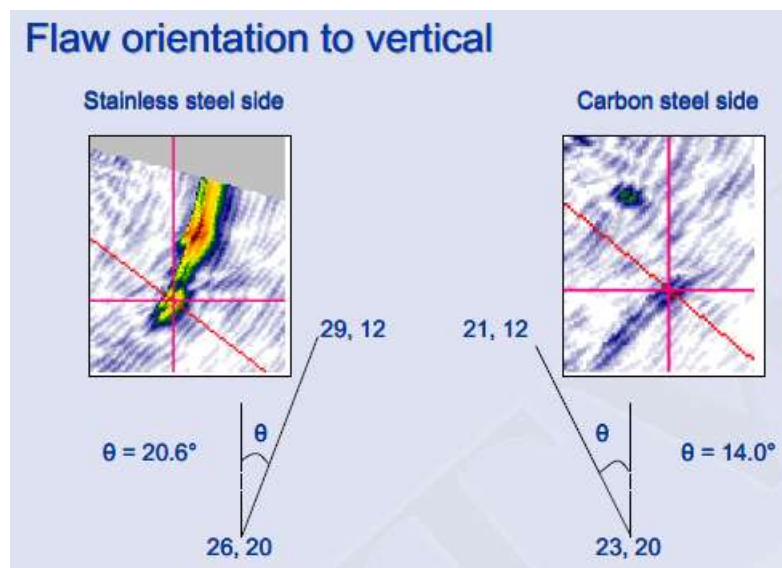


Figure 100 Evaluation of the orientation of Flaw 2 using the linear phased array (PA) technique with the probe on either side of the weld.

Figure 101 shows the data from the TRL-1 technique where Flaw 2 was detected from the stainless steel side. Note that the S/N is greater than 6dB and the near surface noise is near absent. In contrast the technique using the 2D probe shows significant surface noise which can mask the echoes from the flaw; however, by reducing the effective aperture size (ie the number of elements) it was possible to detect Flaw 2 but with much less S/N performance, as shown in Figure 102.

The S/N performance of the 2D-1 technique was in general poorer than the TRL-1 technique but was found to be similar to the conventional manual and linear PA techniques. The conventional automated technique (see Appendix E) made use of probes with single and twin radiating elements and the S/N performance was variable. In the conventional automated scans specific probes were selected as 'search' units for various zones of the weld and other focused twin probes were used for sizing the indications (see Appendix E).

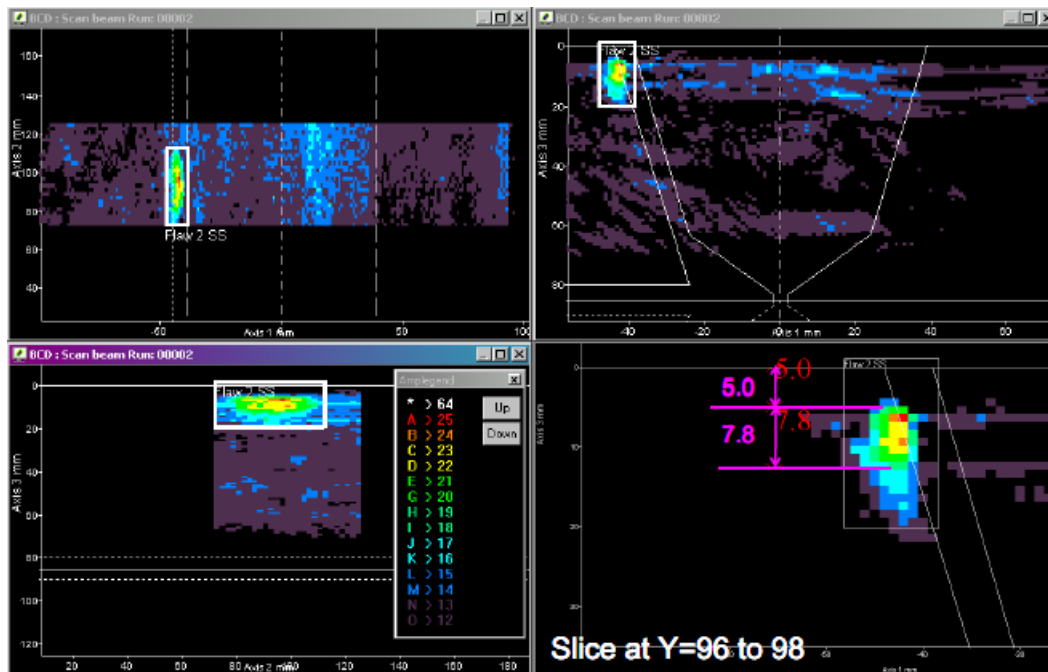


Figure 101 Flaw 2 detected and sized using the TRL-1 technique from the stainless steel side.

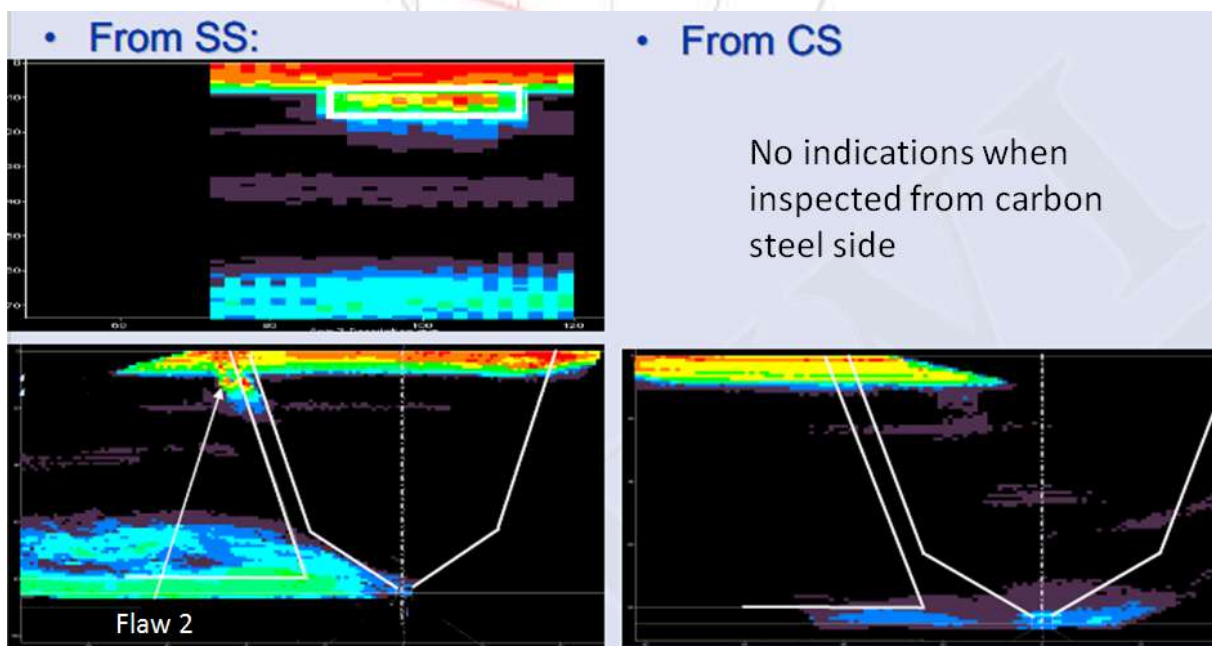


Figure 102 Flaw 2 detected and sized using the 2D-1 technique from the stainless steel side (left) and the carbon steel side (right).

The difficulty for finding and characterising Flaw 2 was its proximity to the top surface and its orientation, which is not favourable to reflect sound from. It was found that all the techniques were able to detect and size the flaw, with the approach through the weld metal giving the greater success.

7.2.2 Flaw 3

Flaw 3, unlike Flaw 2, was ideally oriented on the buttering to weld interface near the root for near specular approach of the sound beam from the stainless steel side, travelling through the weld. Figure 103 shows the summary of performance for all the techniques and Figure 104 shows the sectioned Flaw 3 along its mid-length point.

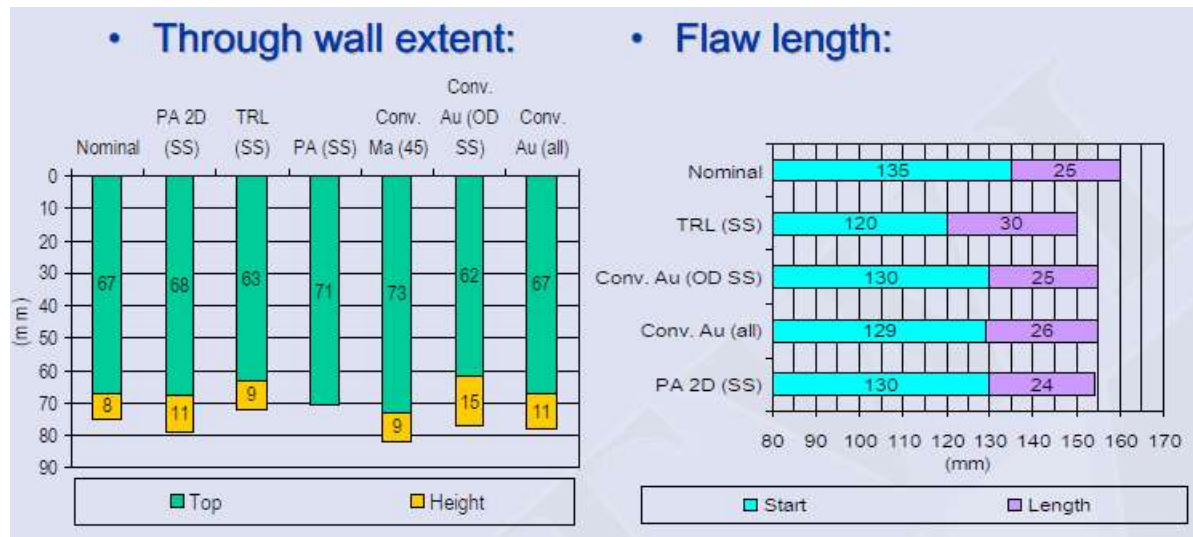


Figure 103 Graphs showing the comparison of the position, through-wall and length measurements made by the baseline techniques for Flaw 3. Refer to key on page 95.

None of the techniques were able to measure all the parameters (through-wall position, through-wall size, flaw length start and flaw length) accurately. The greatest error (+7mm) in through-wall size was recorded by the conventional automated technique (from the stainless steel side) and the greatest error in length wise positioning and size was recorded by the TRL-1 technique. The poor performance of the TRL-1 technique in lengthwise characterisation is thought to be due to the same limitations as in the case of Flaw 2.

Figure 105 shows the nominal position of Flaw 3 along with the conventional manual data using the 45 and 60° beams. As for Flaw 2 the plotted position of the flaw varied when using different beams. Figure 106 shows the inspection data using the linear PA technique when the full array was used, but without focusing. The incident angle on the flaw indicates that the flaw is specular to the beam when the beam angle is ~52°, however the actual incident beam angle to be perfectly specular should theoretically be 45°.

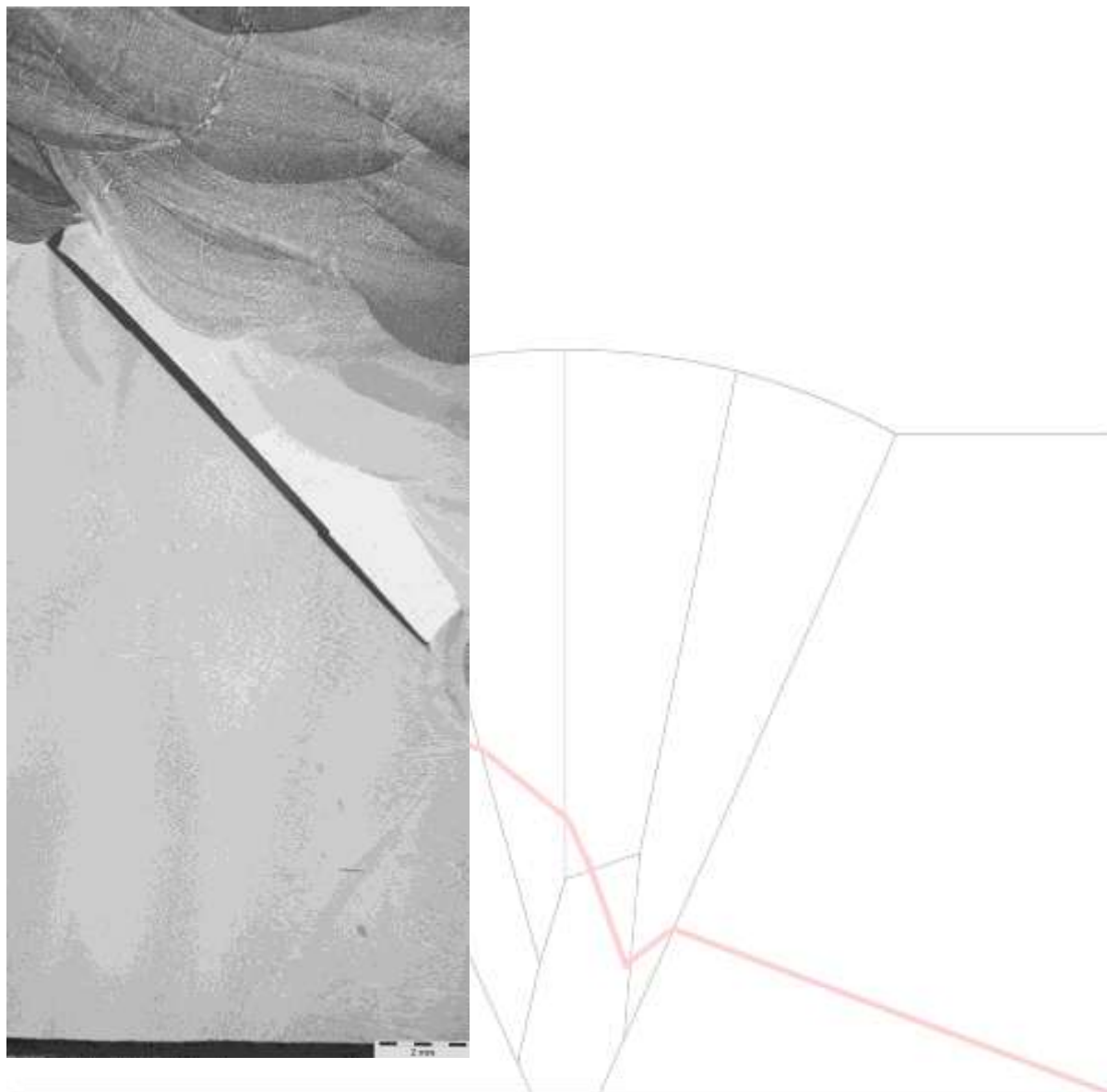


Figure 104 Sectioned view of Flaw 3 through the central point along its length.

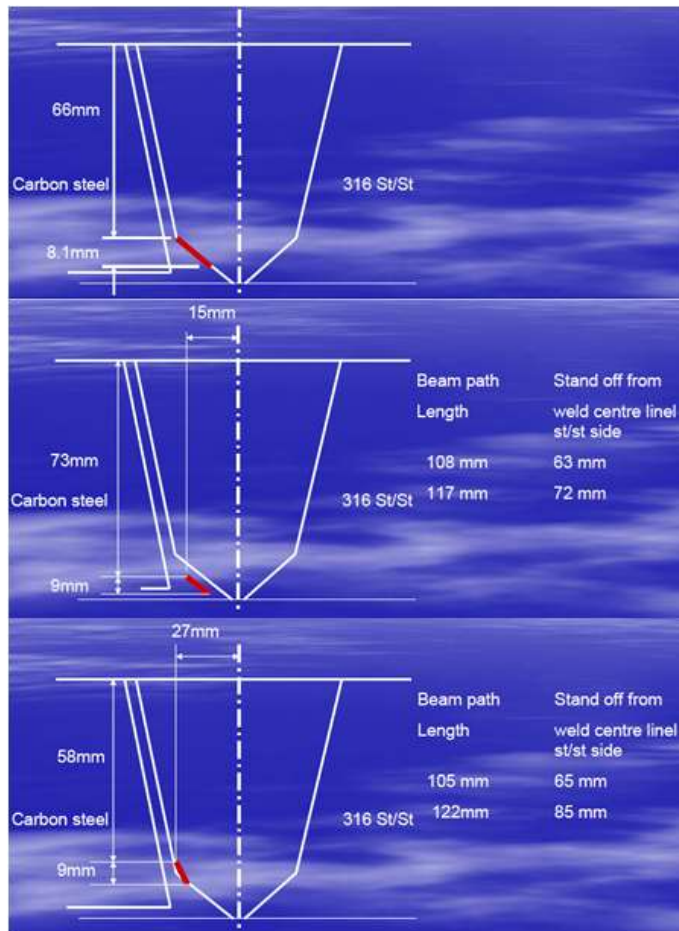


Figure 105 Inspection of Flaw 3 using the conventional manual technique; nominal (top), 45° beam (middle) and 60° beam (bottom).

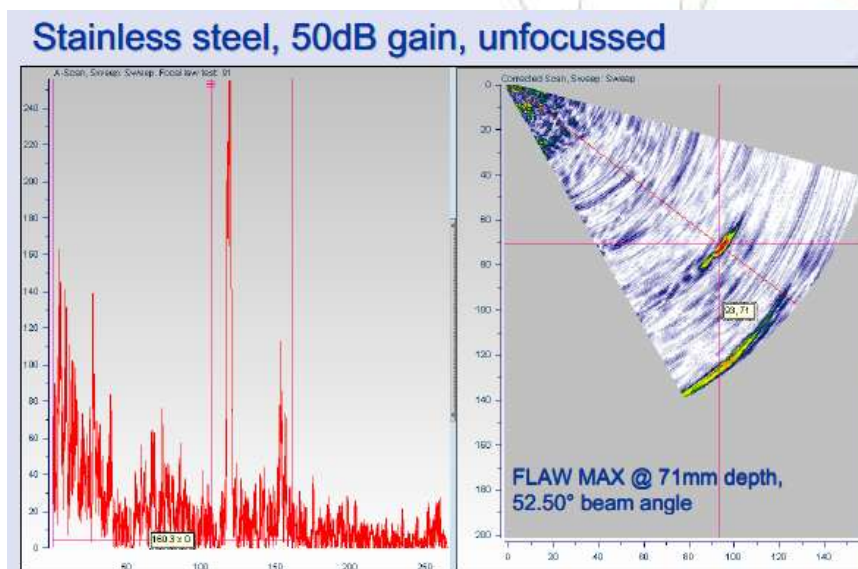


Figure 106 Detection of Flaw 3 using the linear PA technique when the full array was used without focusing the sound field.

By contrast, when the beams were focused to depths near that of Flaw 3 using the linear PA technique, the flaw was less clearly detected, as shown (in the case of focusing to 50mm) in Figure 107. Additionally, the variability of the flaw echo along the weld direction was severe enough for the operator to be unable to confidently measure the through-wall size of Flaw 3 using the linear PA technique.

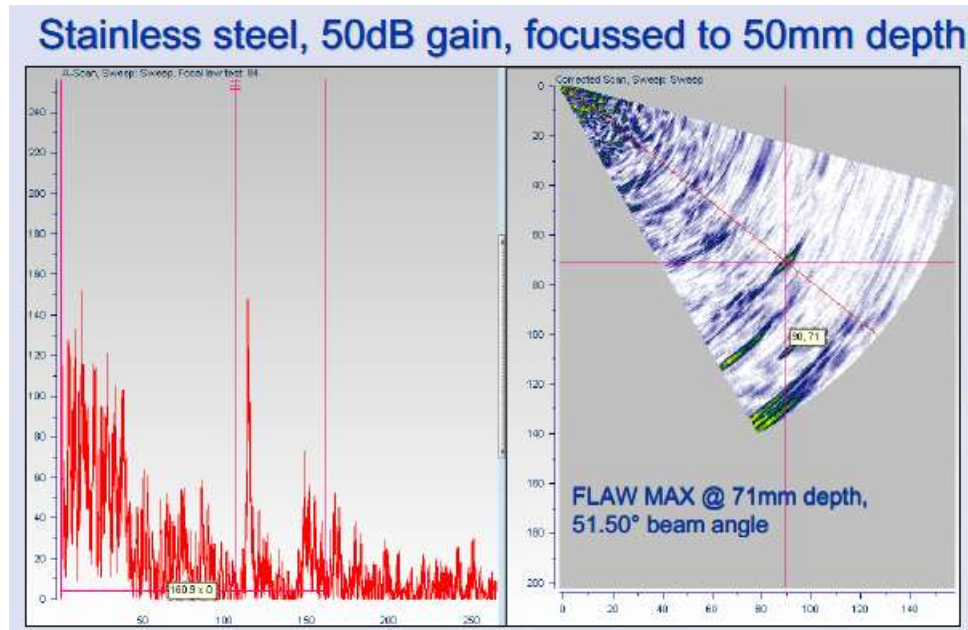


Figure 107 Detection of Flaw 3 using the linear PA technique when the full array was used to focus the sound field to the depth of 50mm (flaw was at a depth of 70mm).

Figure 108 shows the detection and characterisation of Flaw 3 using the TRL-1 technique, focusing the sound field to the depth of Flaw 3; the probe was placed on the stainless steel side with the sound beam travelling through the weld metal. The S/N performance of the TRL probe is again significantly better than those of the other techniques (note the S/N of the linear PA technique in Figures 106 and 107). However, the orientation of the flaw was unfavourable for inspection from the carbon steel side, as shown in Figure 109 where the TRL-1 technique was used and even with increasing sensitivity (ie reducing S/N quality) it was not possible to detect any diffracted signals from the region near the edges of Flaw 3.

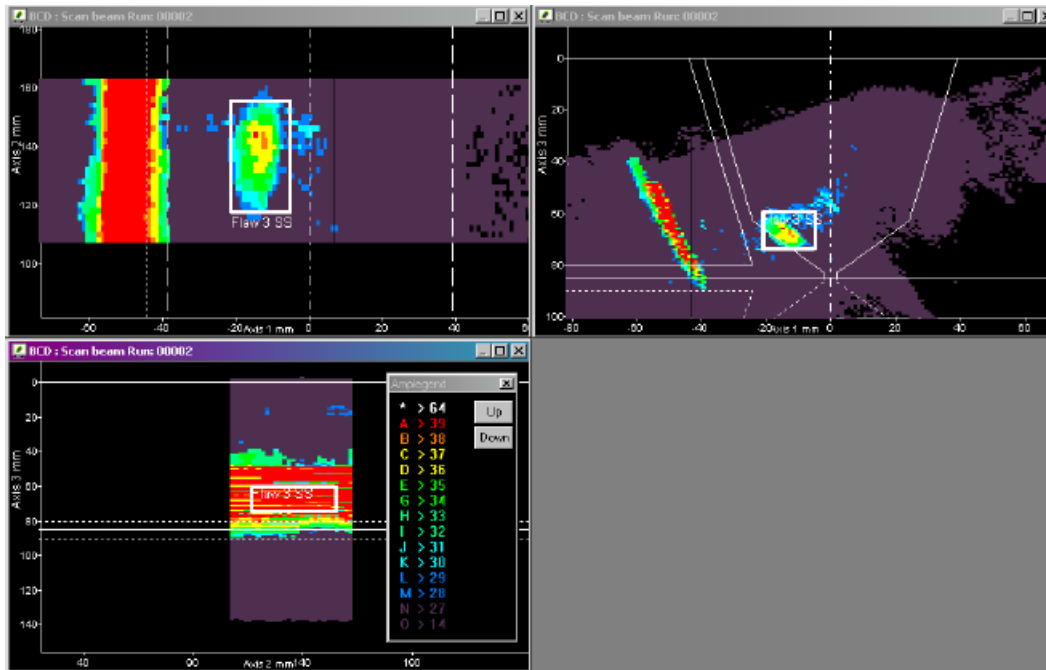


Figure 108 Inspection of Flaw 3 using the TRL-1 technique with the probe placed on the stainless steel side and focusing the sound to the depth of the flaw.

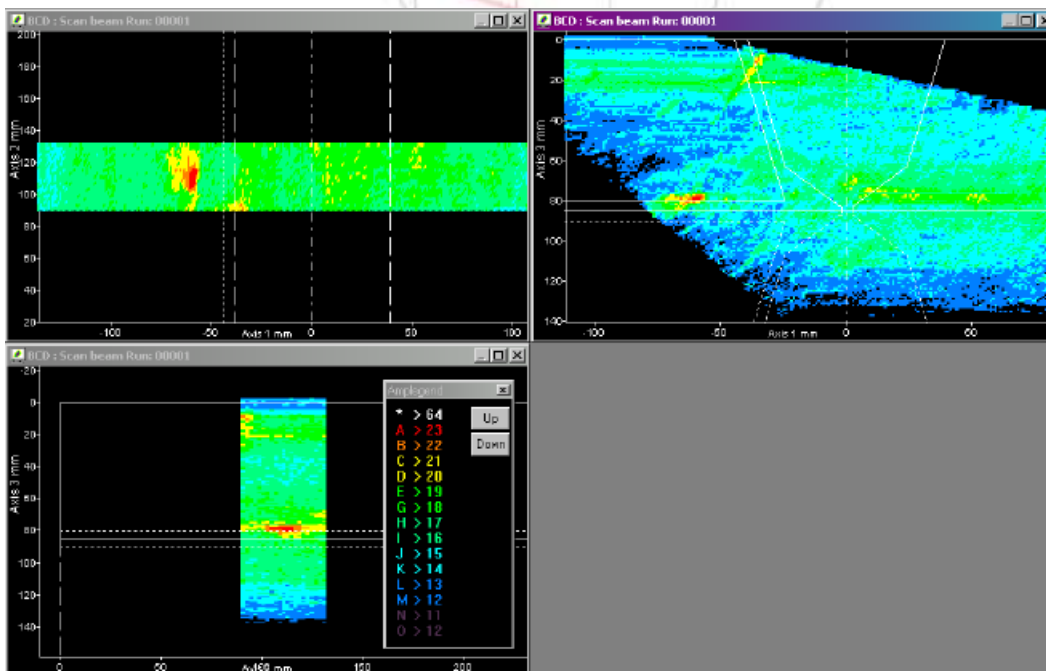


Figure 109 Inspection for Flaw 3 using the TRL-1 technique with the probe placed on the carbon steel side and focusing the sound to the depth of the flaw.

Figure 110 shows the detection of Flaw 3 using the 2D-1 technique from the stainless steel side, with poorer S/N performance in comparison to the TRL-1 technique.

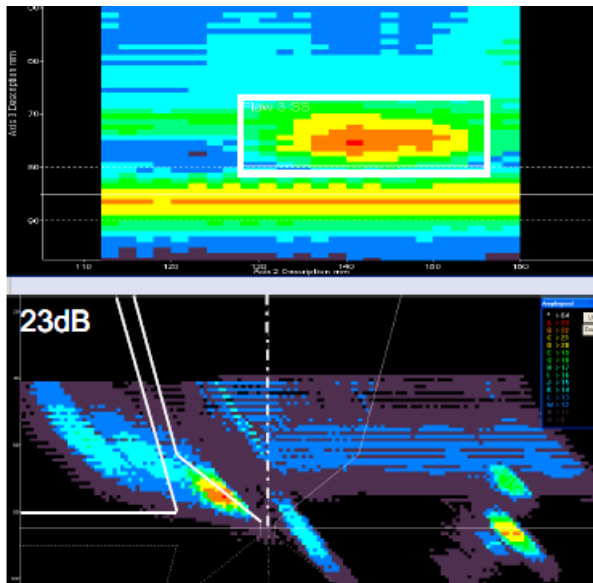


Figure 110 Inspection for Flaw 3 using the 2D-1 technique with the probe placed on the stainless steel side and focusing the sound to the depth of the flaw.

7.2.3 Flaw 4

Figure 111 shows the summary of the performance of all the techniques when inspecting for Flaw 4 and Figure 111 shows the sectioned view of Flaw 4 at its mid-length position.

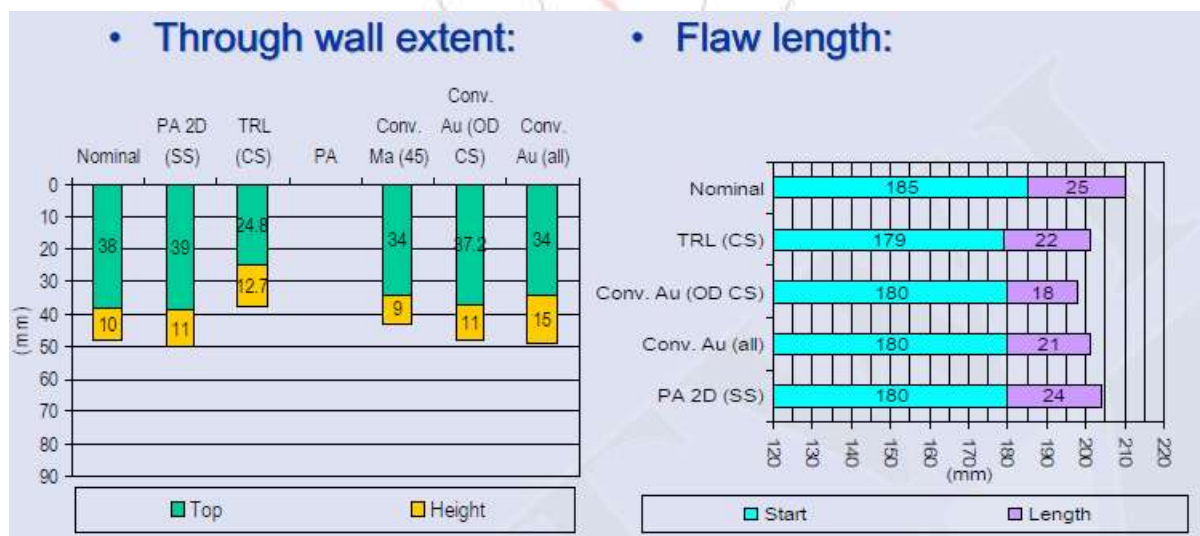


Figure 111 Graphs showing the comparison of the position, through-wall and length measurements made by the baseline techniques for Flaw 4. Refer to key on page 95.

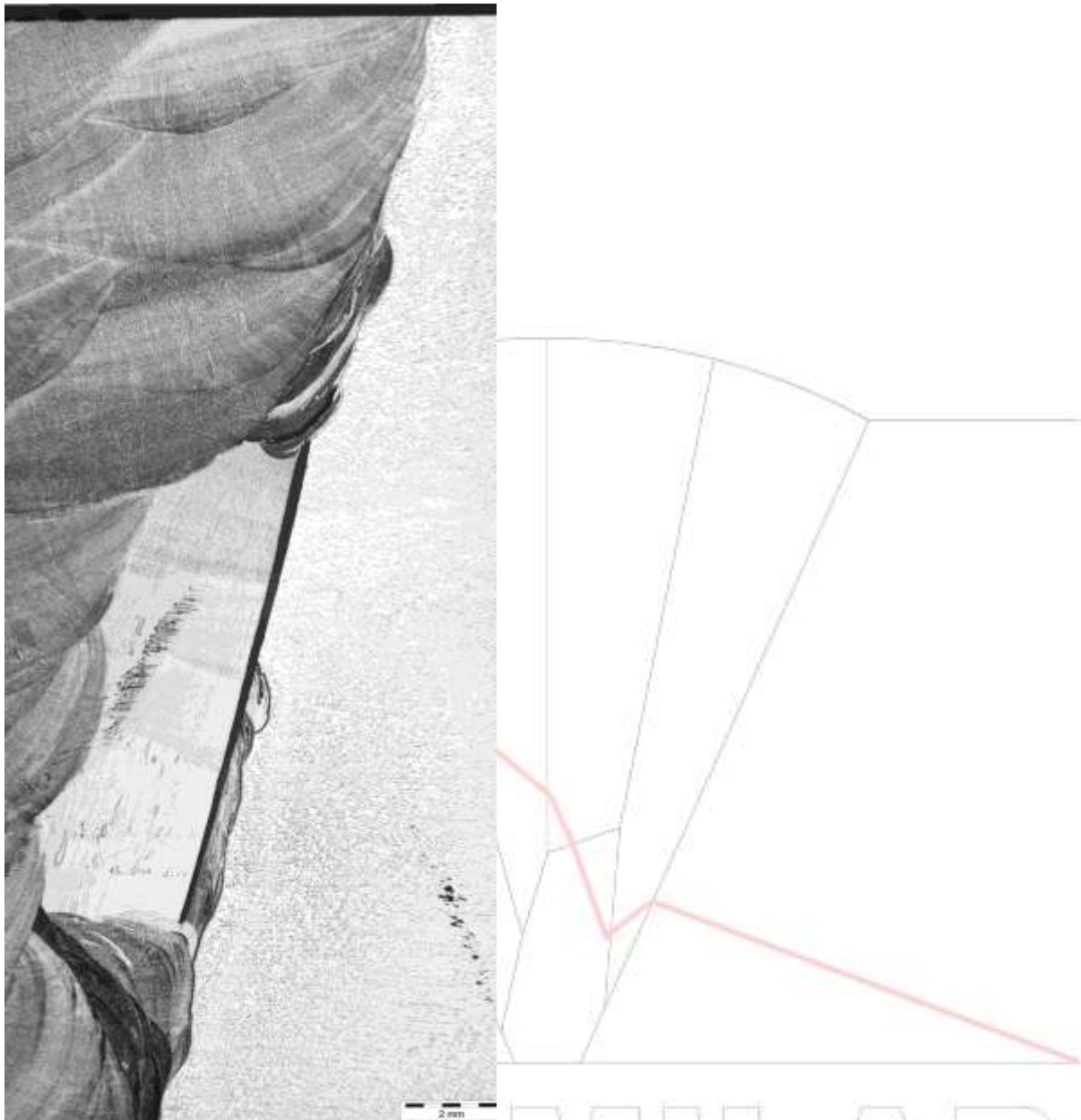


Figure 112 Sectioned view of Flaw 4 through the central point along its length.

The best performance in through-wall positioning and sizing was achieved by the 2D-1 technique (to ~1mm) with the probe placed on the stainless steel side (ie through detection of diffraction signals), as shown in Figure 113. Note also the echoes from the parent stainless steel near mid-wall thickness which are thought to be inclusions/segregations and the loss of near surface resolution due to the very strong (saturated) surface echoes.

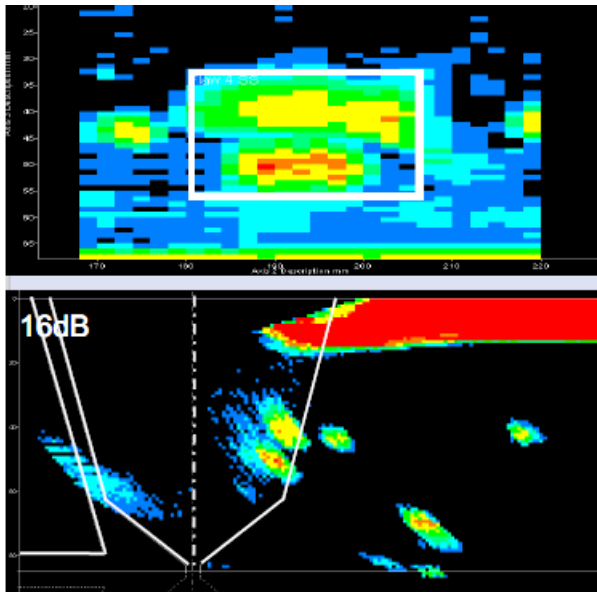


Figure 113 Inspection for Flaw 4 using the 2D-1 technique with the probe placed on the stainless steel side and focusing the sound to the depth of the flaw.

Figure 114 shows the detection and sizing of the same flaw from the carbon steel side with the sound going through the weld metal and using the TRL-1 technique, which offered the best S/N performance for the task but its performance in through-wall positioning had an error in-excess of 10mm.

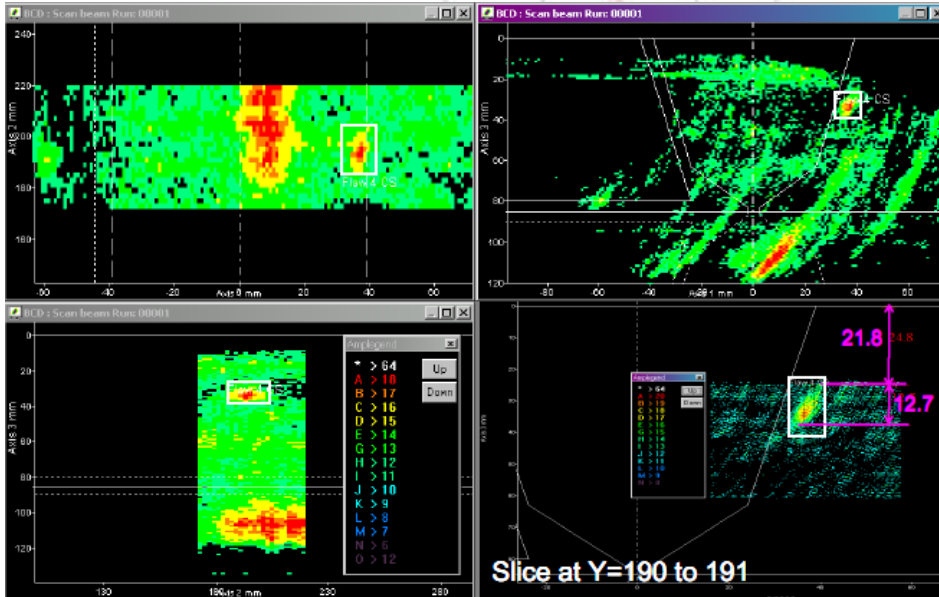


Figure 114 Inspection for Flaw 4 using the TRL-1 technique with the probe placed on the carbon steel side and focusing the sound to the depth of the flaw.

The conventional manual technique was also able to detect and size Flaw 4 using the max amplitude technique. Figure 115 shows the nominal position of Flaw 4, the plotted position using a 60° beam when the probe is placed on the carbon steel side (ie travelling through the weld metal) and an illustration of the S/N performance when using the 60° beam.

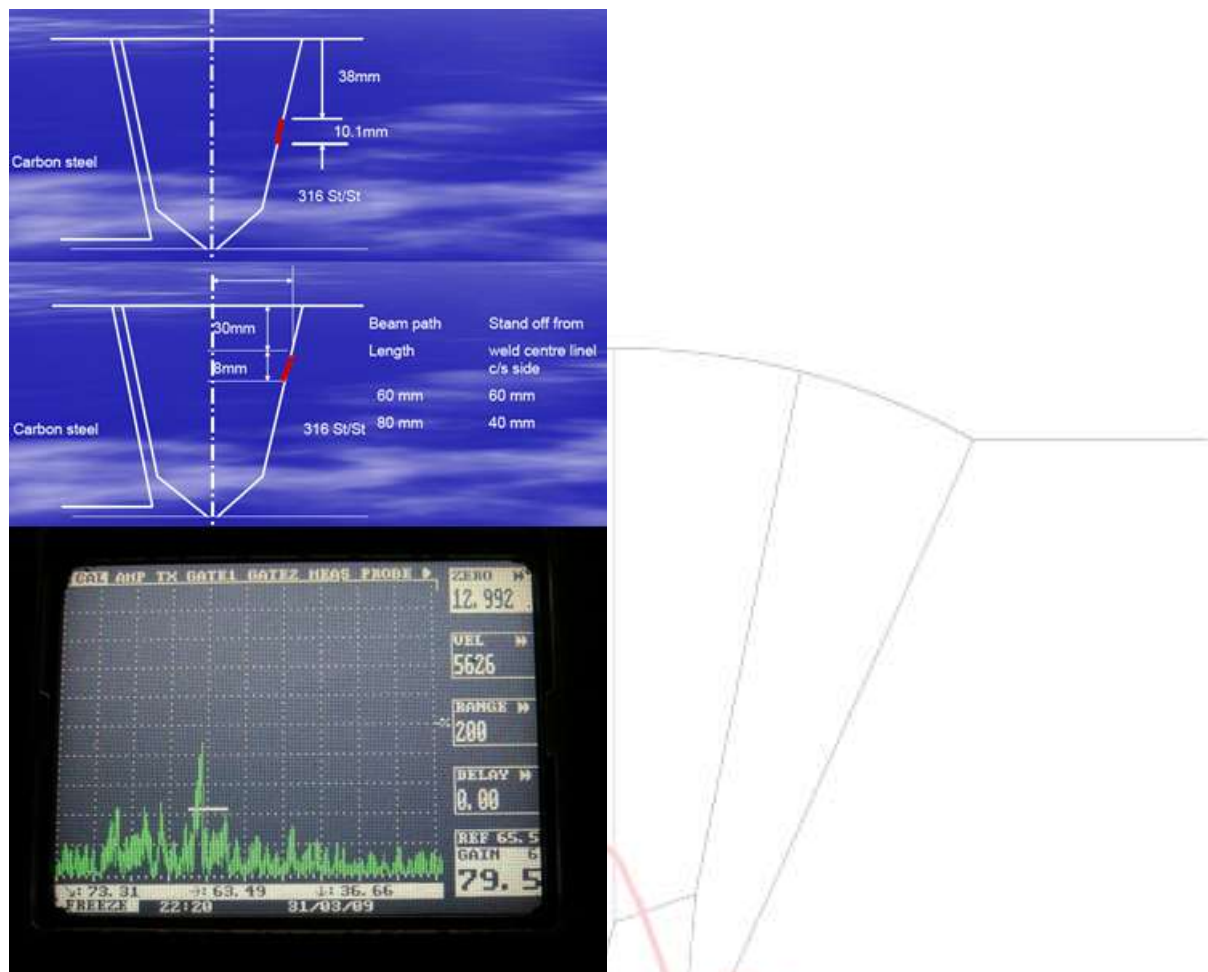


Figure 115 Inspection of Flaw 4 using the conventional manual technique from the carbon steel side; nominal (top), 60° beam (middle) and the S/N performance of the 60° beam (bottom).

The distortion of the sound field and grain noise was severe enough for effective interpretation to be not possible when using the linear PA technique; Figure 116 illustrates the difficulty of identifying the flaw signal confidently against the background grain noise level when using the linear PA technique with the sound traversing through the weld metal. In general the inspection for Flaw 4 using the various different techniques proved to be difficult when the sound had to traverse the weld metal and it was only possible to detect the tip diffracted signals from the stainless steel side with the system gain at high levels.

The length positioning of Flaw 4 was consistent amongst all the techniques, starting ~180mm from the datum with a difference of -5mm from the nominal measured value. The greatest error in flaw length sizing was registered by the conventional automated technique from the carbon steel side (-7mm).

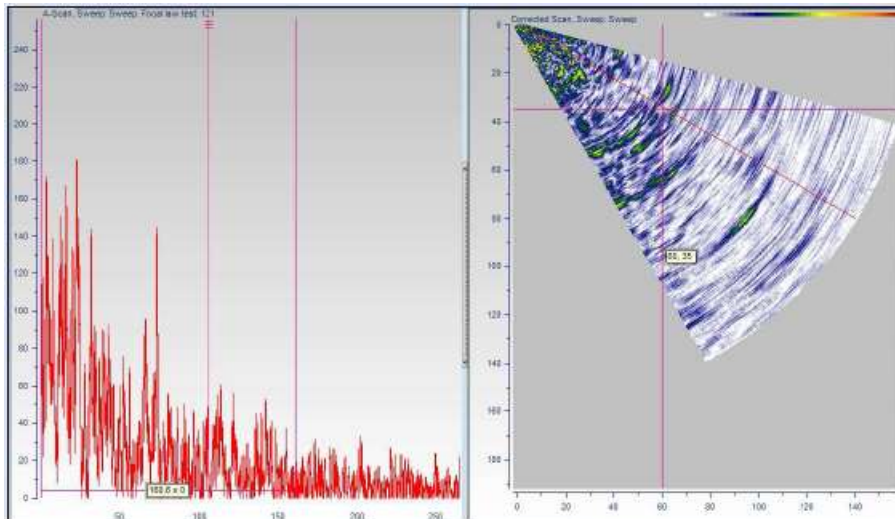


Figure 116 Inspecting for Flaw 4 using the linear PA technique with the probe on the carbon steel side, showing the level of back-scattered grain noise.

7.2.4 Flaw 5

The performance of all the techniques for inspection of Flaw 5 is shown in Figure 117. It was not possible to detect and size Flaw 5 using the 2D-1 technique from either the carbon steel or stainless steel sides. Flaw 5 was introduced on the interface between the buttering and the parent carbon steel (see Figure 10).

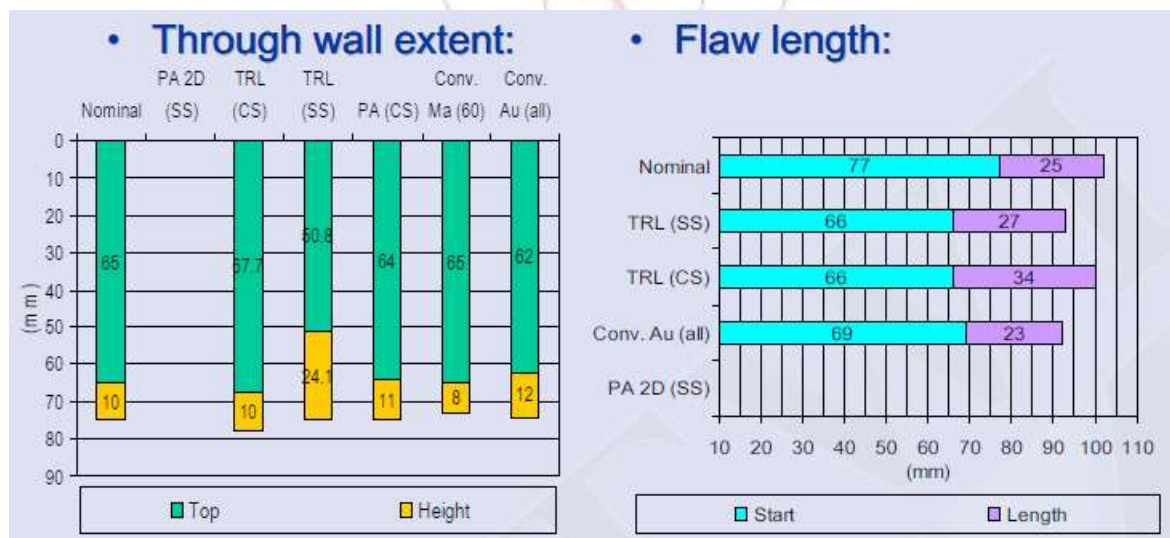


Figure 117 Graphs showing the comparison of the position, through-wall and length measurements made by the baseline techniques for Flaw 5. Refer to key on page 95.

Despite the unfavourable orientation Flaw 5 was detected and sized from the carbon steel side by the TRL-1 technique as shown in Figure 118. When using the TRL-1 technique from the stainless steel side it was difficult to identify the echoes from the flaw in comparison to other echoes, some of which were geometric, as shown in Figure 119.

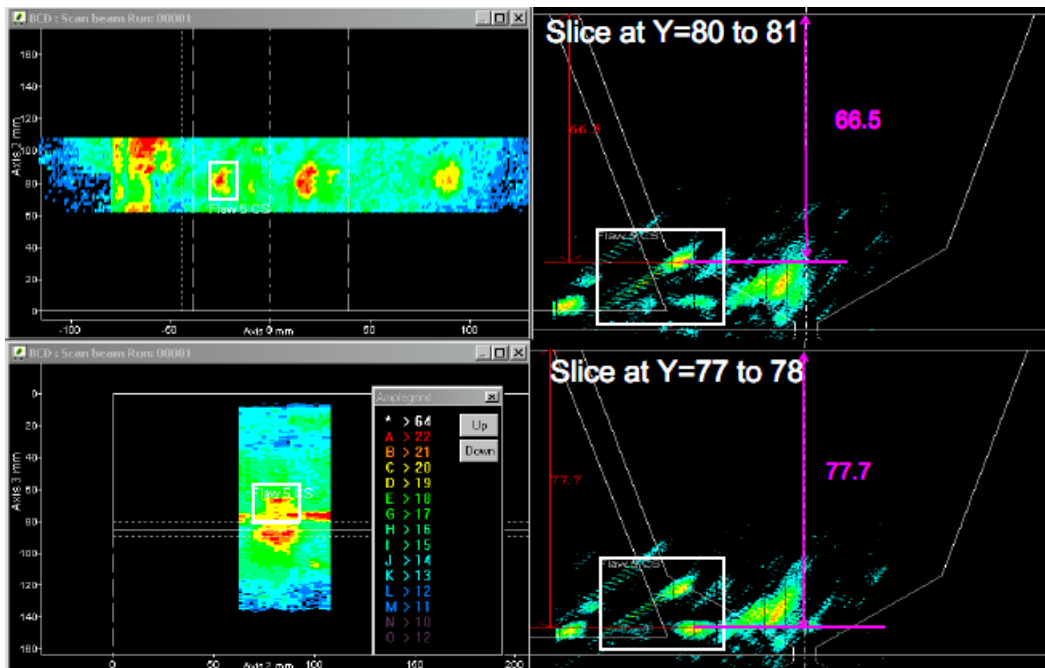


Figure 118 Detection and sizing of Flaw 5 from the carbon steel side using the TRL-1 technique; two cross-section views are shown on the right at 77 and 80mm from the datum.

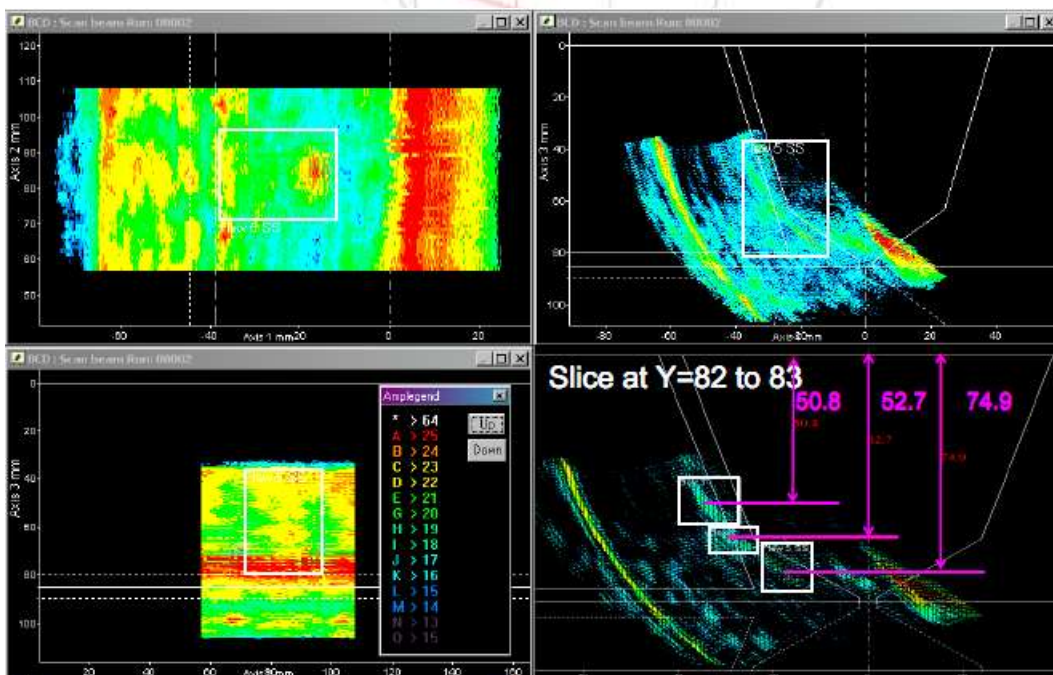


Figure 119 Detection of Flaw 5 from the stainless steel side using the TRL-1 technique showing the cross-section view at 82mm from the datum.

Inspection using the linear PA technique was able to detect (but not size) when the sound had to travel through the weld (see Figure 120) but the operator deemed it possible (with some confidence) to size Flaw 5 from the carbon steel using diffracted echoes, as shown in Figure 121.

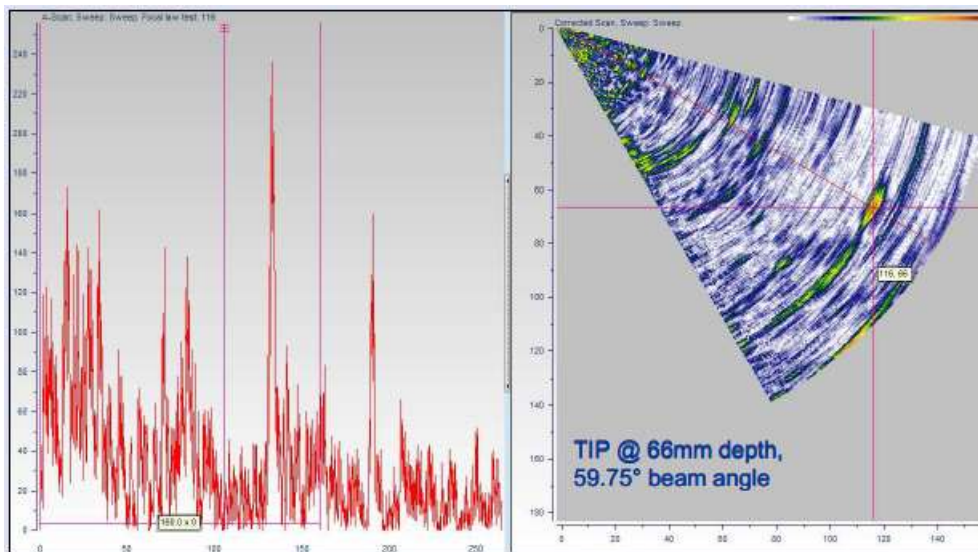


Figure 120 Detection of Flaw 5 from the stainless steel side using the linear PA technique.

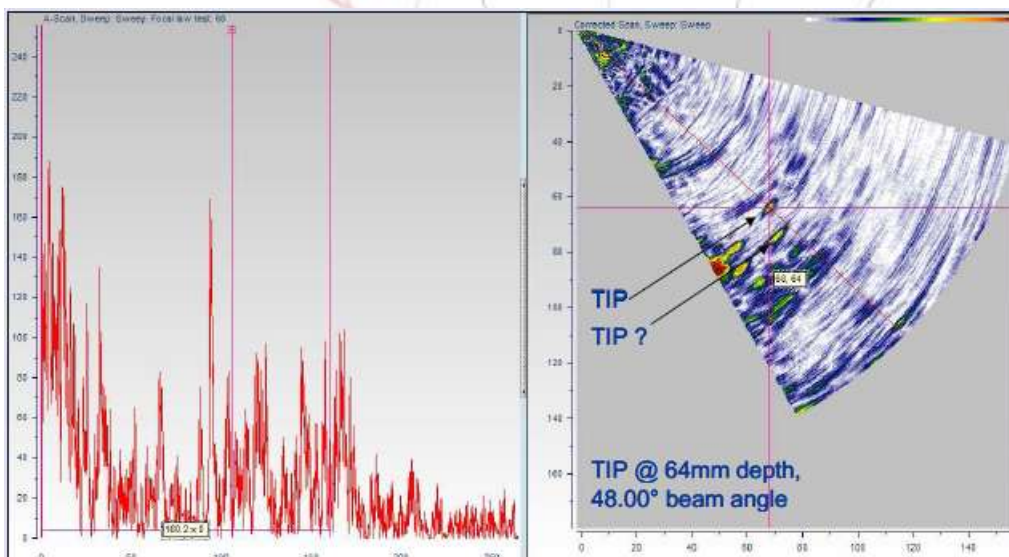


Figure 121 Detection of diffracted echoes from the tips of Flaw 5 using the linear PA technique from the carbon steel side.

The positioning and sizing of the conventional manual technique from the stainless steel side is likely to have been severely influenced by the weld metal. Figure 122 shows the plotting performance when using the 60° beam from the stainless steel side. Flaw 5 was difficult for all the techniques but surprisingly the length sizing error of the TRL-1 technique from the carbon steel side was far worse (+9mm) than when the sound had to travel through the weld (error of +2mm in the length sizing compared to nominal). However the through-wall size of Flaw 5 measured by the TRL-1 technique from the stainless steel side was 24mm, an error of +14mm. This indicates that a scenario where an unfavourably oriented flaw has to be detected through the weld can present significant problems for ultrasonic techniques.

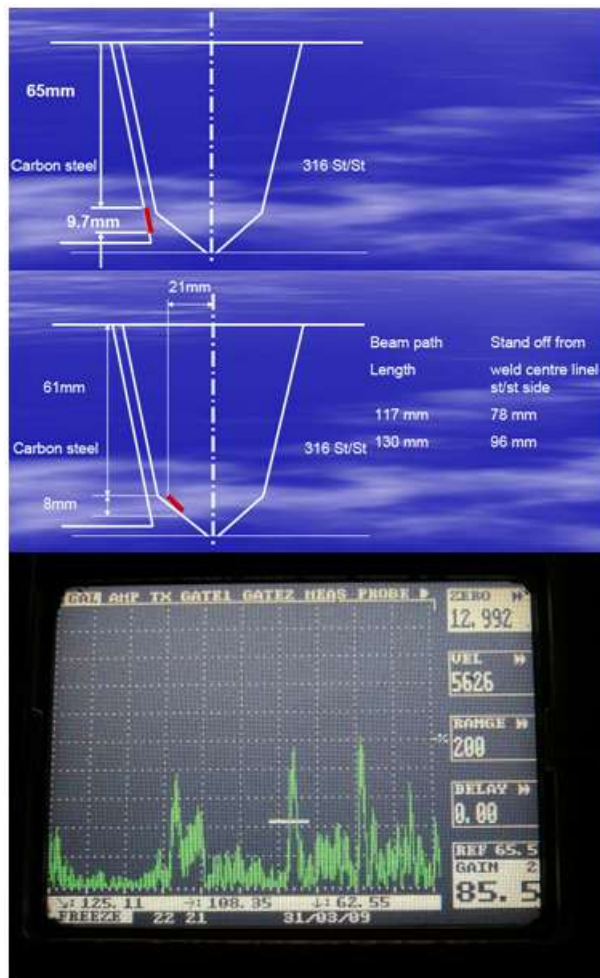


Figure 122 The detection and sizing of Flaw 5 using the conventional manual technique from the stainless steel side; nominal (top), 60° beam (middle) and the S/N performance of the 60° beam (bottom).

7.2.5 Flaw 6

Figure 123 summarises the performance of the techniques for inspection to detect and size Flaw 6, which is similarly oriented and positioned to Flaw 4 but is half the size in the through-wall direction. The conventional automated inspections oversized the flaw height by 5mm and the TRL-1 technique again substantially undersized the length of the flaw (error of -10mm to nominal). The best performance was achieved by the 45° beam of the conventional manual technique from the carbon steel side (ie traversing the weld) with good S/N and, in the through-wall direction, positioning the flaw with an error of +1mm and sizing accurately as 5mm, as shown in Figure 124.

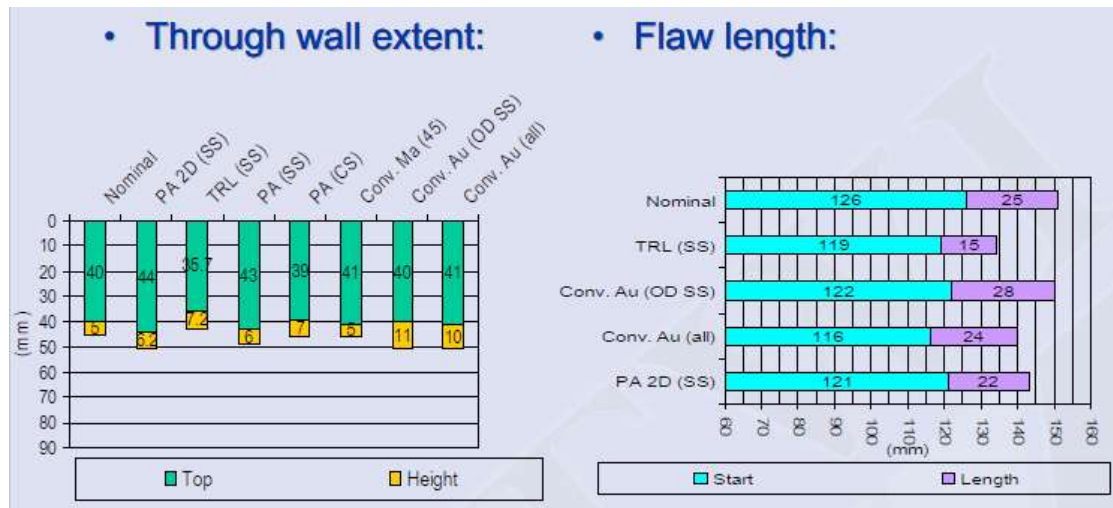


Figure 123 Graphs showing the comparison of the position, through-wall and length measurements made by the baseline techniques for Flaw 6. Refer to key on page 95.

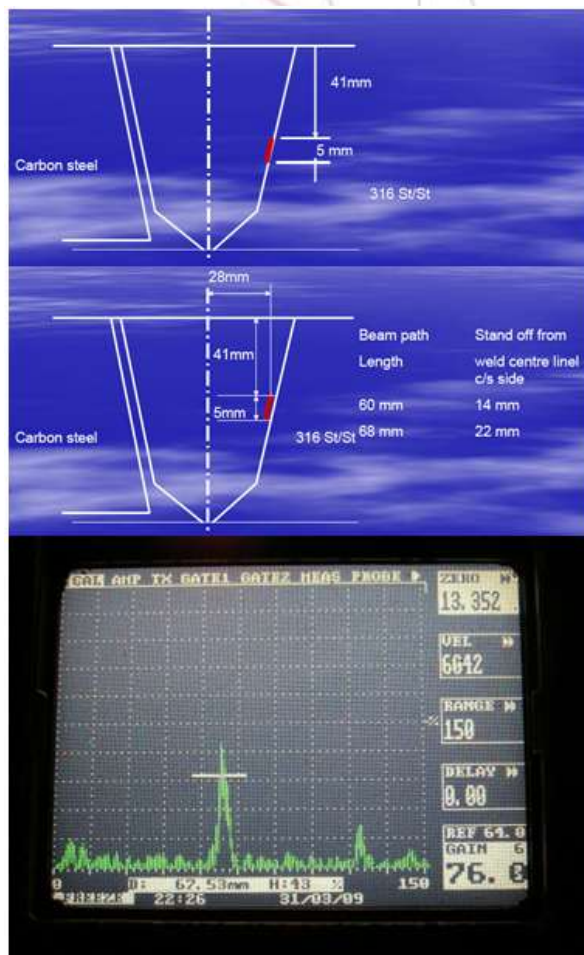


Figure 124 The detection and sizing of Flaw 6 using the conventional manual technique from the carbon steel side; nominal (top), 45° beam (middle) and the S/N performance at the 45° beam (bottom).

The 2D-1 technique was able to detect and size the flaw, but with poor S/N performance, as shown in Figure 125. In contrast, the S/N performance of the linear PA technique from the stainless steel side was much better, as shown in Figure 126.

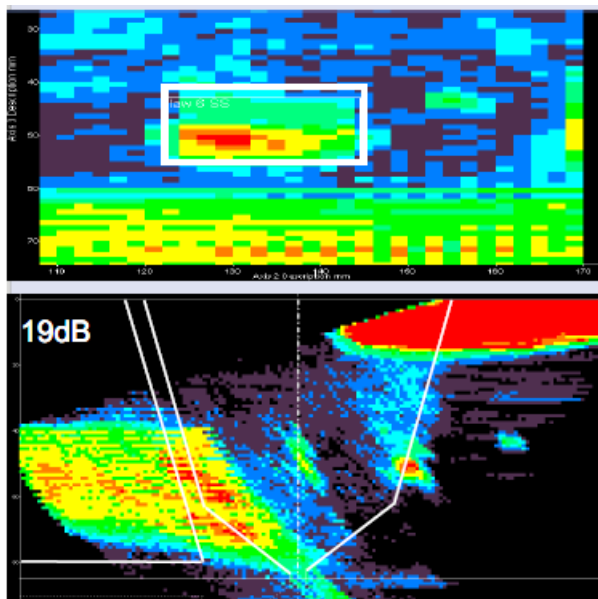


Figure 125 Detection and sizing of Flaw 6 using the 2D-1 technique from the stainless steel side.

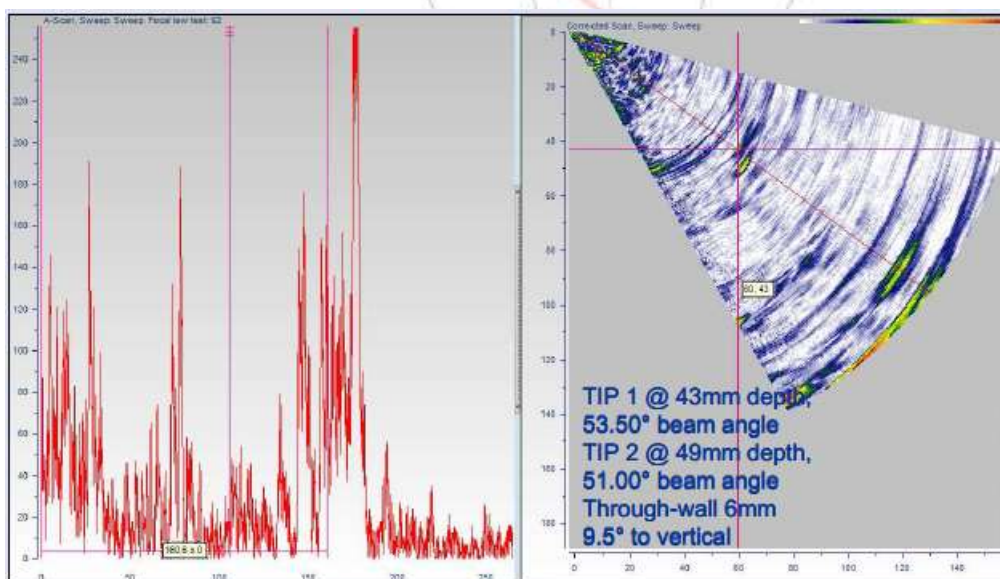


Figure 126 Detection and sizing of Flaw 6 using the linear PA technique from the stainless steel side through the detection of diffracted signals from the flaw tips.

The TRL-1 technique was also able to detect the diffracted signals from the flaw tips and thereby undertake sizing, as shown in Figure 127.

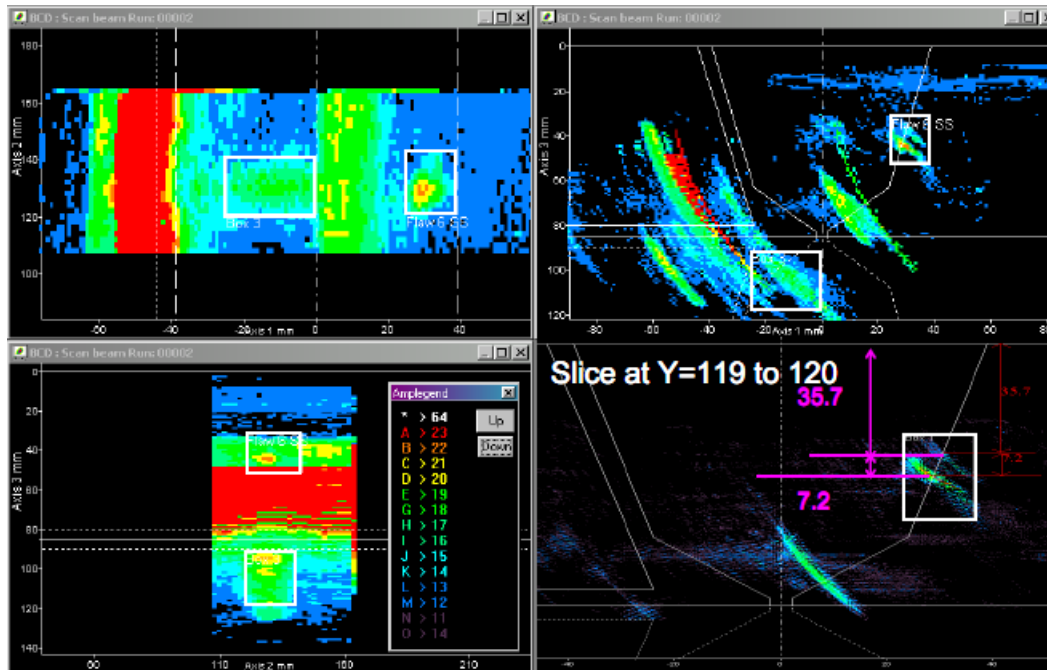


Figure 127 Detection and sizing of Flaw 6 using tip diffracted signals using the TRL-1 technique from the stainless steel side.

7.2.6 Flaw 7

The detection and sizing performance of all the techniques in inspection for Flaw 7 is shown in Figure 128. Flaw 7 was introduced as a rough centreline crack at mid-thickness of the weld (see Figure 12). All the techniques except the linear PA technique could find and size Flaw 7; the linear PA technique could only detect the flaw, as shown in Figure 129.

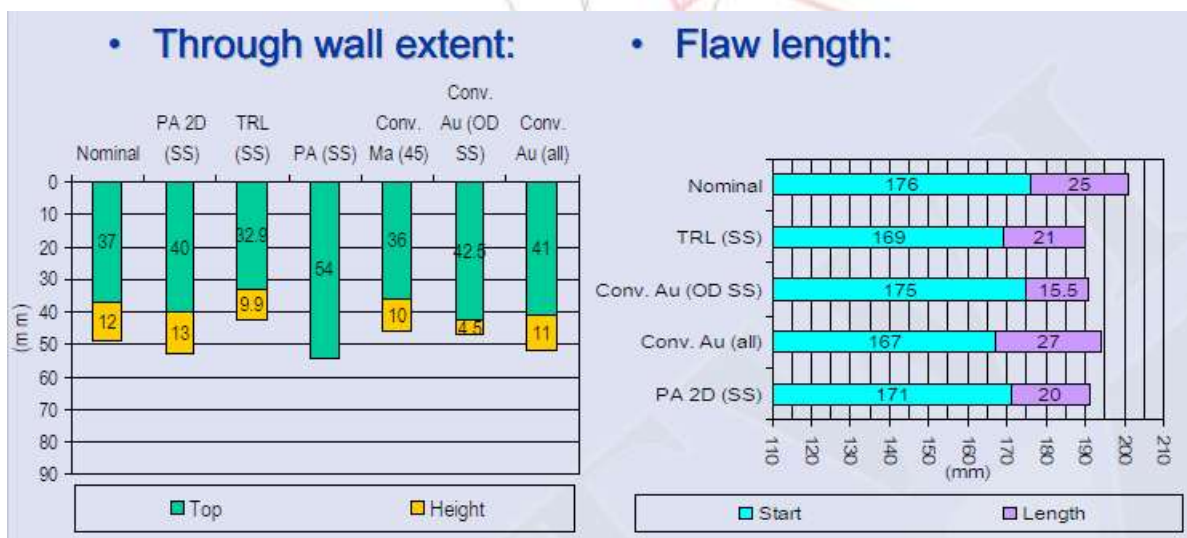


Figure 128 Graphs showing the comparison of the position, through-wall and length measurements made by the baseline techniques for Flaw 7. Refer to key on page 95.

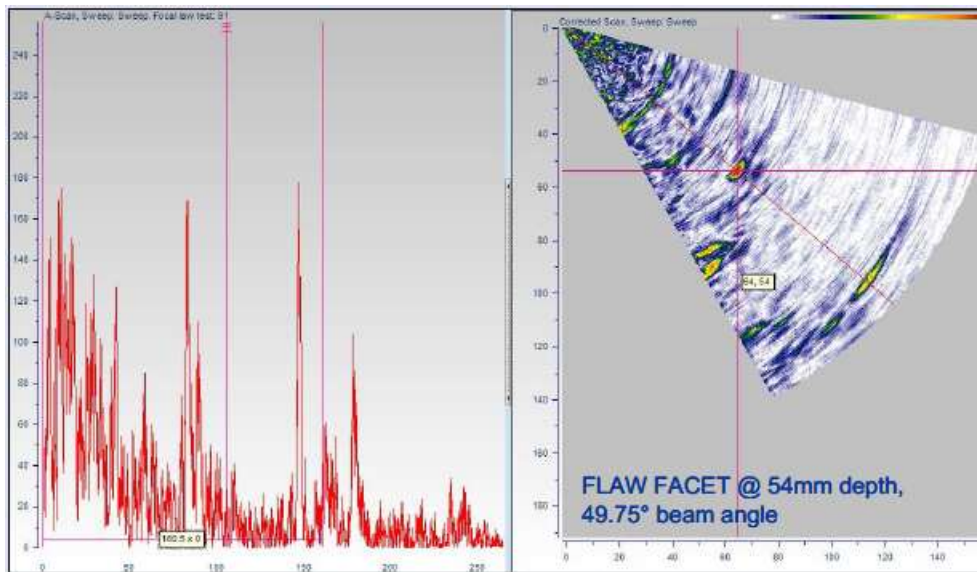


Figure 129 Detection of Flaw 7 using the linear PA technique from the stainless steel side.

Flaw 7 was also found and sized by the conventional manual technique from the stainless steel side using 45, 60 and 70° beams, as shown in Figure 130. Flaw 7 was readily detected by all the techniques when travelling through the weld to stainless steel parent interface. However, the flaw could not be detected when travelling through the buttering layer (ie from the carbon steel side). This is illustrated by the data from the 2D-1 technique, as shown in Figure 131, where the flaw is clearly identified from the stainless steel side but could not be found from the carbon steel side.

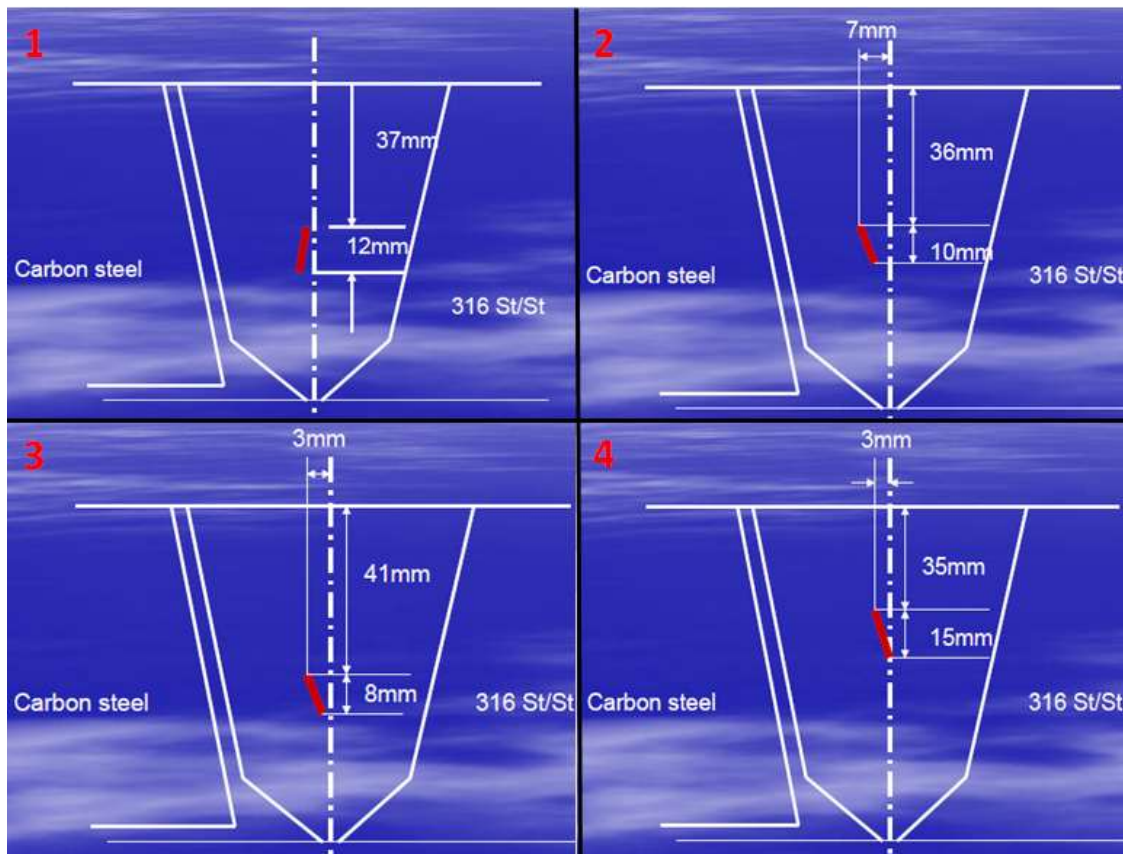


Figure 130 The detection and sizing of Flaw 7 using the conventional manual technique from the stainless steel side; nominal (1), 45° beam (2), 60° beam (3) and 70° beam (4).

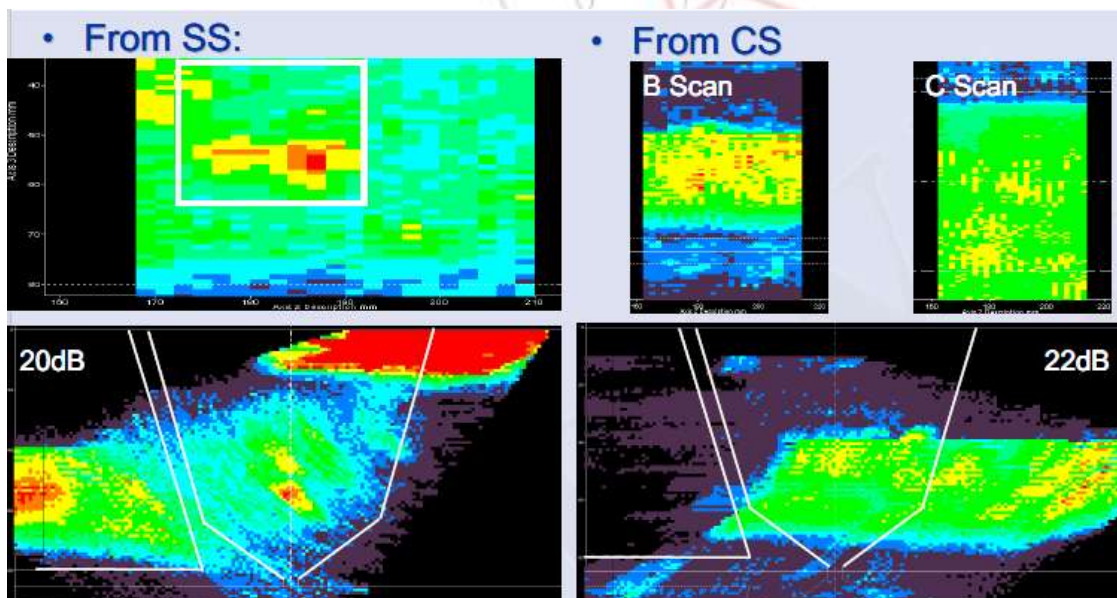


Figure 131 Detection of Flaw 7 by the 2D-1 technique from the stainless steel side (left) and from the carbon steel side (right).

The best S/N performance was again achieved by the TRL-1 technique, as shown in Figure 132. In general, Flaw 7 did not present a challenge to any of the techniques as long as the beams did not have to traverse the buttering layer. The rough nature of the flaw (ie the presence of flaw facets at different orientations) presented an advantage for detection but made the sizing of the flaw a little more difficult as the extreme facets had to be selected for the sizing.

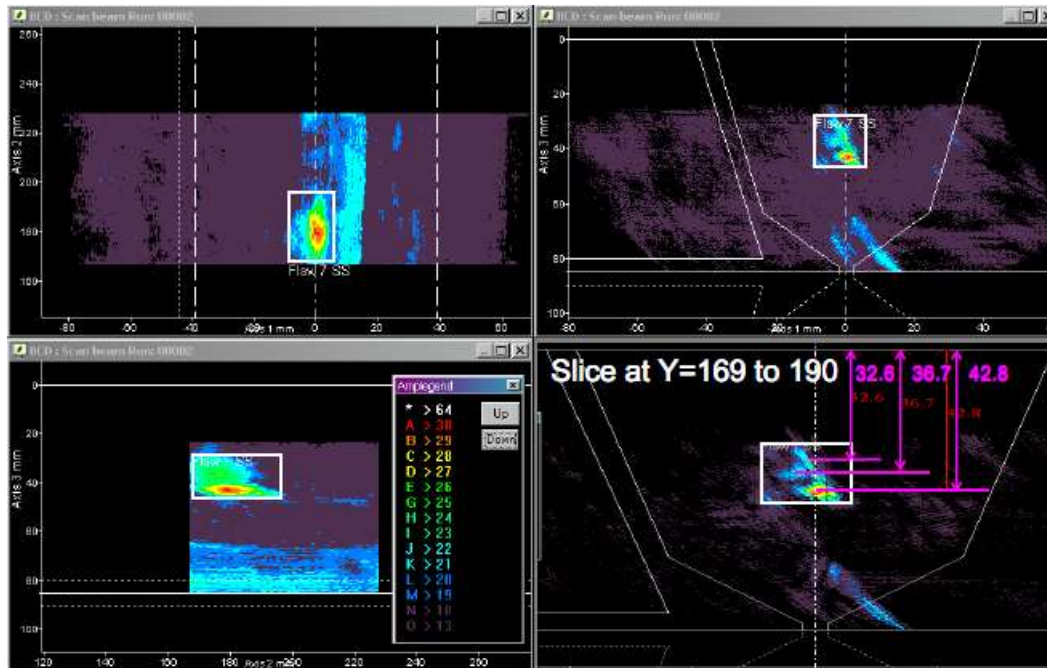


Figure 132 Detection and sizing of Flaw 7 using the TRL-1 technique from the stainless steel side.

7.2.7 Flaw 8

The detection and sizing performance of all the techniques in inspection for Flaw 8 is shown in Figure 133. Note that the TRL-1 technique could not be evaluated as the flaw proximity to the edge of the specimen in comparison to the width of the probe was not well conditioned for the TRL-1 technique; note that the need to remove material for the reference/validation block (see Figure 178 in Section 7.4) and for EBSD led to this compromise. Flaw 8 (see Figure 13) represents a smooth root lack of fusion 3mm high and breaking the back wall of the specimen; it was generated as an EDM notch. The presence of both the buttering layer and the weld metal, and the small size of the flaw, makes its detection and sizing difficult. However, all the techniques were able to detect the flaw from the stainless steel side and again the buttering proved to be an obstacle preventing detection from the carbon steel side. This is illustrated in the case of the 2D-1 technique in Figure 134.

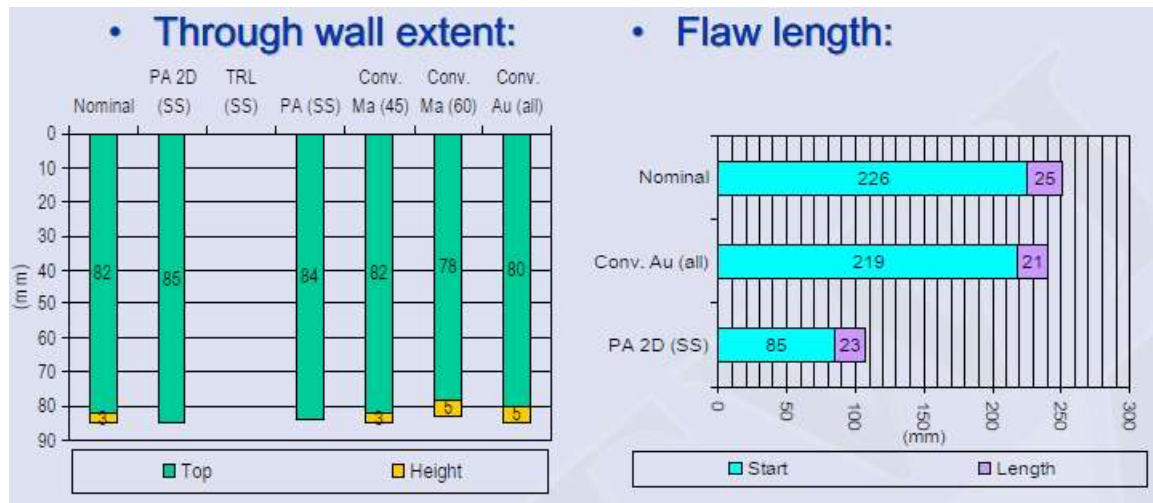


Figure 133 Graphs showing the comparison of the position, through-wall and length measurements made by the baseline techniques for Flaw 8. Refer to key on page 95.

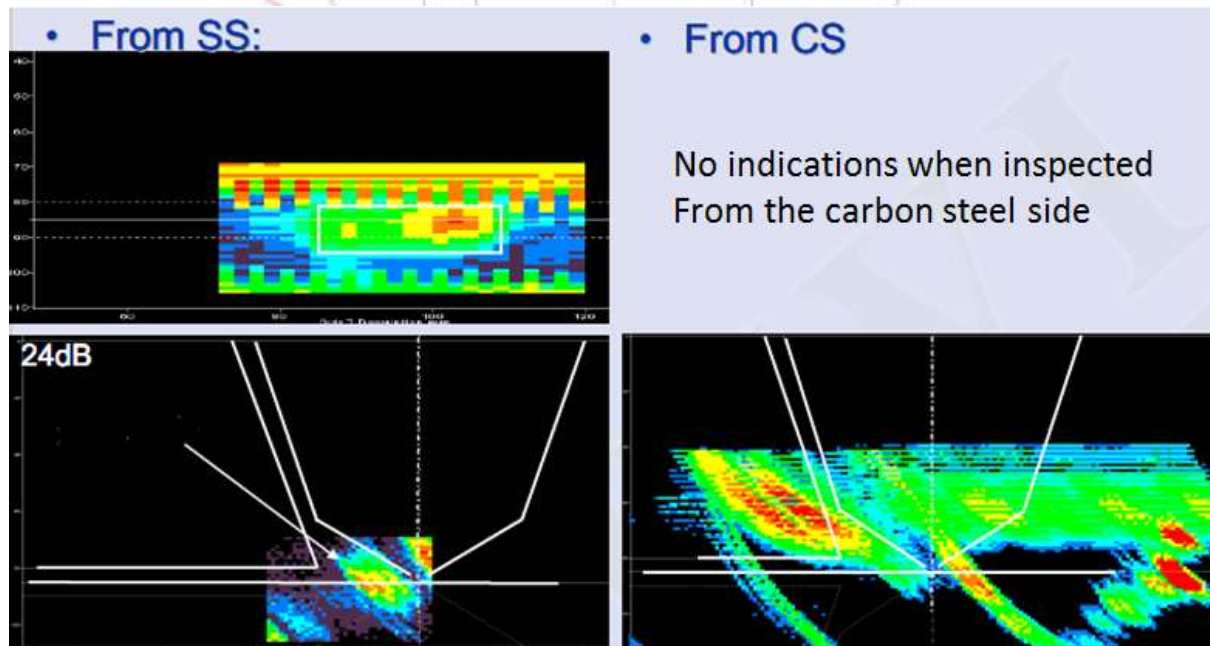


Figure 134 Detection of Flaw 8 (shown with a white arrow) from the stainless (left) and carbon (right) steel sides.

Similarly Flaw 8 was quite readily detected from the stainless steel side by the linear PA technique but could not be sized, as shown in Figure 135. Only the conventional techniques (both and manual and automated) were able to size the through-wall dimension of the flaw, reporting 3mm (error of 0mm) in the case of the manual and 5mm in the case of the automated techniques. Note however that typical conventional procedures specify a size range (eg <3mm) related to the minimum sizeable capability of the technique and hence the values reported by the techniques represent that minimum sizing capability. In the case of all the phased array techniques, sizing was only performed when clearly identifiable diffraction echoes were detected or the operator felt confident that the beam-flaw interaction was at or close to the specular regime.

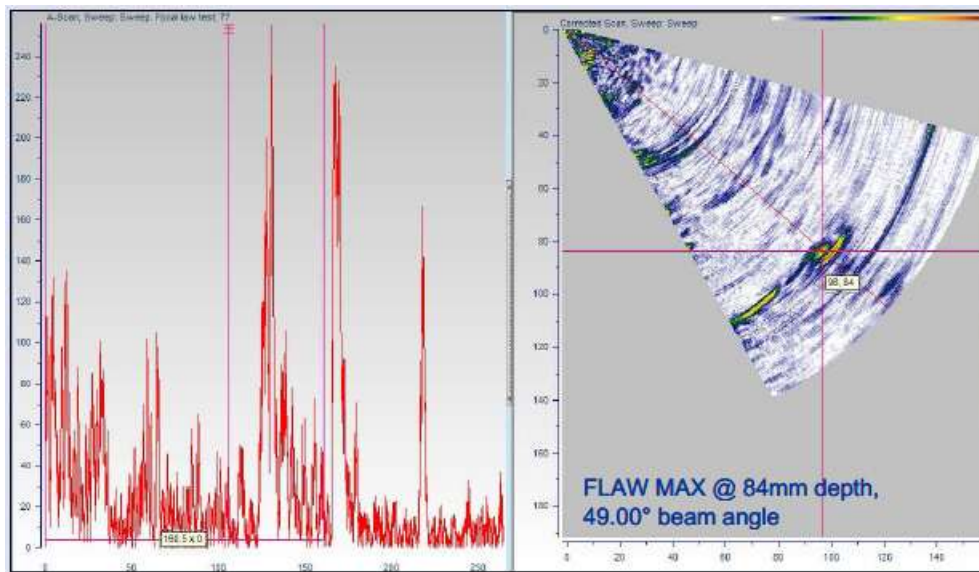


Figure 135 Detection of Flaw 8 from the stainless steel side by the linear PA technique.

7.2.8 General discussion

In summary, the conventional manual technique was able to detect all the flaws using the grain interference method to set the sensitivity; the plotting and sizing results however varied from probe to probe. A compression 0° probe was used to assess the attenuation on the specimen by setting the back wall signal to 80% of full screen height (FSH); the gain required in the parent stainless steel was 45.5dB, that of the parent carbon steel was 51dB and that of the weld was 74dB. This represents a marked difference between the three regions of the weld and it is known that the properties of the weld changes with sound propagation directions (anisotropy), affecting beam angle differentially.

The linear PA technique illustrated the 'toughness' of the weld to allow effective sound propagation, in particular when the sound had to travel through the weld metal or the buttering. Through-wall sizing errors were up to 5mm and diffraction signals could be detected effectively only when the flaws were on the fusion boundaries where the sound did not have to traverse the distortive buttering or weld media. A significant dead zone due to the surface was evident.

In general, the best S/N performance was achieved by the TRL-1 technique (see Appendix A for an additional example of using TRL probes) and the worst using the 2D-1 technique. Additionally, the TRL-1 technique was better at penetrating the buttering layer than the other techniques but suffered from the worst length sizing capabilities of all the techniques.

The 2D-1 technique was implemented with skewed beams also to explore capabilities to determine any skew orientation to the detected flaws. The array configuration (18 x 7) was specified with enough elements along the secondary axis to be able to steer the sound beam by up to $\pm 10^\circ$ in the secondary plane. The secondary plane is parallel to the welding direction and any flaws which are not perfectly in this plane, ie skewed, would be more sensitive to an appropriately skewed beam – that is, a skewed beam should increase the likelihood of detecting skewed flaws.

Figure 136 shows data on using skewed beams for inspecting Flaw 3. Comparing the signal strength from the flaw when the beam is skewed -4° and $+4^\circ$ to when the beam was not skewed (ie 0° beam), the echo strength from the flaw when the beam was $+4^\circ$ is reduced implying that the flaw is tending away from being specular. Hence the preferred skew of the flaw can be inferred from comparing the skewed data.

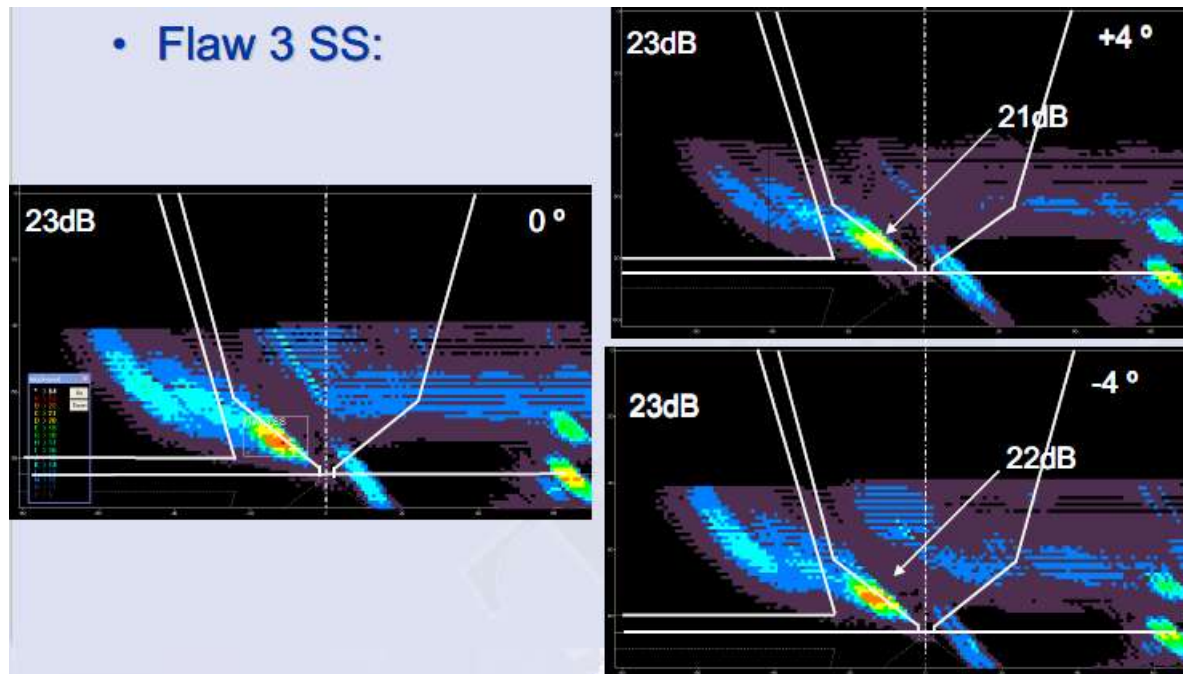


Figure 136 Data showing the signal strength from Flaw 3 when the beam is skewed $\pm 4^\circ$ from nominal 0° beam.

Investigations on Flaw 4, as shown in Figure 137, reveal similar sensitivity to the incident beam, ie sensitivity to skew, which indicates the orientation of the flaw itself. A negatively skewed beam (-7°) leads to a 3dB drop in maximum diffracted signal amplitude whereas only a 1dB drop when the beam is skewed positively to $+7^\circ$.

Data from using skewed beams to inspect Flaw 7, the rough centreline crack, implies that flaws need not have preferential orientation. Figure 138 shows that both $\pm 4^\circ$ beams lead to similar reflected amplitudes (to within 1dB) to when the beam was not skewed. Even when the beams are skewed to $\pm 8^\circ$ the amplitudes are still within 3dB of that at 0° skew. This is consistent with the nature of rough cracks which remain reflective due to their faceted nature.

The study showed that the use of 2D arrays allows to infer any tilt or orientation to the flaws but measuring the actual tilt will require the system to undertake scans with several beams (similar to a sector scan but over the secondary plane). The specification of the array will determine the limits to which the beams can be skewed and it is important that these limits are not exceeded, as the break down in the sound field characteristics could lead to unforeseen phenomena (primarily through the generation of side energy lobes). Additionally, skewed beams are more likely to be useful for detecting smooth flaws (which are more sensitivity to incident beam directions) than rough faceted flaws.

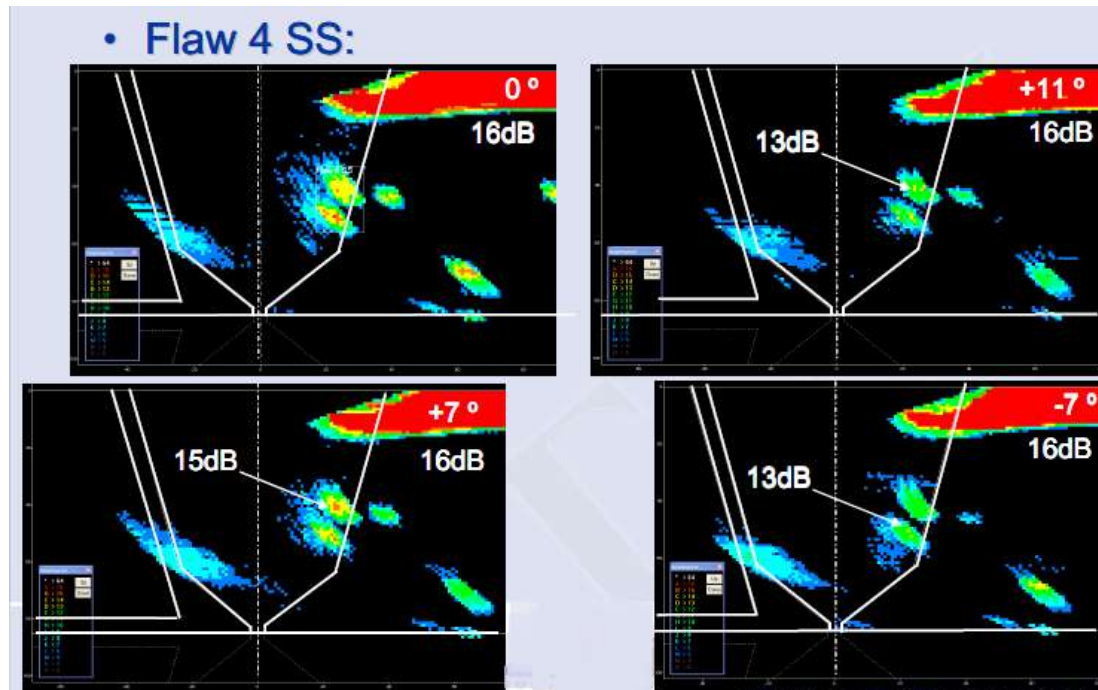


Figure 137 Data showing signal strength from Flaw 4 when the beam is skewed by +/- 7° and +11° from nominal 0° beam.

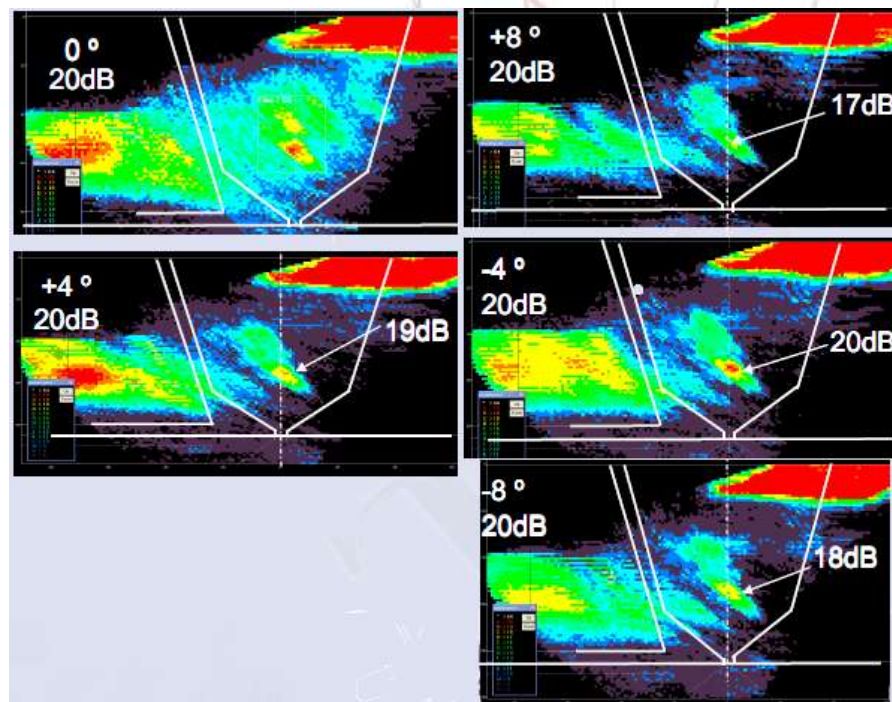


Figure 138 Data showing signal strength from Flaw 7 when the beam is skewed by +/- 4° and +/- 8° from nominal 0° beam.

The data from the baseline inspections show that the use of phased array techniques does not lead to any appreciable improvement in the sizing capability. The work done has highlighted the areas where the use of phased array techniques could provide significant

logistical advantages in comparison to both the manual and automated conventional techniques.

A key parameter that was measured as part of the baseline inspections was the total time taken to complete the inspection, from when the specimen is presented to when the inspection report is submitted. The conventional manual inspection of all the flaws in the specimen took one week, with 5 hours to set up and 30 hours for scanning and interpretation. Four probes were used, three for the actual scanning. The phased array manual inspection (the linear PA technique) took 2 hours for the setup (including calibration of the one linear array probe) and 10 hours for scanning and interpretation.

The conventional automated inspection (see Appendix E) is estimated to have taken a week including setup, scanning and interpretation. The technique made use of many probes (more than five), but the inspection was done from both the inside and outside (top) surfaces of the specimen, whereas all the other inspections were done from only one (the top) surface.

The TRL-1 technique made use of only one probe. The setup time was estimated to be 0.5 hour per flaw (ie 4 hours in total) and 15 hours for scanning and interpretation - the interpretation was estimated to be 70% of this time. The 2D-1 technique involved the exploration of various inspection concepts and hence was not counted towards evaluating inspection times. Hence, in general, the phased array techniques (linear PA and TRL-1) were less than 50% of the time taken by the conventional techniques. Once inspections are set up, routine inspections should take even less time to implement using mechanical systems.

Both the TRL-1 and 2D-1 techniques can be automated but only one probe needs to be deployed, unlike in the case of the conventional automated technique (see Appendix E). The TRL and 2D probes developed in the project are able to address the full volume of the weld, whereas a number of specific probes were required to interrogate the full weld volume in the conventional automated technique. Hence the total time to complete the inspection in an industrial setting using the phased array techniques should be much less than the conventional technique, which requires changing several probes from the mechanical deployment system.

Using a fewer number of probes will also allow the mechanical deployment system to be simplified, reducing the use of large cumbersome probe pans containing several probes generating a range of discrete beam angles. This should also allow designers to minimise the chances of mechanical failures leading to introduction of debris into containment areas.

Another key logistical advantage of phased array techniques (and other automated data collection techniques) is that they inherently provide digital data that can be archived. The data representation of phased array techniques (whether the sector scans of the linear PA technique or the processed representation provided by GUIDE) allow for more intuitive data interpretation by the human operator and also provide future possibilities for automated interpretation of data.

The logistical advantages described above are secondary to the measurement capabilities of the phased array techniques but they come to the fore when they make the techniques attractive for industry through their ability to reduce implementation costs.

7.3 Adapted delay laws (ADL) technique

The concept of generating delay laws through the use of models, as described in Section 6.2, was developed in the DISSIMILAR project as a possible route to overcome the degradation in the inspection quality due to the distortion of the sound by the austenitic weld [16, 17 and 18]. The results of generating the ADLs using the CIVA model is presented in Section 7.3.1 and experimental results of using the ADLs to undertake scanning of the specimen is presented in Section 7.3.2. Additionally, initial results of using a finite element package (PZ Flex) to generate the ADLs is presented and results from attempts to generate the ADLs experimentally (rather than through models) is presented.

7.3.1 Simulated

The ADLs were developed as described in Section 6.2. Figure 139 shows the inspection scenario where the probe was scanned over the flaw with a total of seven positions (P1 to P13) incident on the flaw, assuming straight geometric path of the beam. The beam angle was set to be 46.5° which was perfectly specular to the simulated Flaw 3 at the position P7 when the beam is incident on the central point of the flaw area.

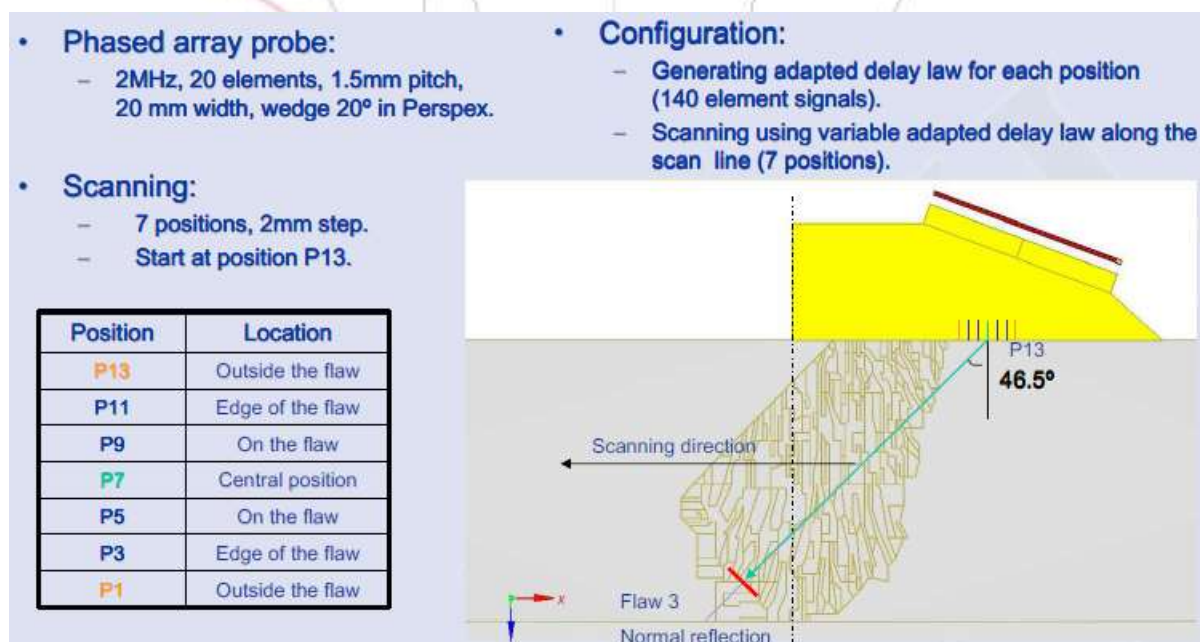


Figure 139 Simulated scanning of Flaw 3 using a linear array probe with beams from seven discrete positions being incident on the flaw.

Figure 140 shows the simulated echo from Flaw 3 when the elements were fired individually in order to generate the ADL at one of the seven positions. Figure 140 shows that the greatest received echo strength was on elements 15 to 20, implying that the lower elements, which would have been incident on the weld fusion interface at oblique angles, appear to lose energy possibly through reflection at that boundary. The received amplitude is not relevant for the generation of the ADL (see Section 6.2) as only the time-of-flight is used to 'reverse' the scenario such that all the element wavelets arrive at the target at the same time and in-phase for constructive interference to take place.

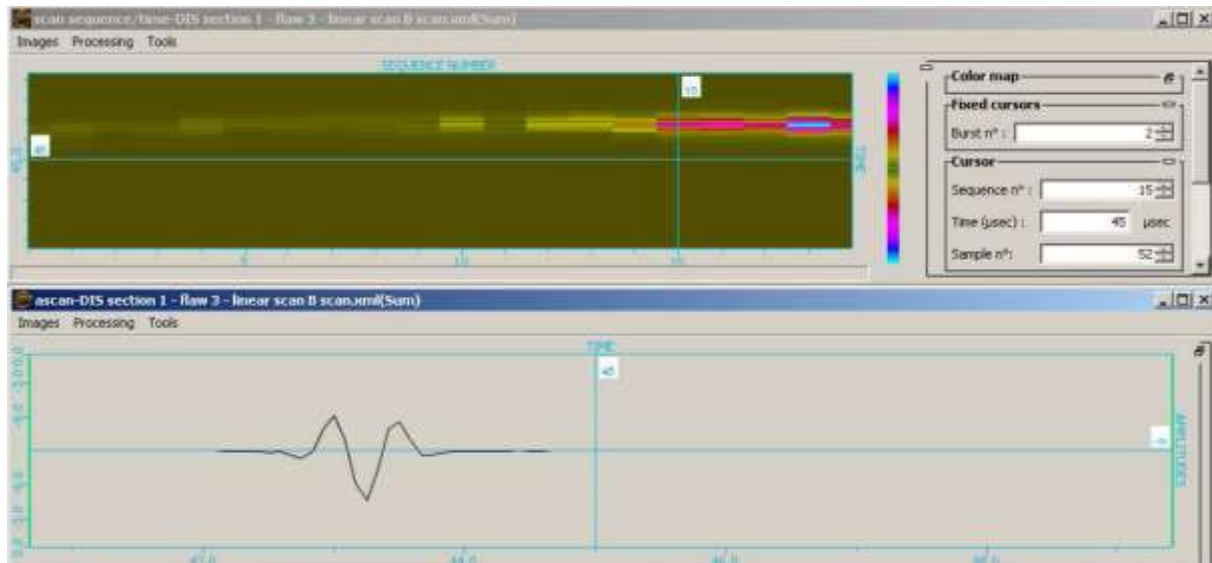


Figure 140 The received echo on element 15 (of the 20 element array aperture) showing that the sound from elements 1 to 15 are weaker relative to the elements 15 to 20.

Hence using the simulated times-of-flight for echoes generated at the simulated Flaw 3, an ADL was generated for each of the seven positions and the delay law curves for each position is presented in Figure 141.



Figure 141 ADLs for each of the seven positions forming the simulated scan over Flaw 3.

The degree of change in the profile of the delay law curve and the changes in delay amplitudes (measured in Nano seconds, ns) is indicative of the anisotropy of the weld medium through changes in the sound velocity. Whereas the isotropic delay law curve is near symmetric this is not the case with the ADLs. The simulated echo from the flaw was then generated when using the isotropic and each of the ADLs separately; the results are presented in Figure 142. In all cases the echo due to the ADLs (fired from their corresponding positions) are larger than that due to the isotropic delay law. Note also the changes in received time at several of the positions between when the adapted and isotropic delay laws were used.

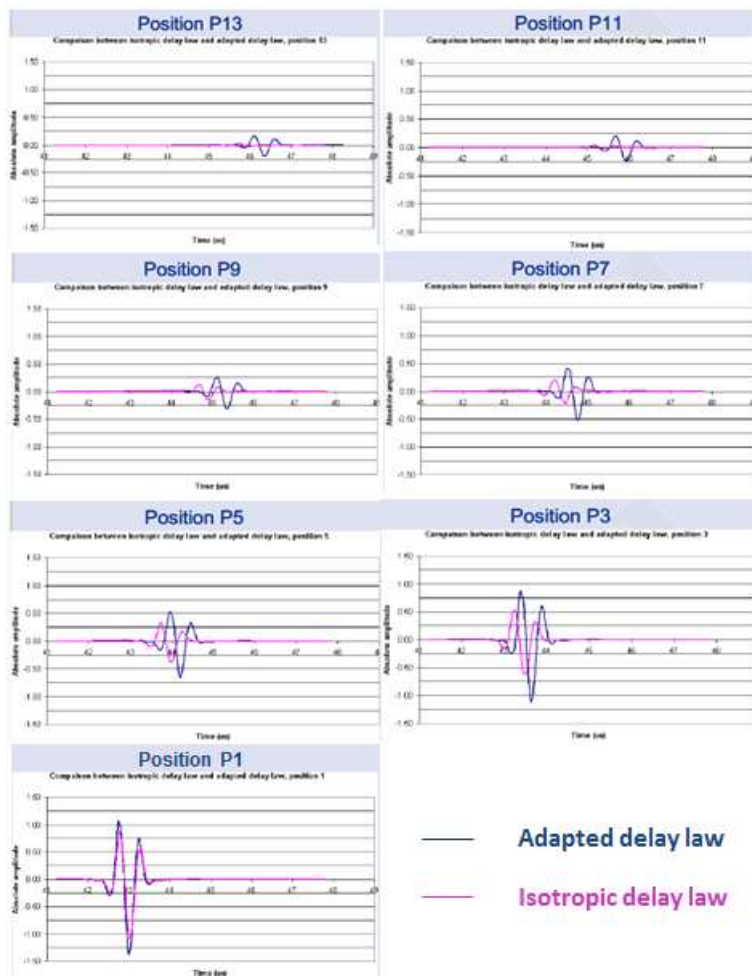


Figure 142 Simulated echoes received from Flaw 3 when using each of the seven ADLs from their corresponding position in comparison to the isotropic delay law.

A further result using the same array as shown in Figure 139 but using 32 elements (instead of 20 elements as above) and with the array placed in position P7 is presented in Figure 143, showing a significant increase in the received amplitude from the flaw when using the adapted delay law. The received amplitude from each of the positions was then plotted to generate the echo-dynamic over Flaw 3; additionally, the echo-dynamic of Flaw 3 assuming that the weld was fully isotropic was also simulated. The echo-dynamic results are presented in Figure 144 showing that the amplitudes due to the use of the ADLs was consistently higher than when the isotropic delay law was used but the echo-dynamic shape (compared to what would be expected had the weld been isotropic carbon steel) was not achieved in the anisotropic weld by either the adapted or isotropic laws.

The use of the flaw itself, which is specular to the beams, for generation of the ADLs is noted as the most well-conditioned scenario and the increase in amplitudes due to the ADLs imply that the sound field coherence is better maintained on incidence on the flaw. However, often the nature of the flaw at a region of the weld is unknown and in such cases the ADLs would need to be developed using the standard SDH reflector.

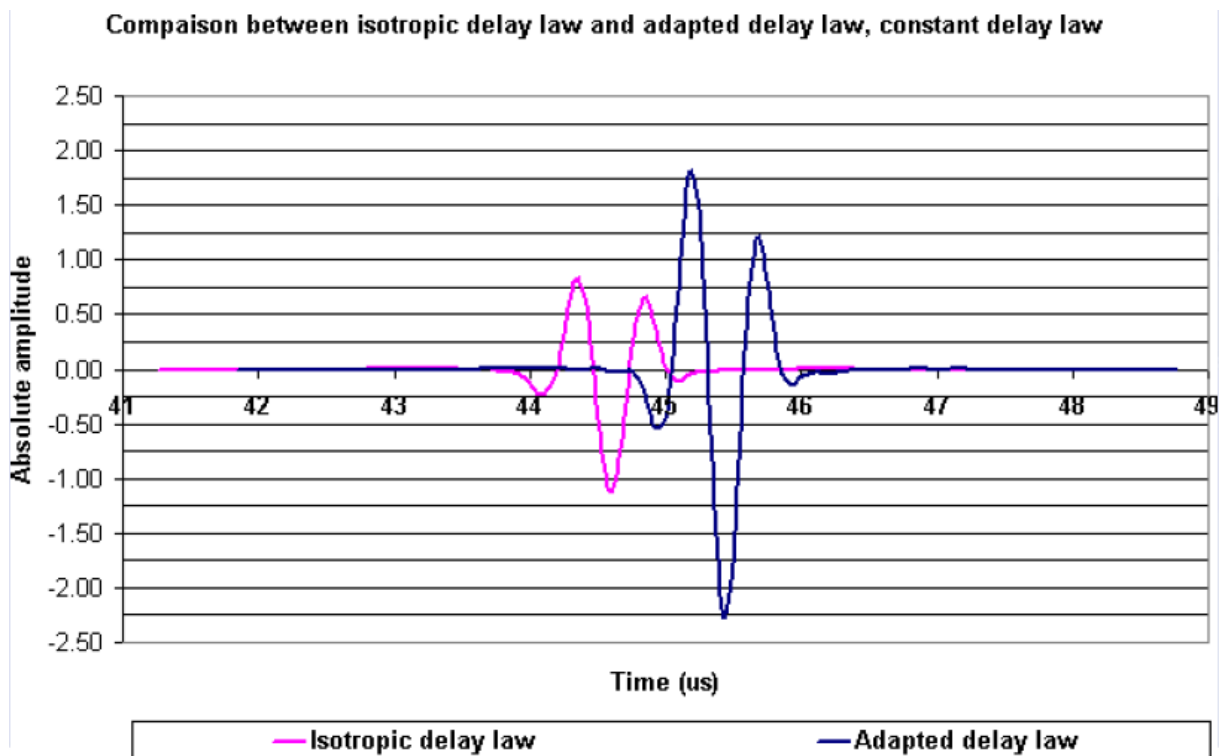


Figure 143 The simulated received amplitudes from Flaw 3 when using isotropic and adapted delay laws; the array used 32 elements and was place in position P7.

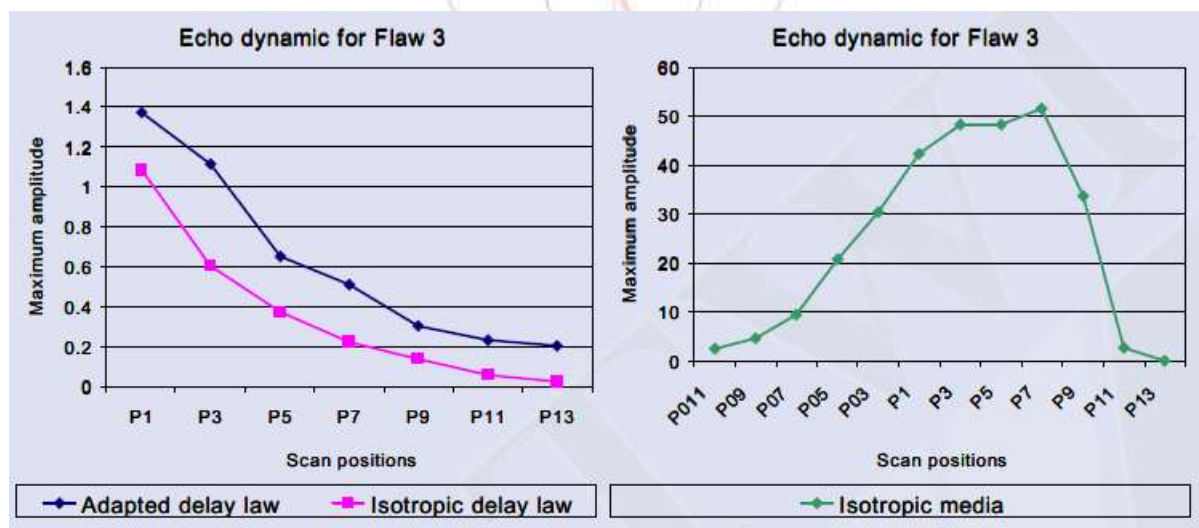
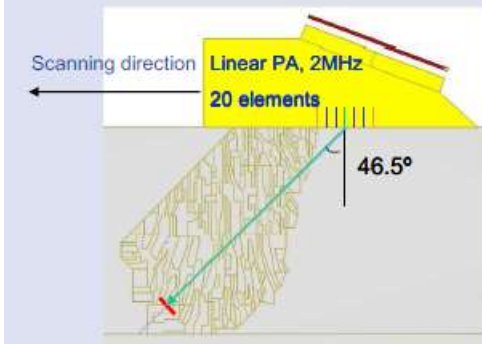


Figure 144 The simulated echo-dynamic pattern from Flaw 3 when using the adapted and isotropic laws (left), and in comparison to the expected shape had the weld been isotropic carbon steel (right).

Figure 145 summarises the two different approaches which could be taken to generate the ADLs through simulation: if the expected nature of the flaw is known and if a generic law better optimised for a region of the weld is required.

1. Using the flaw

- Flaw near specular.
- 13 individual adapted delay laws for each position along the flaw.



2. Using the SDH at the position of the flaw

- Single adapted delay law



Figure 145 Two possible approaches to generate ADLs through simulation: using the expected flaw itself (left) or using a generic SDH in the correction region of the weld (right).

Figure 146 shows the ADL generated using the SDH from position P7 to those using the flaw at three different positions (P1, P7 and P13) showing that the laws appear to be sensitive to the microstructure. There is good confidence in the analytical theory (termed Kirchhoff) used to evaluate the interaction of the sound field with both the specular crack-like Flaw 3 and the SDH [20 and 21] when the medium is isotropic but thorough verification of their validity in a simulated anisotropic medium is yet to be fully accomplished (see Section 7.4).

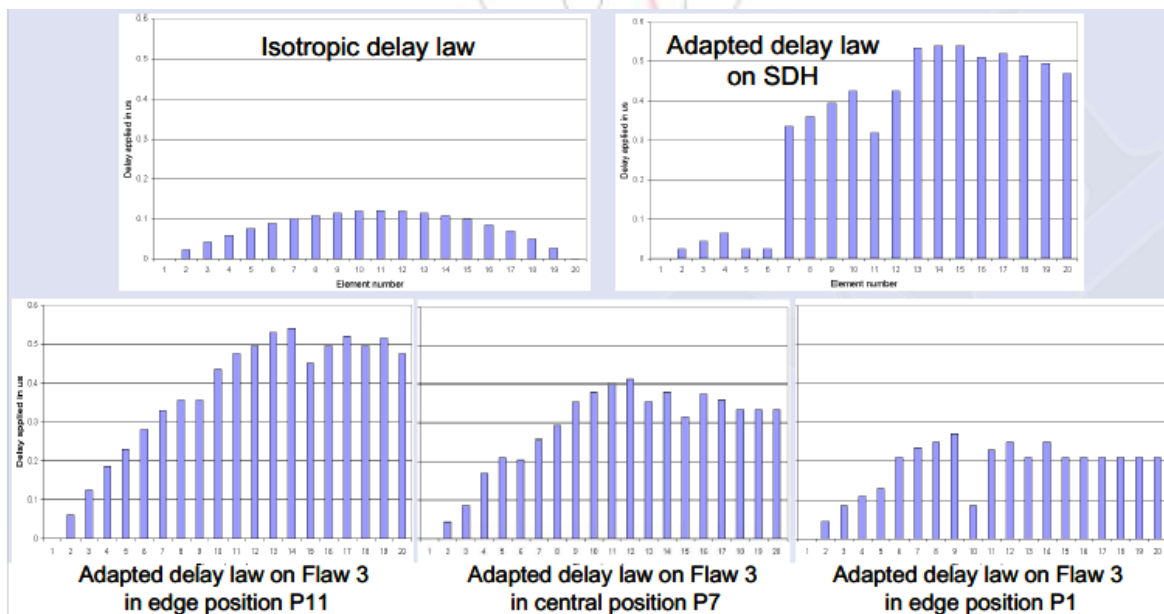


Figure 146 The ADLs generated using a SDH compared to those generated using Flaw 3 (from positions P1, P7 and P13) and with the isotropic law.

Scans over the flaw were then simulated again using the ADLs generated on the flaw, using the SDH and using the calculated isotropic delay law. Further scan positions at 2mm increments from P1 were added (P03, P05, P07, P09 and P011) which were all outside the flaw (assuming isotropic straight beam incidence geometry). The resultant echo-dynamic is presented in Figure 147.

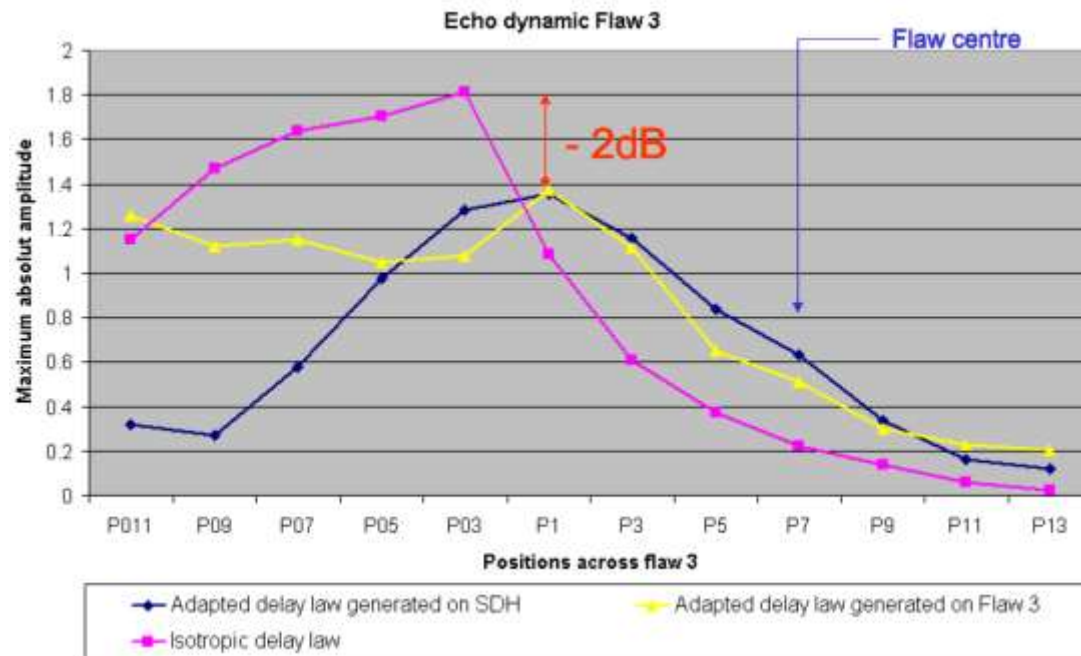


Figure 147 The echo-dynamic from simulated scanning over Flaw 3 using ADLs generated using a SDH, using Flaw 3 and using the isotropic delay law.

Firstly the actual peak echo strength using the isotropic delay law occurs outside of the nominal incidence on the flaw, ie at position P03, and the peak echo is larger than those due to the ADLs generated using either the flaw itself or a SDH. Note that the data between the isotropic delay law and the flaw adapted delay laws (ie pink and yellow curves, respectively) in the region from position P1 to P13 is the same as shown in Figure 144. The echo-dynamic when using the ADL generated from a SDH (ie the blue curve) is closer to the expected echo-dynamic from a flaw such as Flaw 3 and its profile is better than that from the other two cases. All three cases did not position the maximum of the signal over the centre of the flaw as would be required. Hence, in summary, the ADLs did not lead to an increase in the maximum recorded echo strength but, in the case of the ADL generated using the SDH, the echo-dynamic profile of the scan is better than when using the isotropic delay law. As discussed in Section 6.1, the evidence supports the hypothesis that the ADL technique would not be able to correct for positional errors.

Assuming that the incident beam is smaller than the flaw, using the 6dB drop method of sizing the echo-dynamic of the data from the ADL using a SDH, the flaw size is measured as 12mm, a through-wall height of 8.5mm; the through-wall height of the simulated flaw was 8mm.

All the ADLs presented above were generated in the first section of the weld mapped using EBSD (see Section 3). Figure 148 shows the difference in the ADLs generated using section 1 and section 2 of the weld microstructure.

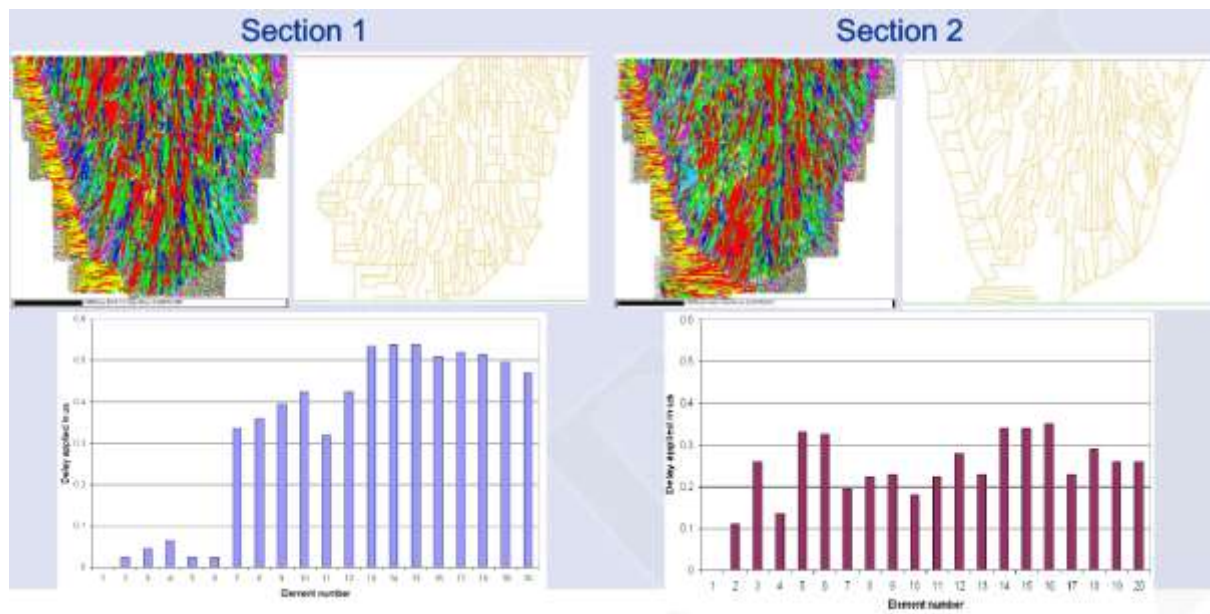


Figure 148 ADL generated using a SDH at the position of Flaw 3 in weld sections 1 and 2.

The echo-dynamics due to the simulated scanning over Flaw 3 in the two weld cross sections is presented in Figure 149.

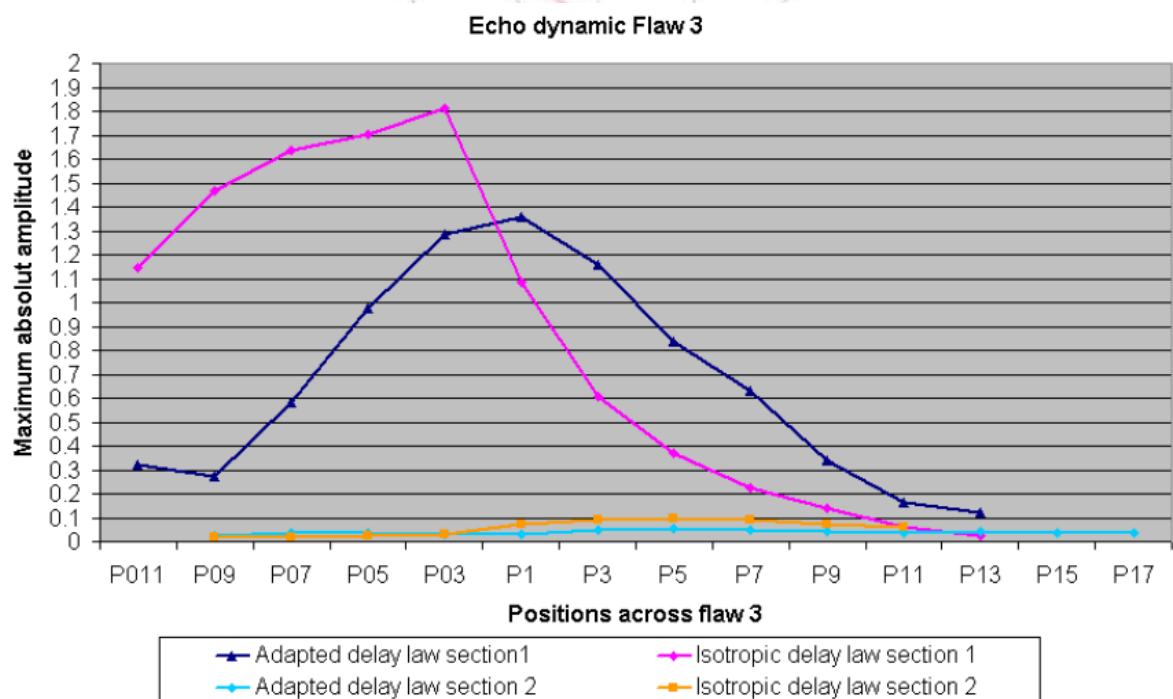


Figure 149 Echo-dynamics over Flaw 3 when scanning is simulated in two weld sections.

Firstly, Figure 149 shows that the absolute amplitudes received from Flaw 3 in section 1 are much higher than in section 2; the data from only section 2 is presented in Figure 150. The performance of the ADL generated using a SDH in section 2 leads to lower received

amplitudes from the flaw, in comparison to the isotropic delay law. However, the amplitudes due the use of both delay laws in section 2 are much lower than in section 1 implying significant differences in attenuation due to the microstructures of sections 1 and 2. Note, however, that the echo dynamic profiles over the actual flaw position are better in section 2.

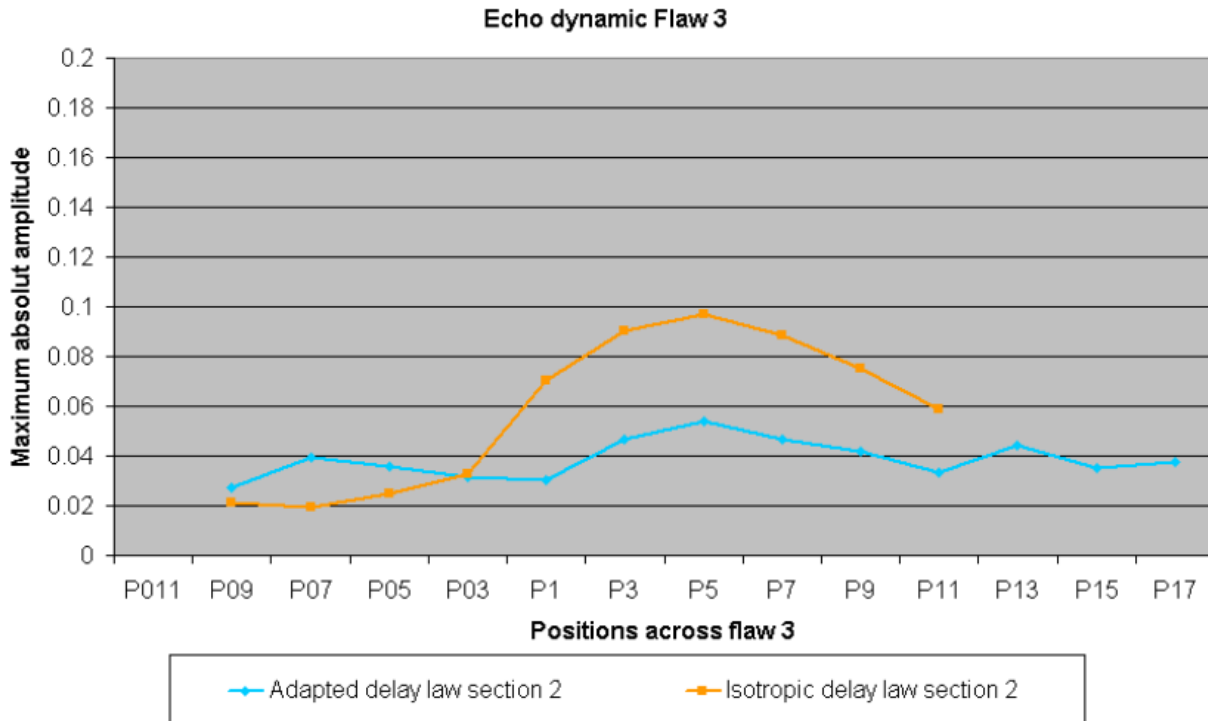


Figure 150 Echo-dynamics over Flaw 3 when scanning is simulated in section 2.

Figure 151 shows the received amplitudes on each of the elements on the array when generating the ADL on the SDH. Firstly, the data shows that, in comparison to section 1, the echoes returning to the elements in section 2 is much reduced, implying severe relative attenuation. Secondly, the data also shows that sound amplitudes returning to some of the elements is higher than for others, implying that some elements contribute much less to illuminating the region of the flaw.

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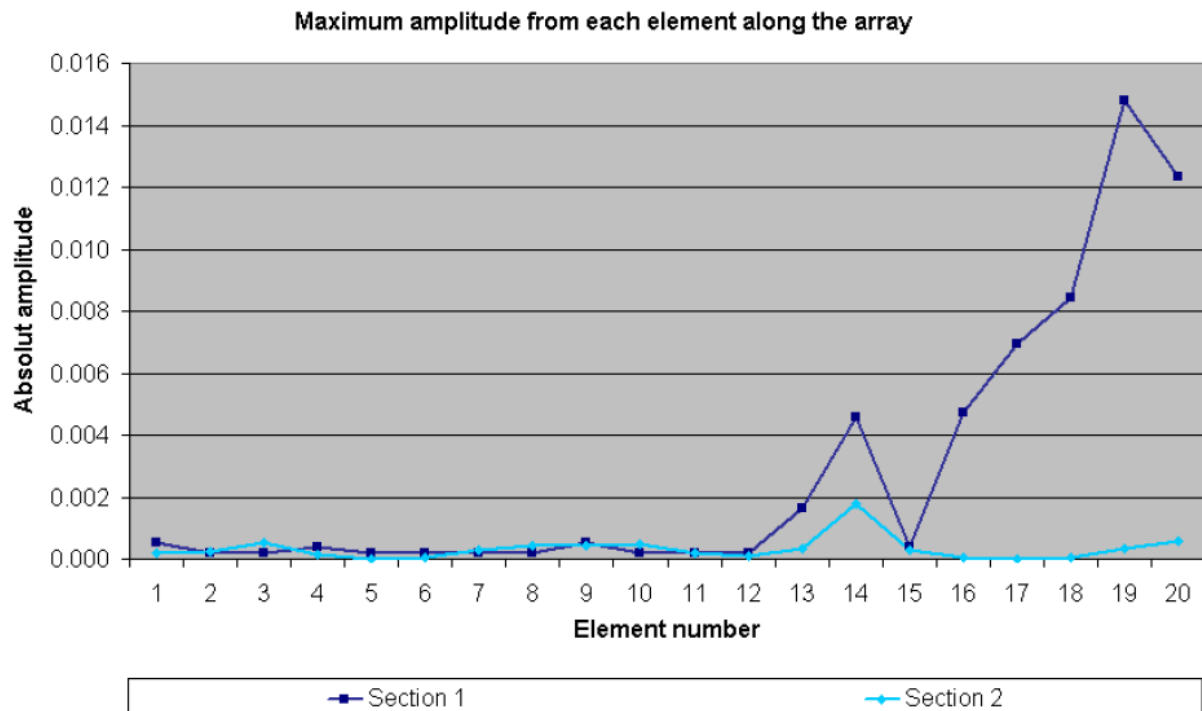


Figure 151 Received amplitudes on each of the elements when generating the ADLs using a SDH in weld sections 1 and 2.

Differences in the microstructure are further highlighted in Figure 152 through ray-tracing, where the red and green rays emanating from the probe for the different elements represent the theoretical shear and longitudinal wave paths, respectively. The path taken by the rays is dependent on the properties of the medium, ie the microstructure, through which they travel. Hence the results show (see the difference in behaviour of the rays from element 14 in sections 1 and 2) that there are significant differences in the mapped sections. This highlights the discrepancy between the experimental assessment of weld uniformity (see Section 3.6) which concluded that the weld was relatively uniform and the results in Figure 152 which appears to suggest significant differences between the mapped welds. The issue could be due to the mapping of the microstructure but there is also experimental evidence (using the validation block, see Section 7.4) that the actual microstructure can be variable depending on the angles at which the beams travels with respect to the dendritic grains.

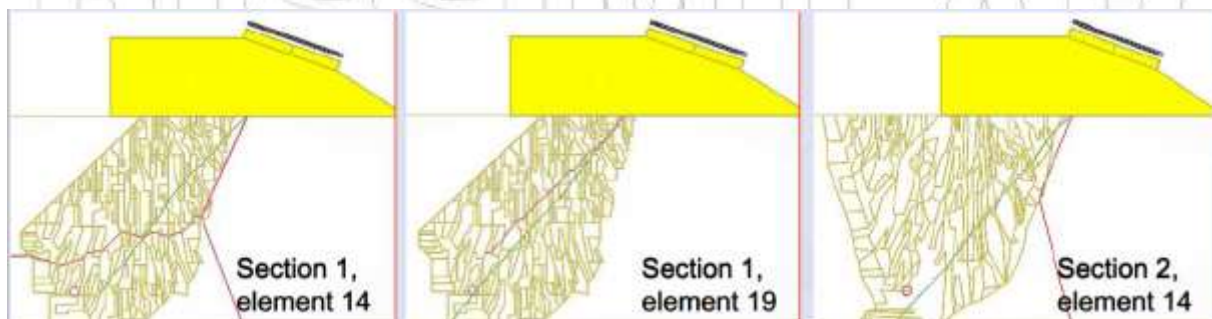


Figure 152 Ray-tracings of shear (red) and longitudinal (green) waves emanating from elements of the array in weld sections 1 and 2.

ADLs were also generated for inspection of Flaw 4 using SDHs placed at the position of the flaw and one half of the TRL probe developed in the project (a 1.5MHz 32 x 2 array). In the case of inspecting Flaw 4, as shown in Figure 153, the sound from the array has to traverse the buttering layer, which was found to be difficult experimentally (see Section 7.2). Additionally, the work done above on Flaw 3 made use of the 32-bit version 9 of CIVA whereas the models for inspection of Flaw 4 made use of the 64-bit version 10 of CIVA. Hence it was assumed that there were no changes in the mathematical calculations between versions (eg in Kirchhoff interaction theory, refraction at boundaries etc) and it was found that simulation times in version 10 were orders of magnitude quicker.

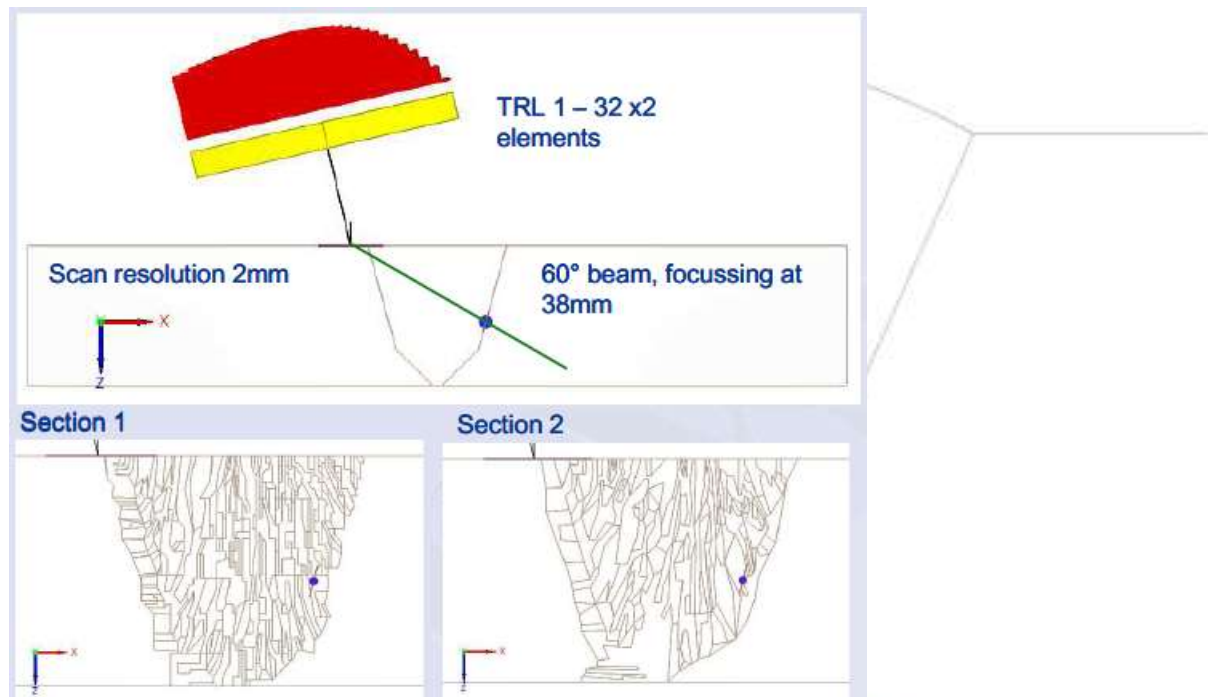


Figure 153 Generating ADLs for inspection of Flaw 4 in weld sections 1 and 2.

The Kirchhoff theory was used to generate the ADLs using a SDH but another theory termed the Geometric Theory of Diffraction (GTD) was used for evaluating the interaction of the sound with Flaw 4. Kirchhoff theory has been validated for use near specular incidence [20] but it is not able to deal with scenarios where the interaction will give rise to diffracted echoes, for which GTD is better suited. GTD has been validated for use in many of the models developed by British Energy [20] but the limits to its validity as utilised in CIVA, in particular when used in the anisotropic medium of the weld, has not been fully established.

Figure 154 shows the delay laws generated in section 1 (ADL 1) and section 2 (ADL 2) in comparison to the isotropic delay law calculated by CIVA and ArrayGen. There are in total 64 elements in the array (represented on the x-axis) and the magnitude of the delays for the elements (represented on the y-axis) implies that the isotropic velocities assumed for the calculated laws - Iso (CIVA) and Iso (AG) – closely matches the velocities in the anisotropic weld, as expressed through the stiffness coefficients. The profile of ADL 1 is similar to those of the isotropic delay laws but ADL 2 suggests severe variability between elements. The profile of the ADL in section 2 is again indicative of (1) the complexity of the microstructure and (2) its difference when compared to the microstructure of section 1.

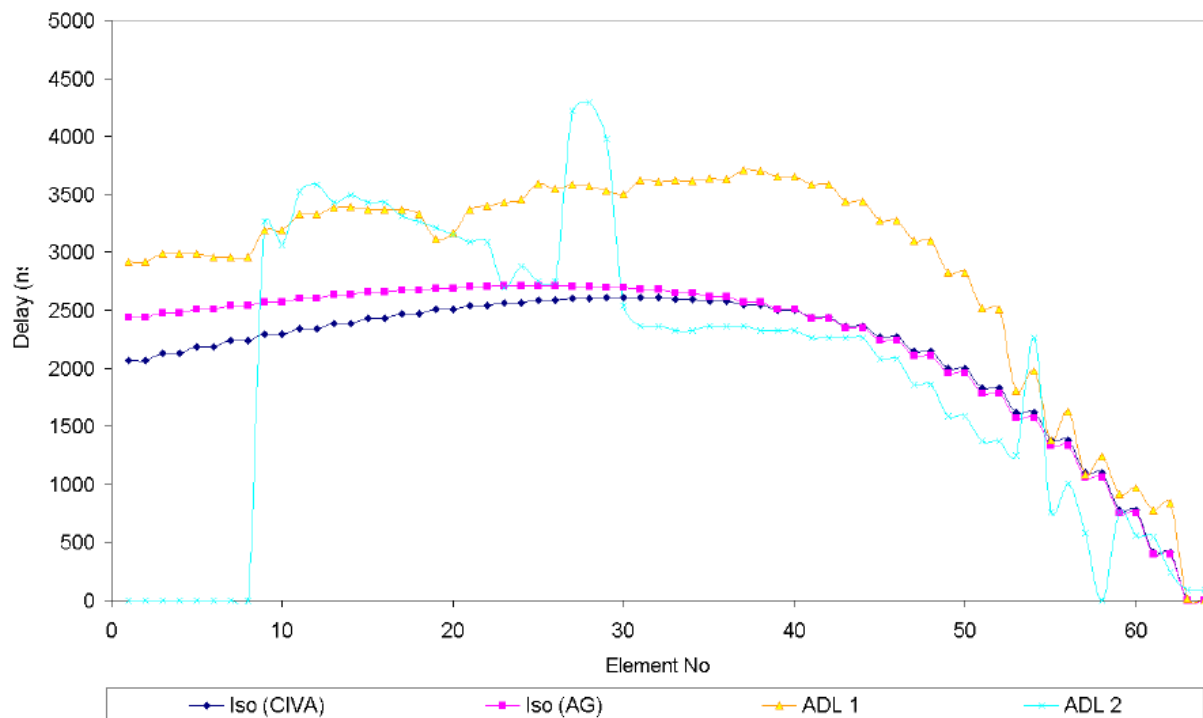


Figure 154 ADLs generated using a SDH in weld sections 1 and 2 for inspection of Flaw 4.

The received signal amplitudes on each element of the array are presented in Figure 155 for each of the weld sections. The received elemental signal amplitudes are higher when generating the ADL in section 2 but the distribution of the amplitudes again indicates the degree of distortion being induced by the microstructure of the second weld cross section in comparison to the first weld cross section.

The scanning for Flaw 4 was then simulated, as in the case of Flaw 3, and the results are presented in Figure 156 for section 1; note that the theory used for the interaction of the sound with the flaws was GTD. The results appear to be consistent with the experimental data discussed in Section 7.2, in terms of the loss in amplitudes, differences in plotting, sizing and the effects due to distorted sound fields. In the anisotropic weld the isotropic delay law plots the echoes from the flaw inside the weld whereas the ADL plots the flaw outside the weld and both suggest spatial distortion due to the flaw tips. The results of inspection through section 2 are similar, as presented in Figure 157. In both cases (ie inspection through sections 1 and 2) the method by which CIVA presents the scan data makes it difficult to identify diffraction signals and hence size the flaw; note that in the case of the isotropic delay law being used to inspect in an isotropic weld, the diffracted signals can be clearly resolved allowing for the flaw to be sized.

In summary, in section 1, the ADL profile (shape and amplitude) is similar to the two isotropic delay laws generated by CIVA and ArrayGen; however, only 10 elements contribute significantly towards illuminating the flaw using the ADL. The improvement in signal amplitude when using the ADL is estimated to be less than 2dB; the simulated position and size of the flaw using the ADL is also larger than when the isotropic delay law was used. The ADL generated in section 2 suggests significant local microstructural variation and the received amplitudes from each element also suggest significant differences in attenuation.

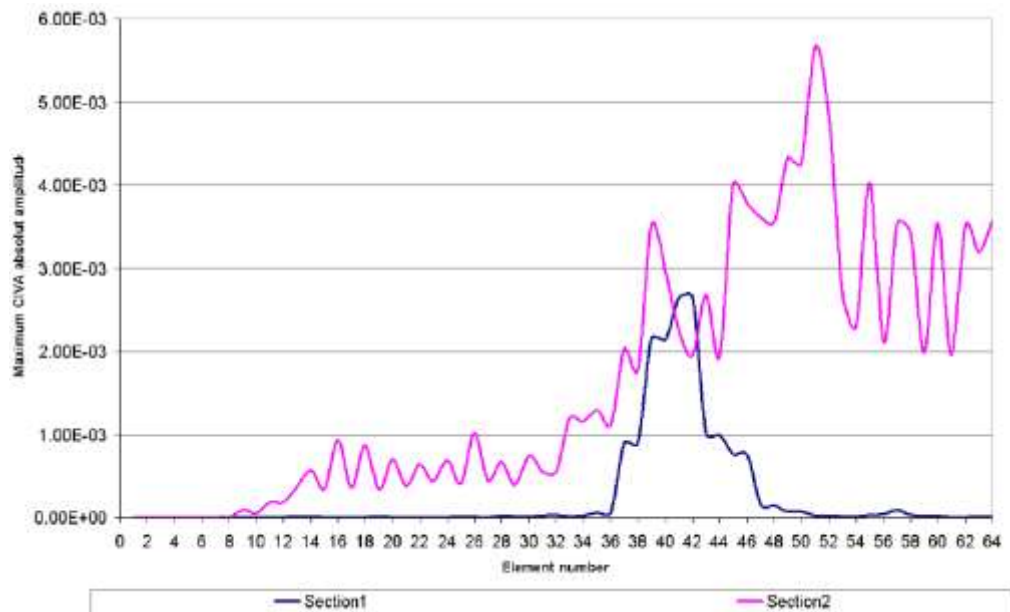


Figure 155 Received signal amplitudes on each element of the array when generating the ADL using a SDH in each of the two weld sections.

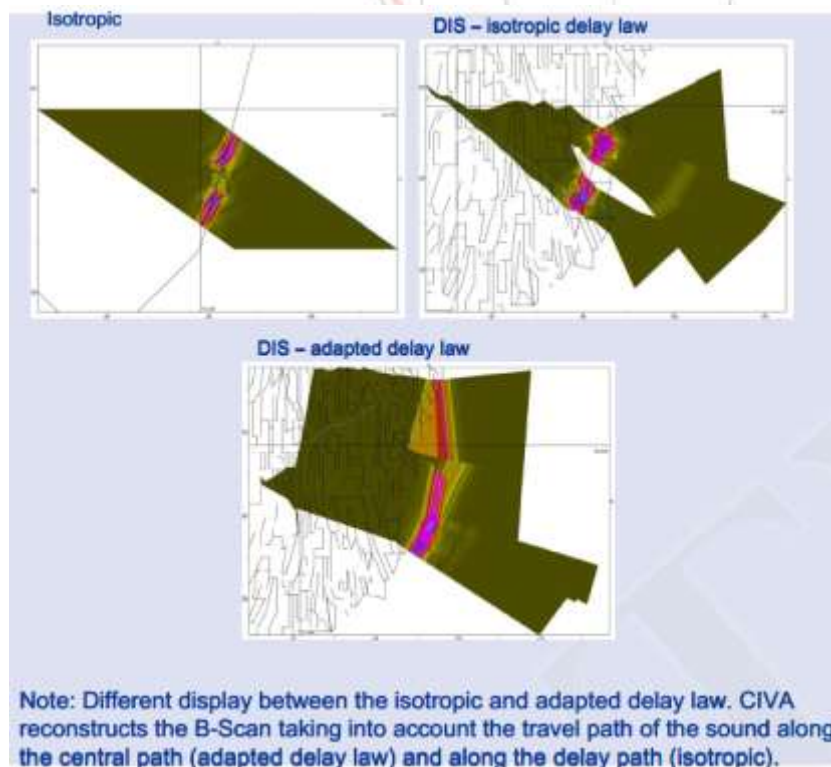


Figure 156 Simulated scanning results for inspection of Flaw 4 using the GTD theory of interaction; isotropic weld, isotropic delay law (top left), anisotropic weld, isotropic delay law (top right) and anisotropic weld, ADL (bottom).

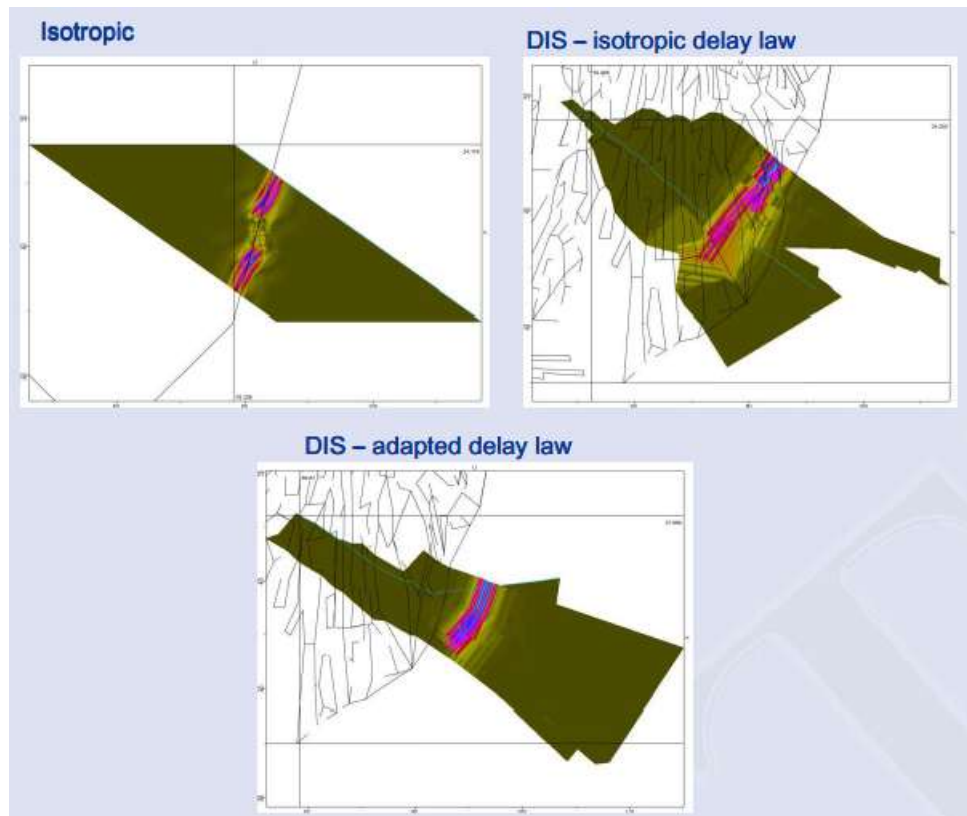


Figure 157 Simulated scanning results for inspection of Flaw 4 using the GTD theory of interaction; isotropic weld, isotropic delay law (top left), anisotropic weld, isotropic delay law (top right) and anisotropic weld, ADL (bottom).

As the sound travels through the weld it traverses several 'grains' or major orientation regions. As discussed in Section 3, the orientation unification processing leads to the selection of several major orientations with the misorientation parameter selected such that the whole weld can be described and mapped using a limited number of regions assigned one of the major orientations. The size of the regions, and hence the misorientation parameter and number of major orientations, is governed by placing the inspection within the Rayleigh scattering regime (minimum scattering criterion). A further route to simplify the weld description was explored to follow the orientation unification method in order to limit distinct regions and hence reduce simulation times. The aim was to consider the behaviour of the sound beam as it passes from a region of one major orientation into another one.

The minimum scatter criterion for the weld specimen and inspection frequencies of the project states that the minimum size of the 'grains' or regions will be 300µm but they could be larger. The propagation of the sound by the model is subject both to the orientation of these regions (termed domains for the study) and their size. Figure 158 describes the two tests performed as part of the study, one test to investigate orientation changes and the other to investigate changes in the size of the regions or domains. Four major orientations were chosen: red, lime green, yellow and blue. The sound was generated by a single element 25.4mm in diameter. The path of the longitudinal wave is represented by the green line in Figure 158, deflecting from domain to domain due to changes in property. The model is used to calculate the beam cross section at as the beam emerges from its travel into the last domain.

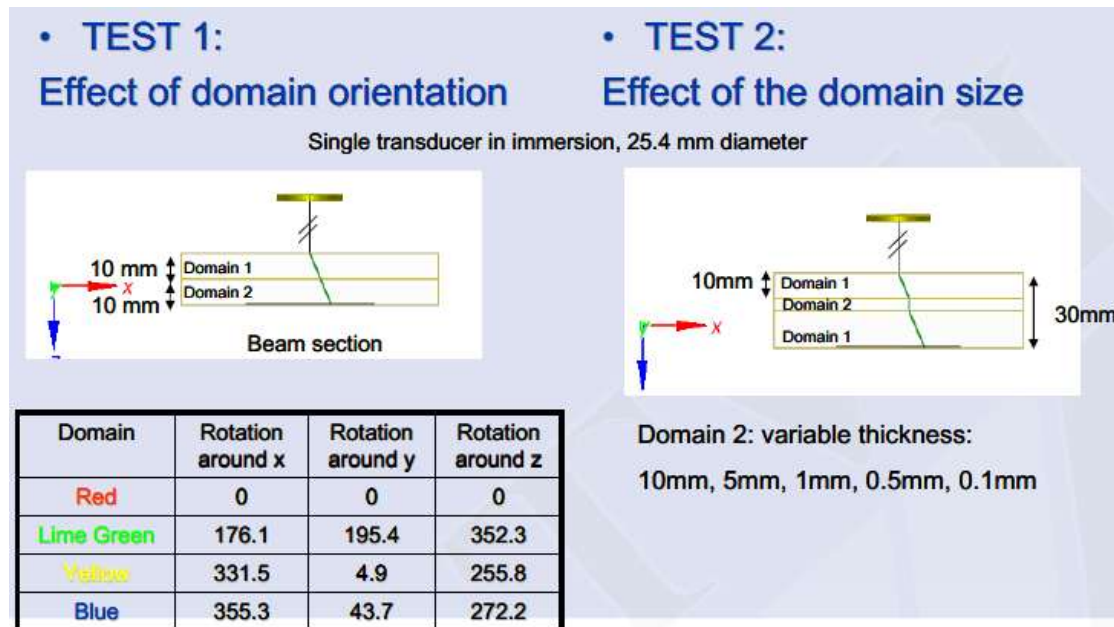


Figure 158 Tests to study the effect of changes in the orientation and sizes of distinctly different regions (domains).

The two primary orientations found in the buttering are red and yellow. Figure 159 shows the effect on the propagating sound when travelling between these two different orientations; note that the isotropic domain case is when Domains 1 and 2 in Figure 160 Test 1 are isotropic.

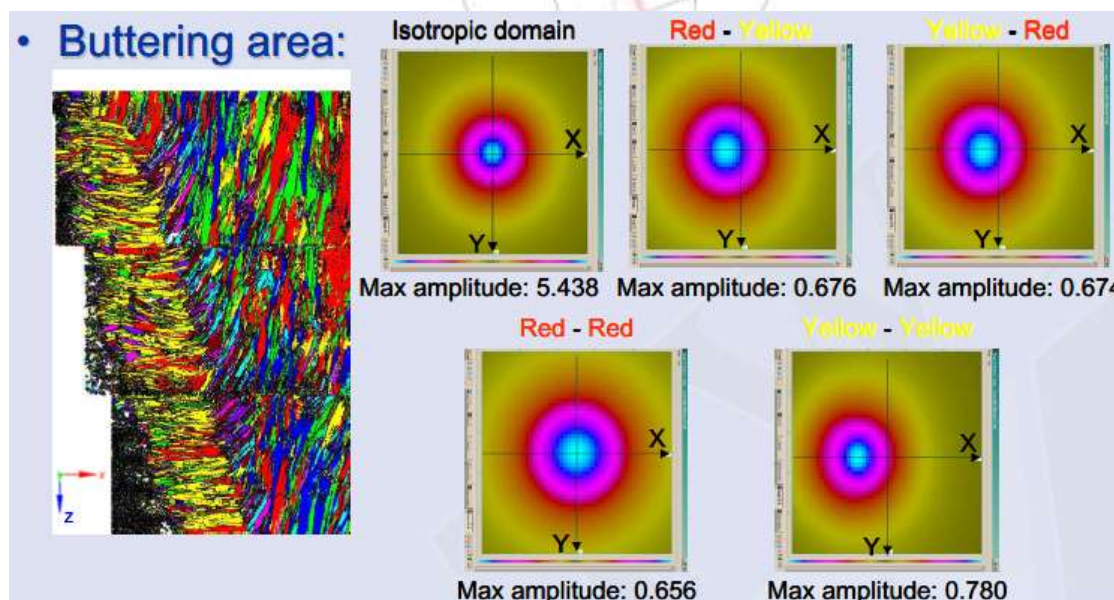


Figure 159 Study of the influence on the propagating sound beam due to changes in the two major orientations found in the buttering.

The key parameters are the cross beam width (ie changes in size) and changes in position with respect to the datum, which is the origin of the x-y plane. Red to red leads to the greatest increase in beam size and yellow to yellow leads to the greatest shift in position.

The beam travelling from red to yellow and from yellow to red lead to the same level of deflection and change in beam size. Compared to the reference isotropic scenario the change in amplitude in all cases is severe leading to a loss of about 18dB but remains similar in all cases involving the orientations.

Within the weld body itself orientations represented by lime green and blue are also largely present in addition to red and yellow. Figure 160 shows the orientation study (Test 1) in the body of the weld section 1. The losses in amplitude in comparison to the reference isotropic cases are similar to the buttering case, about 18dB.

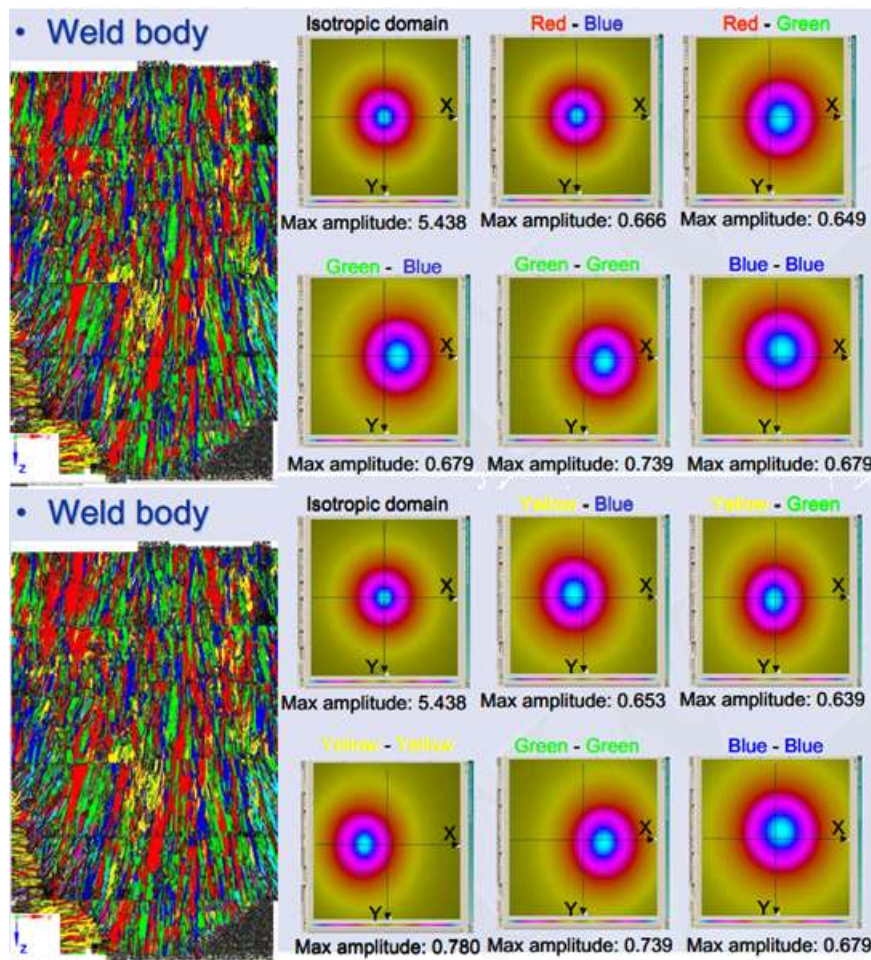


Figure 160 Study of the influence on the propagating sound beam due to changes in the two major orientations found in the weld.

Changes in amplitude compared to the isotropic cases for the different possible scenarios are presented in Figure 161. Similarly the changes to the beam on the x-y plane (termed misorientation) with respect to the isotropic case are presented in Figure 164.

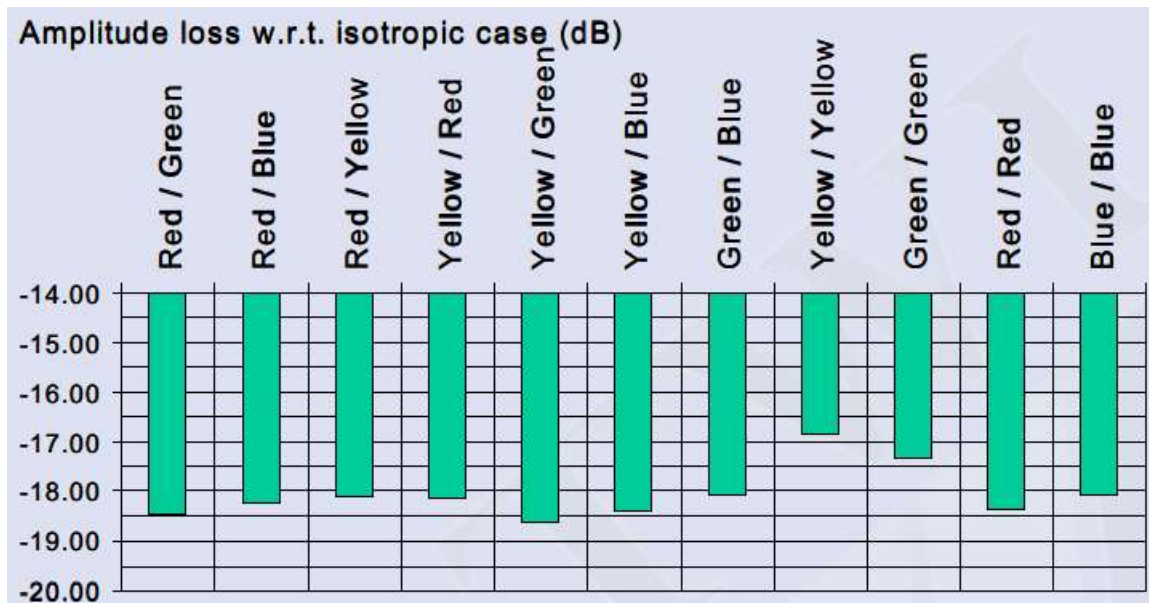


Figure 161 Summary of changes in amplitude in the different scenarios (Test 1).

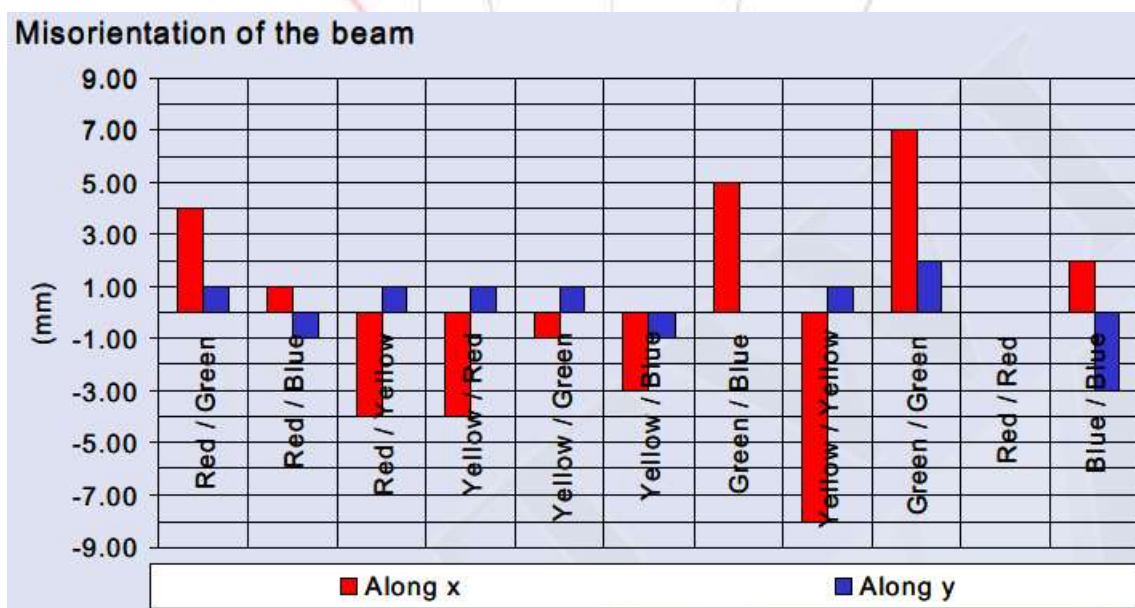


Figure 162 Summary of changes in the beam direction with respect to the isotropic case in the different scenarios (Test 1).

The Test 2 scenario using the red and green orientations is presented in Figure 163 for differing thicknesses of the sandwiched Domain 2 (see Figure 158). The results show that there is no significant change in the deflection of the beam or its size when the sandwiched region is less than 1mm, in comparison to the case where the sandwiched region is 1mm.

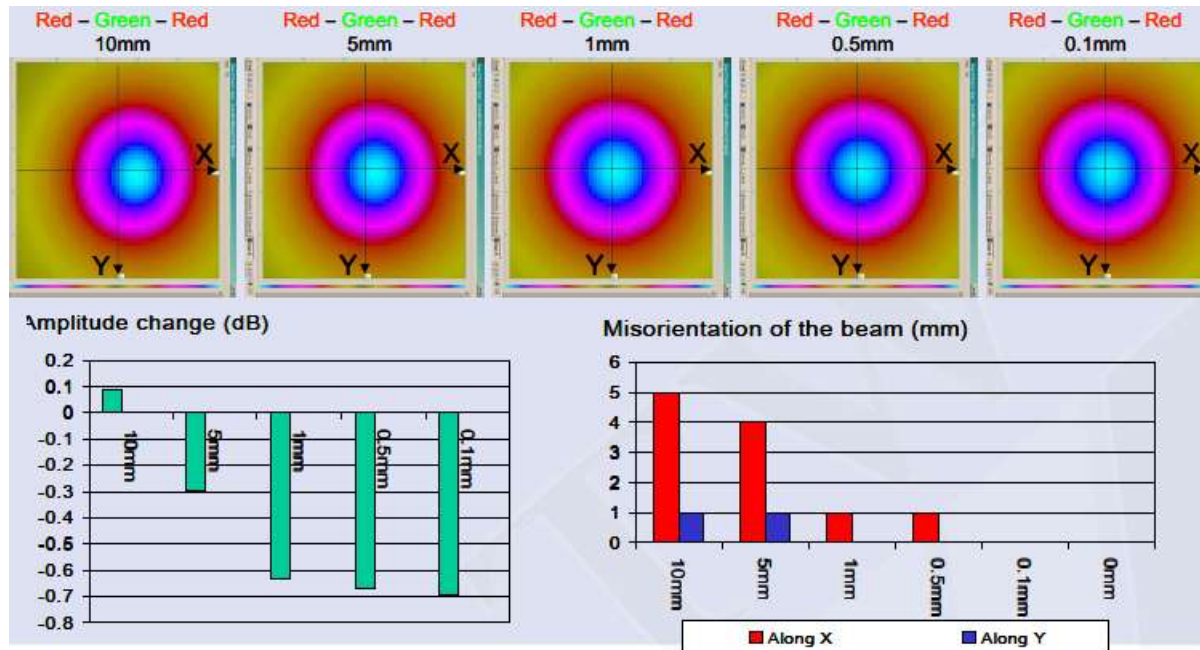


Figure 163 Study of the influence on the propagating sound beam due to changes in the thickness of a green region between sandwiched between red regions (Test 2).

A similar result was found in the case of a red region sandwiched between two yellow regions, as shown in Figure 164, where there is no significant change to the propagating beam when the region is less than 1mm, in comparison to the case when the sandwiched region is 1mm.

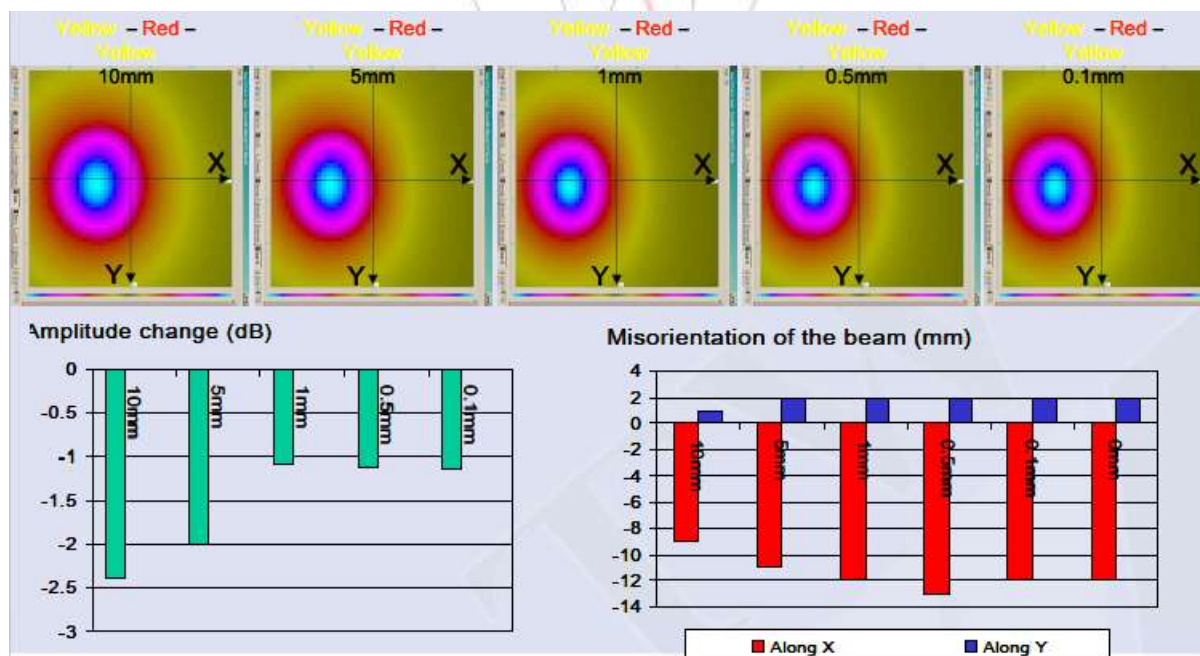


Figure 164 Study of the influence on the propagating sound beam due to changes in the thickness of a red region between sandwiched between yellow regions (Test 2).

The results of the limited study presented here shows that changes in amplitude are not significantly affected by the changes in domain; however note that CIVA does not take into account scattering losses (see Section 7.4). Since scattering losses are not calculated in CIVA, it could be possible to increase the minimum region size to 1mm as regions smaller than this do not seem to impact the propagation of the sound (Test 2). Hence smaller regions will be merged into the closest, largest and most similar region.

Parametric studies such as the examples presented here should lead to a greater understanding of the sound propagation in the inhomogeneous anisotropic medium, possibly leading to further processing methods to aid in reducing the modelling times while capturing the propagation characteristics sufficiently.

7.3.2 Experimental

The ADLs developed, as described in Section 7.3.1, were then used to scan the specimen and compare with scans using the conventionally calculated isotropic delay laws. Figure 165 shows the experimental setup with the probe described in the simulations sitting on the DISSIMILAR specimen and connecting (dashed red circle) to the British Energy X-Y scanning frame to implement automated scanning using MIPS. The collected data was then processed in GUIDE for presentation in this document.

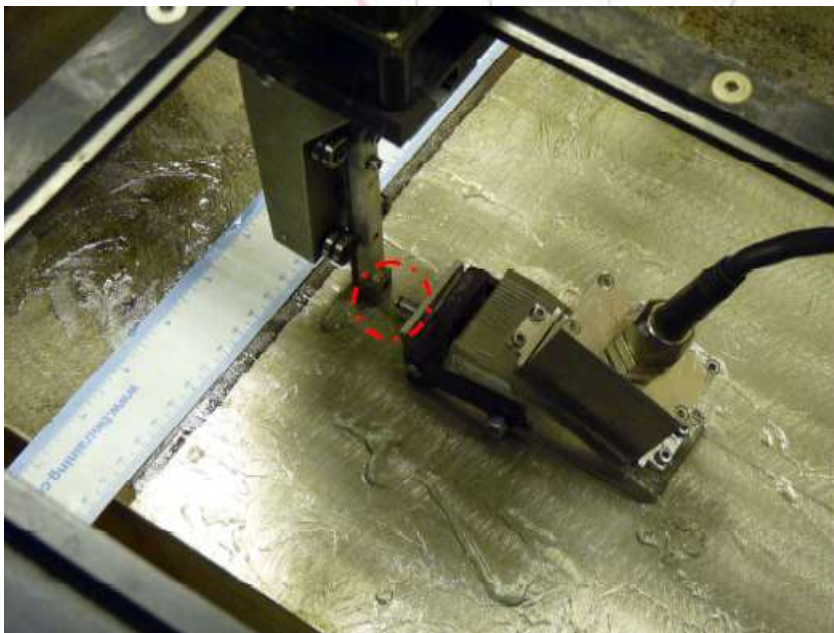


Figure 165 The 2MHz linear array probe being connected to the British Energy scanning frame to undertake experimental validation of the ADLs generated for Flaw 3.

Line scans were performed to recreate the simulated scans over Flaw 3 described in Section 7.3.1 using both the ADL generated using a SDH and isotropic delay laws. Figure 166 shows the experimental echo-dynamic over Flaw 3 due to the ADL and the calculated isotropic delay law. The peak value of the echo-dynamic using the ADL was about 1dB smaller than that using the isotropic delay law. However, the 6dB drop size provided by the ADL is closer to the size of the actual flaw in comparison to the size measured on the isotropic echo-dynamic.

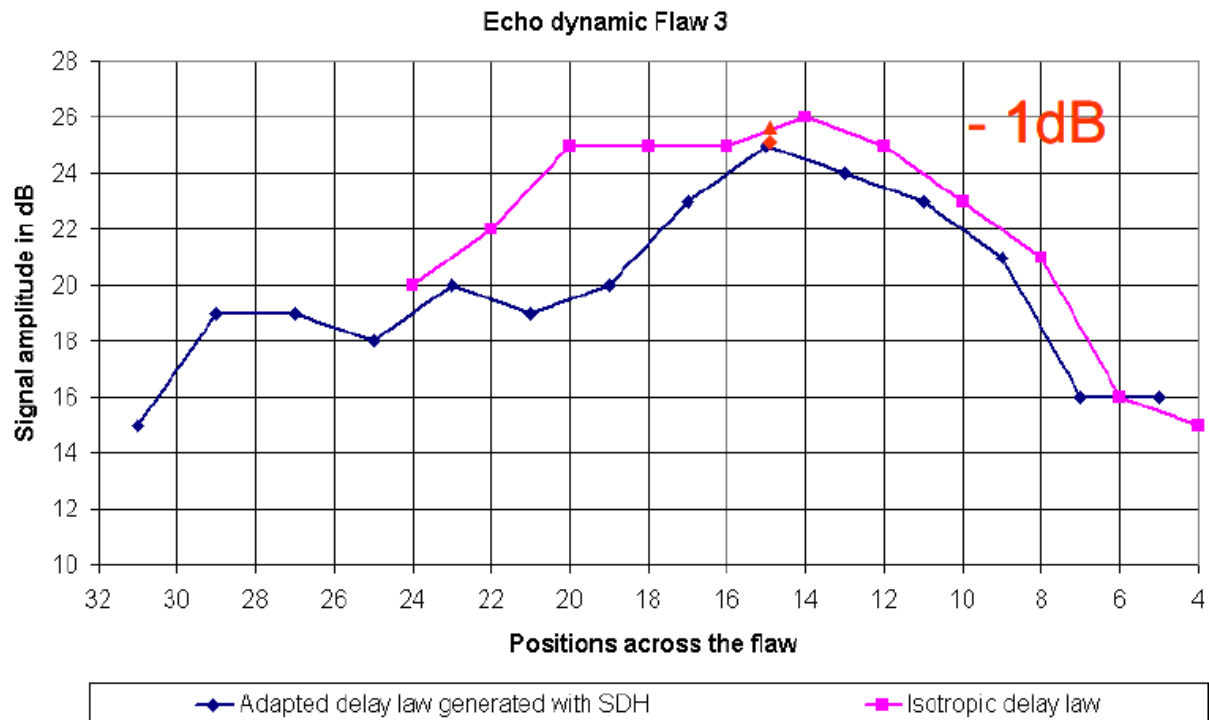


Figure 166 The experimental echo-dynamics over Flaw 3 using the adapted and isotropic delay laws.

There are several issues to address between the simulated weld and the actual weld:

- The actual stiffness coefficients of the particular alloy used in the weld was not evaluated using single crystals (see Section 7.4)
- The simulated weld was smaller due to loss in thickness due to cutting of coupons for EBSD scanning
- Lengthwise microstructure variations between the section used to generate the ADL and the actual weld region where the flaw is present

Experimental evidence (see Section 3.6) showed that microstructural variation along the length of the weld did not significantly affect amplitude or positioning of echoes generated by Flaw 1. However, simulated evidence (see Section 7.3.1) suggests that the ADLs being developed appear highly sensitive to changes in microstructure between EBSD mapped weld sections, and between domains of differing orientations and sizes. In effect, the results presented in Figure 166 suggest that no significant improvements in received amplitude could be achieved through the use of ADLs, contrary to the simulated evidence.

The ADLs generated in Section 7.3.1 at the different positions were then used to implement a position dependent inspection, ie at a given position the corresponding ADL was fired. To execute this inspection concept, the extended flaw file capability of GUIDE was utilised such that the actual position dependent inspection was implemented virtually during processing in GUIDE. Figure 167 shows the positions of the simulated inspection which was recreated experimentally. Assuming the sound beams travel in a straight line (which is inherent within the GUIDE processing system), the echo received from the ADL at its corresponding inspection position is stitched together next to the other positions within GUIDE

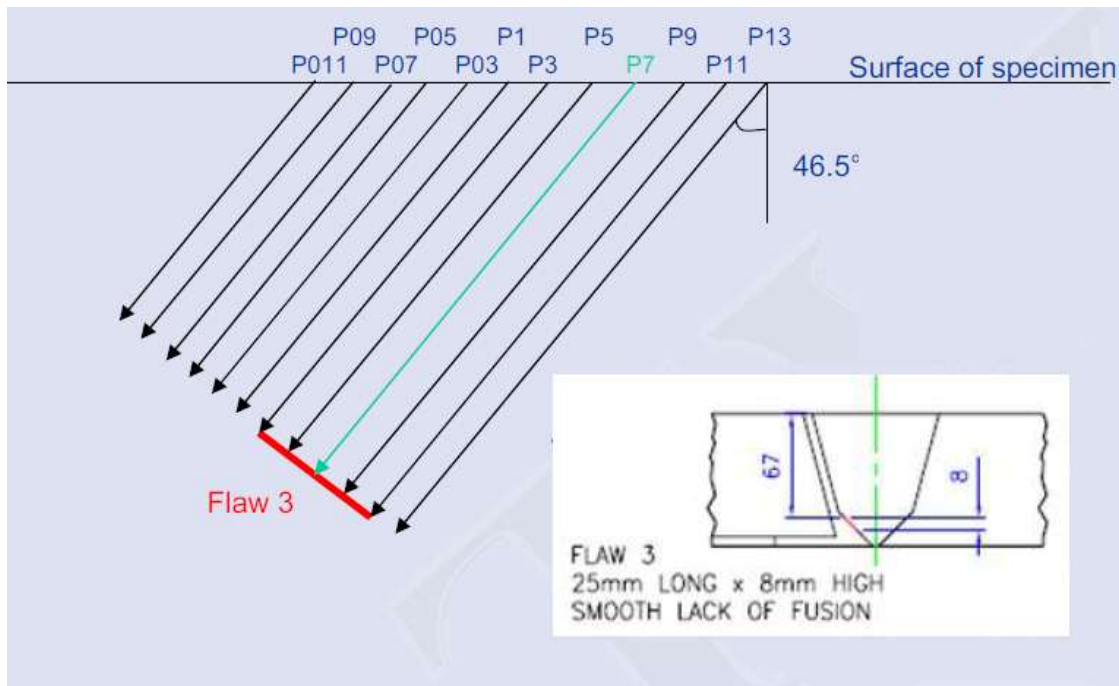


Figure 167 The positions over Flaw 3 where ADLs were generated and which are then used to implement a position dependent inspection virtually within GUIDE.

Data is collected over all the positions in Figure 167 using all the ADLs and the results of the scans are shown in Figures 168 and 168.

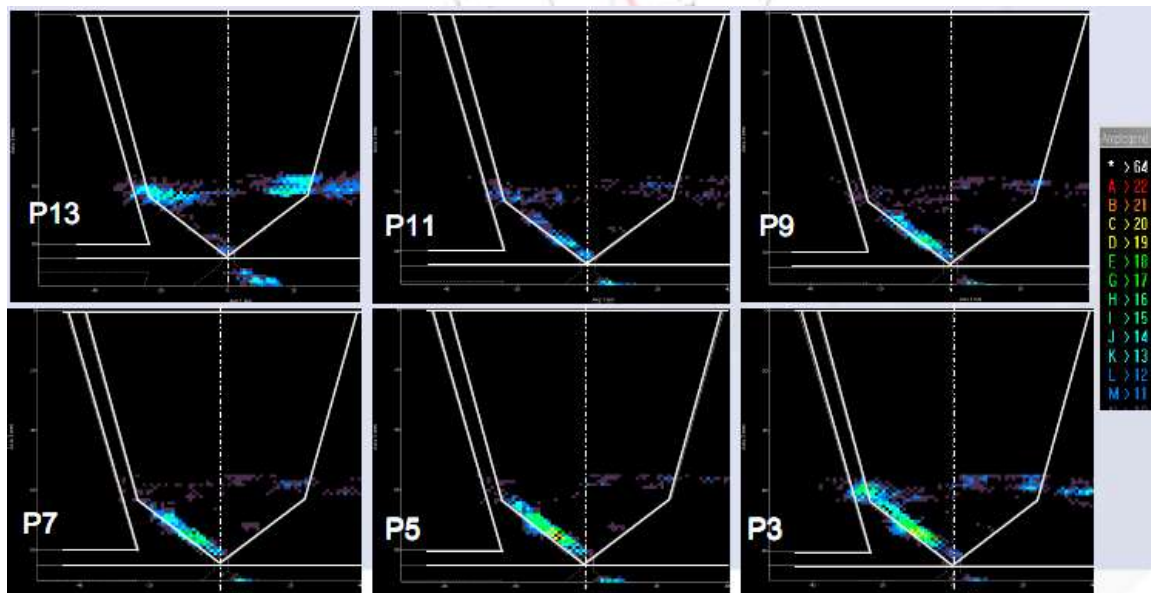


Figure 168 Results of scans over Flaw 3 using ADLs generated for positions P13, P11, P9, P7, P5 and P3.

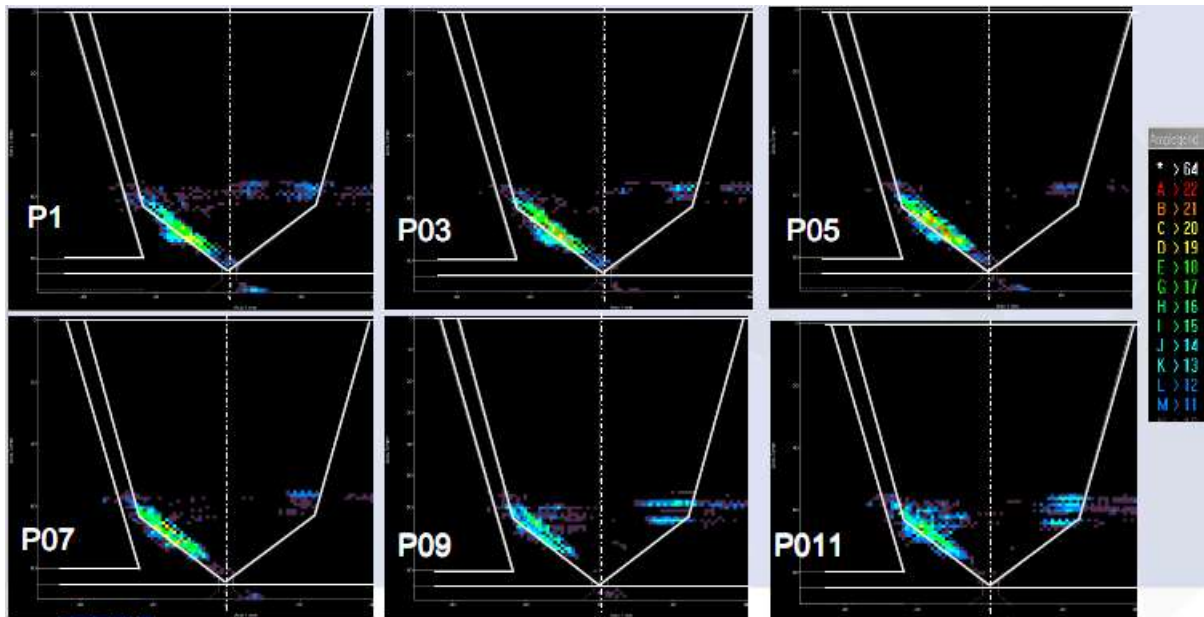


Figure 169 Results of scans over Flaw 3 using ADLs generated for positions P1, P03, P05, P07, P09 and P11.

The scans using each of the ADLs have variable performance, some better than others in detecting the flaw with good S/N and received echo amplitudes; ADLs generated at positions P13 and P11 were particularly poor in detecting the flaw.

Figure 170 describes the process of executing a position dependent scan using the data shown in Figures 168 and 169 within GUIDE.

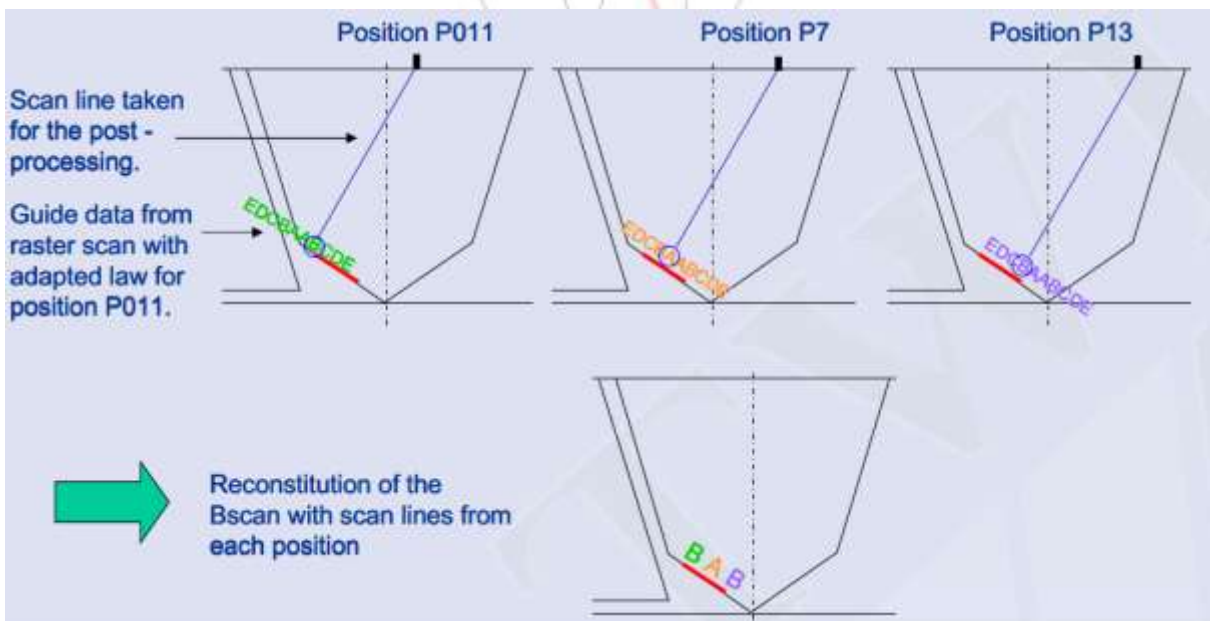


Figure 170 Executing a position dependent scan virtually using a group of MIPS scan data, selecting the relevant data and stitching the scan image back together.

Figure 171 shows the data from scanning using the isotropic delay law and Figure 172 shows the results from the position dependent scan using all the ADLs generated using Flaw 3 (see Section 7.3.1).

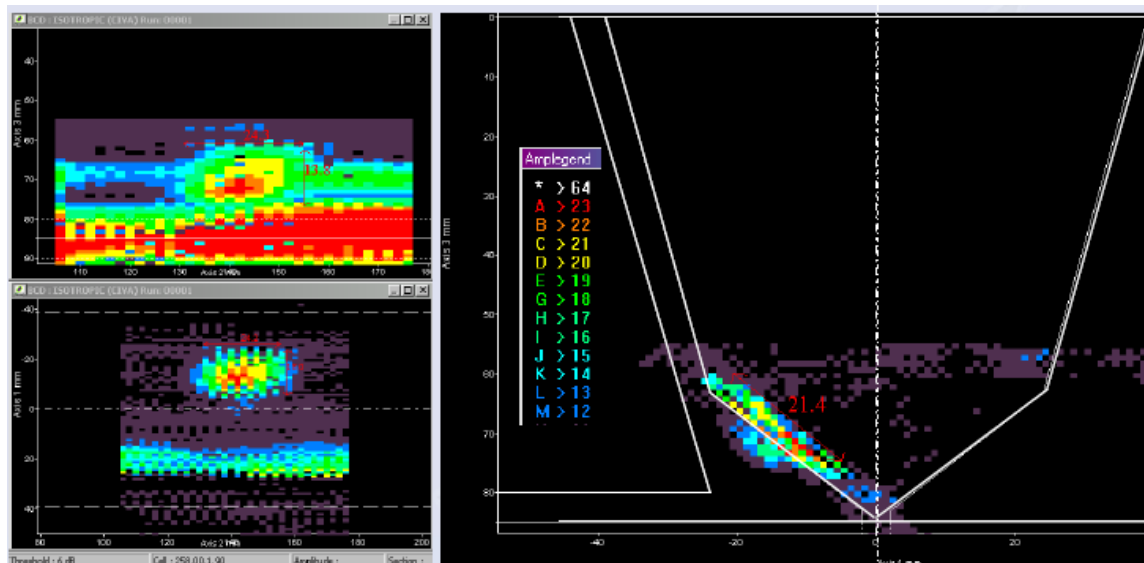


Figure 171 The scan over Flaw 3 using the calculated isotropic delay law.

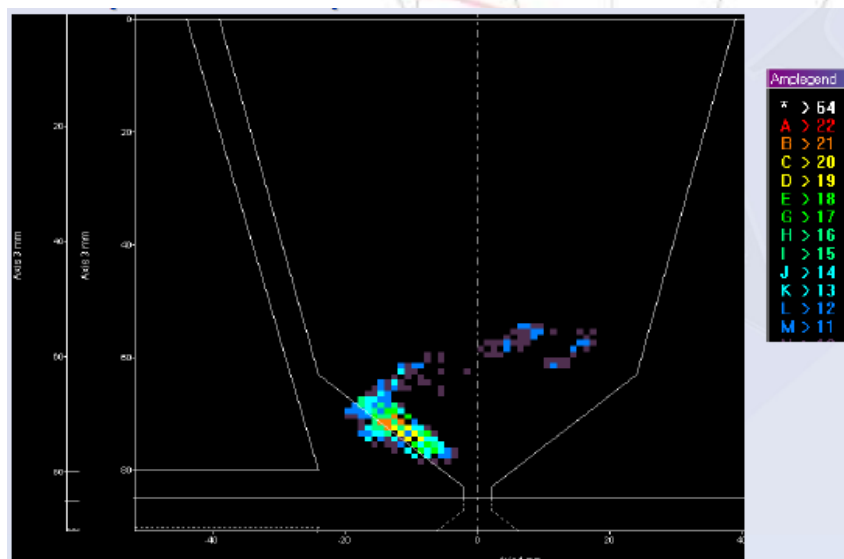


Figure 172 The scan over Flaw 3 using the generated ADLs using Flaw 3.

The experimental validation results again show that the use of the ADL does not lead to a significant increase in sensitivity to the flaw as suggested by simulation results (see Section 7.3.1). Hence in summary, the evidence generated in the DISSIMILAR project suggests that the concept of generating ADLs using simulations is viable, in that it gives similar performance to conventional phased array techniques, but the use of ADLs does not appear to increase the sensitivity of the inspection to flaws which lie specular to the incident beam. The time and budget only allowed for a limited study and further investigations on other flaws in different orientations and different parts of the weld should be undertaken in future efforts.

A study was conducted to generate ADLs experimentally, ie without using models and simulations. The probe developed in a previous project and described in Appendix A was used along with a British Energy reference block in immersion. Figure 173 shows the reference block containing the SDH target which was used as the target to generate an ADL and the probe which is a TRL type of 2.5MHz with 16 x 4 elements on each lobe with a pitch of 2mm x 3mm, respectively, including a wedge angle of 13° built into the housing.

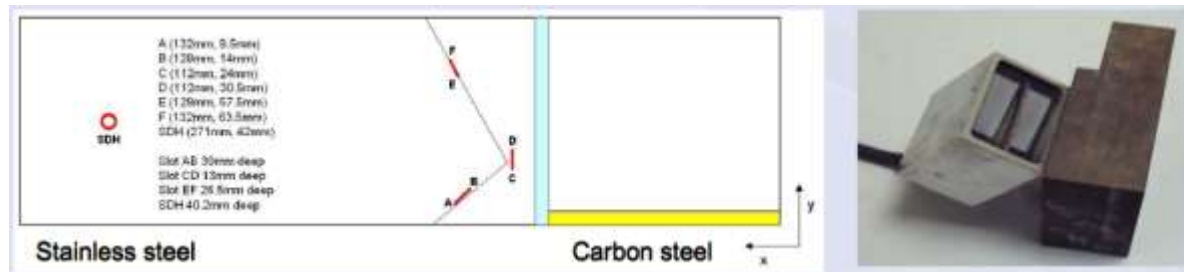


Figure 173 The reference block and TRL probe used for experimental generation of ADLs.

The method was to fire on an element in the transmit lobe of the probe and listen to the echoes on a different element in the receive lobe of the probe. Figure 174 shows the A-scans recorded on a selection of transmit-receive pairs; the probe was placed on the stainless steel side targeting the SDH – ie the sound did not penetrate the weld.

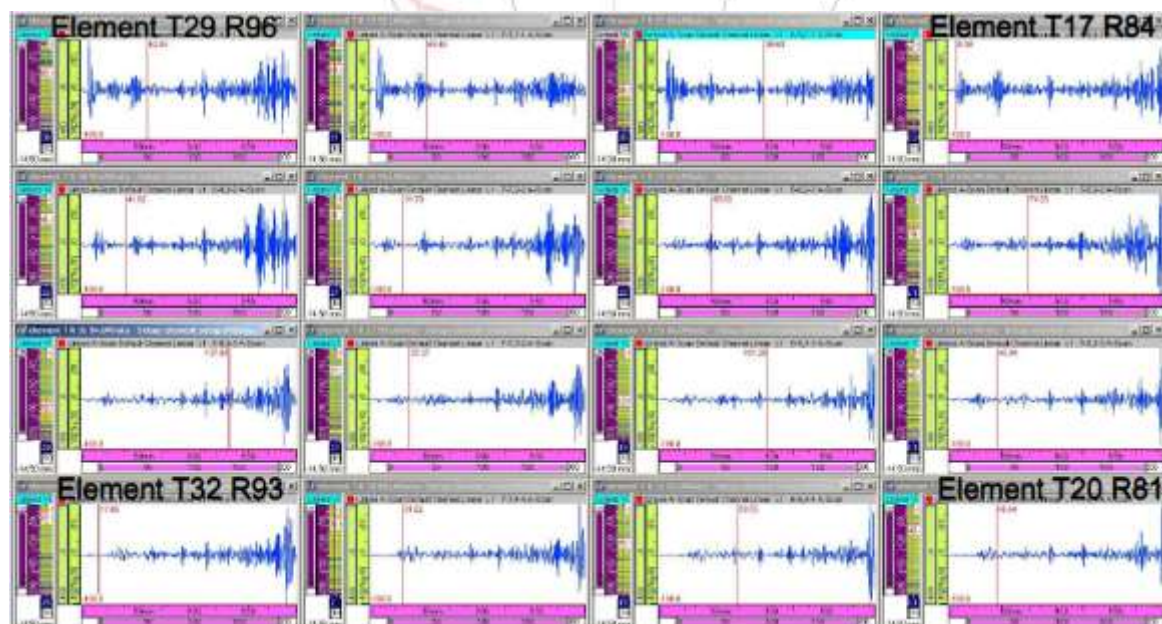


Figure 174 A-scans recorded for a selection of transmit-receive pairs.

Identifying the echo from the SDH proved to be difficult even in the relatively clean material of the reference block. The expected position of the echo due to the SDH was calculated but the S/N quality of the signals was judged to be poor. The quality of the signals, in particular at the relatively high frequency of 2.5MHz, when the probe was used to detect slot EF (see Figure 173) through the weld was severely degraded. Hence the ADLs could not be generated; however further investigation of experimental methods similar to the limited study presented here warrant further investigation (see Section 10.2).

7.4 Model validation

The CIVA model was used as the primary platform for the simulation of inspections and generation of the ADLs (see Sections 6.2 and 7.3.1). Its use in isotropic media for use as conceived in the DISSIMILAR inspections has been validated by TWI [20, 21] and elsewhere. The key aspect of the model, its treatment of sound propagation in inhomogeneous anisotropic media, has not yet been fully validated. The intention was to validate the model using a specially grown single crystal made of the alloy used in the DISSIMILAR specimen weld. However, the attempt at growing the single crystal was not successful and hence an alternative method using the weld itself was explored.

In a single crystal of an alloy the unit cubic crystal is aligned in a specific direction. Hence the elastic properties of the macro single crystal specimen are a function of the unit cubic crystal. Importantly for validation, the single crystal specimen can then be introduced into the model as a homogenous medium which takes the cubic stiffness constants of the unit cubic crystal. Then the simulated propagation of sound (measuring amplitudes and spatial field characteristics) can be verified against experiments identically recreating the simulations.

Methods of growing single crystals have been developed recently for fabricating single crystal turbine blades for their superior mechanical properties. The Bridgman growth process (see Figure 175) involves generating a wax model which is used to create an investment shell to create a mould. The molten metal is then introduced into the mould at temperatures of around 1500°. The crystal is then grown slowly as the liquid-to-metal interface is slowly moved. The grains grow along the $\langle 001 \rangle$ crystallographic direction since the unit cube is FCC.

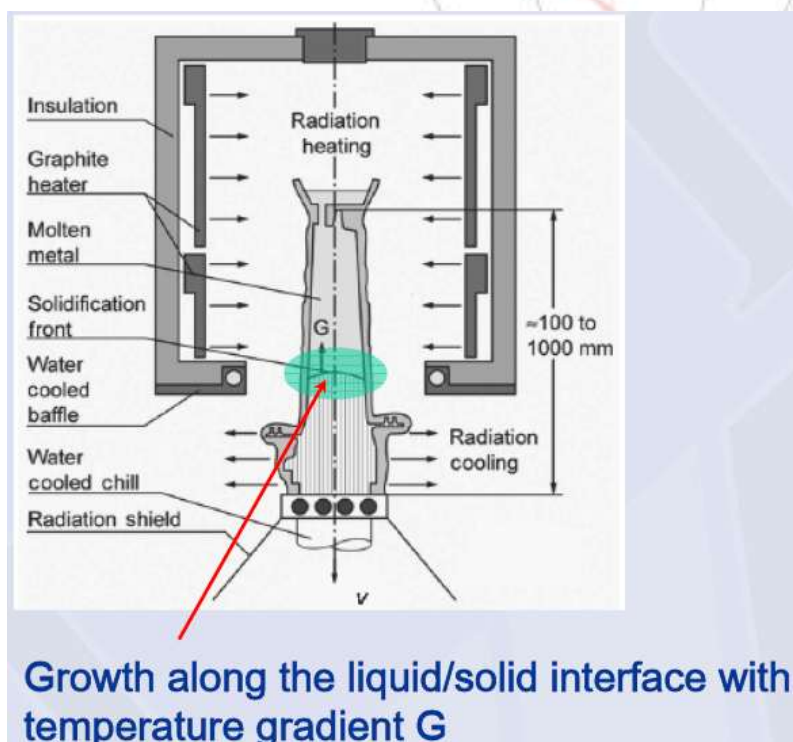


Figure 175 The Bridgman single growth process for a single crystal turbine blade (image courtesy of Rzeszow University of Technology, Poland).

Figure 176 shows the cylindrical rod of diameter 20mm and length of 70mm which was grown using TIG consumable rods of the Inconel alloy used as the DISSIMILAR specimen weld filler. Analysis in SEM showed that the growth was now successful and differential boundaries had been introduced (see Figure 177). It was deemed that the specimen would not be used for the validation or for evaluating elastic stiffness constants (see Section 3.7)



Figure 176 The Inconel alloy single crystal cylinder (20mm diameter, 70mm length) grown for the validation of the model in the DISSIMILAR project.

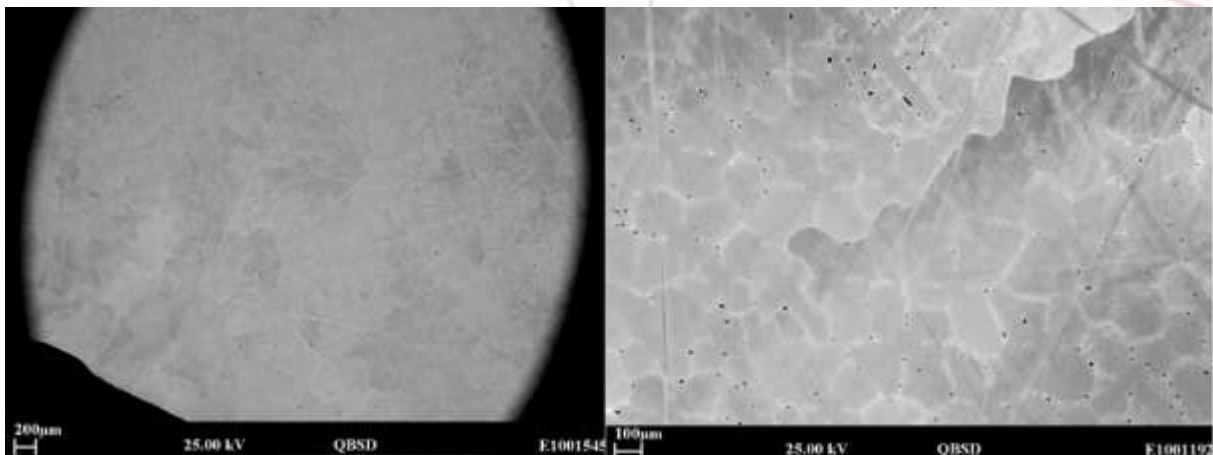


Figure 177 The SEM scan of the single crystal rod on the root side (left) and possible boundaries within the specimen (right).

An alternative method was then explored using a coupon from the reference weld block extracted from the DISSIMILAR specimen. Figure 178 shows the extraction of the coupon into which five 3mm SDHs were introduced. The dimensions and target SDHs were similar to a standard carbon steel reference block shown in Figure 179. Both the weld coupon (hereafter termed the validation block) and the carbon block were then scanned using a 12.5mm diameter 3.5MHz immersion probe in a scanning tank; the concept is described in Figure 180.

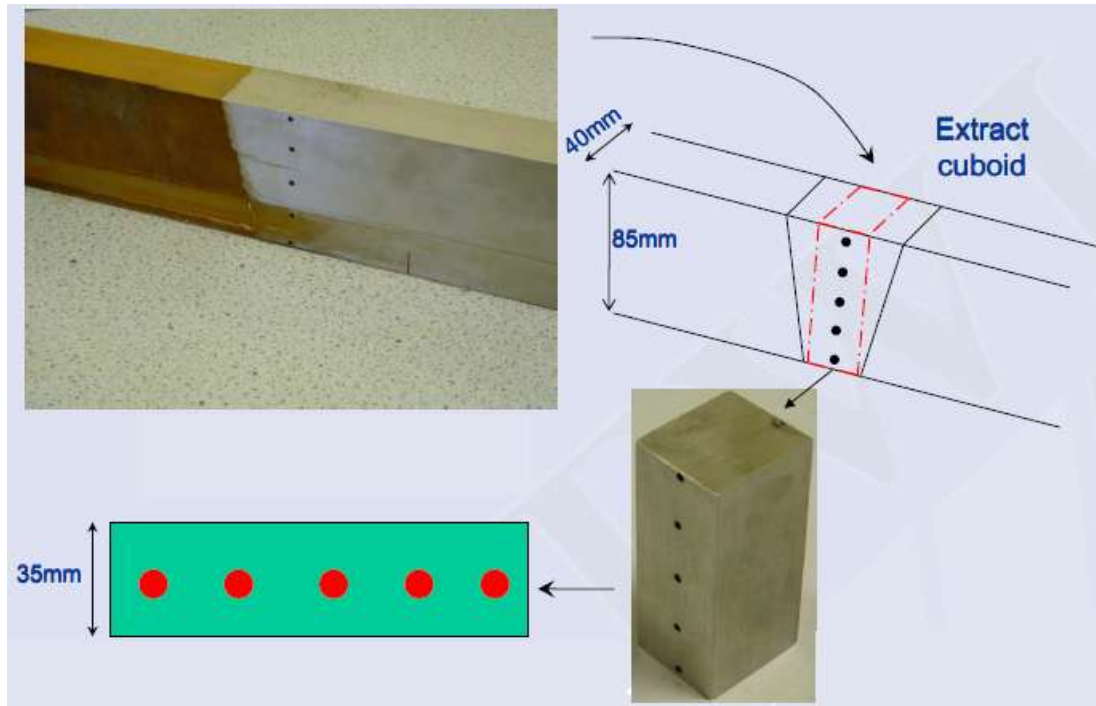


Figure 178 Extraction of a coupon from within the weld towards validation of the model.



Figure 179 The reference carbon steel calibration block containing target SDHs and dimensions similar to the coupon extracted from the weld (see Figure 175).

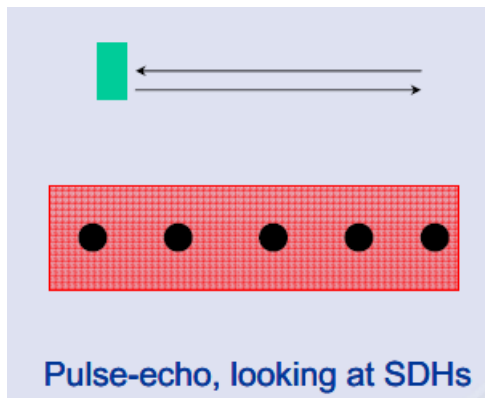


Figure 180 The validation block and the carbon block are raster scanned in an immersion tank using identical probe (green block above) and standoff distances; the system gain value is selected to be able to set the back wall signal to near 80% FSH.

The scan of the carbon block is shown in Figure 181 and the scan of the validation block is shown in Figure 182.

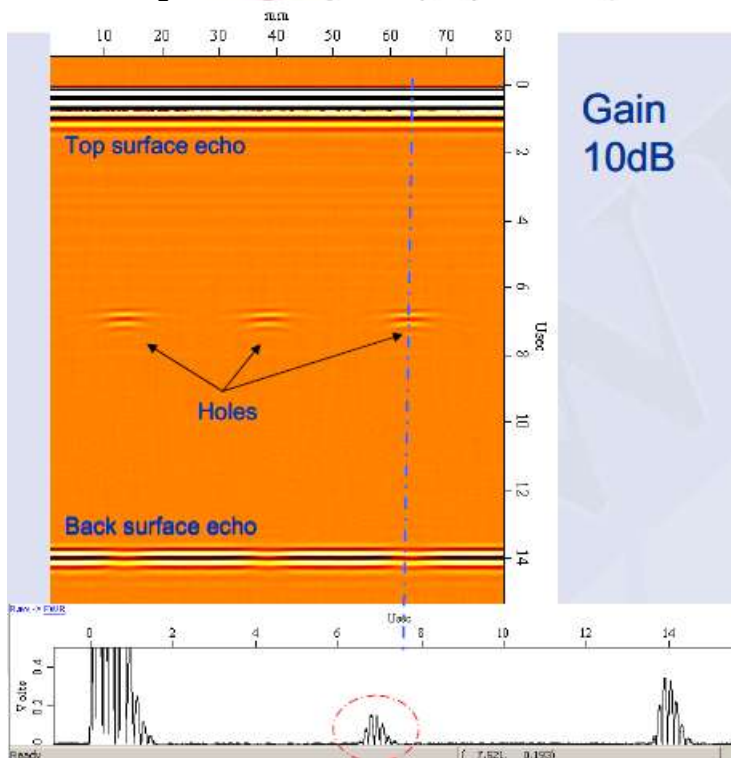


Figure 181 A scan of the carbon steel block showing three SDHs with equal echo amplitudes, equidistant from each other at the same depth from the top surface, consistent with the actual physical positions shown in Figure 176. The A-scan data is along the dotted blue line through one of the target SDHs.

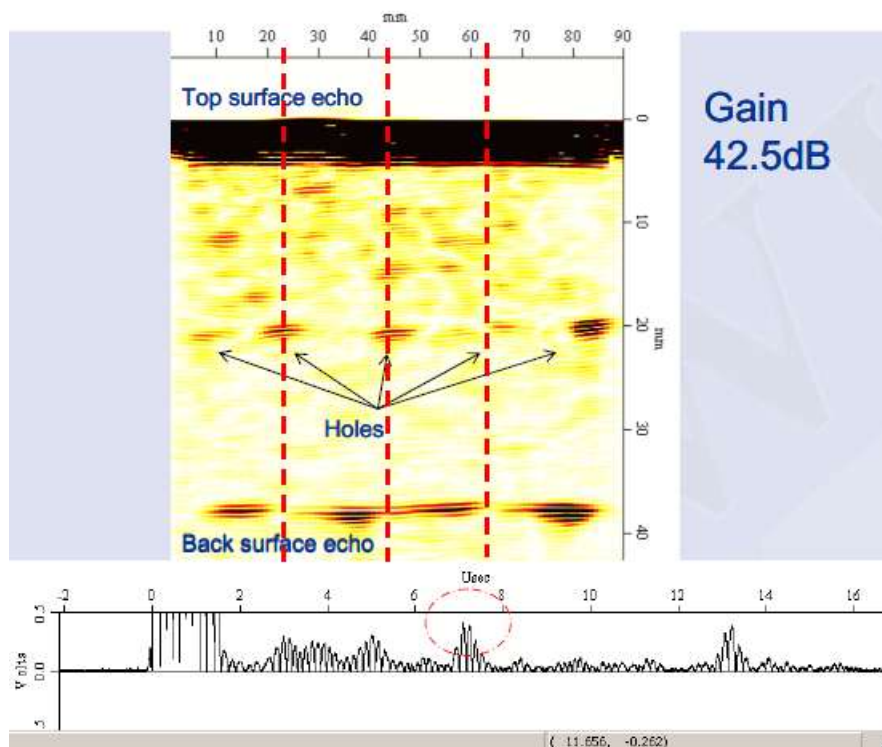


Figure 182 A scan of the validation block showing the effects of sound field distortion with unequal amplitudes from the targets, errors in positioning, increased attenuation (note the increase in gain required to put the back wall signal to 80% FSH) and much reduced S/N performance. The dotted red lines indicate positions of the target SDHs and the A-scan data is along the leftmost line.

The aim of the validation effort is to check the results from the simulation predictions against the data presented in Figures 181 and 182. The scan performed in the tank was then simulated using CIVA and the carbon steel block and the results are shown in Figure 183. The result of the simulation is consistent with the experimental data given in Figure 183: equal amplitudes from the target SDHs and the positioning of the echoes are consistent.

The corresponding simulation using the validation block is presented in Figure 184 where the weld microstructure is introduced as the weld medium from the two EBSD mapped weld sections. The echoes returned from the target SDHs are no longer coherent and appear to be subject to the type of distortion presented in Figure 182. Hence qualitatively, the model appears to be simulating the effects observed in reality. To undertake the validation of the model, the returned echoes in the simulation must be compared to the experimental echoes generated in the actual validation block; however, the actual microstructure of the experimental validation block is different (by an unknown degree) to the simulated microstructure. This gives rise to an error or inaccuracy between the simulated and experimental cases, and furthermore this error is difficult to quantify.

Figure 185 shows, for the two weld sections, the simulated signals returned from a SDH target in the carbon steel block (same signal was received from all three) and the signals from the three SDHs in the validation block along the dotted red lines shown in Figure 182 are plotted at the bottom. The relative difference in signal strength between the SDHs in the carbon steel and the validation block is $(42.5-10)\text{dB} + 13\text{dB} = 45.5\text{dB}$.

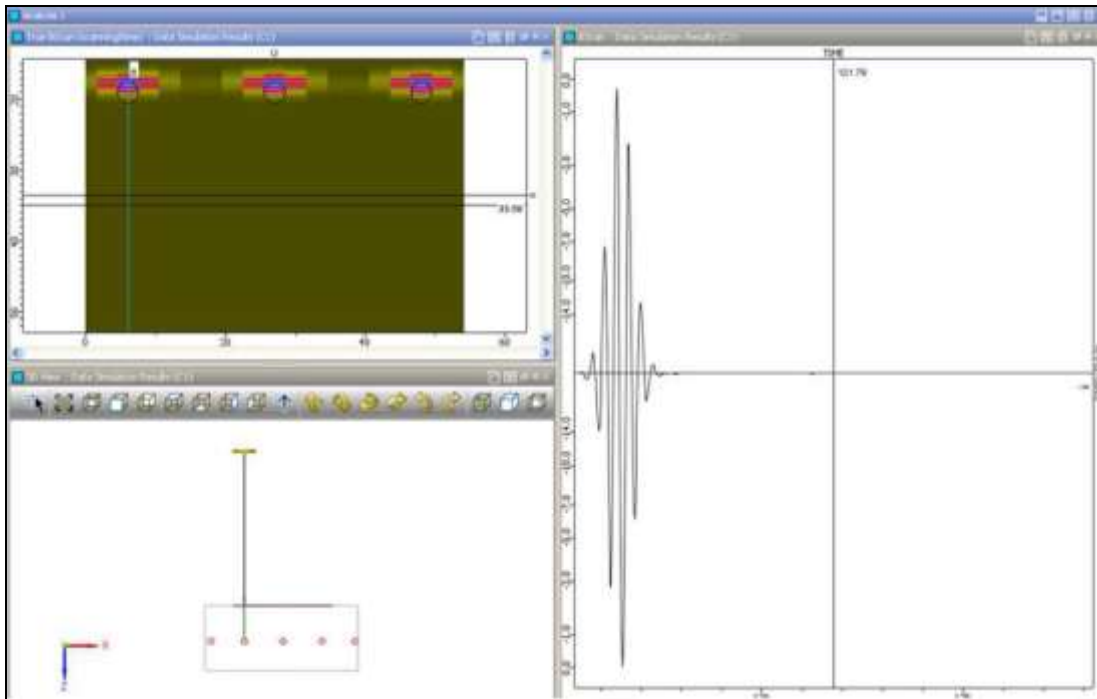


Figure 183 Simulation result of the immersion inspection of the carbon steel block.

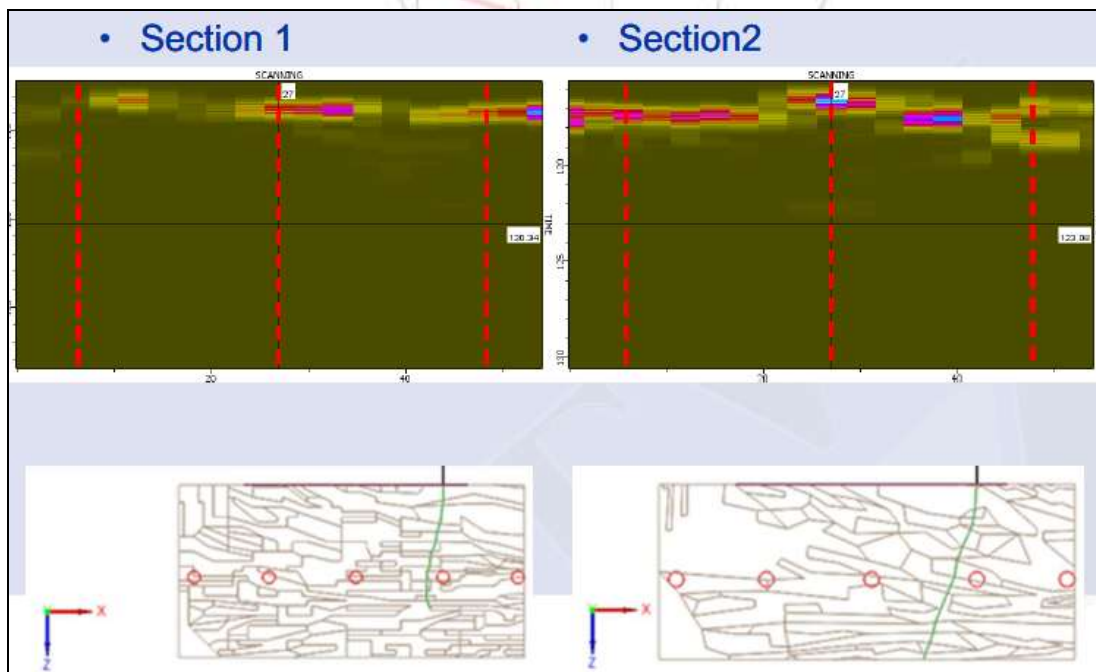


Figure 184 Simulation result of the immersion inspection of the validation block. The dotted red lines show the position of the three middle SDHs and the images below show the microstructural maps of the two sections input into the model to simulate the validation block.



Figure 185 Simulated signals from the SDHs in the carbon steel (top) and the validation block (bottom) for the two different weld sections.

To complete the validation, the simulated signals shown in Figure 185 must be compared to the A-scan data shown in Figure 182. However, note the absence of the grain scattered echoes evident in Figure 182 but not in the simulated signals of Figure 185. This is because the CIVA model is known to not take into account attenuation due to scattering (hence the absence of noise and only signals due to introduced targets). There will therefore be a large discrepancy between the predicted amplitude levels and the actual attenuation as scattering is the single largest attenuation mechanism in coarse grained materials [2]. Hence validation of the CIVA model using amplitudes of received signals is not relevant.

In terms of the times-of-flight to targets predicted by the model there is good agreement between the results of the simulations and the experimental data using the validation block; the discrepancies measured in time which are less than errors in positional differences between reality and the simulations (<1mm). The result also explains the remarkable similarity in amplitudes and profile shapes between the calculated delay laws and the simulation generated ADLs, as shown in Figures 154 and 166. The evidence suggests that the use of the CIVA model is suitable for the generation of the ADLs which is dependent only on accurately simulating the times-of-flight. However it would not be suitable for use in predicting signal amplitudes and hence studies for setting sensitivities during inspections in such inhomogeneous coarse grained materials.

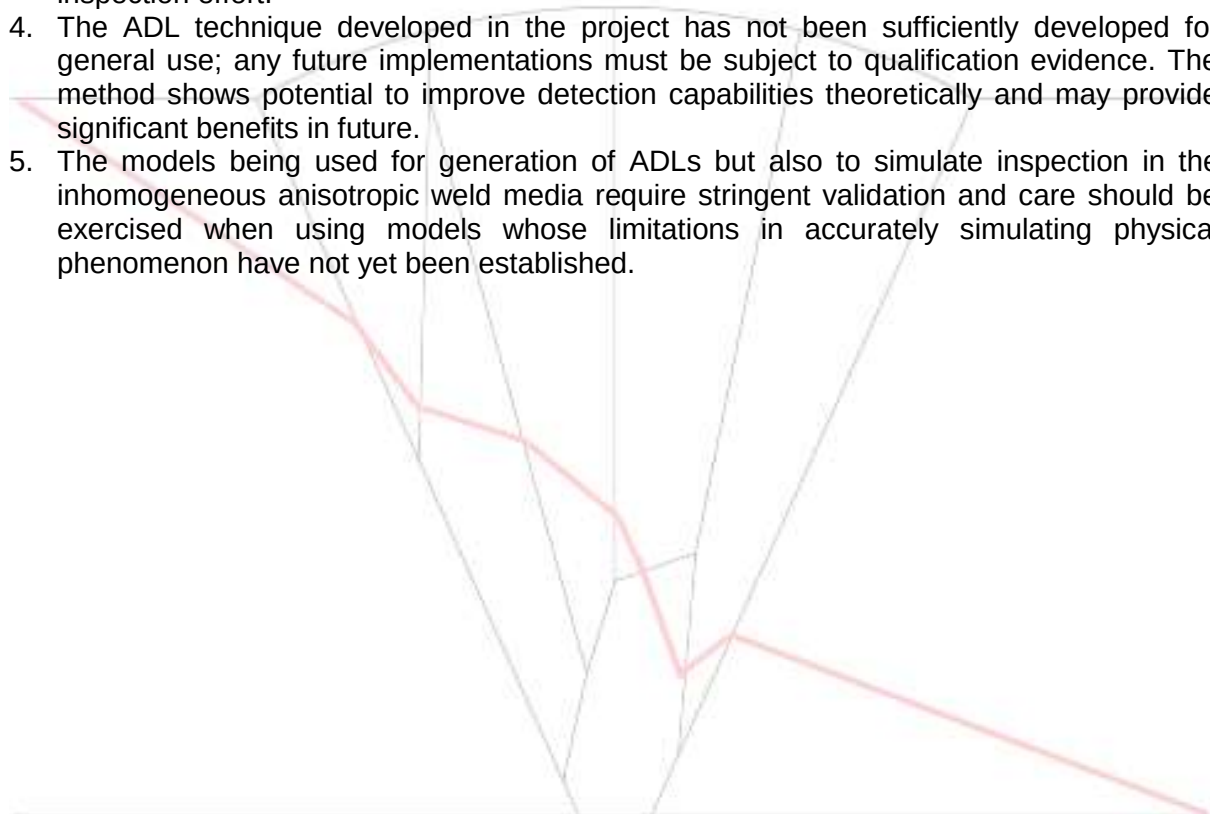
At the commencement of the project the CIVA model was chosen as the primary simulation platform because of the ease with which inspection concepts can be realised within its dedicated framework. However finite element models were also investigated and a discussion of their capabilities is presented in Section 10.3 and demonstration of their ability to generate ADLs as wells as being able to simulate grain scattering effects.

8 Conclusions

1. The performance of the phased array techniques in detection, positioning and sizing was not appreciably better than conventional ultrasonic techniques.
2. The signal-to-noise performance of the transmit-receive longitudinal (TRL) technique was substantially better than that of the other techniques.
3. The ability to skew the beam allows for better determination of the three dimensional (3D) orientation of a flaw; the use of a two dimensional (2D) array allows a range of skewed beams to be generated at increments smaller than 1° enabling the measurement of defect tilt and/or skew (ie 3D orientation). The same precision would require multiple conventional probes generating each skewed beam individually, leading to greater costs.
4. The primary justifications for using phased array techniques include:
 - Versatility; one probe can generate a range of beams and hence perform the function of numerous conventional probes that are each able to generate only a single beam.
 - Inspection time; phased array techniques reduce the total time for inspection and hence reduce the overall costs through increasing operating revenue.
 - Dosage; reducing the inspection times also leads to a reduction in the time personnel will be exposed to radiation, presenting a strong safety case for the use of phased array technology in radioactive environments.
 - Debris; the likelihood of introducing debris into the containment area is reduced as phased array systems (through their versatility) can be designed to be less complicated to deploy mechanically.
 - Digital data archiving; data can be digitally stored for future analysis and reference.
5. The impact of the microstructure, in particular its variation along the welding direction, will dictate whether the modelling route to generating ADLs can be implemented cost effectively. In reality, it is unlikely that the entire weld volume can be quantified accurately and cost effectively; additionally, the weld used for quantification would not be the same as that inspected (assuming the quantification process is destructive). Hence there will be a degree of variation between the weld being modelled and the actual one being inspected. If the degree of difference is too large then the ADLs generated will not be applicable for inspection.
6. The EBSD technique was successfully used to map a cross section of the dissimilar weld, identifying different areas (such as buttering and cladding) and, through the use of a processing method developed in the project termed orientation unification, allowed the weld to be quantified in the ultrasonic model.
7. The limited work done in the project shows no appreciable benefit, in terms of detection and sizing of flaws, in using the ADL technique. The increases in received signal amplitude predicted theoretically could not be verified experimentally; reasons for this may include not being able to sufficiently capture the actual microstructural condition (see 6 above) and/or inaccuracies in the ultrasonic model (which has not been fully validated for this application).
8. The evidence based on the validation block shows good qualitative correlation between prediction and experimental data in the sound distortion in the coarse grained weld material. However, the CIVA model used for generating the ADLs was not fully validated as the single crystal specimen intended for this purpose was not successfully grown.

9 Recommendations

1. To achieve effective inspection of coarse grained, inhomogeneous and anisotropic material, the signal-to-noise performance of the ultrasonic system must be optimised. Hence techniques making use of transmit-receive longitudinal probes are recommended.
2. Two dimensional array probes are recommended for determining the three dimensional orientations of flaws.
3. The use of validated modelling tools to explore the capability of the phased array techniques being developed is highly recommended, as models offer a cost effective route for designing, checking and eliminating potentially costly shortcomings in the inspection effort.
4. The ADL technique developed in the project has not been sufficiently developed for general use; any future implementations must be subject to qualification evidence. The method shows potential to improve detection capabilities theoretically and may provide significant benefits in future.
5. The models being used for generation of ADLs but also to simulate inspection in the inhomogeneous anisotropic weld media require stringent validation and care should be exercised when using models whose limitations in accurately simulating physical phenomenon have not yet been established.



10 Future directions

The work done in the DISSIMILAR project was aimed at the evaluation of the current state-of-the-art with regard to the tools available for the inspection of the particular case of coarse-grained inhomogeneous and anisotropic austenitic welds. The following three aspects were identified as areas under development which may provide a way forward in the near future and improve present ultrasonic inspection capabilities for this special class of fusion joints.

10.1 Array probe capabilities

During the course of the project several aspects of probe manufacture were identified as critical to fabricating probes with the characteristics identified in Section 4.2. The goal is to increase the bandwidth of the signal to above 80% of the centre frequency, which requires mastering manufacturing processes such as lapping, electroding methods, matching layer thicknesses and selecting material with the right characteristics for damping. These aspects are commercially sensitive and will not be discussed further in this document.

Another important aspect of probe technology is enhancing the capabilities offered by different array configurations. Annular array configurations offer the possibility to focus the sound energy to smaller volume, leading to smaller beam sizes. This offers the possibility to increase the S/N performance and also improve the sizing capability of techniques. Figure 186 shows three annular arrays (one pure annular with rings only and two with segmented rings) whose sound field characteristics were studied through simulations.

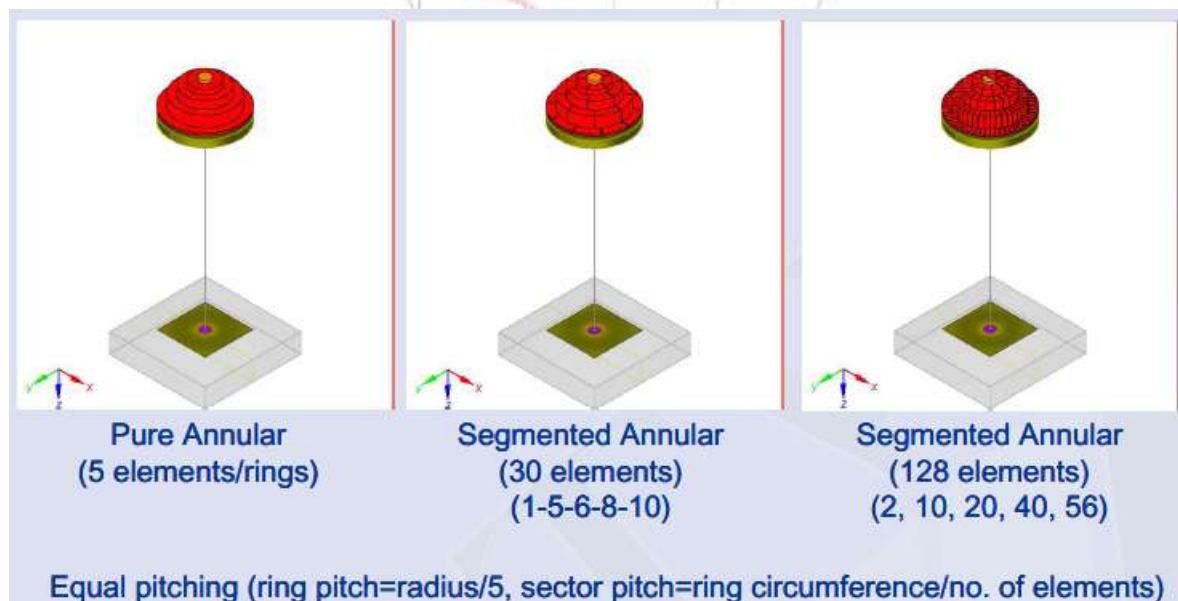


Figure 186 Annular arrays investigated for sound field characteristics.

All the arrays were of 2MHz frequency and were used to focus at 100mm depth from the probe face (the beam widths were measured at a distance of 94mm from probe face). The diameter of all the arrays was 30mm with a near field range of 437mm implying the focusing was to a factor of 0.23. The beams were steered to 0, 0.6, 1.7, 2.9, 5.7 and 8.5° and the 6dB beam width was then measured, as shown in Figure 187.

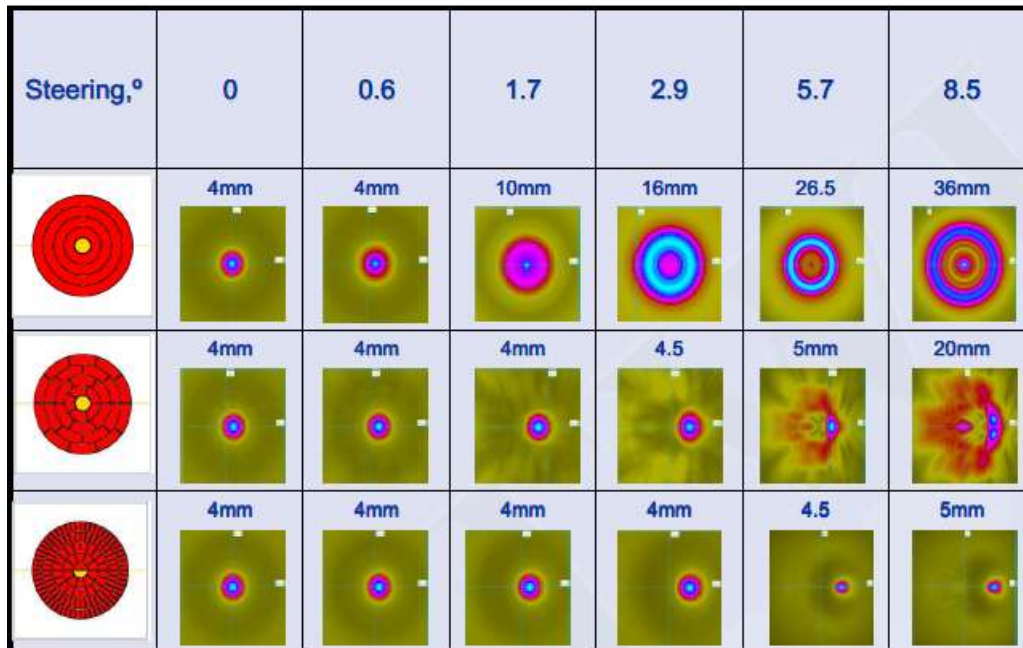


Figure 187 Simulated sound fields when the beam is steered up to 8.5° using the three different annular array configurations.

The results show that with a 128 element segmented annular array very tight beam spots can be maintained at high steering angles whereas the sound field integrity fails at lower steering angles when using both the low element count segmented annular array and the pure annular array. This array configuration should be investigated in future for application to the inspection of dissimilar / austenitic welds.

Another potential array configuration (introduced in Section 4.6) which shows potential for greater manipulation of the 3D sound field is based on aperiodic fractal designs [22]. Fractal designs offer the possibility to achieve similar performances to 'conventional' configurations but with a much lower element count. Such sparse arrays, based on fractal shapes, have been shown to offer remarkable focusing and steering performance. Figure 188 shows two sparse array designs with a total number of elements less than 128 but over a large area and Figure 189 shows inspection data from a prototype spiral array design probe.

Further concepts which should be investigated in the future include:

1. Hard wired 1.5D array configuration: When the beams are required to be steered in only one plane, then a fully 2D array configuration could be replaced by a 1.5D concept where the symmetry between the left and right halves can be electronically expressed by physically connecting them to the same wires, as described in Figure 190. This exploits the fact that the delay laws on either side of the line of symmetry are identical and is ideally suited when the secondary axis is used for focusing.
2. Two way transmission using TRLs: In the TRL technique explored in the project the sound was transmitted from one half of the TRL probe and received on the other. The sound travels through a scattering medium but reciprocity may not be maintained. Hence if the travel path of the sound is reversed, then the grain structure may affect the propagation differently. Hence by transmitting in both directions and using signal processing techniques inspection capabilities could be enhanced (see Figure 191).

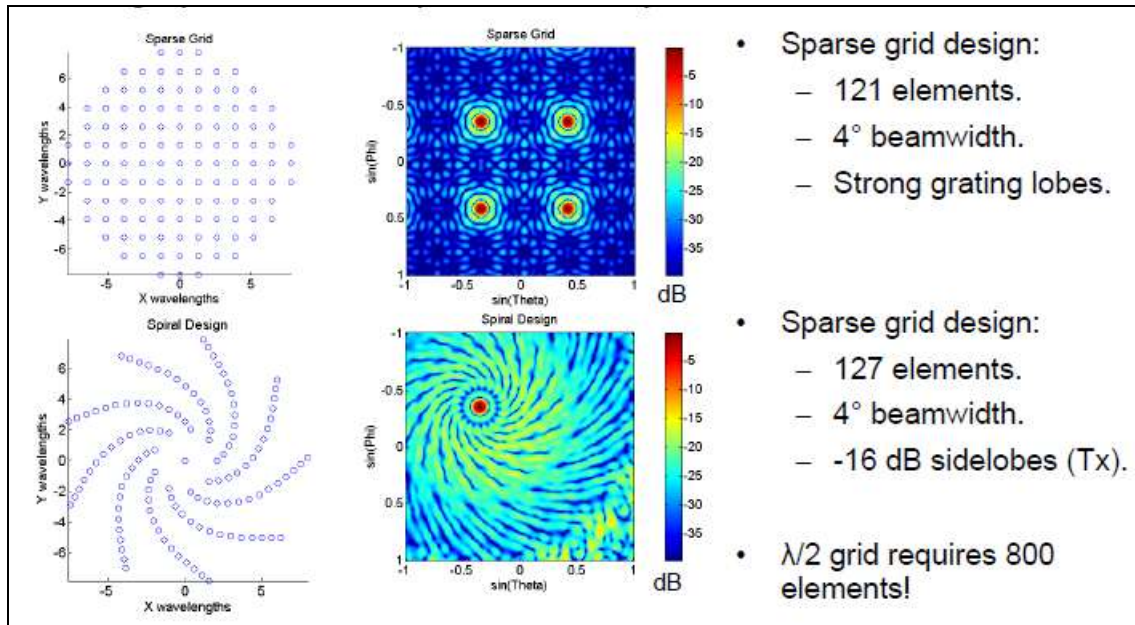


Figure 188 Two examples of sparse array configurations based on fractal designs.

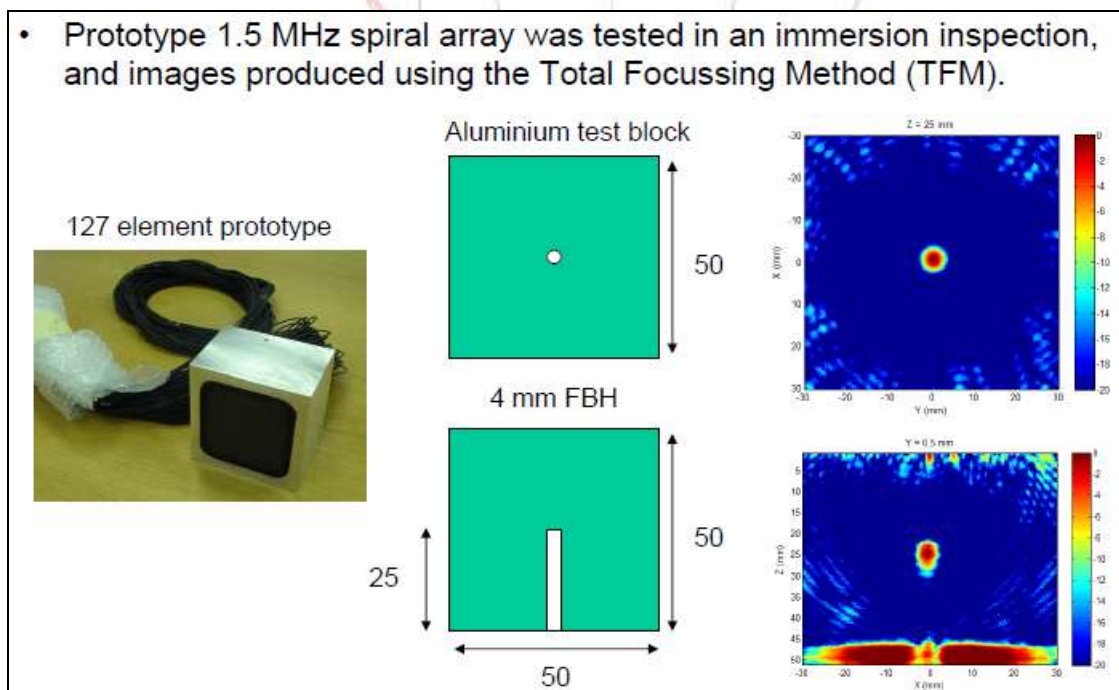


Figure 189 Inspection results from a prototype spiral array design probe; the TFM method is described in Section 10.2.

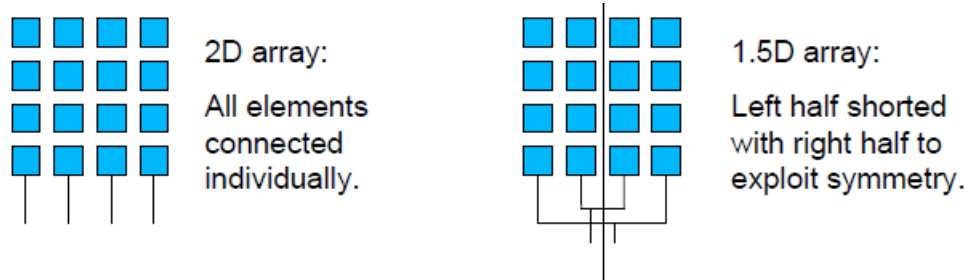


Figure 190 The hard wired 1.5D array configuration which is only feasible when no steering along the secondary plane is required.

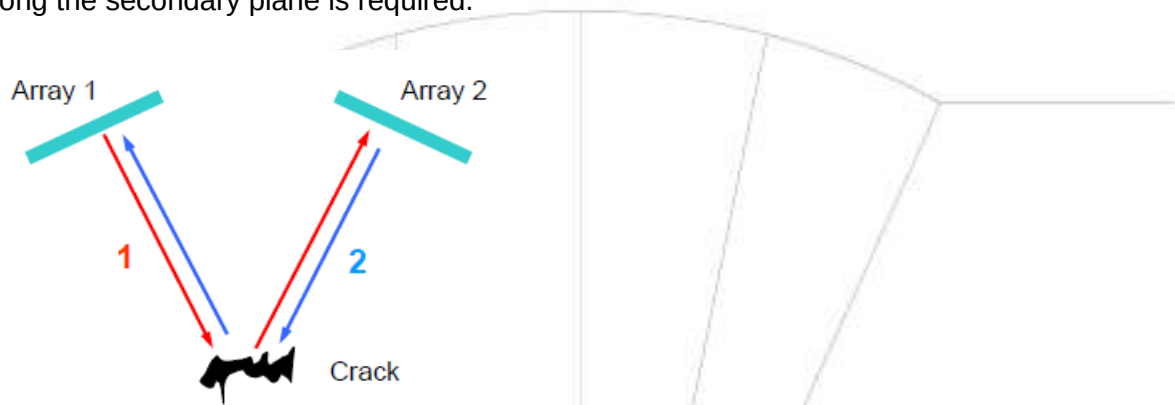


Figure 191 Transmitting both ways using a TRL configuration as the effect of the grain structure on the propagating sound wave may be different in both directions.

10.2 Inspection techniques based on full matrix capture of data

Post-processing techniques making use of the full matrix capture (FMC) of data are an avenue for exploration in future efforts. In FMC, each element on the array is fired and the signal received on all elements of the array is recorded. The result is a data matrix that contains all possible transmit-receive combinations on the array. This data matrix can then be manipulated, applying virtual delay laws, such that techniques can be implemented virtually. Techniques based on FMC have been shown to have advantages over conventional phased array techniques for inspection of isotropic carbon steel material [23].

The use of techniques based on FMC for austenitic materials has not been widely explored at the compilation of this document. In the DISSIMILAR project a brief study was conducted using the specimen presented in Appendix A and shown again in Figure 192. A linear array probe of 2.25MHz was used with an 18.5° Rexolite wedge to generate longitudinal waves within the specimen. The FMC data was captured and a post-processing technique termed the Total Focusing Method (TFM) [23] was used to image the data. The TFM algorithm sums together at each imaging point, ie the point within the component, all the received signal amplitude for all transmit-receive pairs within the data matrix. The underlying assumptions of the post-processing technique are that the propagation of sound from the transmitter to the receiver is along straight lines (subject only to refraction at the component / wedge boundary) and that the velocity is constant.

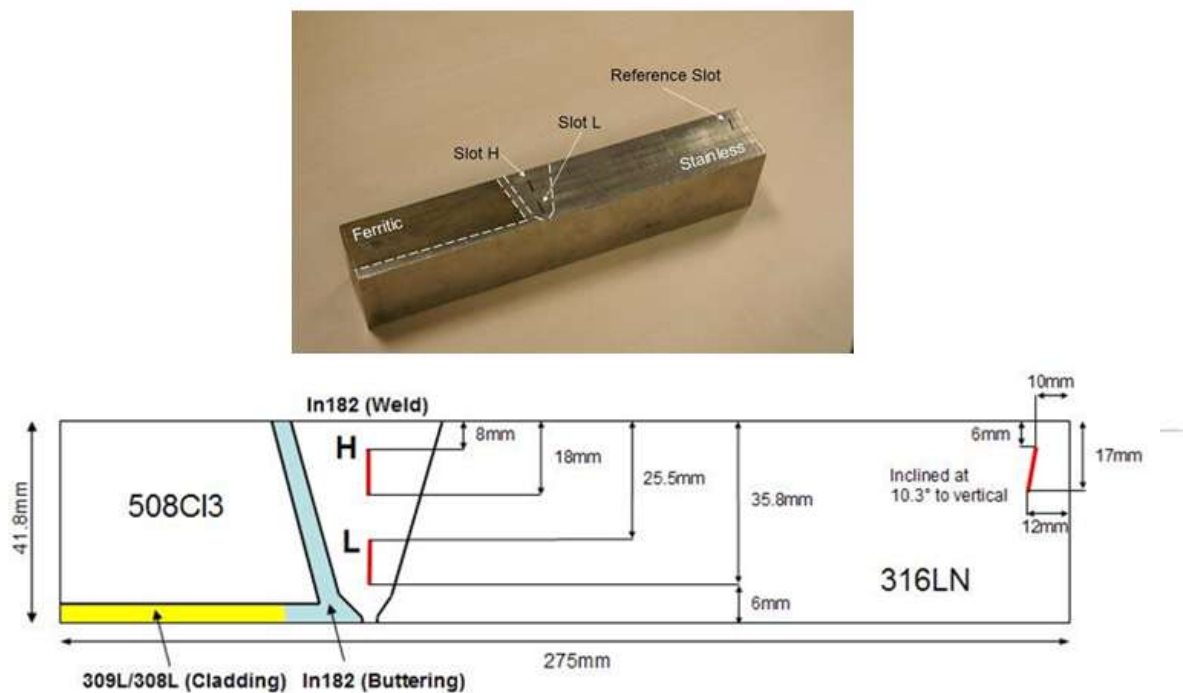


Figure 192 Specimen used for investigating the use of FMC techniques (see Appendix A).

Inspection was performed with the probe placed on either the carbon (ferritic) steel side or the stainless steel side and looking at the two slots H and L shown in Figure 192. Figure 193 shows the results from imaging the reference slot which was used to calibrate the technique; note that the imaging amplitude is automatically normalised to the highest amplitude in the imaging region by the processing algorithm.

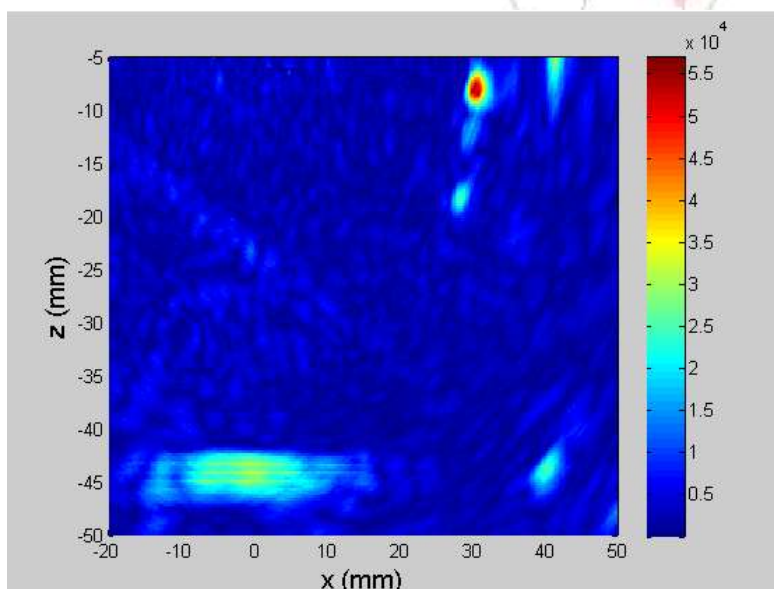


Figure 193 Image of the reference slot in the specimen showing the back wall, block corner and tips of the slot (compare to images A10 – A12 in Appendix A).

Figure 194 shows imaging of slots H and L from the stainless steel side with the probe placed at four different positions which lay close to each other. The data shows that the level of distortion is similar to that observed in the validation block (see Figure 182) and the performance is similar to the other ultrasonic techniques (see Section 7).

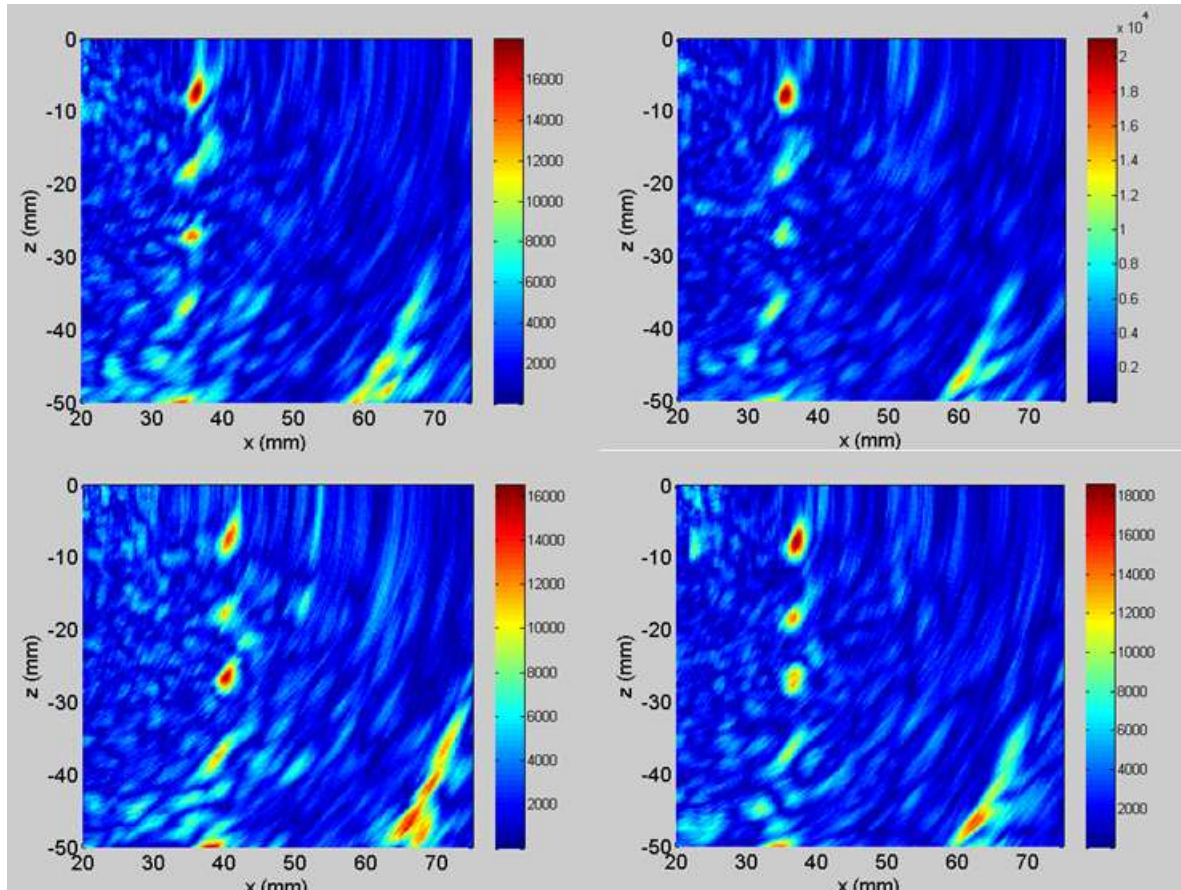


Figure 194 Images of slots H and L in the specimen with the probe placed on the stainless steel side of the weld (compare to images A13 – A19 in Appendix A).

The grain scatter gives rise to a significant level of back scattered echoes which manifest themselves in the image after the TFM processing. Additionally the echo amplitudes received from the slot tips fluctuate for the different positions which are not significantly spaced apart.

The probe was then placed on the carbon steel side and the slots were again imaged, this time the sound having to traverse the buttering layer. Figure 195 shows images of the bottom slot from the carbon steel side at two differing but nearby positions and Figure 196 shows an image of the top slot from the carbon steel side. In both figures the manifestations of sound field distortion as observed in other ultrasonic techniques is evident.

This study has shown that post-processing techniques (such as TFM) which make use of FMC data will suffer similarly to other ultrasonic techniques unless the microstructural conditions are accounted for in the processing algorithms. This will inevitably require the weld microstructure to be described in some fashion to the algorithms so that they can process the data to take into the effects due to the inhomogeneity and anisotropy.

The evidence to date shows that where 'active' phased array is able to penetrate a given volume of weld, then post-processing methods using FMC data will also work. However, future investigations should consider in depth the relationship between sound frequency and attenuation for implementation of FMC because in FMC the sound wave from a single element is required to penetrate the weld, reach the target and be received back on all elements of the array. Elements of typical arrays are small and the sound emanating from them is highly divergent, which may require special considerations for probes intended to be used for FMC of data, leading to modifications in the probe specification methods described in Figure 86.

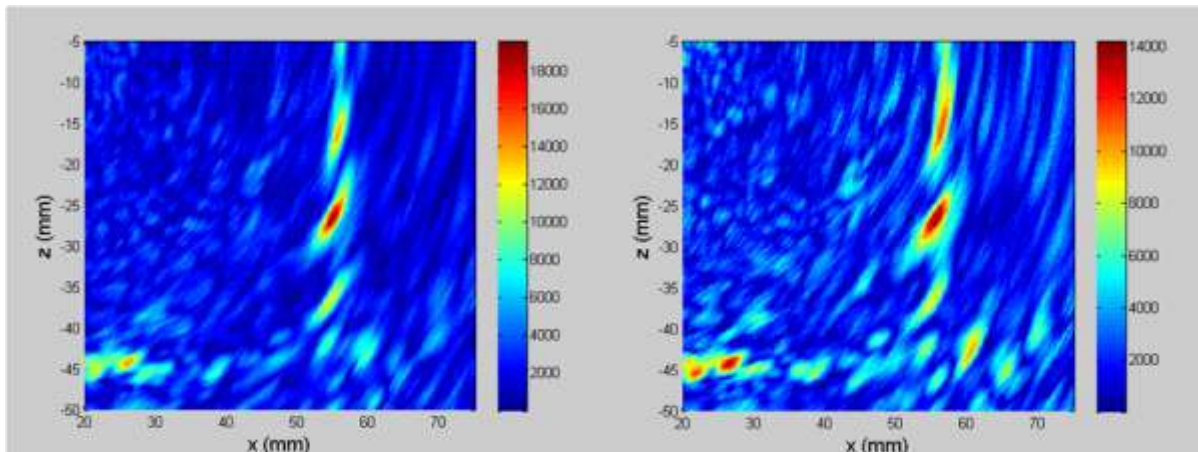


Figure 195 Images of slot L (near the root) in the specimen with the probe placed on the carbon steel side of the weld (compare to image A23 in Appendix A).

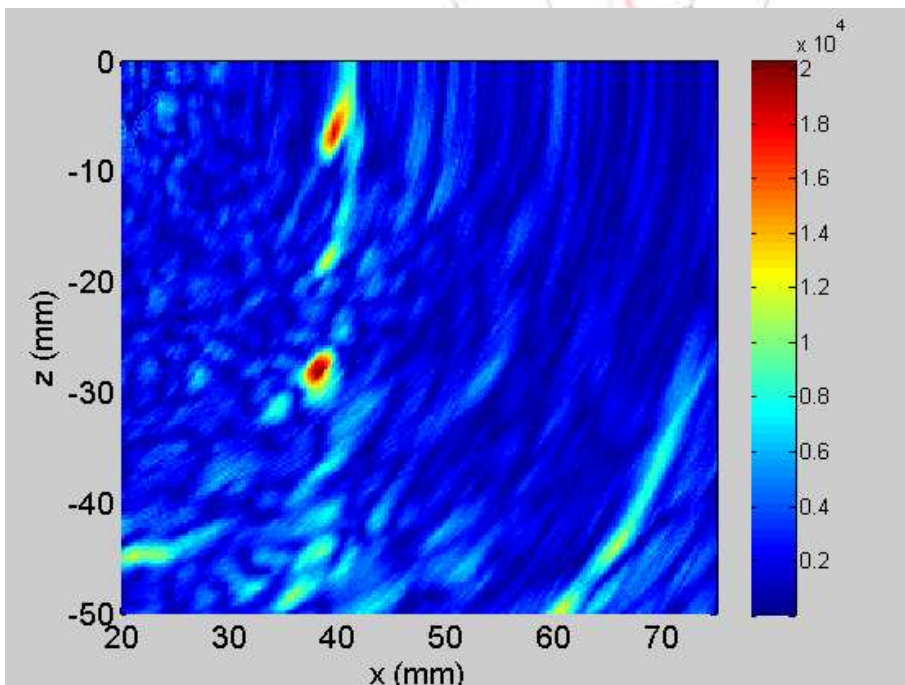


Figure 196 Image of slot H (near the top surface) in the specimen with the probe placed on the carbon steel side of the weld (compare to images A20 – A22 in Appendix A).

10.3 Finite element modelling packages

Two finite element (FE) packages were investigated during the course of the DISSIMILAR project: PZ Flex with a time domain solver and the general purpose ABAQUS using a variety of solvers. At the commencement of the project it was decided that the FE packages did not have the tool boxes available to adequately describe a complex inspection scenario (to include probes, wedges, components, techniques etc) which remains the case at the conclusion of the project. However, the inability to deal with grain scattering by the CIVA platform was identified as a short coming and the simulation times with CIVA (both the 32-bit version 9 and the 64-bit version 10) were deemed to be limiting factors to introducing the novel ideas generated into wider industrial use. Hence FE models were investigated primarily to establish whether it was possible to describe the weld microstructure into them and whether it was possible to generate ADLs.

PZ Flex was used to model a simple inspection scenario over the DISSIMILAR weld using a linear 1.5MHz array composed of 128 elements, as shown in Figure 197 [24]. A particular advantage of using PZ Flex was the introduction of the weld microstructure map which was done quickly and cost effectively by scanning in a colour map and assigning the orientations to each colour. In CIVA the orientations assigned to each region was input manually taking a considerable amount of time (estimated to be 3 working days).

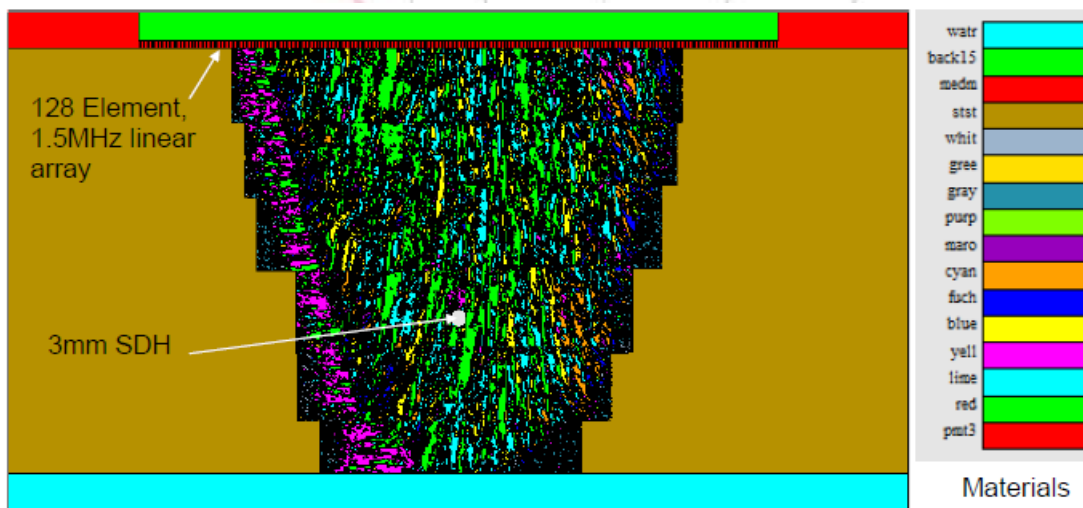


Figure 197 The inspection case modelled in PZ Flex using the weld microstructure mapped using EBSD, introduced using colour coded maps

Introduced into the middle of the weld was a 3mm SDH target. Then FMC data collection was simulated (taking 90mins to complete), followed by a simulated implementation of the TFM post-processing method (taking 60secs per image). The results after the TFM are presented in Figure 198 which shows both the distorted echo from the target SDH as well as the scatter due to grains (which could not be evaluated in CIVA). The FMC data was then processed using the concepts behind generating ADLs and the result is presented in Figure 199 which shows that the amplitude and integrity of the echo from the target SDH is imaged better, implying the integrity of the sound field is better maintained. Note, however, that the background grain scatter noise level was not suppressed by the modified processing.

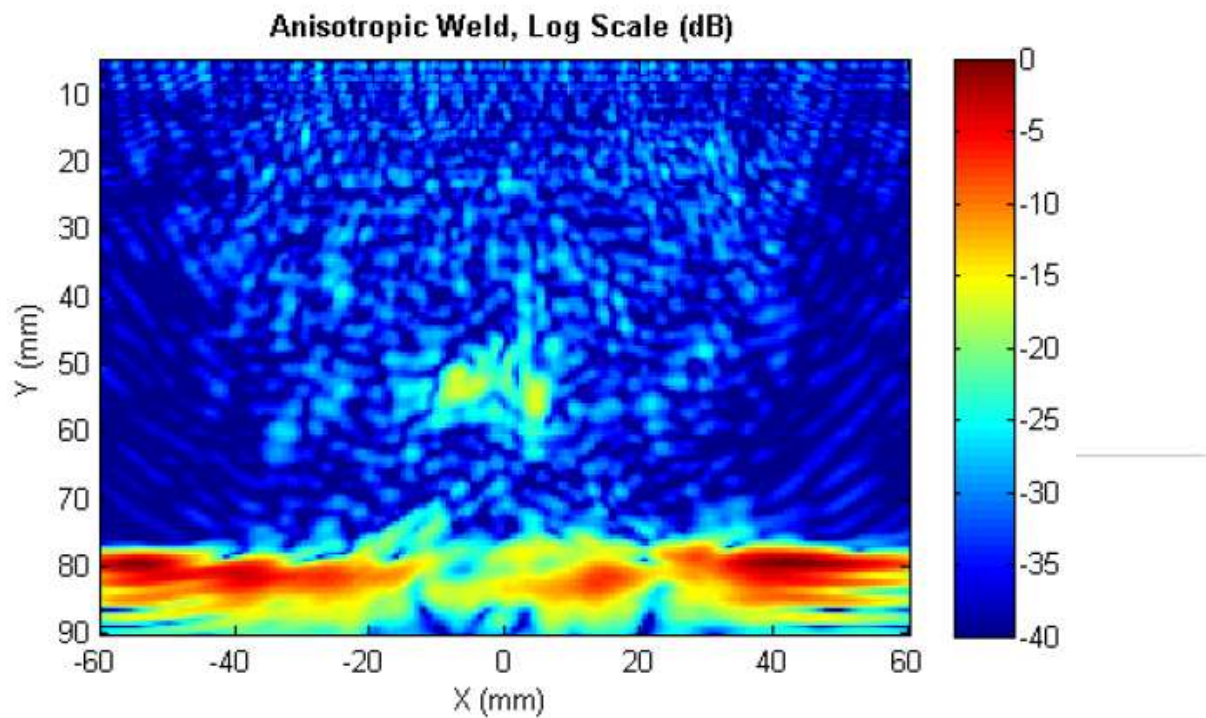


Figure 198 Image of the weld containing the target SDH using a virtual application of TFM.

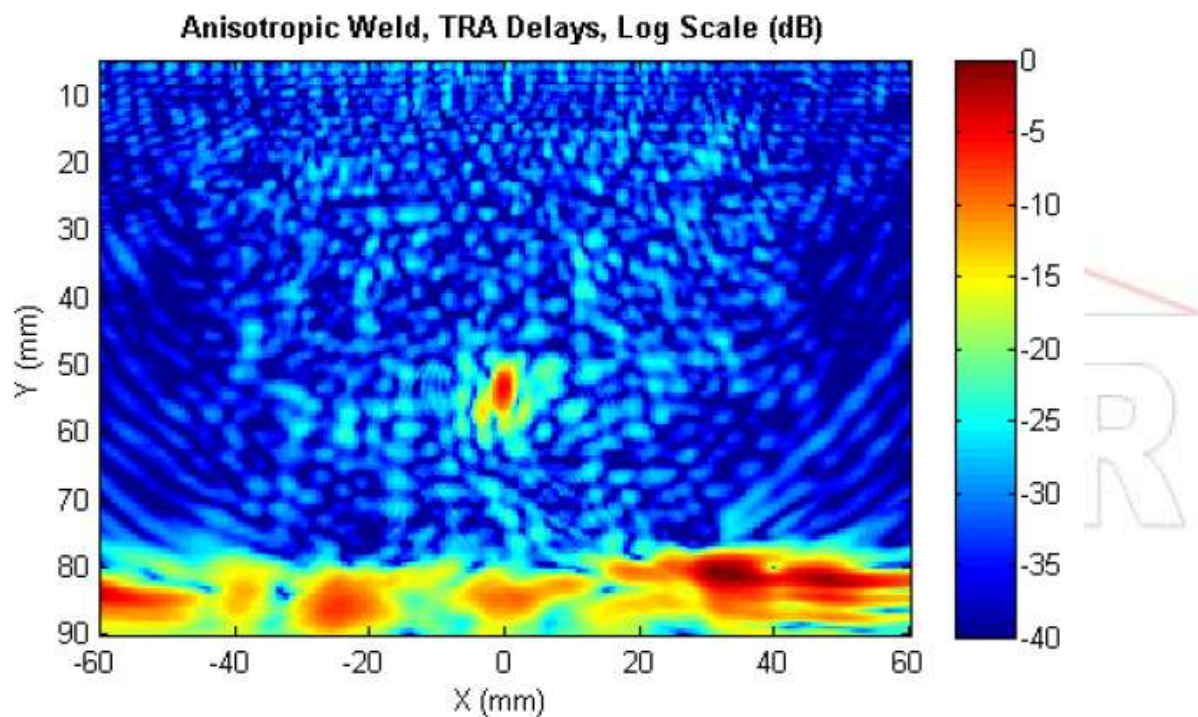


Figure 199 Image of the weld containing the target after using time reversal concepts to adapt the processing.

ABAQUS was used to model the validation block presented in Section 7.4 and was used to generate an ADL to investigate the possibility to use the model as an 'anisotropic delay law calculator'. ABAQUS is a general purpose FE code and is hence open to configuration. A key advantage presented by the package is the ability to code in the EBSD map at its full 40 μ m resolution. This will eliminate the orientation unification processing step to generate a weld microstructure map where the boundaries are set through assumptions. The raw EBSD map (see Figure 27) is input (as a text file) directly into ABAQUS and the raster grid used by the EBSD scanner will become the FE grid, containing millions of elements and nodes.

Figure 200 shows the concept where a linear array probe containing 32 elements is used to scan the validation block, which in the first instance is introduced into the model using the boundaries generated after the orientation unification step.

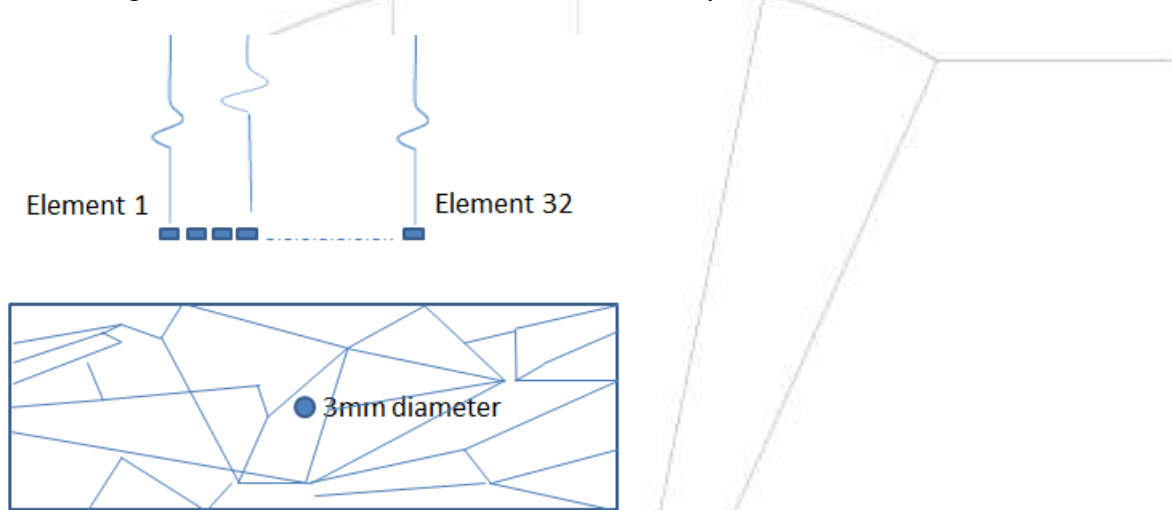


Figure 200 The scenario introduced to the ABAQUS model; a 32 element 4MHz linear array is used for the inspection, focusing the sound to the position of the target SDH.

Figure 201 shows the propagation of the wave front from a single element when the validation block is considered to be isotropic (image is at a time just before impact on the SDH) and Figure 202 shows how the integrity of the wavefront is broken when it travels through the anisotropic weld structure.

Note that in both Figures 201 and 202 the blue region represents the validation block, ie the medium. Note also that, like PZ Flex and unlike CIVA, ABAQUS is able to evaluate back scattered grain echoes. At the time of writing, work is ongoing to use ABAQUS to implement a validation of the ADL concept, the model and the stiffness coefficients.

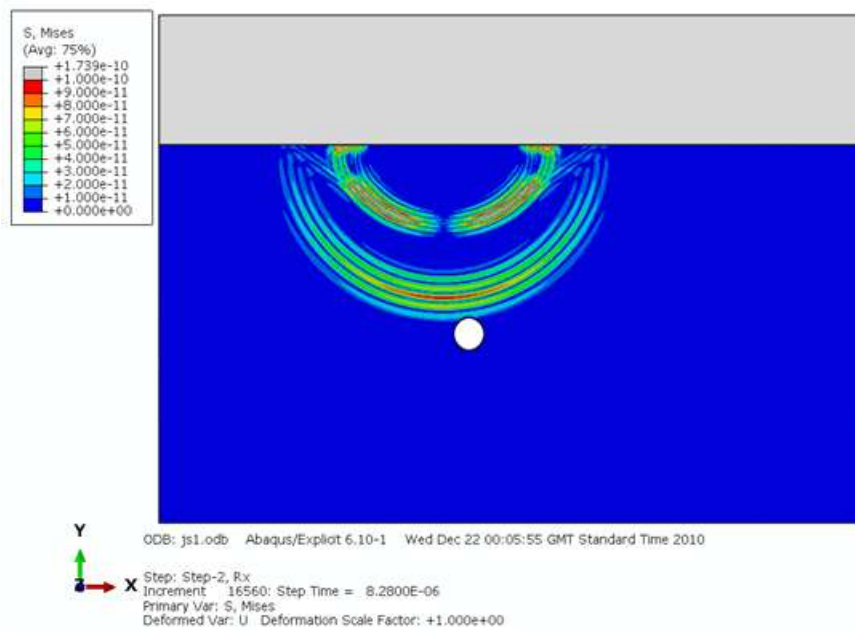


Figure 201 Wave front from a single element of the array just before impact on the SDH; the validation block was assigned isotropic carbon steel values.

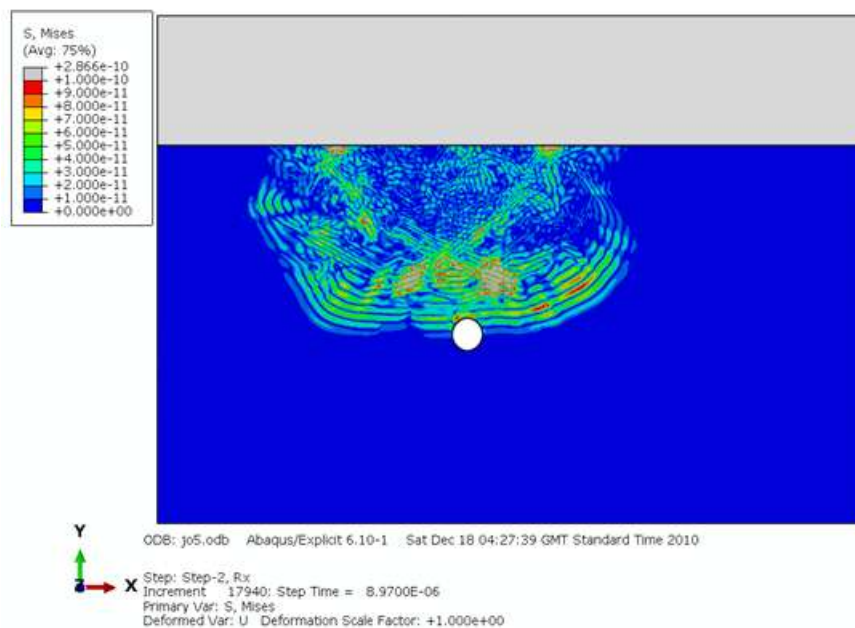
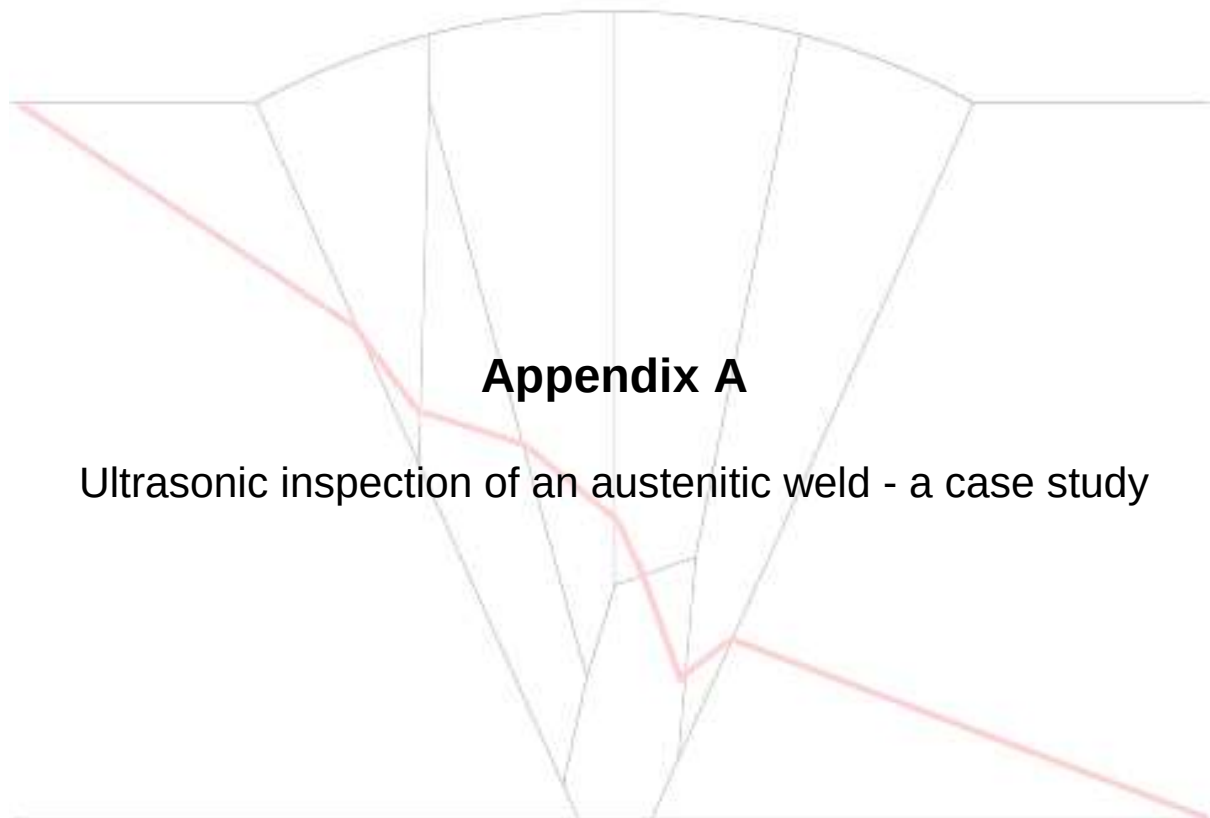


Figure 202 Wave front from a single element of the array just before impact on the SDH; the validation block was assigned the orientation information as mapped by EBSD.

11 References

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A1 Specimen

The specimen is representative of the surge end nozzle shown in Figure A1.

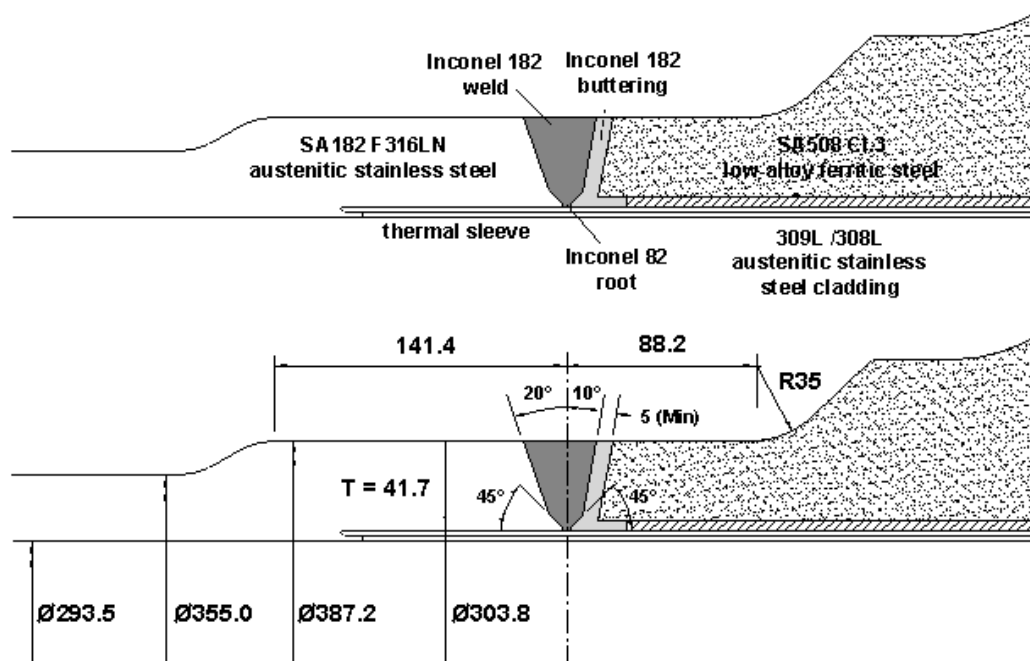


Figure A1 Diagram showing the geometry and dimensions of the surge end dissimilar weld configuration (Copyright to British Energy Generation Ltd).

Figure A2 shows an image of the specimen (T1509) on the side with 2 vertical slots (approximately 40mm deep) embedded along the centre line of the weld. In addition a reference slot approximately 40mm deep is placed in the stainless steel parent, near the edge of the block. The reference slot is inclined by approximately 10.3° to the vertical

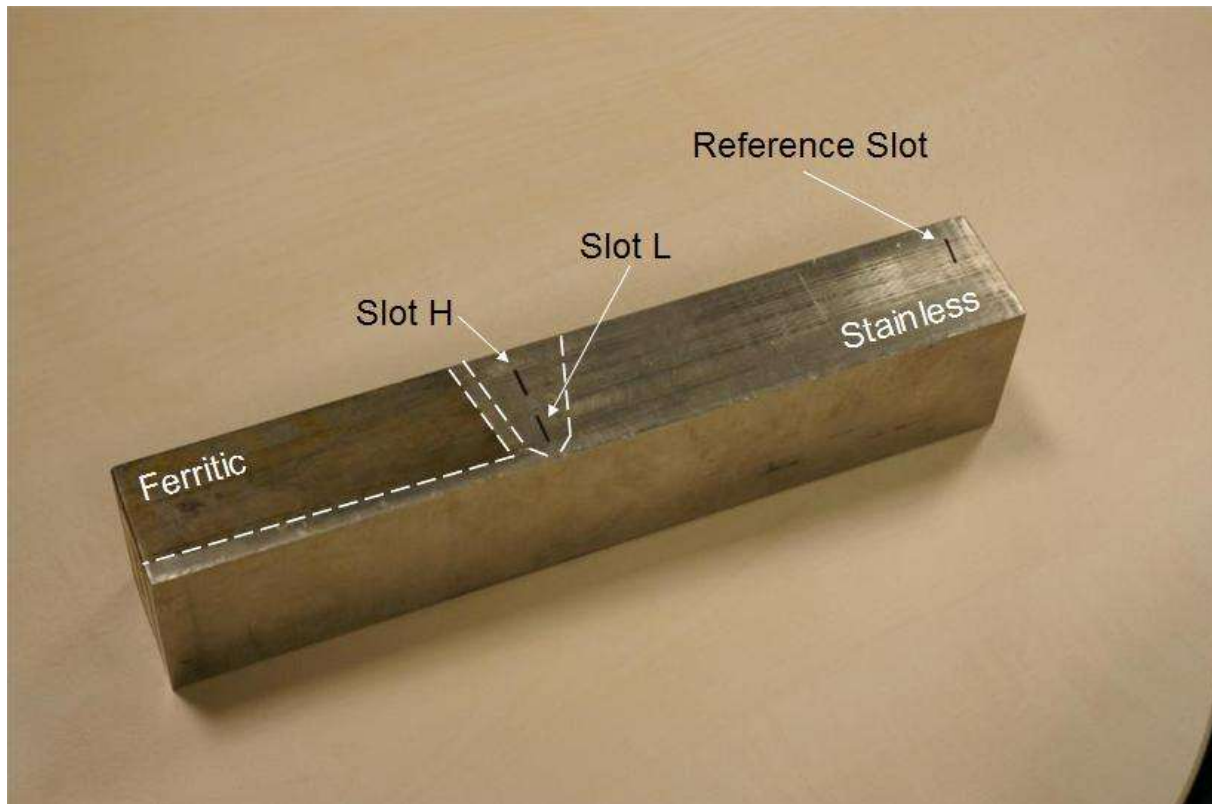
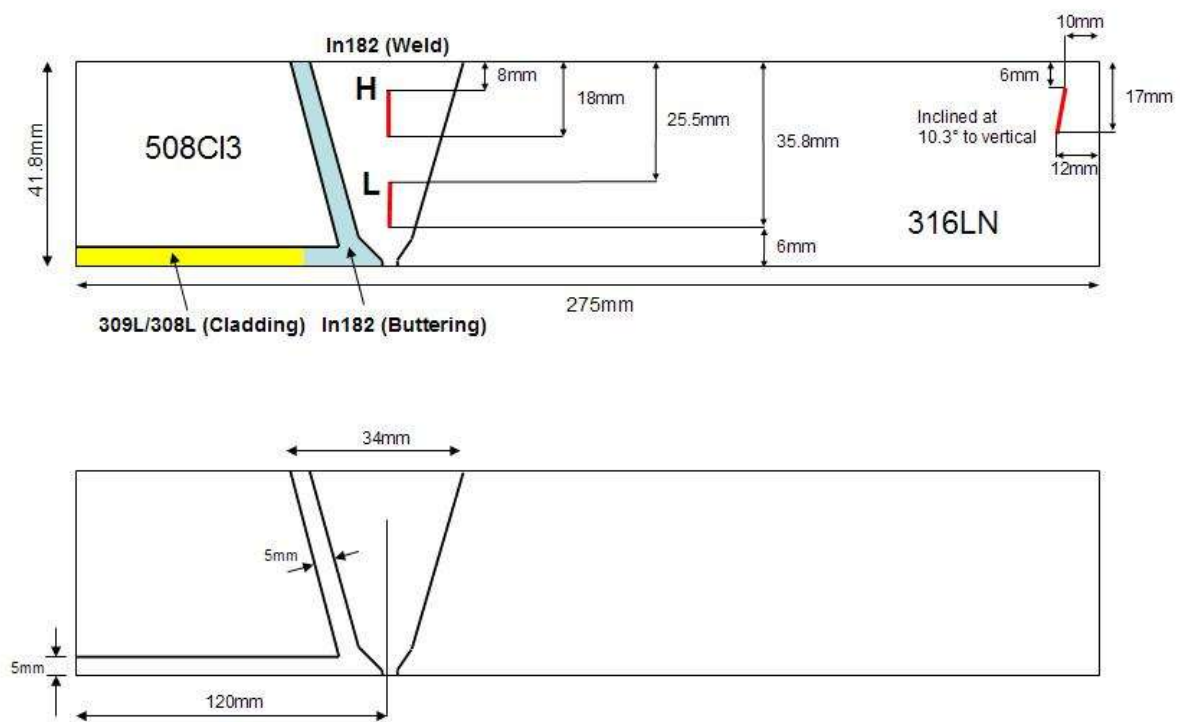


Figure A2 Image of specimen T1509 showing two vertical slots along the centreline of the weld and a reference slot in the stainless parent near the edge of the block.

Figure A3 shows the dimensions of the block, position of the slots and geometry of the dissimilar weld. On the side opposite to the one with the slots three small porosity type flaws are visible on the surface, as shown in the macrograph of Figure A4, and positional information is given in Figure A5. The total number of micro-porosity flaws located under the optical microscope number more than 6, as well as the three visible to naked eye.

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Not to scale

Figure A3 Dimensions of specimen T1509 on the side with slots; slot near the cap is termed slot H and the other as slot L, along with the reference slot.

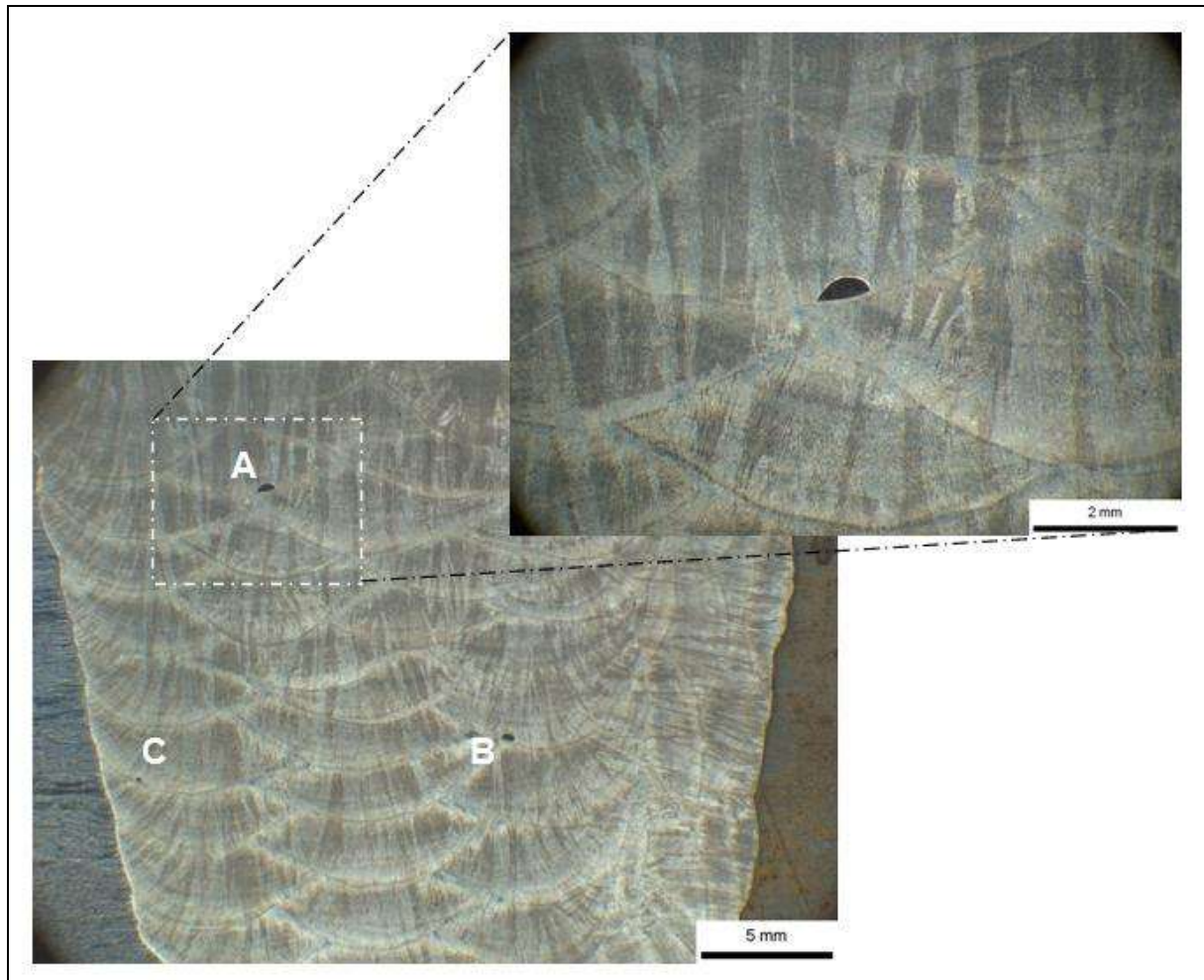


Figure A4 Macrograph of the side containing the three sub-millimetre porosity type flaws visible to the naked eye, with flaw A magnified.

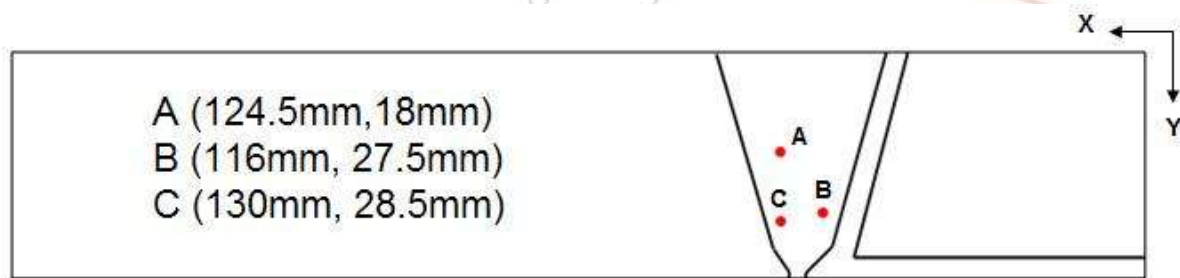


Figure A5 Positional diagram of the side containing the porosity type flaws, shown in a Cartesian coordinate system with the origin at the top right corner (ferritic parent).

A2 Approach

The aim of the study is to detect and position the slots within the weld body using the TRL probe [A1]. Calibrations are performed on a ferritic calibration block with target 3mm side drilled holes (SDH) at depths of 7, 18, 29 and 39mm from the top surface. In this work a longitudinal velocity of 5900m/s is assumed (ferritic) and an attempt to correct for the stainless steel is made through the use of the wedge delay trim.

A3 Results and discussion

The results are presented as sector scans on a dimensionally accurate weld overlay to aid interpretation.

A3.1 Calibration scans

Figures A6 to A7 show the calibration scans on the 3mm side drilled holes (SDHs) along with the gain setting to place the target signal at 80% of full screen height (FSH). In the present work, the 45° beam is used for detection, with all signal-to-noise (S/N) ratio values measured along this beam.

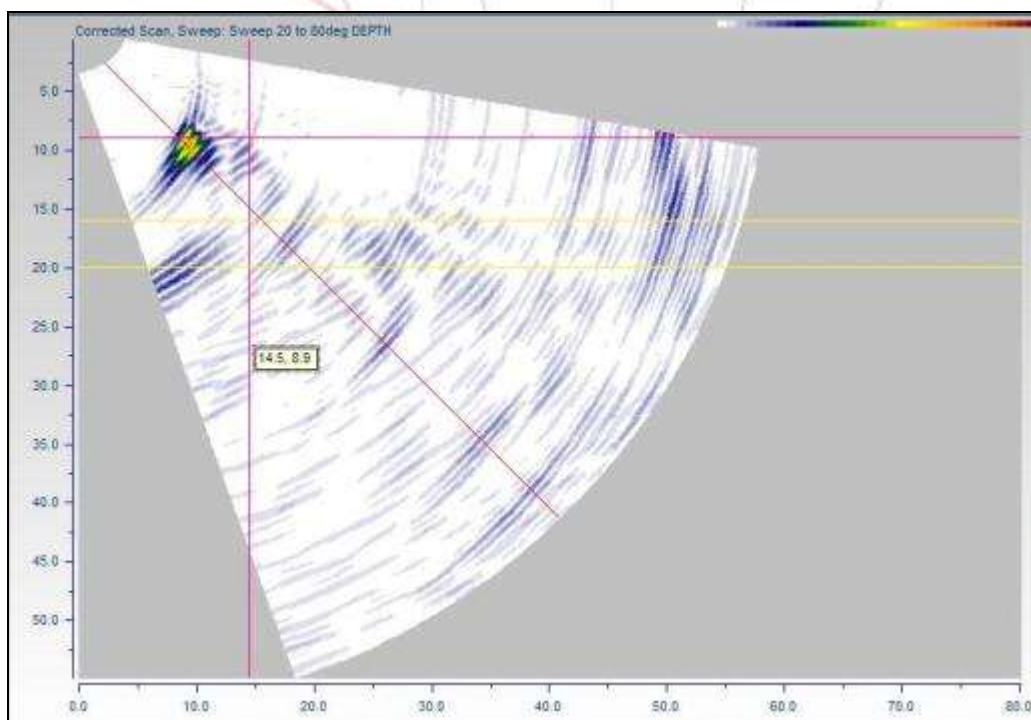


Figure A6 Calibration SDH at a depth of 7mm, measured at a gain of 38.5dB when target signal is at 80% FSH.

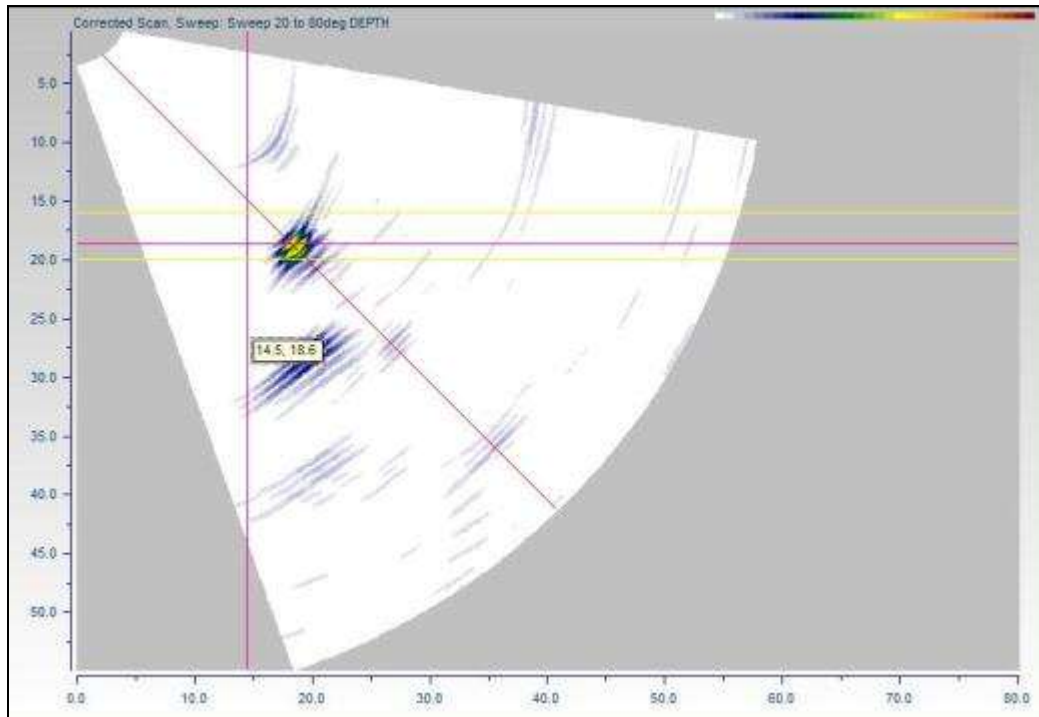


Figure A7 Calibration SDH at a depth of 18mm, measured at a gain of 30.75dB when target signal is at 80% FSH.

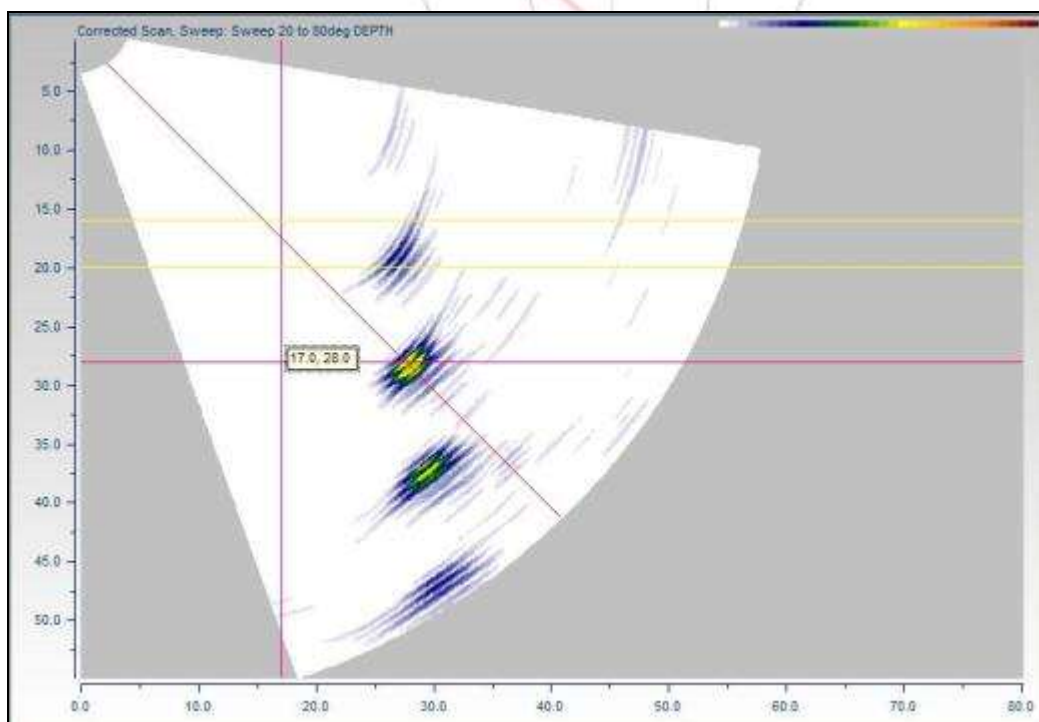


Figure A8 Calibration SDH at a depth of 29mm, measured at a gain of 31.5dB when target signal is at 80% FSH.

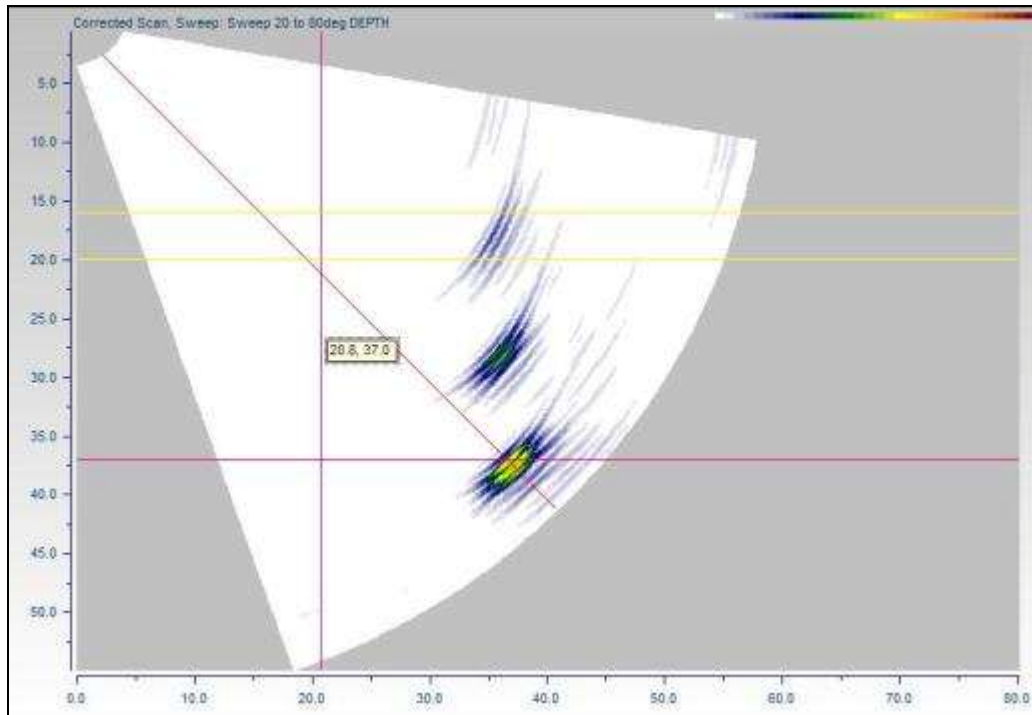


Figure A9 Calibration SDH at a depth of 39mm, measured at a gain of 34dB when target signal is at 80% FSH.

A3.2 Scan from stainless steel parent

Figure A10 shows the diffracted signal from the tip of the reference slot along the 45° beam line; the focal law is set to focus at a depth of 6mm, with the wedge delay trimmed by +0.9μs to place the echo at correct depth. The gain to place the signal at 80% FSH is 45.5dB, which is 7dB higher than calibration (see Figure A6). The beam is highly focused at depths near the surface; hence with a very tight field depth the beam is not sensitivity to other features of the component. Note the faint echoes from the vertical side wall of the component.

Figure A11 shows the diffracted signal from the root of the reference slot along the 45° beam line; the focal law is set to focus at a depth of 17mm, with the wedge delay trimmed by +0.9μs, as for the tip echo (Figure A10). The gain at 80% FSH is 46dB, similar to that of the tip echo. Figure A12 shows the diffracted signal from the root of the reference slot but with no delay trim, ie 0μs. Note that the measured depth of the root signal is 15.3mm when trimmed and 17mm with no trim. The actual measured position of the slot root is at 17mm (see Figure A3). Therefore, the trim applied to correct for the tip depth position (as shown in Figure A10 where the tip echo is correctly measured at a depth of 6mm) leads to an error of 1.7mm in the depth of the root echo. The delay trim value is a global correction that affects the 'system'; hence, the error is due primarily to the inaccurate material velocity input.

However, both Figures A11 and A12 show the corner echo and the back wall echo from the specimen; they are better positioned with respect to the material without the trimmed delay (Figure A12) than when the delay is trimmed with the value used to correct for the tip echo position.

All subsequent data presented in the report do not trim the wedge delay in order to better understand the mechanisms involved in the positioning of echoes within the material.

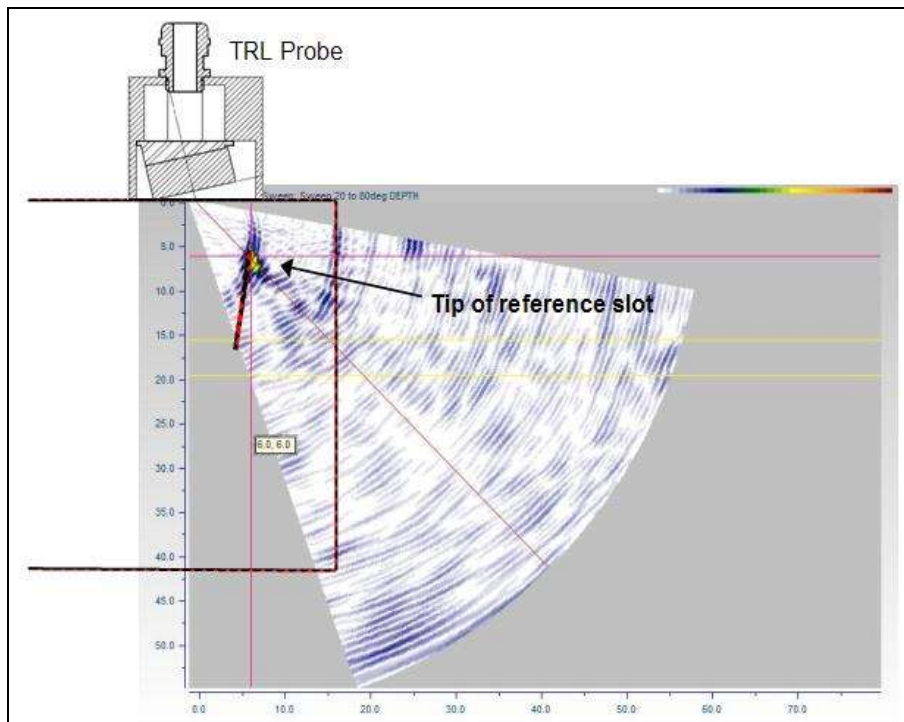


Figure A10 Diffracted signal from the tip of the reference slot along the 45° beam line.

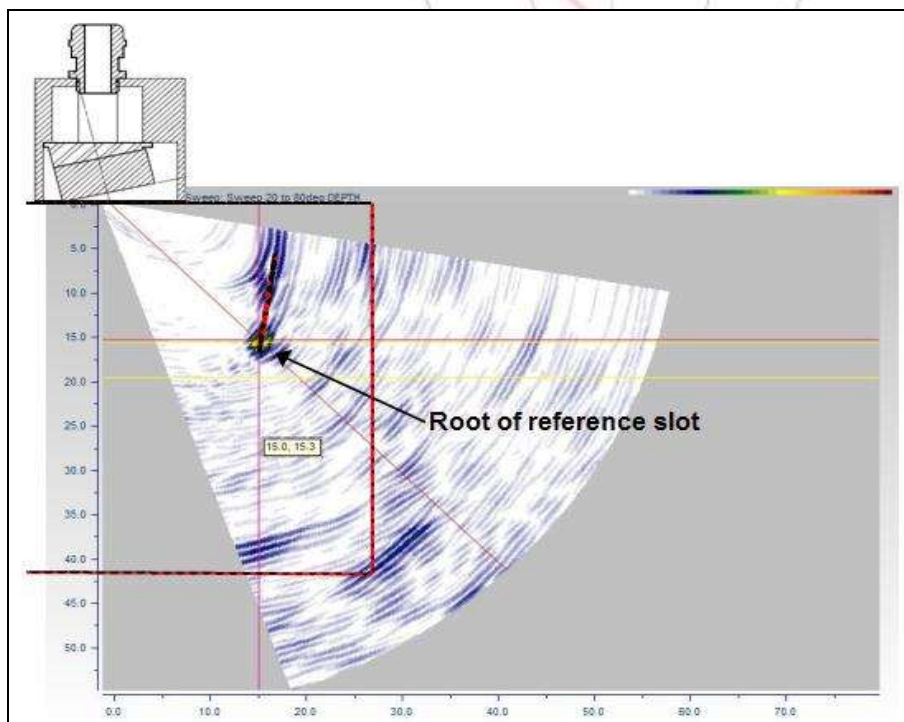


Figure A11 Diffracted signal from the root of the reference slot along the 45° beam line.

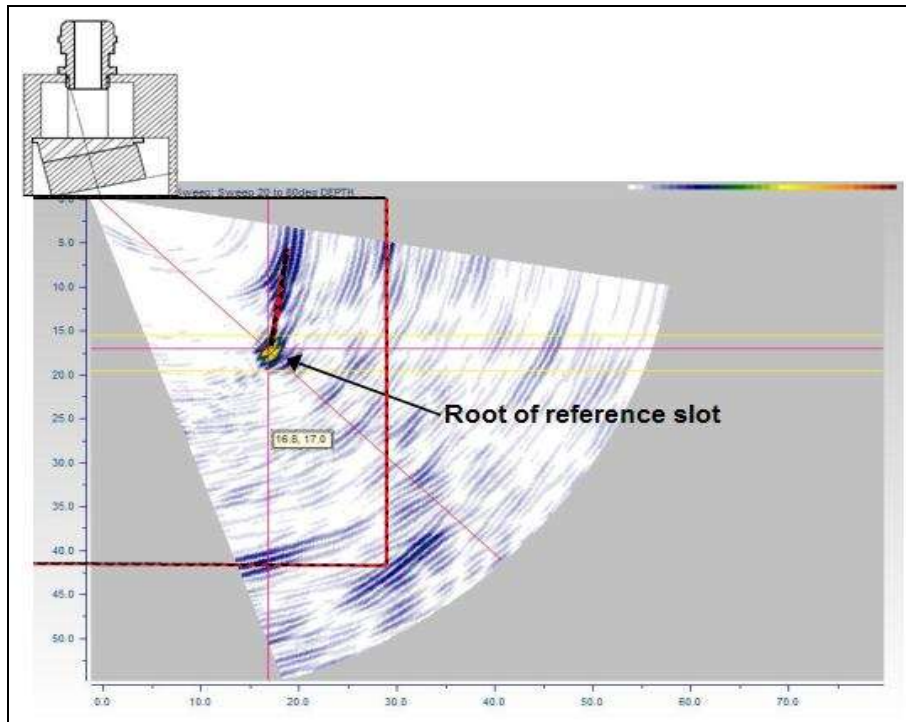


Figure A12 Diffracted signal from the root of the reference slot, without trim of the delay.

Figures A13 and A14 show detection of slot H with the probe focusing at depths of 8 and 18mm, respectively, where the weld overlay is dimensionally accurate.

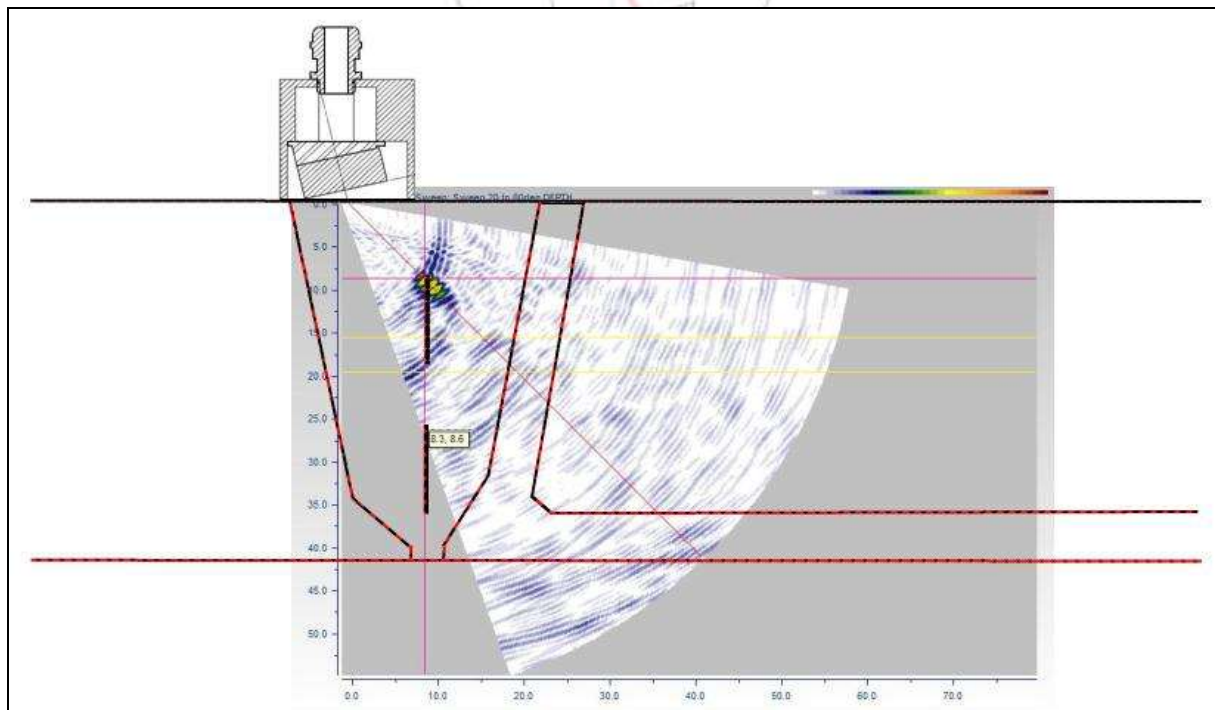


Figure A13 Diffracted signal from the tip of slot H along the 45° beam; the gain is set to 50.25dB for 80% FSH.

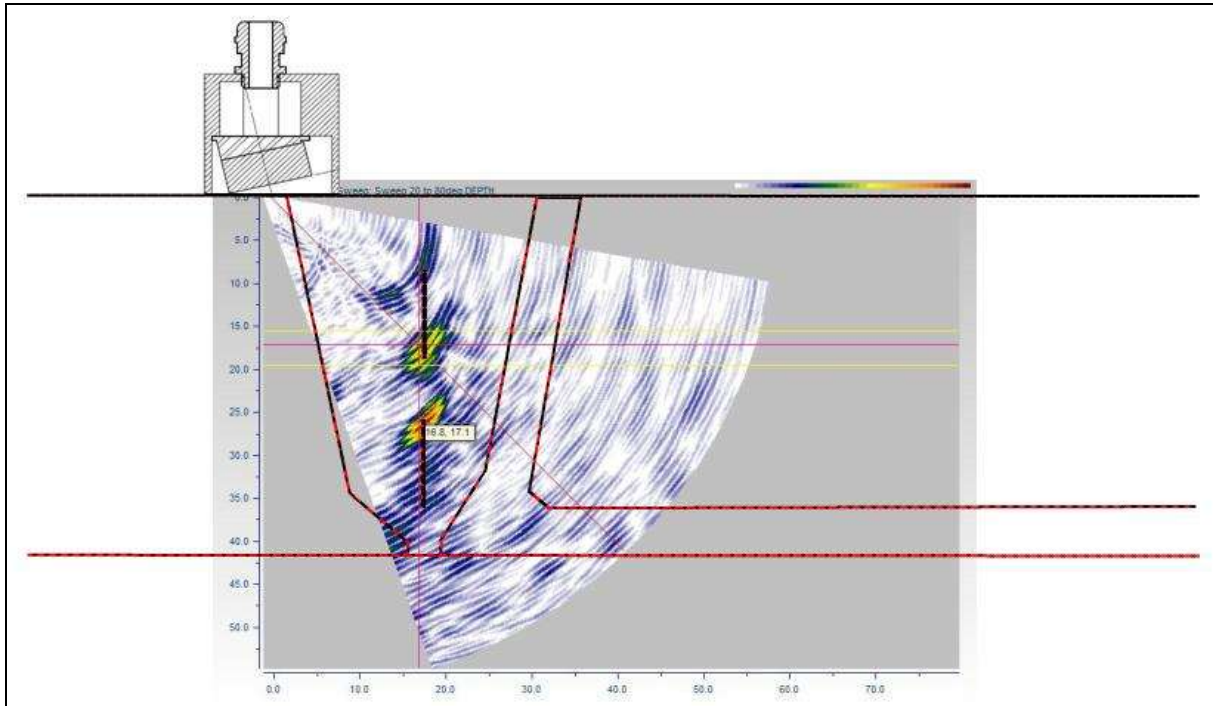


Figure A14 Diffracted signal from the root of slot H along the 45° beam; the gain is set to 53.5dB for 80% FSH.

The gain settings to place the tip and root diffracted echoes at 80% FSH height are 11.75dB and 22.75dB greater the corresponding calibration values, respectively. This illustrates firstly the weakness of diffracted signals with respect to SDHs at the same range, but also the greater scattering attenuation of the coarse grained material. Figure A15 shows the measured A-scan along the 45° beam line, with the measured S/N greater than 6dB.

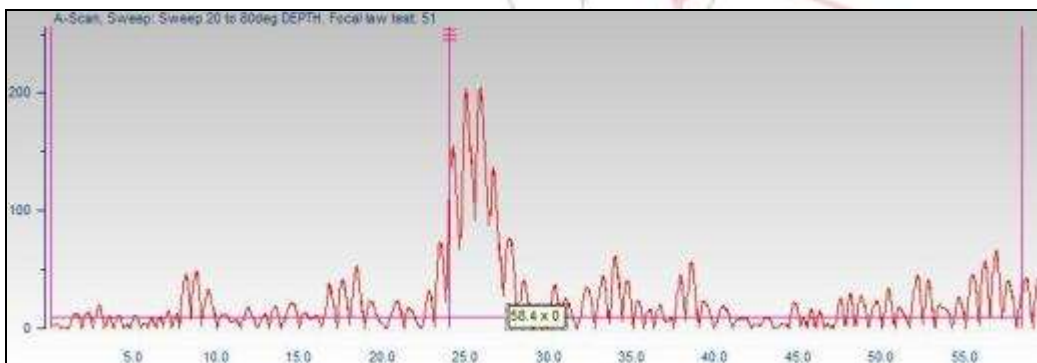


Figure A15 Measured A-scan along the 45° beam for the root diffracted signal from slot H.

In Figure A14 the probe is programmed to focus at the depth of slot H root, but a strong signal is received from the tip of slot L. This could be due to beam skewing, where the actual direction of sound energy is not propagating to the intended depth/position within the material. However, when focused at the depth of the tip of slot L as shown in Figure A16, the root of slot H is not illuminated strongly. This is an illustration of local anisotropic material conditions strongly influencing beam forming within the weld volume. In addition, the gain is 15dB above the calibration setting, whereas it was 22.75dB to detect root of slot H at a lower depth.

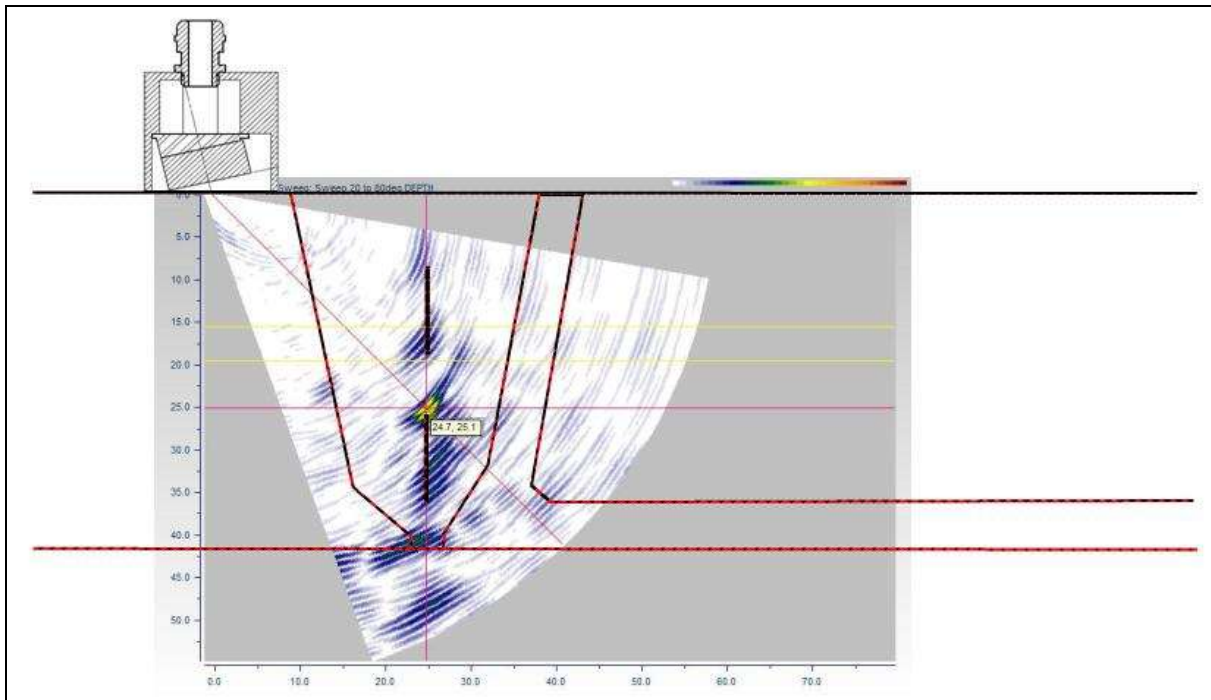


Figure A16 Diffracted signal from the tip of slot L along the 45° beam; the gain is set to 46.5dB for 80% FSH.

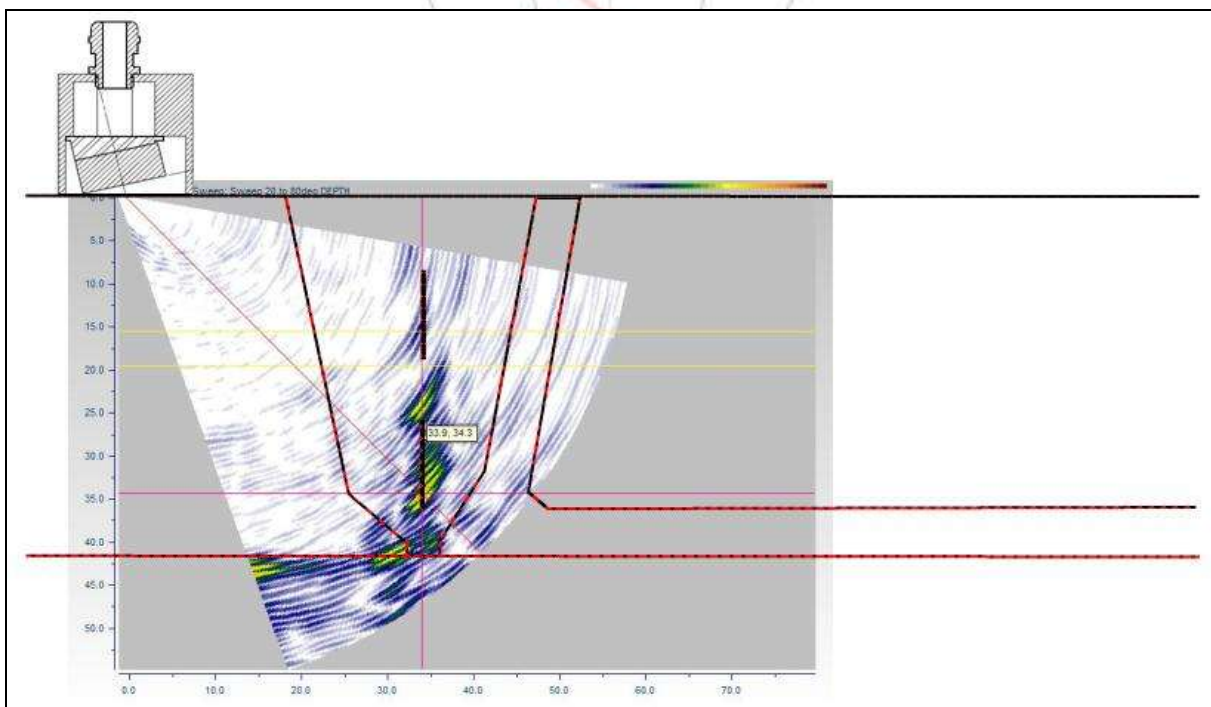


Figure A17 Diffracted signal from the root of slot L along the 45° beam; the gain is set to 49.5dB for 80% FSH.

In Figure A17, focusing at the root of slot L it is also possible to detect signals from the weld root due to acoustic impedance mismatch leading to a corner effect type echo. The

measured depth of the root signal in Figure A17 is 34.3mm (the actual depth is 35.8mm); the measured depth of the tip signal while focusing at the root is 24mm, giving a slot height of 10.3mm. The actual slot height was also measured at 10.3mm, possibly implying that error in through-wall sizing may not be significant [A1].

The focal law was changed to a 'distance' type, where the sound is focused at a distance ahead of the probe index point. Figure A18 shows probe focusing along a vertical line corresponding to the centreline of the weld where the 45° beam impacts on the tip of slot L. The beam strength along the 45° beam line is stronger than at beam angles corresponding to the root of slot L, as well as the tip and root of slot H. This has implications towards the design of inspection procedures.

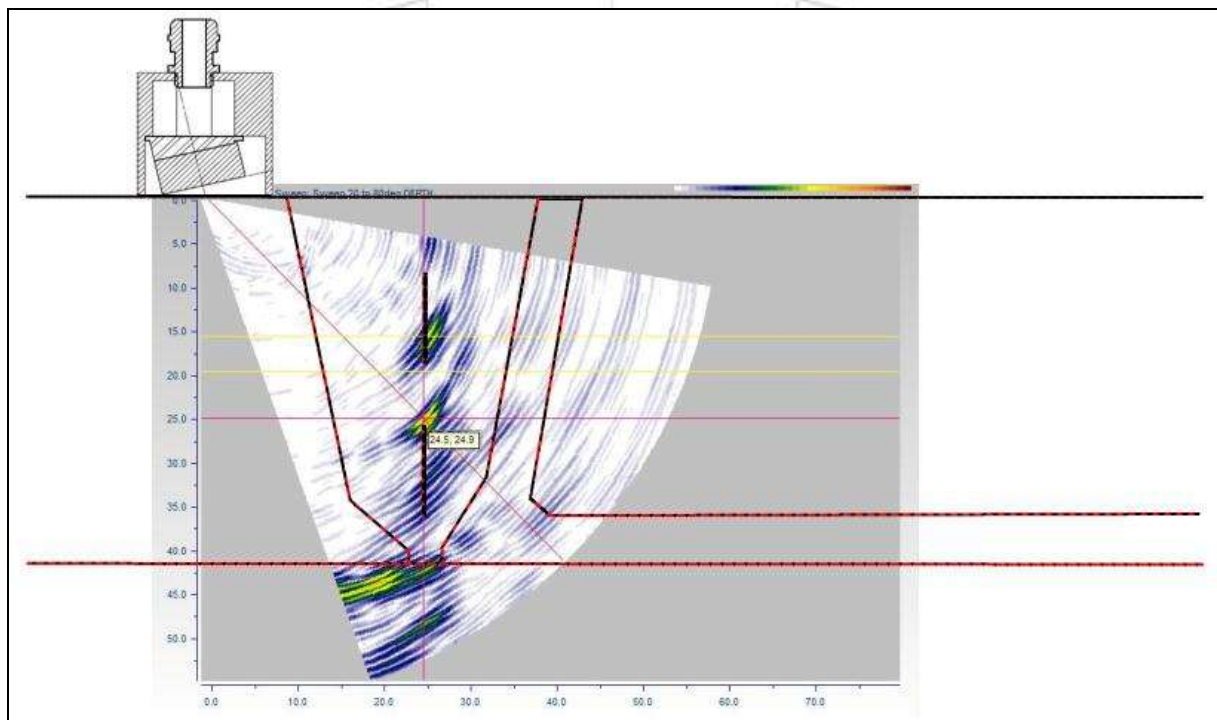


Figure A18 Focusing along a vertical line corresponding to the centreline of the weld where the 45° beam is incident on the tip of slot L.

Figure A19 shows detection of a possible porosity point within the weld volume, as shown in Figure A4, because the signal does not have any lateral length within the material. Note also the error in through-wall positioning of the diffracted signals. The law was set to focus at a depth of 22mm where the porosity signal was identified, but positioning of legitimate echoes have significant errors.

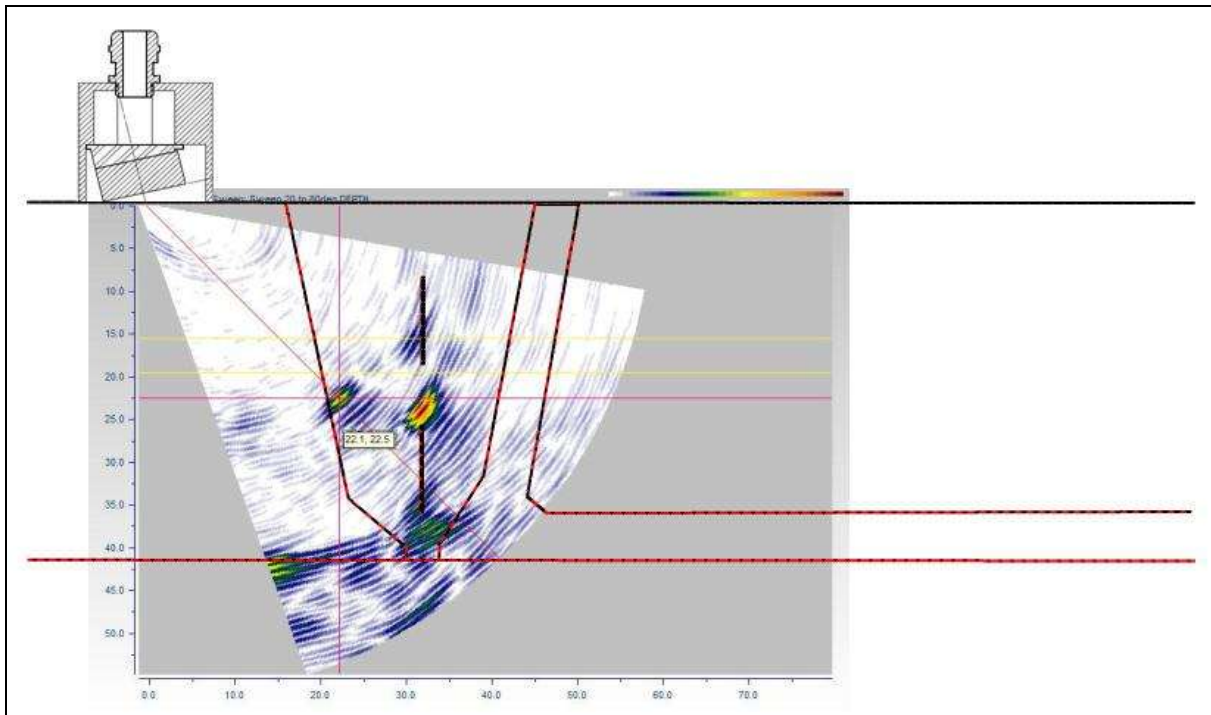


Figure A19 Detection of a point signal that suggests the presence of porosity.

A3.3 Scan through buttering from the ferritic parent

Figures A20 and A21 show the scans for the tip and root diffractions of slot H, with the law focused at the corresponding depths. As before, the tip signal from slot L is stronger than the root signal from slot L when focused at the depth level of the root of slot L (Figure A21), implying the presence of distortive effects.

Figures A22 and A23 show the tip and root diffractions from the tip and root of slot L, with the law focused at the corresponding depths. The gain settings for detection of the tip and root signals are 10.5dB and 18.25dB above calibration gains at the corresponding depths. Figure A23 also shows that severe beam distortion could be taking place when focused at the depth of the root of slot L, with strong echoes from the weld root and back wall.

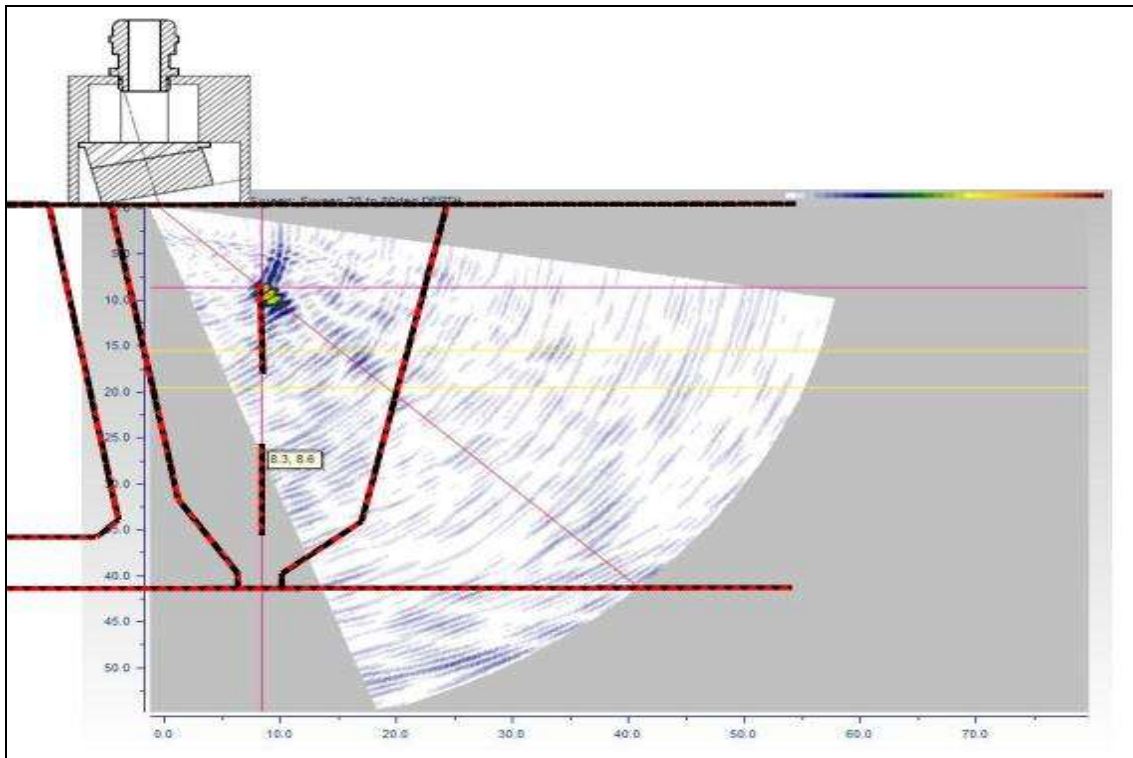


Figure A20 Diffracted signal from the tip of slot H along the 45° beam; the gain is set to 48dB for 80% FSH.

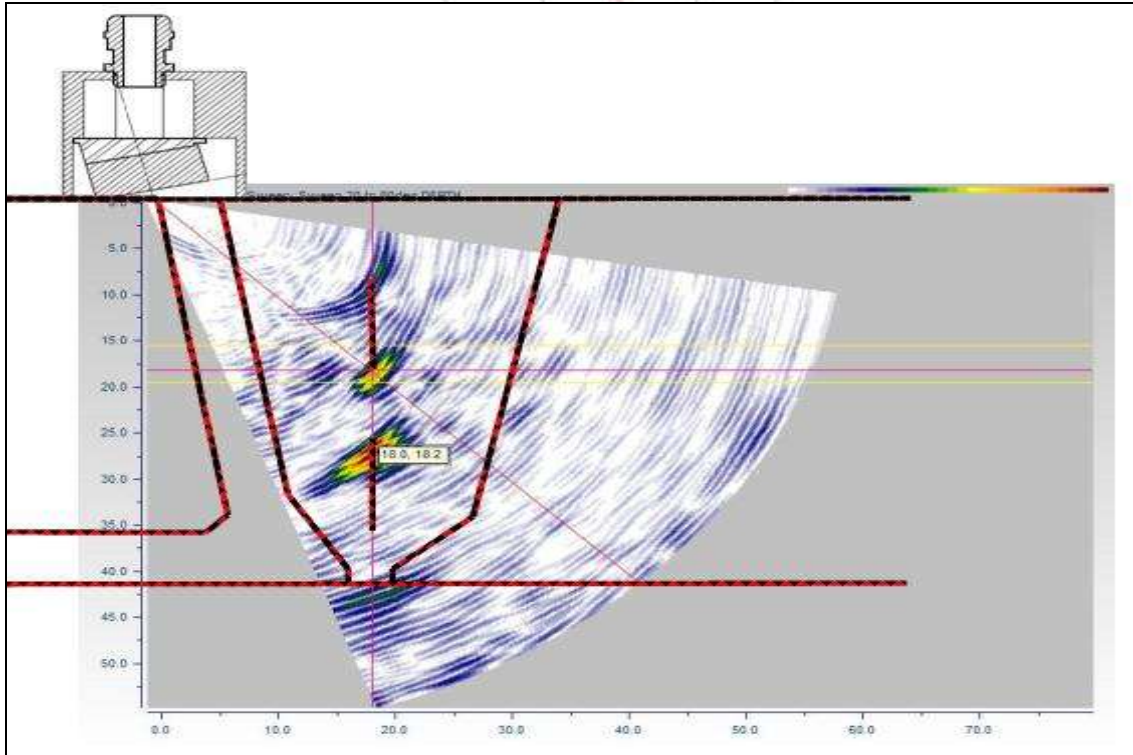


Figure A21 Diffracted signal from the root of slot H along the 45° beam; the gain is set to 52dB for 80% FSH.

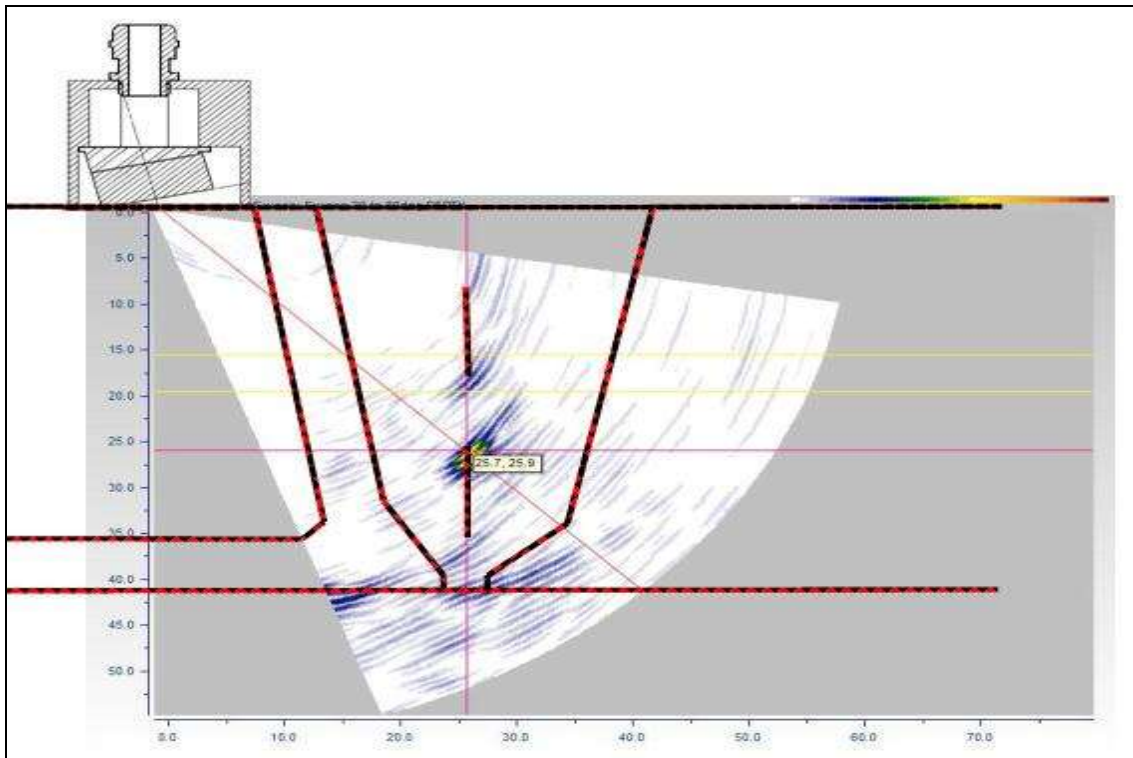


Figure A22 Diffracted signal from the tip of slot L along the 45° beam; the gain is set to 42dB for 80% FSH.

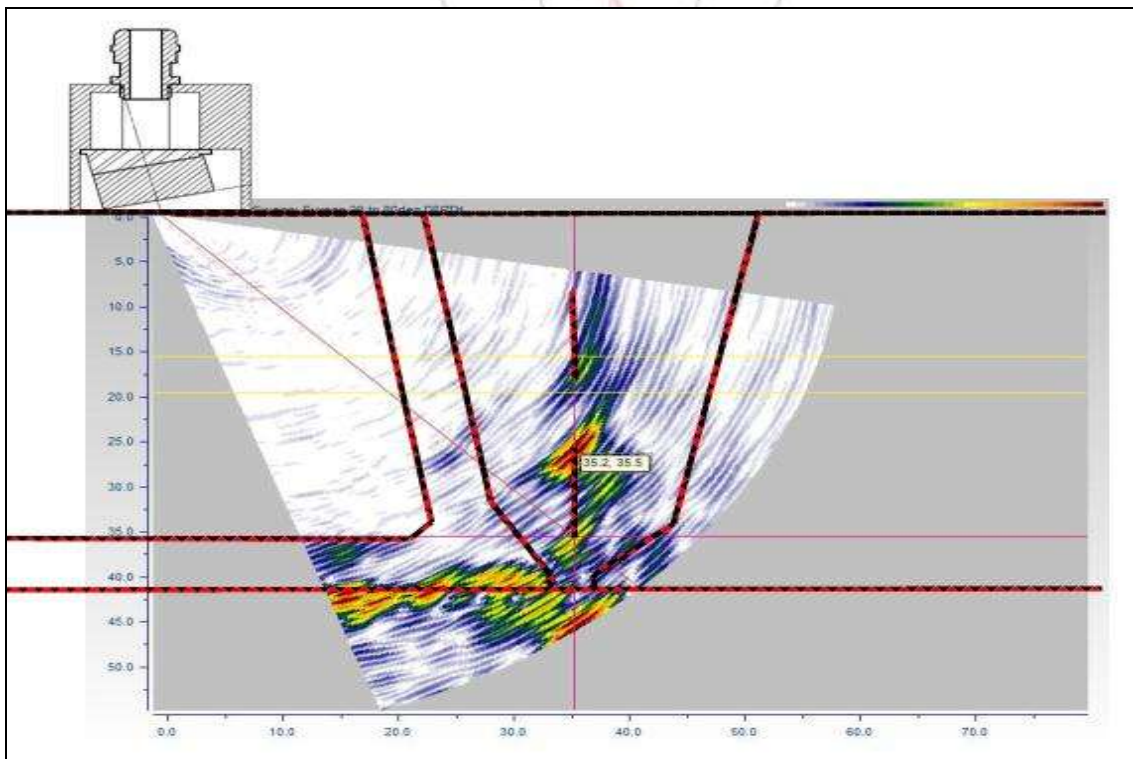


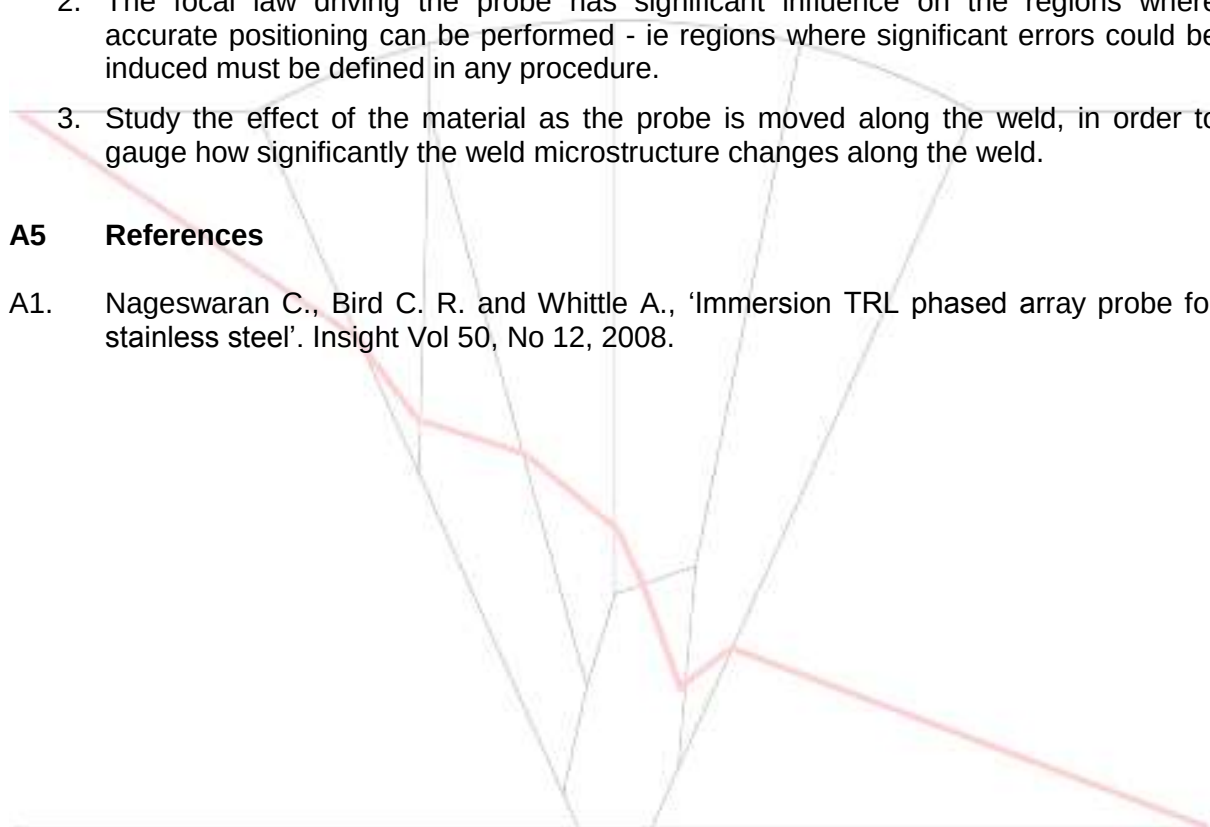
Figure A23 Diffracted signal from the root of slot L along the 45° beam; the gain is set to 52.25dB for 80% FSH.

A4 Recommendations

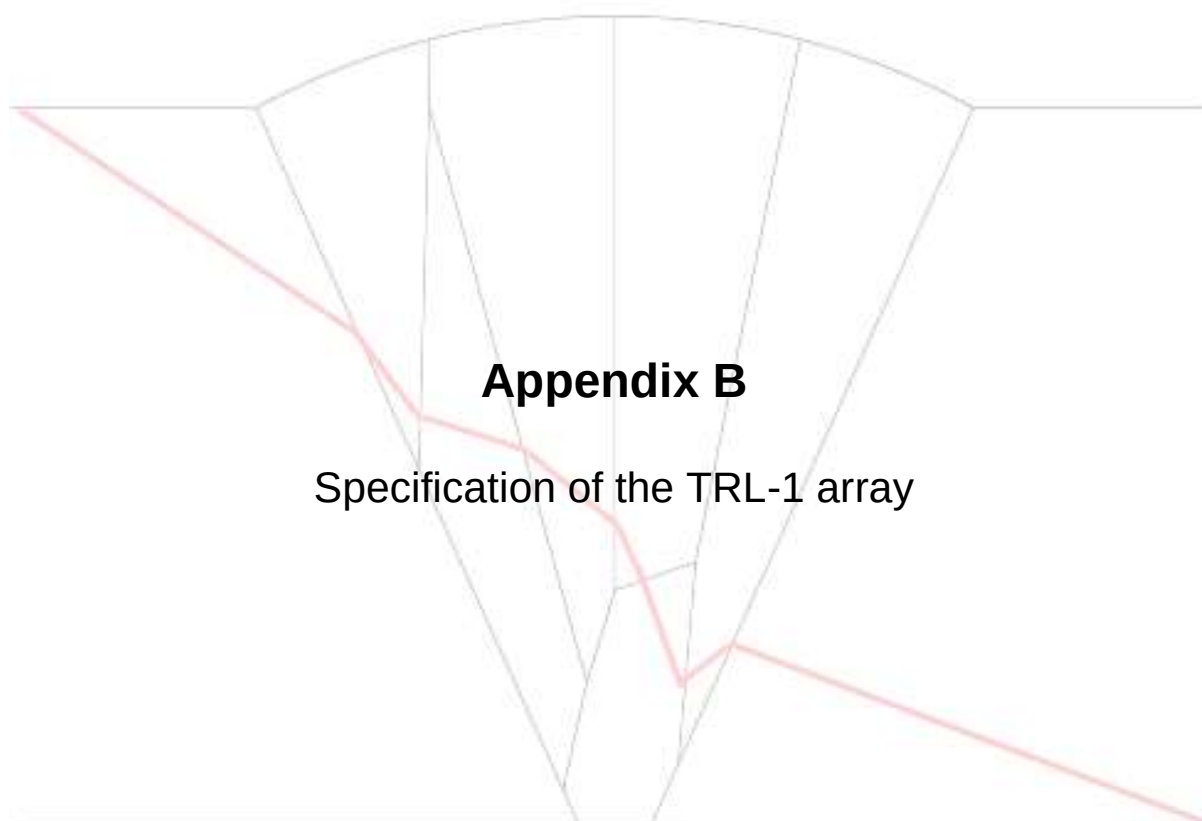
1. The work was performed with the nominal velocity set to that of ferritic steel (5900m/s). Positioning accuracy is greatly dependant on knowing the actual velocity of the sound wave along the propagation direction; hence, an essential task will be to measure the velocity of the stainless steel parent at different beam angles. Test blocks of the actual stainless steel material (or similar) need to be sourced, with SDHs at various ranges.
2. The focal law driving the probe has significant influence on the regions where accurate positioning can be performed - ie regions where significant errors could be induced must be defined in any procedure.
3. Study the effect of the material as the probe is moved along the weld, in order to gauge how significantly the weld microstructure changes along the weld.

A5 References

- A1. Nageswaran C., Bird C. R. and Whittle A., 'Immersion TRL phased array probe for stainless steel'. Insight Vol 50, No 12, 2008.



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Appendix B

Specification of the TRL-1 array

DISSIMILAR

B1 Description

This document is the specification of the phased array probe TRL-1 generated after iteration 3 of the first level specification study (see Section 4.4.1).

B2 Ultrasonic parameters

Parameter	Value	Comments
Probe type	Transmit – Receive	
Generated wave type	Longitudinal	
Array type	2D matrix	
Number of elements on primary axis (np)	32	See diagram
Element pitch of primary axis (pp)	4mm	See diagram
Number of elements on secondary axis (ns)	2	See diagram
Element pitch of secondary axis (ps)	6mm	See diagram
Inter element spacing	0.1mm	
Frequency	1.5MHz	
Bandwidth (-6dB)	≥ 80%*	
Pulse length (-20dB)	≤ 1.69μs*	
Wedge material	Water	
Wedge angle (i)	13.1°	See diagram
Wedge surface	N/A	
Wedge condition	N/A	
Roof angle (r)	2.5°	See diagram
Distance between the two inside edges of the array (l)	11mm	See diagram
Homogeneity in sensitivity	± 1 dB between adjacent elements	
Inter element cross talk	< -40dB	
Parasitic / internal echoes	<-60dB relative to a flat target echo*	

*measured in the conditions below

B3 Physical and electrical parameters

Parameter	Value	Comments
Overall length	~150mm	Dependent on holding frame
Overall width	~100mm	Dependent on holding frame
Overall height (with cable connector)	>100mm	
Cable	50Ω multi-coaxial with overall shielding	

Cable output	On top, centred plus cable restraint	
Cable length	5m	Halogen free jacket
Cable test	Simulated impedance at the end of the cable to be calculated	
Electrical matching	None	
Housing material	Stainless steel	Only materials approved for use in a Reactor Pressure Vessel
Connector type	Hypertronics compatible with R/D-Tech FOCUS	
Water coupling system	N/A	

B4 Identification/engraving

DISSIMILAR

TRL 1.5 MHz – 32x2 Elts

4mm Pitch Primary Axis

6mm Pitch Secondary Axis

Elements No 1 and 32 positions to be shown

B5 Using conditions*

Parameter	Value	Comments
Chemical constraints	Contact with water or ultrasonic water based gel	
Temperature	0° to 40° (storage) 10 to 40° (functioning)	
Excitation	Negative pulse 200V maximum (measured in 50 Ω environment)	
Max Repetition Frequency	10kHz	
Shocks and Vibrations	Operation on a submersed robotic delivery system	
Nuclear Radiation	None	
Normative Constraints	None	

B6 Pre-delivery checks

- ✓ Impedance measurement for all the elements at the nominal frequency.
- ✓ Inter-element coupling measurement on 2 pairs of elements.
- ✓ Checks performed in water on a flat target in pulse echo mode at 25mm to 100mm distance.
- ✓ Excitation signal: 1 negative pulse.
- ✓ Sensitivity homogeneity for all the elements.
- ✓ Temporal response & frequency spectrum measurement for 8 elements.

B7 Documentation to be supplied

Specifications of the probe
 Overall drawing of the probe
 Measurement results

B8 Guarantee

One year guarantee against design and manufacturing defects.

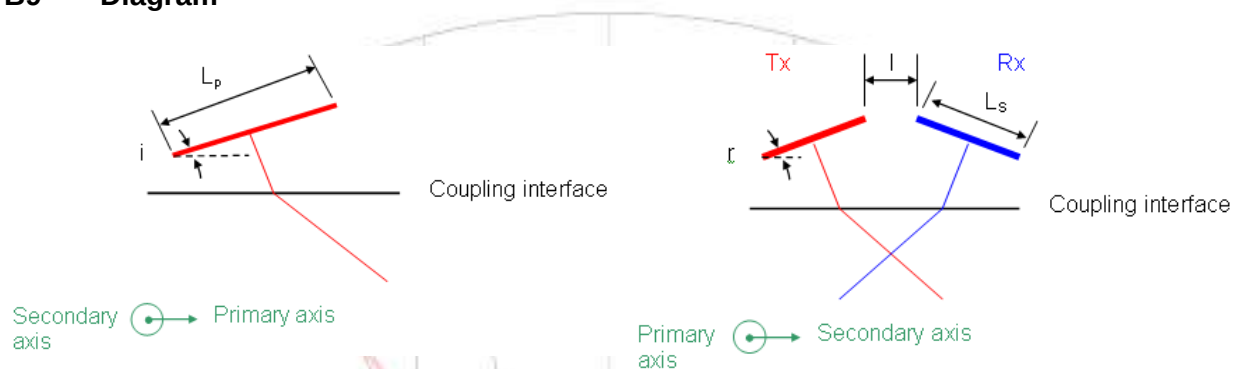
B9 Diagram

Figure B1: TRL-1 probe profile along the primary axis

Figure B2: TRL-1 probe profile along the secondary axis

Tx: Transmit array.

Rx: Receive array.

L_p : Aperture along the primary axis ($n_p \times p_p$).

L_s : Aperture along the secondary axis ($n_s \times p_s$)

i : Wedge angle.

r : Roof angle.

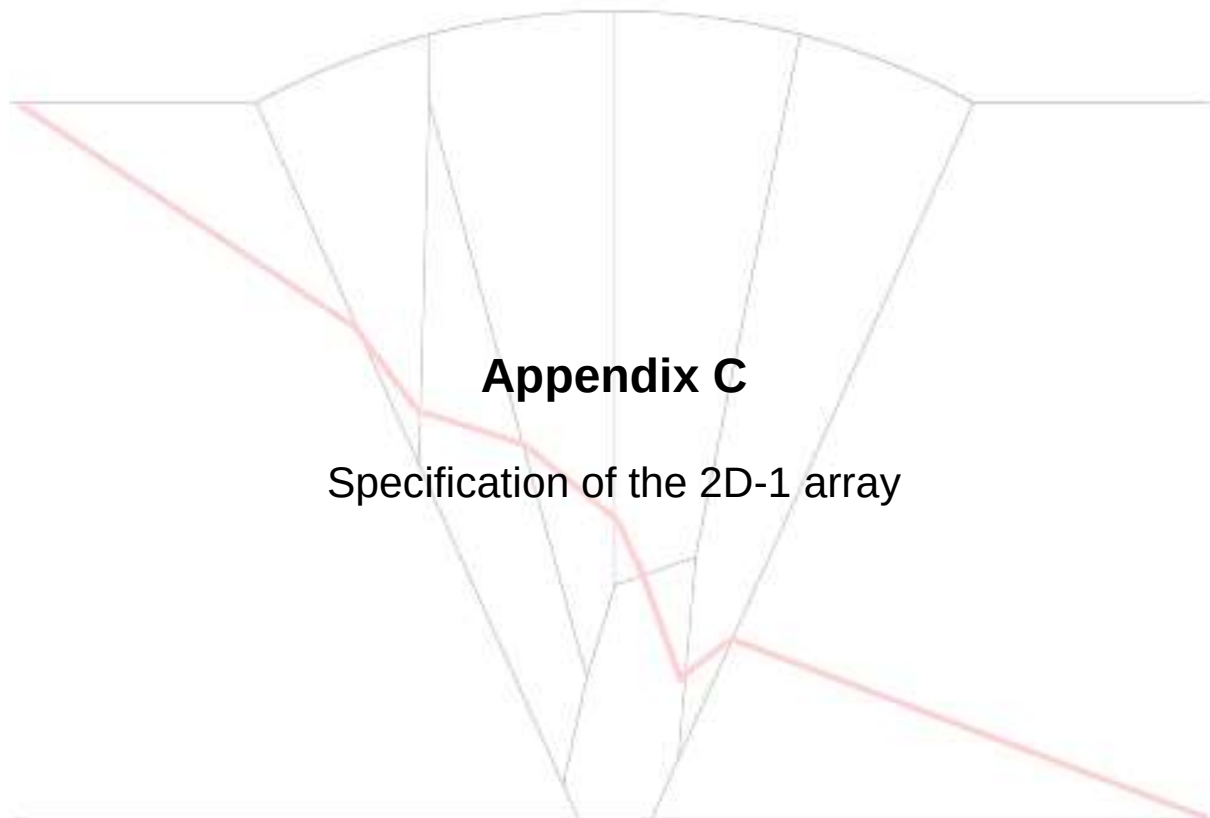
l : Distance between the two inside edges of the array.

n_p : Number of element along the primary axis.

n_s : Number of element along the secondary axis.

p_p : Element pitch along the primary axis.

p_s : Element pitch along the secondary axis.



DISSIMILAR

C1 Description

This document is the specification of the array probe 2D-1 generated from first level specification study (see Section 4.5).

C2 Ultrasonic parameters

Parameter	Value	Comments
Probe type	2D Array	
Generated wave type	Longitudinal	
Array type	2D matrix	
Number of elements on primary axis (np)	18	
Element pitch of primary axis (pp)	3.5mm	
Number of elements on secondary axis (ns)	7	
Element pitch of secondary axis (ps)	6.4mm	
Inter element spacing	0.1mm	
Frequency	1.5MHz	
Bandwidth (-6dB)	$\geq 80\%^*$	
Pulse length (-20dB)	$\leq 1.69\mu s^*$	
Wedge material	Rexolite	
Wedge angle (i)	18.5°	See diagram
Wedge surface	N/A	
Wedge condition	N/A	
Homogeneity in sensitivity	± 1 dB between adjacent elements	
Inter element cross talk	< -40dB	
Parasitic / internal echoes	<-60dB relative to a flat target echo*	

**measured in the conditions below*

C3 Physical and electrical parameters

Parameter	Value	Comments
Overall Length	96mm	
Overall Width	96mm	
Overall Height (without cable connector)	54mm	
Cable	50Ω multi-coaxial with overall shielding	
Cable Output	On top, centred plus cable restraint	
Cable Length	5m	Halogen Free Jacket
Cable Test	Simulated impedance at the end of the cable to be calculated	

Electrical Matching	None	
Housing Material	Stainless steel	Only materials approved for use in a Reactor Pressure Vessel
Connector Type	Hypertronics compatible with R/D-Tech FOCUS	
Water Coupling System	N/A	

C4 Identification/engraving

DISSIMILAR

2D Array 1.5 MHz – 18x7 Elts

3.5mm Pitch Primary Axis

6.4mm Pitch Secondary Axis

Elements No 1 and 18 positions to be shown

C5 Using conditions*

Parameter	Value	Comments
Chemical constraints	Contact with water or ultrasonic water based gel	
Temperature	0° to 40° (storage) 10 to 40° (functioning)	
Excitation	Negative pulse 200V maximum (measured in 50 Ω environment)	
Max Repetition Frequency	10 kHz	
Shocks and Vibrations	Operation on a submersed robotic delivery system	
Nuclear Radiation	None	
Normative Constraints	None	

C6 Pre-delivery checks

- ✓ Impedance measurement for all the elements at the nominal frequency.
- ✓ Inter-element coupling measurement on 2 pairs of elements.
- ✓ Checks performed in water on a flat target in pulse echo mode at 25mm to 100mm distance.
- ✓ Excitation signal: 1 negative pulse.
- ✓ Sensitivity homogeneity for all the elements.
- ✓ Temporal response & frequency spectrum measurement for 8 elements.

C7 Documentation to be supplied

Specifications of the probe
Overall drawing of the probe
Measurement results

C8 Guarantee

One year guarantee against design and manufacturing defects.

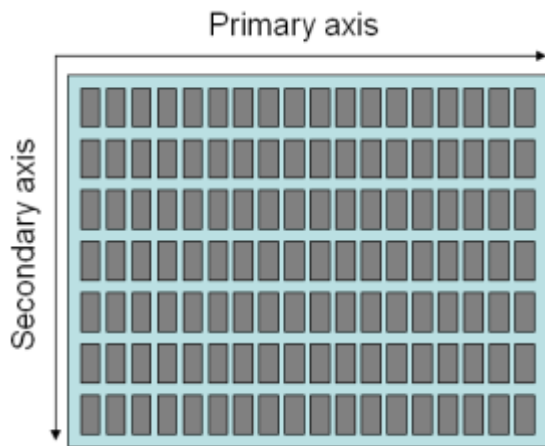
C9 Diagrams

Figure C1: 2D-1 array probe profile along the primary axis and secondary axis

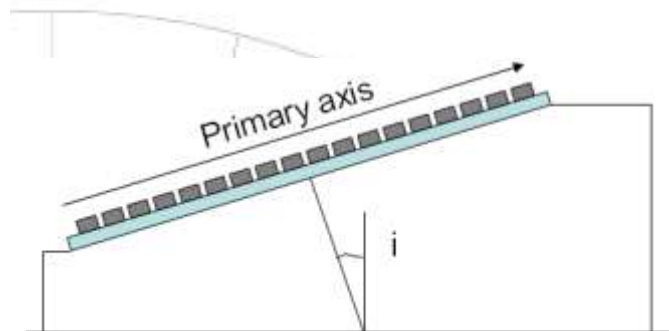
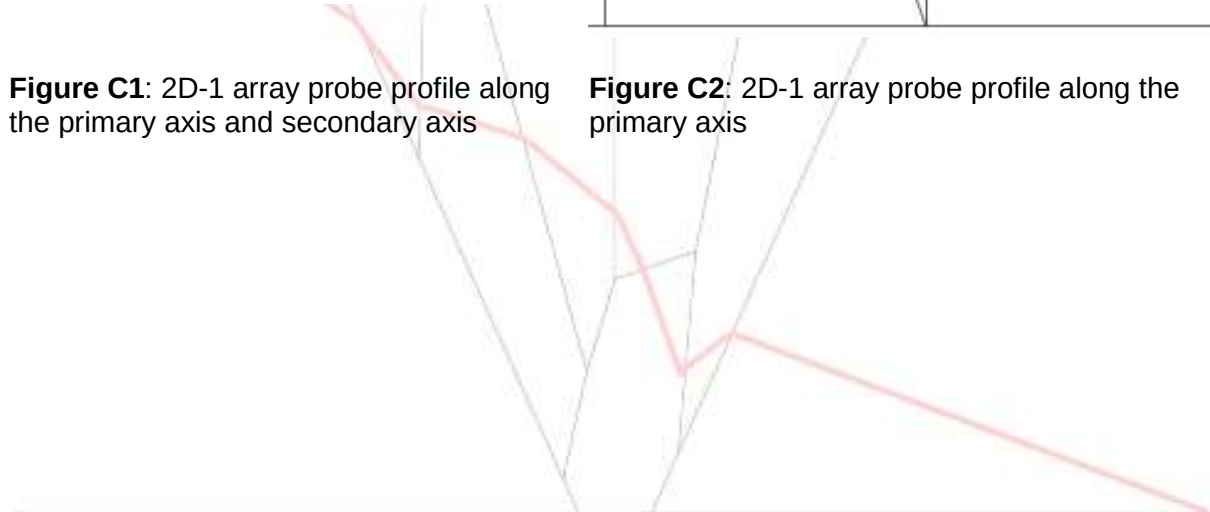
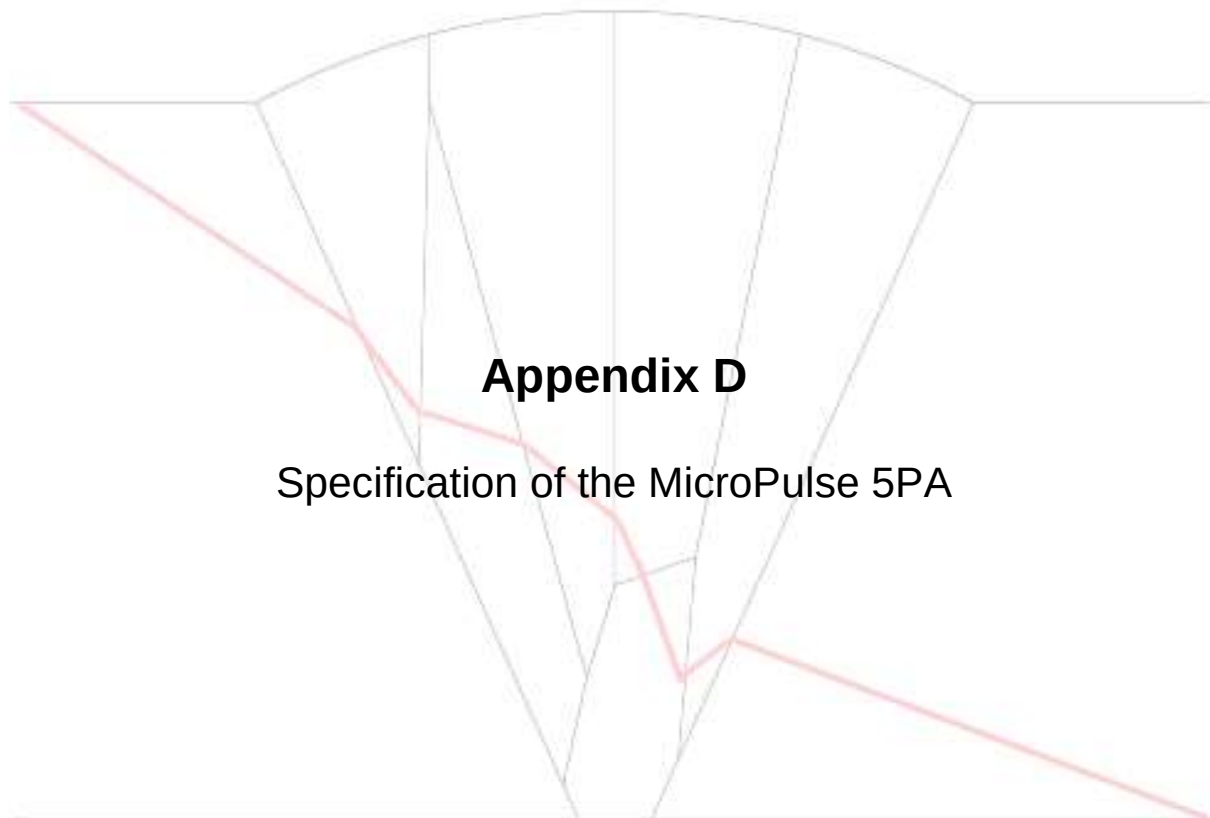


Figure C2: 2D-1 array probe profile along the primary axis





Appendix D

Specification of the MicroPulse 5PA

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Product overview

Phased Array MicroPulse (64/64, 128/128, 256/256, 512/512, all channels may be used for beam forming). The unit has the flexibility to output individual A-scans prior to summation and optional separate channels for high-performance pulse-echo and TOFD (available in multiples of 16 channels).

Software platforms

PNL ArrayGen with SimulUS beam modelling software as standard and compatible with British Energy MIPS/GUIDE and UTEX Winspect / InspectionWare. Open data format and long-established MicroPulse command language mean that the users have the option to write their own applications.

Contact details

Peak NDT Ltd
Unit 1, Enterprise Way,
Jubilee Business Park
Derby
DE21 4BB

Tel: +44(0)1332 738752 fax: +44(0)1332 73887 e-mail: sales@peakndt.com

NOTE: Peak NDT Ltd. reserves the right to change these specifications without notice.

Specification of phased array channels

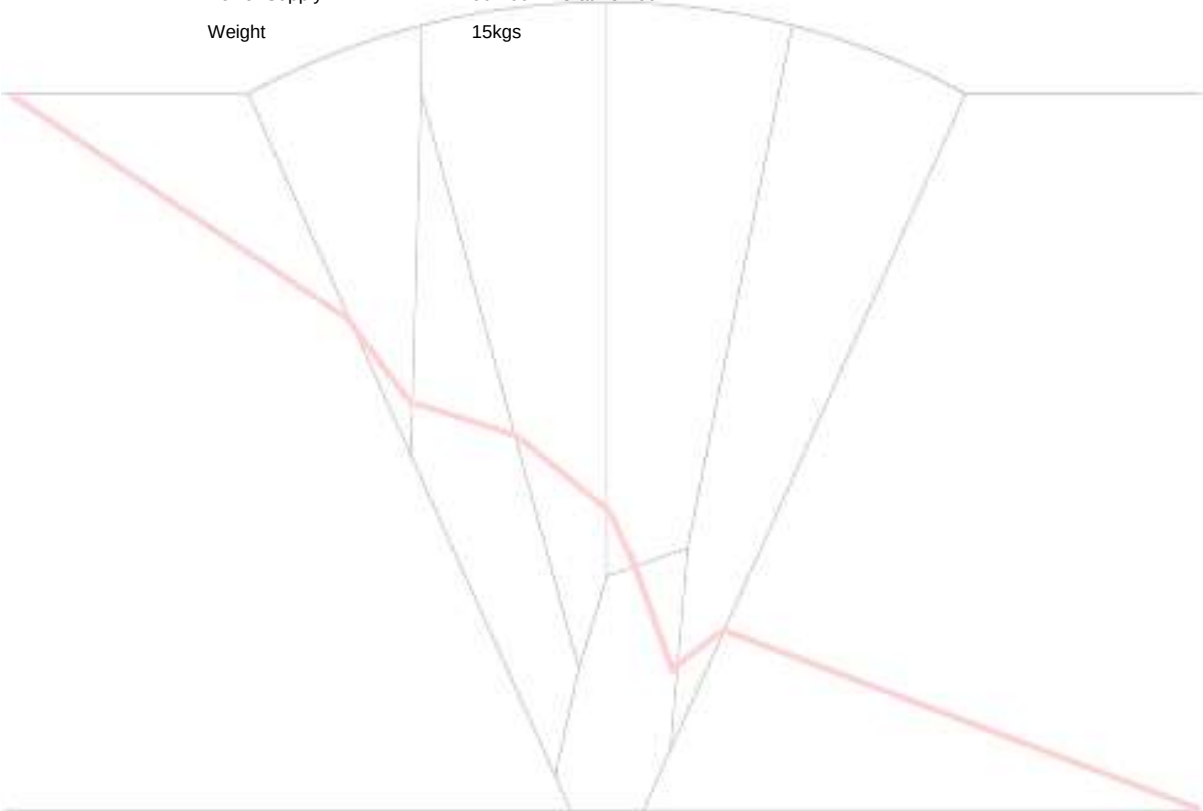
	Parameter	Range	Step Size
Pulser	Pulser Type	Negative square wave	N/A
	Pulser Voltage	5 to 200Volts	5Volt
	Pulser Rise Time	<5ns	N/A
	Pulser Width	20nsec to 500nsec	2nsec
	Pulse Repetition Frequency	1Hz to 20kHz	1Hz
	Pulser Delay	0 to 25000nsec	1nsec
Receiver	Gain	70dB	0.25dB
	Input Noise	2nV typical	N/A
	Gain Linearity	Better than 0.25dB	N/A
	Input Impedance	50Ω	N/A
	Bandwidth	0.75MHz to 20MHz (-3dB)	N/A
	Filters	0.75MHz to 5MHz (-3dB) Bandpass Filter 5MHz to 10MHz (-3dB) Bandpass Filter 2MHz to 10MHz (-3dB) Bandpass Filter 0.75 to 20MHZ Broadband	Discrete selection
	Receiver Delay	0 to 25000ns	1nsec
	Dynamic Depth Focusing	At 100MHz realtime	N/A
	Channel Crosstalk	Better than 60dB between channels at 2MHz	N/A
Distance Amplitude Correction	DAC Dynamic Range	0 to 40dB	0.25dB
	DAC Trigger	Transmit pulse or material interface echo	User selectable
	No of DAC curves	256 utilising up to 64kbytes	N/A
	DAC update	40dB/μsec	N/A
	DAC clock rate	0.78125MHz, 1.5625MHz, 3.125MHz, 6.25MHz, 12.5MHz and 25MHz selectable	
Digitiser and Digital Processing	ADC Resolution	12 bits	N/A
	ADC Rate	10, 25, 50 and 100MHz	
	Number of ADC's	One per channel	
	Element Summing	Up to 512 channels	N/A
	Rectification	No Rectification Fullwave +ve halfwave -ve halfwave	Discrete selection
	Post Rectification Filter	None and 7 selectable settings	
	Gates	1 gate of up to 32k sample points	N/A
	Gate Delay	64k sample points from trigger or I/F echo	
	Hardware Peak Processing	for each gate up to 80 peaks (N + largest), first peak, largest peak	
	Peak Threshold	5 to 2047%	½%
	Averaging	2 to 256 realtime	
	GRE	1 element, n elements or summed waveform	

Specification of conventional channels

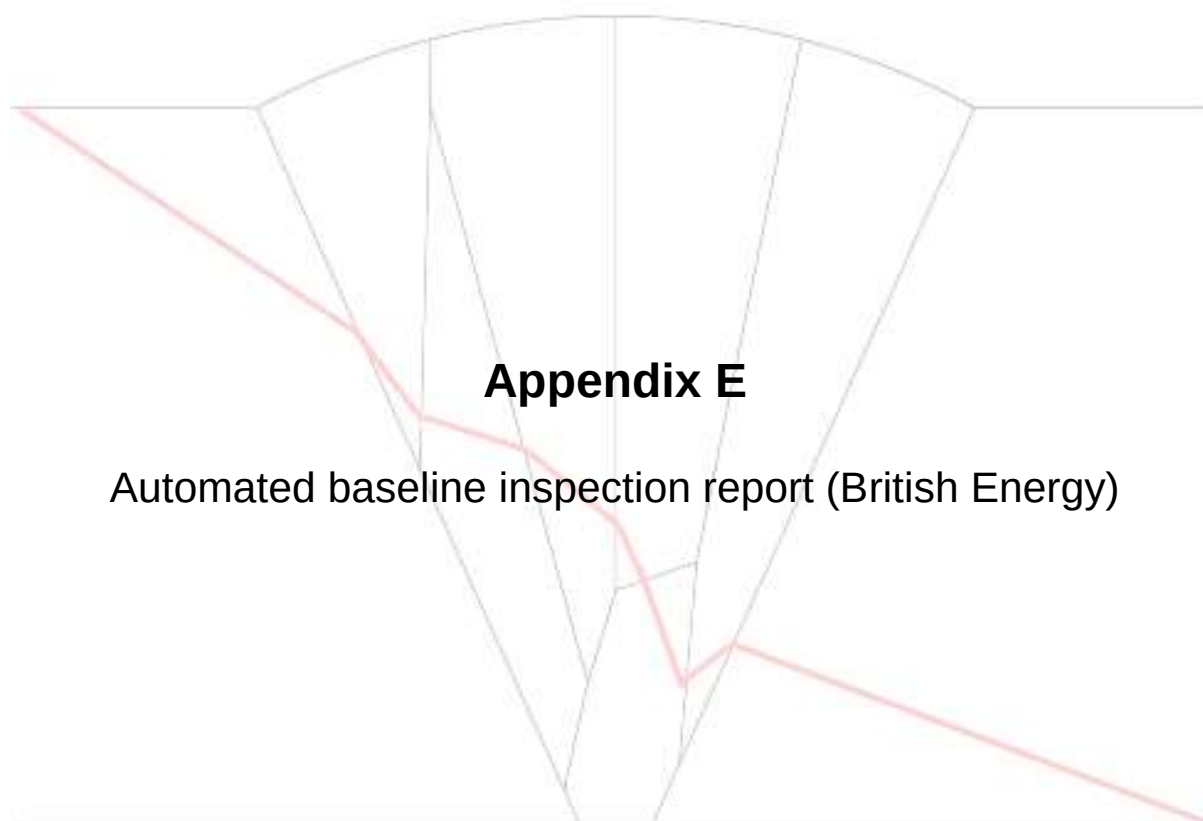
	Parameter	Range	Step Size
Pulser	Pulser Type	Negative square wave	N/A
	Pulser Voltage	50 to 300Volts	50Volt
	Pulser Rise Time	<5ns	N/A
	Pulser Width	20nsec to 500nsec	2nsec
	Pulser Damping	50Ω to 660Ω in 8 steps	N/A
	Pulse Repetition Frequency	1Hz to 20kHz	1Hz
Receiver	Gain	70dB	0.25dB
	Input Noise	2nV typical	N/A
	Gain Linearity	Better than 0.25dB	N/A
	Input Impedance	660Ω	N/A
	Bandwidth	0.75MHz to 25MHz (-3dB)	N/A
	Filters	0.75MHz to 12MHz (-3dB) Bandpass Filter	Discrete selection
		2.5MHz to 18MHz (-3dB) Bandpass Filter	
		3MHz to 22MHz (-3dB) Bandpass Filter	
		3MHz to 25MHz (-3dB) Bandpass Filter	
		0.5MHz Bandpass Filter	
		1MHz Bandpass Filter	
		2MHz Bandpass Filter	
		4MHz Bandpass Filter	
		5MHz Bandpass Filter	
		10MHz Bandpass Filter	
		5MHz 2 nd order TOFD Bandpass Filter	
		10MHz 2 nd Order TOFD Bandpass Filter	
	Channel Crosstalk	< 60dB between channels at 2MHz	
Distance Amplitude Correction	DAC Dynamic Range	0 to 40dB	0.25dB
	DAC Trigger	Transmit pulse or material interface echo	User selectable
	No of DAC curves	32 utilising up to 32kbytes	N/A
	DAC update	40dB/μsec	N/A
	DAC clock rate	0.78125MHz, 1.5625MHz, 3.125MHz, 6.25MHz, 12.5MHz and 25MHz selectable	
Digitiser and Digital Processing	ADC Resolution	12 bits	N/A
	ADC Rate	10, 25, 50 and 100MHz	N/A
	Rectification	No Rectification	Discrete selection
		Fullwave	
		+ve halfwave	
		-ve halfwave	
	Post Rectification Filter	None and 7 selectable settings	N/A
	Gates	1 gate of up to 32k sample points	
	Gate Delay	64k sample points from trigger or I/F echo	
	Hardware Peak Processing	for each gate up to 80 peaks (N + largest), first peak, largest peak	
	Peak Threshold	5 to 2047%	½%
	Averaging	2 to 256 realtime	

General specifications

Connectors and Interfaces etc	Phased Array Connector	160-pin female connector. Hypertronics™ HLMYJPAPF1600
	Conventional UT Connector	Triaxial 1S connector. Lemo ERA.1S.650.CTL
	Interface	Gigabit Ethernet capable of up to 20Mbyte per second
	Encoders	4 axes of 32 bit encoder inputs accepting encoders between 5 and 15Volt and at rates of up to 700kHz
	Digital I/O	8TTL compatible inputs and 8 open collector outputs capable of sinking up to 400mA
	Oscilloscope Outputs	Trigger, Gate, A-scan. Showing either an individual channel or a summed waveform (reconstituted analogue signal obtained from digitised waveform)
	Case Size	450mm x 380mm x 170mm
	Power Supply	90-260 VAC at 45-100Hz
	Weight	15kgs



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Appendix E

Automated baseline inspection report (British Energy)

DISSIMILAR



Engineering

Report

TSB Sponsored Project: Phased Array Ultrasonic Inspection of Dissimilar Metal Welds

MIPS / GUIDE Automated Ultrasonic Inspection of 'DISSIMILAR' Project Test Welds - 'Conventional' Fingerprint Inspection

By: **JE Pearce, IG Lincoln**

Date: **July 2009**

British Energy Generation Limited
Central Engineering Support
Engineering Technology Branch
Inspection Group

**BRITISH ENERGY GENERATION LIMITED
CENTRAL ENGINEERING SUPPORT**

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SUMMARY SHEET

Project: **TSB Sponsored Project: Phased Array Ultrasonic Inspection of Dissimilar Metal Welds**

Document Title: **MIPS / GUIDE Automated Ultrasonic Inspection of 'DISSIMILAR' Project Test Welds – 'Conventional' Fingerprint Inspection**

Document Reference: **E/TSK/GEN/7228/19**

Document Author: **John Pearce, Ian Lincoln**

Date: **July 2009**

Task File Number: **E/TSK/GEN/7228**

Summary

Test specimens comprising 85 mm thick Inconel safe-end transition welds have been produced as part of the TSB sponsored DISSIMILAR Project. As a contribution to the project, BE Inspection Group have performed an automated ultrasonic inspection of the two blocks, using the MIPS / GUIDE system. This was to provide a 'conventional' inspection fingerprint of the welds and the implanted defects, and to provide a baseline of current inspection capability for subsequent comparison with optimised Phased Array ultrasonic inspections.

The two blocks have been scanned from both outer and inner surfaces and both axial directions, using a range of 0° and angled compression wave beams. Additional sizing scans have been implemented to provide the best sizing information possible.

The inspection data has been interpreted by two experienced data interpreters and the findings and measurements have been verified before being tabulated and presented in this report. The results take the form of signal-to-noise ratio values for the defects detected and best estimate positioning and sizing values.

The usual guidelines for effective inspection of thick-section austenitic welds are borne out: use all available scanning surfaces, attempt to minimise beam paths through weld metal, use beams with appropriate arrangements to maintain effective beam shapes, match inspection frequencies to materials, etc..

The capability demonstrated on these test specimens is consistent with BE experience from inspection qualification exercises on similar welds.

Conclusions

- (1) The two test blocks produced under the DISSIMILAR Project have been inspected using BE's MIPS / GUIDE automated ultrasonic inspection system and using methods and techniques typical of the inspection of this type of joint in nuclear power plant.
- (2) The data produced by these inspections provides a 'conventional' fingerprint of the welds, for future comparison with optimised Phased Array inspections.
- (3) All the defects have been detected, with varying margins of signal-to-noise ratio.
- (4) The defects have been positioned and sized within the expected tolerances for this thickness of austenitic weld.
- (5) The results of all the defect detection assessments and positioning and sizing measurements have been 100% verified and tabulated in this report.
- (6) The delivery of this report completes BE's Action 11 from the 3rd Quarterly Meeting.

VERIFICATION CERTIFICATE

Document Title:	MIPS / GUIDE Automated Ultrasonic Inspection of 'DISSIMILAR' Project Test Welds – 'Conventional' Fingerprint Inspection
Project:	TSB Sponsored Project: Phased Array Ultrasonic Inspection of Dissimilar Metal Welds
Document Reference: Revision: Task File Number: QA Grade of document:	E/TSK/GEN/7228/19 000 E/TSK/GEN/7228 4
Author: Section/Group:	John Pearce, Ian Lincoln Inspection Group / Engineering Technology Branch
Verification Applied:	i) Review of MIPS Setups and inspection records ii) Separate and independent interpretation of data iii) Verification of Detection and Signal-to-Noise Ratio Tables iv) Verification of Defect Position and Sizing Tables v) Review of Report, checks for accuracy, Figures, Tables
Technical Reviewer(s): Section/Group: Technical Review Details:	Not applicable. Report produced internally.

DOCUMENT ISSUE / AMENDMENT CERTIFICATE

Date	Authors	Revision	Amendment
July 2009	JE Pearce, IG Lincoln	000	Original Issue

GLOSSARY

BWE	Backwall Echo (strong planar response from far surface, usually from 0° beam)
BWR	Boiling Water Reactor (nuclear plant type)
DAC	Distance-Amplitude Correction (increasing gain with range along beam)
DMW	Dissimilar Metal Weld
EDP	Echodynamic Pattern (characteristic signal response)
EMI	Electromagnetic Interference (noise in ultrasonic signals from external source)
FSH	Full-Screen Height (100% deflection measurement on flaw detector instrument)
GUIDE	Graphical Ultrasonic Inspection Data Evaluation – BE data analysis system
MMA	Manual Metal Arc (welding process)
MIPS	Micropulse Inspection and Processing System – BE data acquisition system
MRF	MIPS Results File (initial output from MIPS – raw data file)
PRF	Pulse Repetition Frequency (control of time gap between probe firings)
PRG	Primary Reference Gain (gain to bring Reference Reflector signal to 80% FSH)
PWR	Pressurised Water Reactor (nuclear plant type)
RGC	Run Gain Correction (additional gain added to modify inspection sensitivity)
RPV	Reactor Pressure Vessel (central part of nuclear power plant)
SDH	Side-Drilled Hole
SNR	Signal-to-Noise Ratio (discrimination between signal and background noise)
TRL	Transmit-Receive Longitudinal (ultrasonic compression wave probe design)
TSB	Technology Strategy Board

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1. Purpose

This report summarises the activities carried out at British Energy, Barnwood, in May and June 2009, in connection with the TSB sponsored 'DISSIMILAR' project on Phased Array Ultrasonic Inspection of Dissimilar Metal Welds. Specifically, the report describes the 'conventional' automated ultrasonic inspection of the 85 mm thick Inconel safe-end transition weld specimen produced under the 'DISSIMILAR' project. The two parts of this specimen were subject to detailed inspection using the British Energy MIPS / GUIDE system, to provide a 'fingerprint' of the welds and the implanted defects, and to provide a baseline of 'conventional' inspection capability for comparison with subsequent Phased Array inspections.

2. Background

The TSB sponsored 'DISSIMILAR' project has the main aim of using Phased Array technology to improve the reliability of inspection of safe-end transition welds (or Dissimilar Metal Welds, DMW, in American parlance). This is to be achieved by:

- i) better knowledge of austenitic weld metal grain alignment, alignment distributions and alignment variations;
- ii) advanced modelling of sound wave propagation through textured and anisotropic weld metal;
- iii) advanced design and prototyping of new Phased Array transducers, employing computer modelling and improved piezo-electric materials;
- iv) high-specification ultrasonic instrumentation, capable of handling high element number arrays;
- v) formulation and testing of advanced delay law algorithms to mitigate for the disruptive effects of propagation through textured and anisotropic weld metal.

As part of this project, a heavy-section safe-end transition weld specimen has been produced, to provide test material to assess weld metal grain alignment and homogeneity, and to test the new inspection equipment and techniques. This weld is 85 mm thick and the original block was more than 600 mm long. It was welded with Inconel 182 filler weld metal, using the Manual Metal Arc (MMA) process and it is generally typical of safe-end transition welds between low alloy steel vessels and stainless steel pipework in light water-cooled nuclear plant (PWR, BWR). Figures 1A and 1B illustrate the dimensions and defect details of the specimen, which was sectioned into two parts, designated Block 'A' and Block 'B' (Figure 2).

As part of their contribution to the project, British Energy offered to perform a 'conventional' automated ultrasonic inspection of the weld specimen, using equipment and techniques typical of those currently employed to inspect such welds in nuclear plant. This would involve the use of the MIPS / GUIDE system and be intended to provide the following:

- i) a 'fingerprint' record of the test specimen weld and the implanted defects;
- ii) a baseline of typical inspection capability using 'conventional' techniques and equipment, for comparison with subsequent Phased Array inspections.

3. Inspection Techniques and Procedure

Due to the specimen's similar thickness to the Sizewell B Steam Generator Primary Nozzle safe-end transition weld, the probe set for that inspection was chosen as the basis for the techniques (11.1), but with a number of additional probes to provide the optimum capability. The full list of probes / beams is given below in Table 1, but they include:

- i) single- and twin-crystal 0° compression;
- ii) twin-crystal angled compression (TRLs) at 1, 1.5 and 2 MHz;
- iii) single-crystal (elliptical) angled compression.

Since the test specimen weld also resembles typical PWR RPV nozzle safe-end transition welds (older US, Westinghouse-design plant), it was decided that inspection from the internal surfaces would also be performed, as that is typically the access for RPV weld inspection.

Scanning would use a XY frame, with the block immersed in water in a custom-made stainless steel container. Scans would be performed from both external and internal surfaces, and in both axial directions. No transverse scans would be performed.

Scanning increments of 2 mm Primary by 4 mm Secondary would be used for search scans (typical for this size of weld). This means that the probes would be fired at every 2 mm pitch along the scanning direction (Primary line) and then the next Primary line would be scanned after a 4 mm sideways (Secondary) step.

Scanning sensitivity would be set to collect material noise ('grass') on all scans, but with the calibration and scanning sensitivity recorded using Ø3 mm Side-Drilled Holes (SDHs) in fine-grain, low-attenuation forged austenitic calibration blocks. MIPS Distance-Amplitude Correction (DAC) would be employed on all scans.

MIPS processing would allow the data from all scans to be plotted relative to the same component co-ordinate system and datum reference points.

Data interpretation would be based on thresholding the data to an amplitude corresponding to the peak grass level, and then marking clusters of indications with Signal-to-Noise Ratios (SNRs) of 6 dB or more. These would then be boxed and collated using the 'Box / Crate' facilities within GUIDE.

Once the main defect areas have been identified, then more detailed sizing scans, using smaller scan increments, and some different probes / beams, would be applied to maximise the sizing and characterisation information.

Defect positioning and sizing are performed using methods corresponding to the echodynamic patterns (EDPs) exhibited by the defects. Generally, Pattern 2 EDPs in the longitudinal direction indicate a smooth reflector with length, and positioning and sizing are done by the 6 dB amplitude drop method. Pattern 2 EDPs in the throughwall direction indicate a planar reflector with significant throughwall extent. These are also sized by the 6 dB drop method. Pattern 3 EDPs often originate from rough defects, and the maximum amplitude method is employed to make estimates of position and extent. The most reliable method for throughwall sizing will be by the detection, identification and positioning of diffracted edge wave signals from defect extremities. Maximum amplitude sizing is used whenever defect tip echoes are visible. All of these sizing aspects are made less straightforward by the characteristics of austenitic weld metal.

4. Physical Setup and Equipment

The inspection of the DISSIMILAR Blocks 'A' and 'B' used a normally-configured MIPS system:

- MIPS PC with printer
- Micropulse
- Motor Controller
- Manipulator

The manipulator used was an existing XY scanning frame with adjustable height feet and modular probe holder fittings. This had sufficient Primary stroke and Secondary travel to cover the scan lengths required. The Primary drive does suffer from a minor degree of backlash, but was acceptable for search scans. For the sizing scans, all data collection was performed whilst scanning in one direction, to eliminate the effects of backlash.

A specially-made stainless steel immersion tank was fabricated to allow the blocks to be scanned immersed in water. The tank was situated on the floor to reduce the need to lift the blocks and to minimise the height to which they would need to be lifted to position them, mainly for handling safety reasons.

Figure 4 shows the setup of the XY frame and the immersion tank.

BE currently uses the Peak NDT Micropulse 4 generation of digital, programmable ultrasonic flaw detectors as its mainstay for automated inspections using MIPS / GUIDE. BE has one Micropulse 5 PA with a second on order.

Block 'B' was scanned first, using a Micropulse 4 (S10056). Block 'A' was scanned later, using a Micropulse 5 PA (S15029) set to mimic a Micropulse 4. Both units had been calibrated within the previous 12-month period, and both were subject to linearity checks (timebase and amplifier) prior to use.

The probe set used for these inspections is detailed in **Table 1** below. These are a combination of single- and twin-crystal compression wave probes, mainly produced by one of the leading manufacturers of such specialised probes, Applus-RTD, Rotterdam, the Netherlands. The probes were all subject to functional performance checks prior to use.

In order to 'harden' the system against noise and electromagnetic interference (EMI), the cabling between the Micropulse and the probes has no inter-connections and is made from high-specification Sühner TriAx cable. The connections at the Micropulse and probe ends are made with Lemo TriAx connectors. The same leads used for scanning were used for the probe checks and the calibration.

The calibration blocks used to check the probes and to set the probe shoe delays and the scanning sensitivity were R25 and R50 radius blocks and a rectangular DAC block with a range of Ø3 mm SDHs at different depths. These blocks are made from low-attenuation forged austenitic stainless steel with a known fine grain size (ASTM 5 or better, by E112-96). These blocks are detailed on the BE Inspection Group Test Block Register database. **Figure 6** illustrate the 3 blocks used for this work. Due to the small differences in velocities between Inconel and austenitic stainless steel, there may be small errors in positioning due to angle and range changes, but there are three different materials in this weld, so a compromise choice needs to be made.

5. Scanning Parameters and MIPS Setup

All the scanning employed the same MIPS PC, running the V1.22 version of MIPS. Each scan with a particular beam, in each of the four surface / direction combinations, is defined with a separate MIPS Setup file. So-called 'long' MIPS codes were used to allow more meaningful Setup naming:

Site Code: **TWI**

Component Code: **BLA, BLB** – Block 'A', Block 'B'

Run Code: **OD0XX** – outer surface, sequential numbering
ID0XX – inner surface, sequential numbering
ODSXX – outer surface, sizing scan
IDSXX – inner surface, sizing scan

20 search scans from the outer surface and 16 search scans from the inner surface were carried out on each block.

Figure 5 illustrates the XYZ co-ordinate system used.

The **X axis** is normal to the weld and **+X** runs towards the austenitic side, **-X** runs towards the ferritic side. **X = 0** is the weld centreline, taken as 250 mm in **+X** from the ferritic end edge.

The **Y axis** is parallel to the weld. **+Y** runs left to right when looking down on the outer surface towards **+X**. **Y = 0** is at the left hand edge when looking down on the outer surface towards **+X**.

The **Z axis** is normal to the surface, with **Z = 0** at the outer surface and **+Z** towards the inner surface.

The use of the MIPS Processing **AG2** Geometry Code allows all the data from all beams to be imaged with reference to the same co-ordinate system and the same datum reference points, regardless of scanning direction or surface. The system is given details of the change of surface and the block thickness, and the geometry code sorts out all the plotting issues. Note that the data is also fully corrected for beam angle and emission point offsets, and effectively plotted in the real-space co-ordinates from which it originated.

Some of the common data entered for use across multiple scans:

Compression Velocity, $V_L = 5750 \text{ ms}^{-1}$

Shear Velocity, $V_T = 3150 \text{ ms}^{-1}$

(velocities for austenitic stainless steel – half the scans are through this material and the calibration blocks are also made of it)

Micropulse Pulser Voltage = 300 V

Micropulse Digitisation Frequency = 25 MHz

Micropulse Peak Detection per Test Gate = 20 = Largest indication + next 19 from front of test

Because it was an inspection on austenitic materials, and high levels of material noise were expected, as each probe was scanned, the associated MIPS Beam was divided into a number of shorter test gates, to ensure that the system's peak detection capacity was not exceeded. Therefore a beam interrogating a range of 95 – 225 mm (130 mm) would have 6 overlapping tests, none more than 30 mm long.

As part of the probe performance checks, the MIPS Beam parameters for each probe are optimised – these include excitation pulse width, receiver bandwidth / filter, signal smoothing and damping.

Along with each search beam, an associated grass coupling check beam was implemented. This monitors a set gate for a specified grass amplitude level, to ensure adequate coupling. Whilst this is done routinely and represents good practice, when scanning in immersion, it really only serves to indicate if the scanning surface is very poor or the probe has tripped over something. No issues with coupling were encountered on any of the scans covered by this report.

The probes were calibrated and the scanning sensitivity was set as follows:

- i) a specific Ø3 mm SDH is chosen to be the Reference Reflector for each beam – usually a hole at a depth corresponding either to the beam focus (TRLs) or at the start of the DAC; the range of this reflector is checked and a gate bracketing this range is entered in MIPS as the Full Calibration gate;
- ii) the amplitude required to bring the Reference Reflector to 80% Full-Screen Height (FSH) is the Primary Reference Gain or PRG. This is set as the MIPS Calibration Gain. A MIPS Full Calibration routine demands that the signal from the Reference Reflector is acquired in the calibration test gate and brought to between 70 and 90% FSH by adjustment of the Calibration Gain; the results of this sequence is automatically printed out, as part of the inspection records;
- iii) with a data acquisition (recording) threshold of 10% FSH, then the applied sensitivity is Ø3 mm SDH + 18 dB; a minimum of 2 dB Run Gain Correction (RGC) is added to bring the applied sensitivity up to Ø3 mm SDH + 20 dB or 10% DAC; this means that the lowest amplitude signal which will be recorded will be one which is 20 dB weaker than that from a Ø3 mm SDH;
- iv) for inspections on austenitic materials, it is general policy to increase the sensitivity until material noise is recorded. At this level, any defect with significant signal-to-noise ratio above the material noise will definitely also be recorded. This usually occurs for sensitivities of Ø3 mm SDH + 20-30 dB, depending on the parent materials and the coarseness of the weld structure.

Clearly, for such inspections on austenitic materials, due to the effects of attenuation, the term sensitivity does not have the same quantitative meaning as it does for other inspections, and many measurements are made relative to peak noise levels. However, BE procedures require all measurements to be referenced to the nominal sensitivity with respect to a Ø3 mm SDH DAC. This helps with inspection repeatability and comparison between data sets.

For all the search scans, the scanning pattern used a 2 mm Primary increment and a 4 mm Secondary increment, both typical for this size of weld. For sizing scans, these increments were reduced to 0.5 x 0.5 mm, and data collection was performed in a single scanning direction to mitigate against the slight backlash on the Primary drive.

The target inspection volume to be covered by the range of search beams was defined as the full volume of weld metal and parent material up to 15 mm from the weld fusion faces, as shown in **Figure 7**. The various different beams are aimed to cover specific areas of this inspection volume and no one beam covers the full volume, rather the coverage combines to provide full, and usually redundant, coverage of the complete inspection volume.

6. Description of Data Files Produced

As noted above, each probe / beam scanned produces a single, separate MIPS Results file. So with 36 search scans per block and 29 sizing scans in total, there were a total of 101 MIPS Results files (.MRFs) comprising 196 MB.

When processed, each MRF produced 2 MIPS Flaw files, one (Beam 01) containing the geometry-corrected data from the inspection beam and the second (Beam 02) the results of the grass coupling monitoring. (The 0° beams did include a 2nd search beam to cover the Backwall Echo (BWE) at reduced gain, so these 4 files produced 3 Flaw files each). Therefore, all assessment work was performed on the Beam 01 files. There were 101 of these produced, totalling 516 MB.

A GUIDE data interpretation PC, running the **V1.13d** version of GUIDE was then used to image the Flaw files, initially producing orthogonal B-, C-, and D-scan views of the complete data volume. The data was examined on a beam-by-beam basis, to establish, to start with, that it was of the correct quality to pass for detailed interpretation and analysis. This involves checking the MIPS records, the calibration printouts and the Run Logs, and comparing the data images to ensure that they match. The scan limits and the limits of the processed data volume were also checked and matched. Then other attributes were checked: scanning surface, beam direction, material noise levels, presence and location of geometric echoes, presence of electromagnetic interference or any evidence of other external noise, evidence that the system's peak detection capacity has been exceeded, etc..

The data was then passed for analysis, in this case for the detection level and signal-to-noise ratio for the implanted defects. This is discussed in detail below.

The interpretation of the data was performed by two experienced data interpreters, both Level 2 in MIPS and GUIDE (**11.2**) and PCN Level 3 in Ultrasonic Inspection of Welds. Both also hold the BE Inspection Group endorsement for Ultrasonic Inspection of Austenitic Stainless Steel Components and Welds on BE Plant (**11.3**) and regularly interpret this type of ultrasonic data.

The MIPS Results files for these inspections have all been supplied to TWI, Cambridge, as the Lead Partner for the Project, on DVD disks. The Flaw files, GUIDE images and Component Profile Overlays were also included.

The data has also been archived into the BE Inspection Group system (**11.4**).

7. Detection Results

7.1 Features of Data (geometric echoes, parent materials, inclusions, attenuation)

The data shows a range of geometric echoes from expected sources: eyebolt holes in top surface, bottom corners at the ends of the block, etc.. These are largely away from the inspection volume and do not interfere with the interpretation of the inspection data. They can help to confirm the correct registration of the inspection system with the datum reference points on the component.

Assessment of the 0° beams (short range twin, longer range single) shows that the Backwall Echo on the ferritic side (with the austenitic cladding) is on average 2 dB weaker than on the austenitic side, but that the austenitic side appears to have a few laminar inclusions spread around the mid-wall region. These are also seen by a number of the TRL angled beams.

Beams scanning from the ferritic side show evidence of the austenitic cladding on the inside surface, with a layer of higher amplitude noise:

- i) short range, near-surface – beams scanning on inner surface;
- ii) long range, far-wall – beams scanning on outer surface – for these beams the noise is added to by the contribution of the steeper shear wave component sweeping the clad surface.

The extent of Defect #1 on the austenitic side caused some obscuration of parts of the weld for beams scanning towards the ferritic side, and it also produced some re-direction effects and occasionally 'ghost' echoes, which were only eliminated by lowering the Pulse Repetition Frequency (PRF).

7.2 Signal-to-Noise Ratio (SNR) Tables

The detectability of the implanted defects was assessed by measuring the difference between the peak defect response and the peak grass amplitude local to the defect. These measurements are presented in **Table 2** below, on a defect-by-defect and beam-by-beam basis.

These measurements are inevitably somewhat subjective. Some are straightforward to assess, some take more manipulation of the images. For these reasons, the measurements are performed twice, independently, and then the results compared and reconciled.

Unsurprisingly, the highest detection margins are for the defects which beams sweep whilst passing through little or no weld metal, and with the beam-to-defect angle close to zero. This can be seen for the inner surface scans hitting defects #4 and #6, which are on the austenitic side fusion face.

Near-surface defects (#2 for outer surface scans, #3, #5 and #8 for inner surface scans) were all detected with good margins. Defects #3 and #5 show a strong directional effect due to their orientation (tilt). **Figures 8** and **9** show example data images.

7.3 Penetration of Weld

Defect #7, which is a rough crack embedded in the middle of the weld, is detected by beams in both directions and from both surfaces, indicating that effective penetration of at least half the weld width is achievable. Defects #4 and #6 can be detected by beams scanning through the full width of the weld, but the beams which manage this are mostly from the 1 MHz elliptical single crystal probes, the detection margins are modest and sometimes detection is via an indirect response. **Figure 10** shows example data images.

Defect #1 (full width slot, 15 mm high) can be detected through the weld, again by the 1 MHz elliptical single crystal beams (45° and 60°). **Figure 11** shows example data images.

7.4 Analysis and Discussion

The usual factors leading to good detection apply: favourable beam-to-defect incidence, minimising beam path lengths in weld metal and suitable focal lengths and crystal sizes to maintain effective beam shapes.

Note that, because the access is there, the scans have used the maximum standoff available to try to reach all parts of the weld with the most effective beam angles. On real plant, often the 'flat' on the carbon steel nozzle side is quite short and, for example, the far-wall regions cannot be scanned with 70° beams from the outer surfaces. In addition, the austenitic stainless steel safe-end itself may only have a short axial length (typical for US plant) and there may be another adjacent weld which restricts the access for higher angle beams.

The results for the inspection of these test blocks are consistent with BE experience on inspecting qualification specimens.

For a weld of this thickness, the typical detection capability claimed for in-service inspection would be:

a smooth or rough planar defect with dimensions 10 mm throughwall extent by 20 mm long or larger; surface-breaking or within 10 mm of the surface and within $\pm 10^\circ$ tilt or skew of the radial-circumferential plane.

8. Positioning and Sizing Results

8.1 Additional Sizing Scans

After analysing the search data, a set of sizing scans was compiled to provide the best positioning, length and throughwall sizing possible. The main principle was to apply beams to achieve oblique incidence on the defects, in order to record diffracted edge wave signals. This is generally the most accurate pulse-echo technique for estimating defect throughwall extent. The downside is that the edge wave signals are usually weak and are not always evident.

Additional 2 MHz 45° TRL probes were used for many of the sizing scans, with an f25 focus probe used for near-surface scans and an f50 focus probe used for defects in the mid-wall region. The sizing scans chosen depended on the responses in the search scan data and generally conformed to the guidelines of applying the beams achieving the shortest range, ranges closest to the probe focus and shortest path lengths through weld metal.

As noted above, the specific sizing scans implemented a very fine scan pattern of 0.5 x 0.5 mm and data was collected in a single direction to minimise the effects of backlash in the manipulator's mechanism.

Sizing scans carried out:

Block 'A' outer surface

ODS21, ODS22, ODS23, ODS24, ODS25, ODS26, ODS27, ODS28

Block 'A' inner surface

IDS21, IDS22, IDS23, IDS24, IDS25, IDS26

Block 'B' outer surface

ODS25, ODS26, ODS27

Block 'B' inner surface

IDS21, IDS22, IDS23, IDS24, IDS28, IDS29, IDS30, IDS31, IDS32, IDS33, IDS34, IDS35

Defect sizing techniques were matched to the Echodynamic Pattern (EDP) exhibited by the defects. Most length sizing used the 6 dB amplitude drop method. Most throughwall sizing used the maximum amplitude method, looking for the maximum in diffracted edge wave signal arcs. As for the detection assessment, the sizing was performed twice, with the initial results being verified by a 2nd data interpreter. Very minor differences occurred between the two sets of sizing results, generally smaller than the differences between one beam and another.

8.2 Defect Positions

For Block 'A', the defect start and end positions along the weld appear to be match the drawing to within approximately 5 mm, mostly 4 - 5 mm low in Y co-ordinate. In Block 'B', this difference increases to match within 8 - 10 mm, possibly due to the material lost in the cut, separating the original block into two parts.

The smooth defects exhibit fairly clear cut start and ends to their length and the 6 dB drop technique should be accurate to within a few millimetres.

Some of the defects show very clear top and bottom arcs and very little scatter in the throughwall extent estimates. Other defects give signals which conflict with the nominal (drawing) values and are harder to reconcile. Defect #1 interferes with beams scanned from the austenitic side inner surface.

Defect #8 is smaller than the minimum throughwall extent for which BE Inspection Group would normally claim sizing capability (for this thickness of weld, this size is usually quoted as 6 mm).

8.3 Best Estimates Defect Sizes

Tables 3 – 9 give the individual measurements for each defect, using the best responses from the sizing scans.

Table 10 summarises this information into best estimates of the defect positions and extents and presents the nominal (drawing) values for comparison. The best estimates are based on judgement of the reliability of particular signals and the level of confidence in results from different beams.

8.4 Analysis and Discussion

As seen, there are some measurements that are very close to the nominal values and others where the measurements are significantly different, but, again, this is not untypical of these kinds of inspections on specimens with implanted defects. There are one or two examples where additional unexplained responses are seen close to expected defect echoes, and these need to be included or discounted as part of the sizing process.

Note that the separations of the defects along the weld, i.e. between the end of one and the start of the next, are very consistent with the drawing, even if the actual positions are a little out.

BE Inspection Group's experience, borne out by other external and independent exercises, is that sizing reliability increases when the results of a number of different beams are taken into account and that diffracted edge wave signals, where they can be detected, provide the most accurate estimate of a defect's extremities.

It also needs to be pointed out that, whilst artificial defects are very useful guides to defect detectability and sizing, real defects sometimes behave differently.

9. Review

The two blocks have been subject to detailed inspection using the MIPS / GUIDE system and a range of 0° and angled compression wave probes. These inspections have conformed to the inspection design approach and quality standard typically used for similar inspections within BE. Scans have been performed in both axial directions, and from both outer and inner surfaces of the blocks.

The data quality and defect detection capability have been assessed and found to be acceptable. The data has been repeat interpreted by two experienced data interpreters and 100% verification of results has been applied.

All defects have been detected, although, as expected, the best detection margins are for defects swept by beams which do not have to traverse significant paths in weld metal. Detection margins for defects when the beams do have to pass through the weld are lower, but the 1 MHz elliptical single crystal beams can penetrate the full width of the weld, and still detect defects.

Note that this weld is probably a little wider than typically encountered on real plant, in that the fusion faces rise 63 mm (85 less 22 = 63) at 15°, whereas the tendency is to try to minimise the amount of weld metal required. But this does mean that the test welds are a difficult challenge for ultrasonic inspection.

The sizing performance is seen to be reasonable and is consistent with the tolerances expected from previous exercises and with the performance claimed for similar inspections on Sizewell B.

The MIPS / GUIDE data has been provided to the Project and the delivery of this report completes BE's Action 11 from the 3rd Quarterly Meeting.

10. Conclusions

- (1) The two test blocks produced under the DISSIMILAR Project have been inspected using BE's MIPS / GUIDE automated ultrasonic inspection system and using methods and techniques typical of the inspection of this type of joint in nuclear power plant.
- (2) The data produced by these inspections provides a 'conventional' fingerprint of the welds, for future comparison with optimised Phased Array inspections.
- (3) All the defects have been detected, with varying margins of signal-to-noise ratio.
- (4) The defects have been positioned and sized within the expected tolerances for this thickness of austenitic weld.
- (5) The results of all the defect detection assessments and positioning and sizing measurements have been 100% verified and tabulated in this report.
- (6) The delivery of this report completes BE's Action 11 from the 3rd Quarterly Meeting.

11. References

- 11.1 **EPD/SXB/NDT/1033/00**, MIPS/GUIDE Ultrasonic Examination Procedure for the Automated In-Service Inspection of Steam Generator Channel Head Primary Nozzle to Safe-End Inlet and Outlet welds, Issue 5, February 2008, BE Inspection Group
- 11.2 BEGL Inspection Group MS Access Database - MIPS/GUIDE Automated Inspection Qualifications - G:\Engineering\ETB\Ltasks\Inspection\Inspection Group General (BPM)\Certification and Registration schemes (Peter Muitt)\British Energy MIPS and GUIDE Register (SINDT 151)
- 11.3 BEGL Inspection Group MS Access Database - Austenitic Inspection Qualifications - G:\Engineering\ETB\Ltasks\Inspection\Inspection Group General (BPM)\Certification and Registration schemes (Peter Muitt)\British Energy Austenitic Register (SINDT 018)
- 11.4 E/PROC/ENG/BI/009, Maintenance of Inspection Group Magnetic Media Register, Revision 001, May 2007

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FIGURE 1A – Outline of DISSIMILAR Block ‘A’

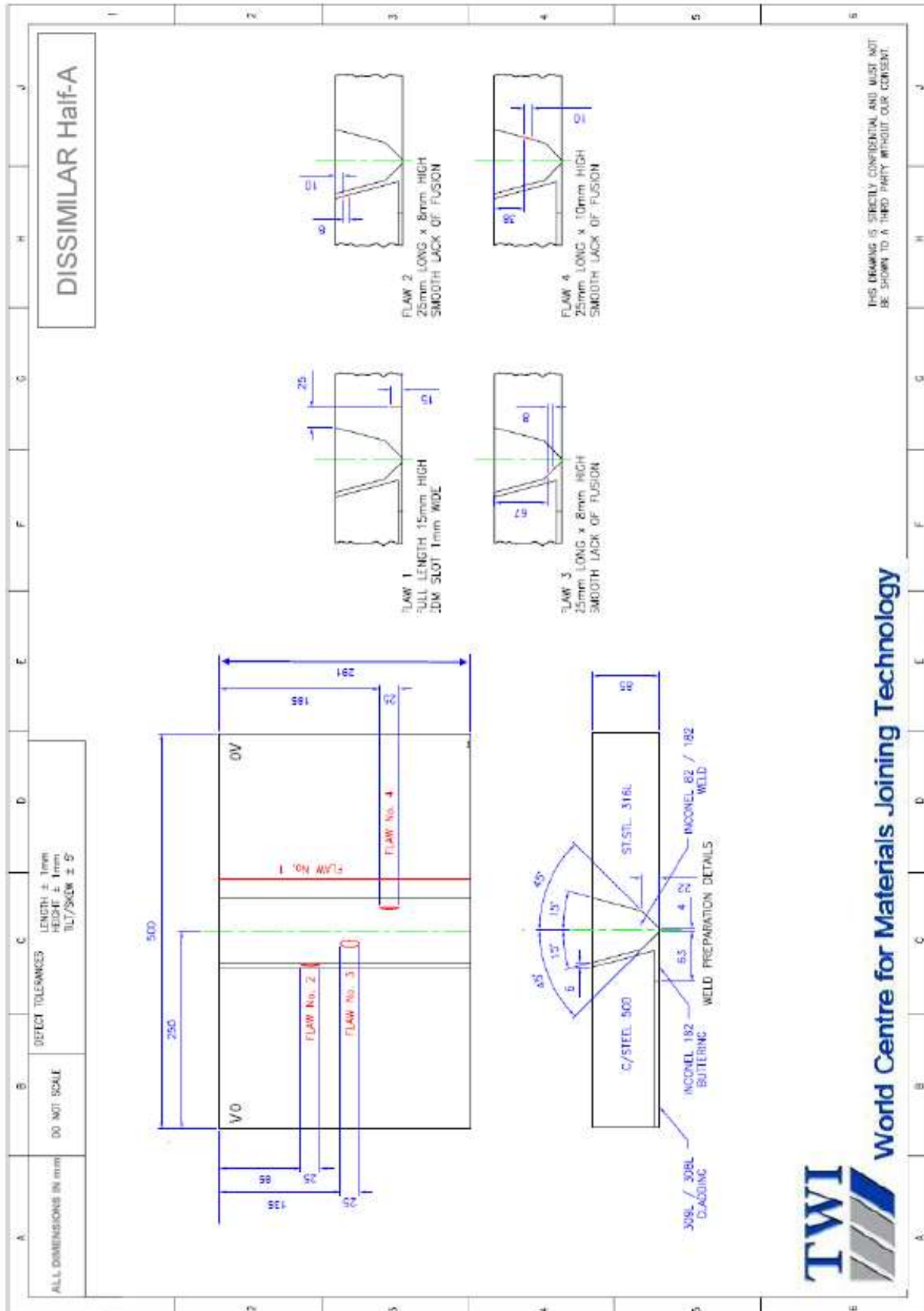


FIGURE 1B – Outline of DISSIMILAR Block ‘B’

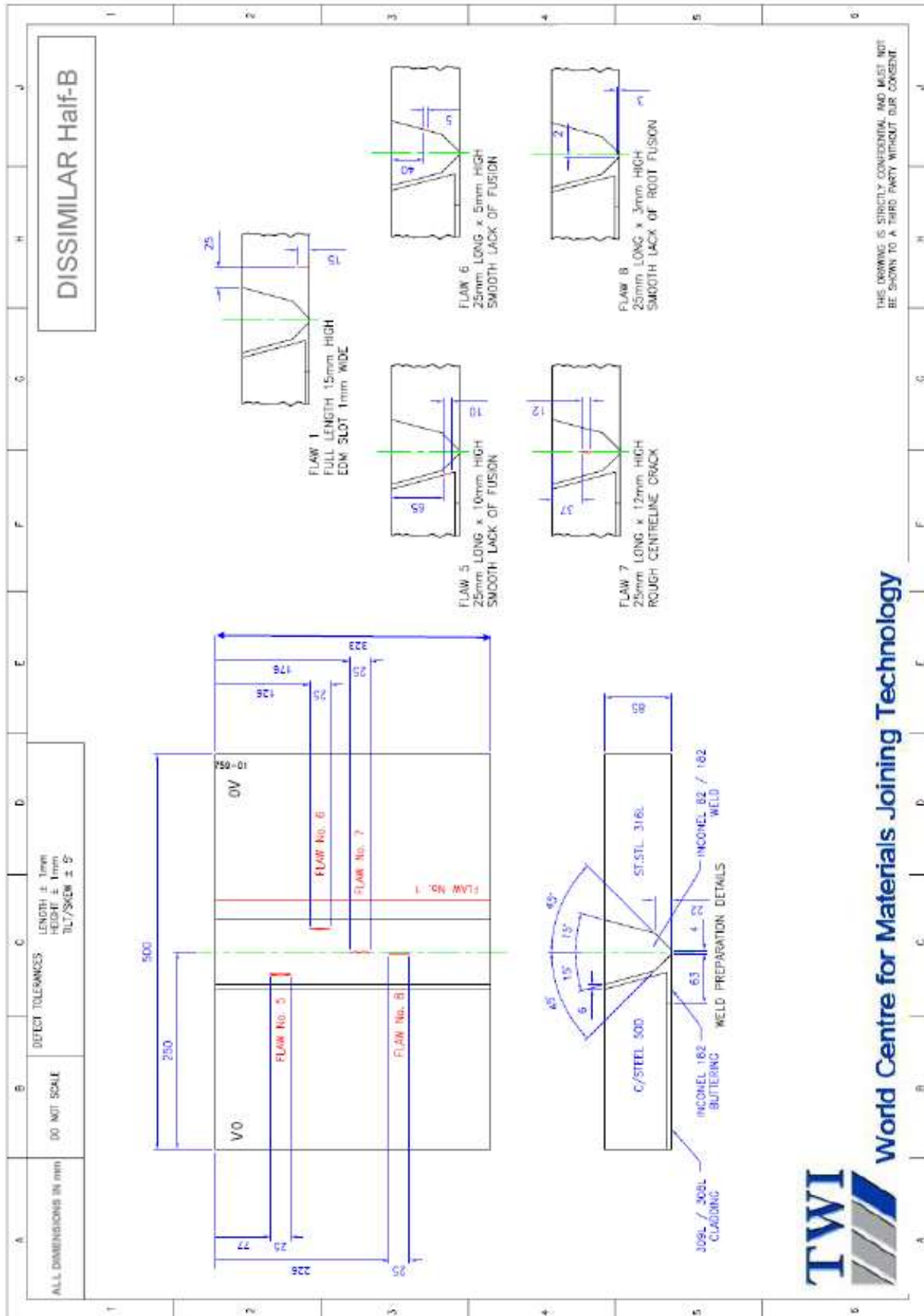


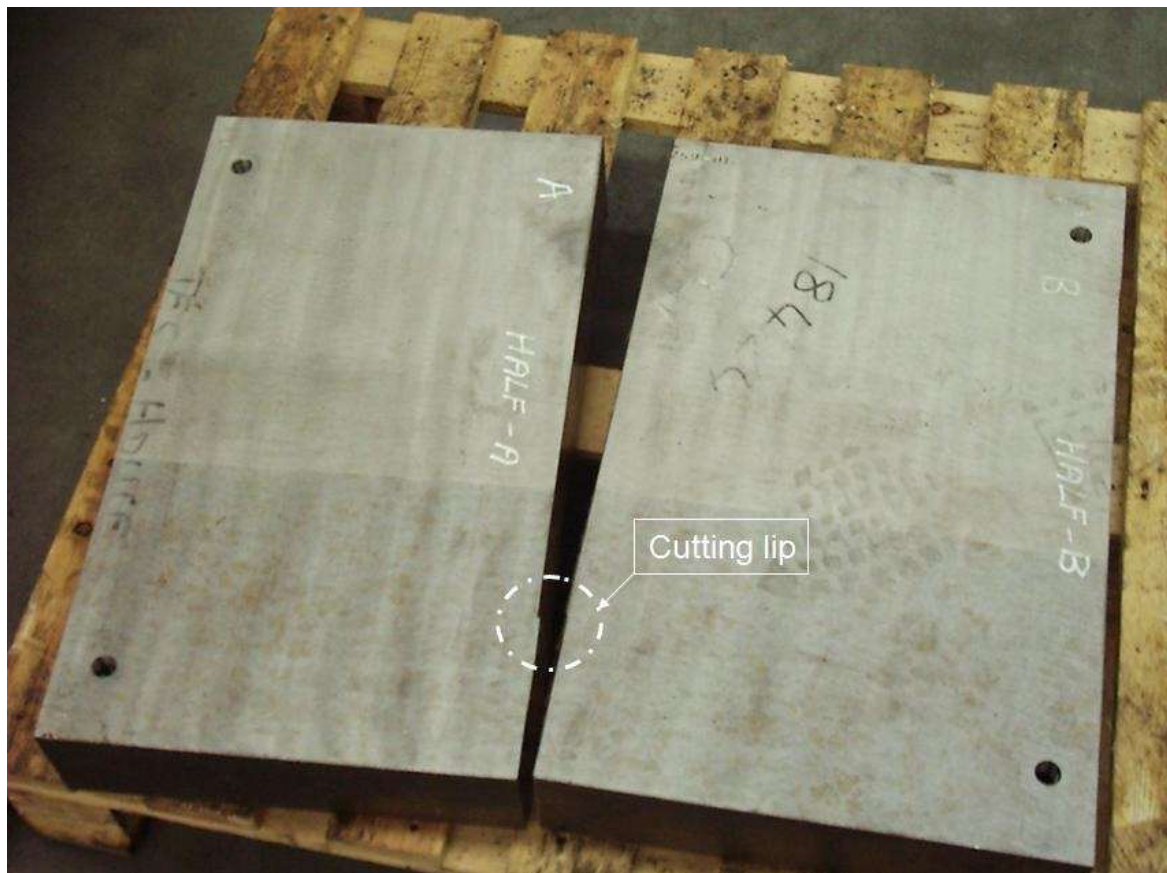
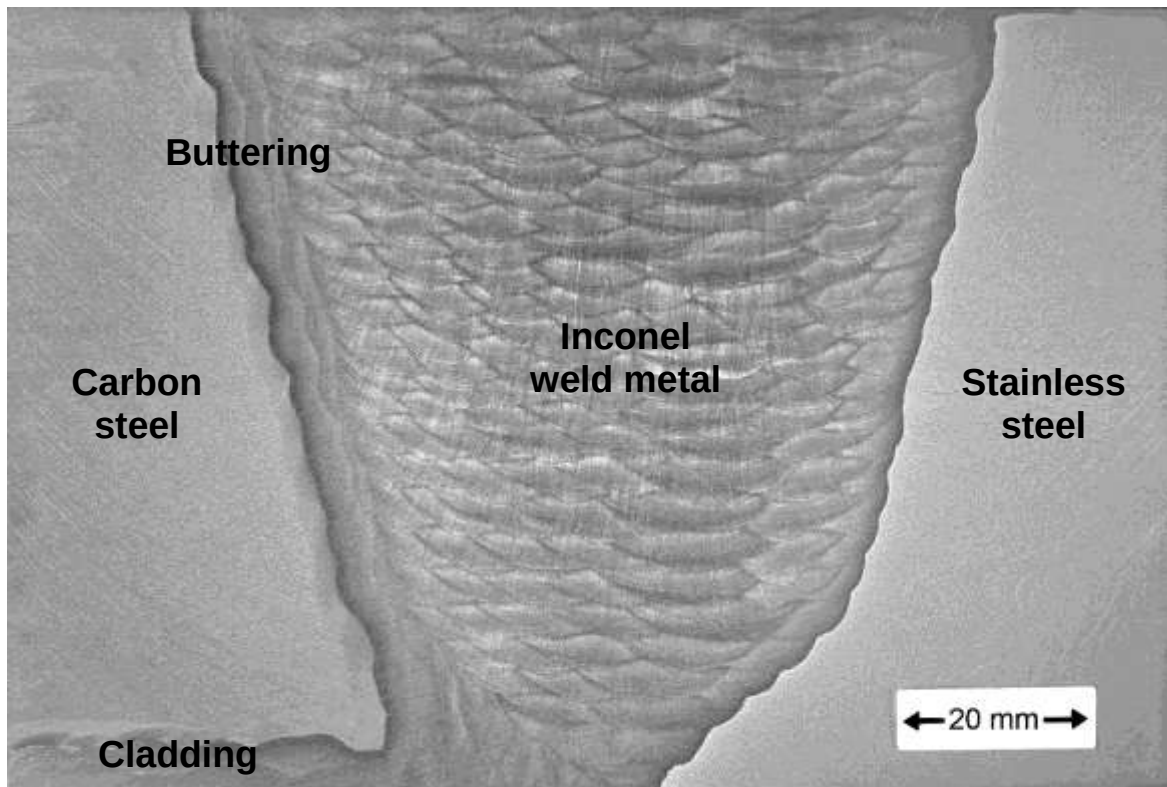
FIGURE 2 – DISSIMILAR Specimen sectioned into Blocks 'A' and 'B'**FIGURE 3 – Etched macrostructure of DISSIMILAR test specimen weld**

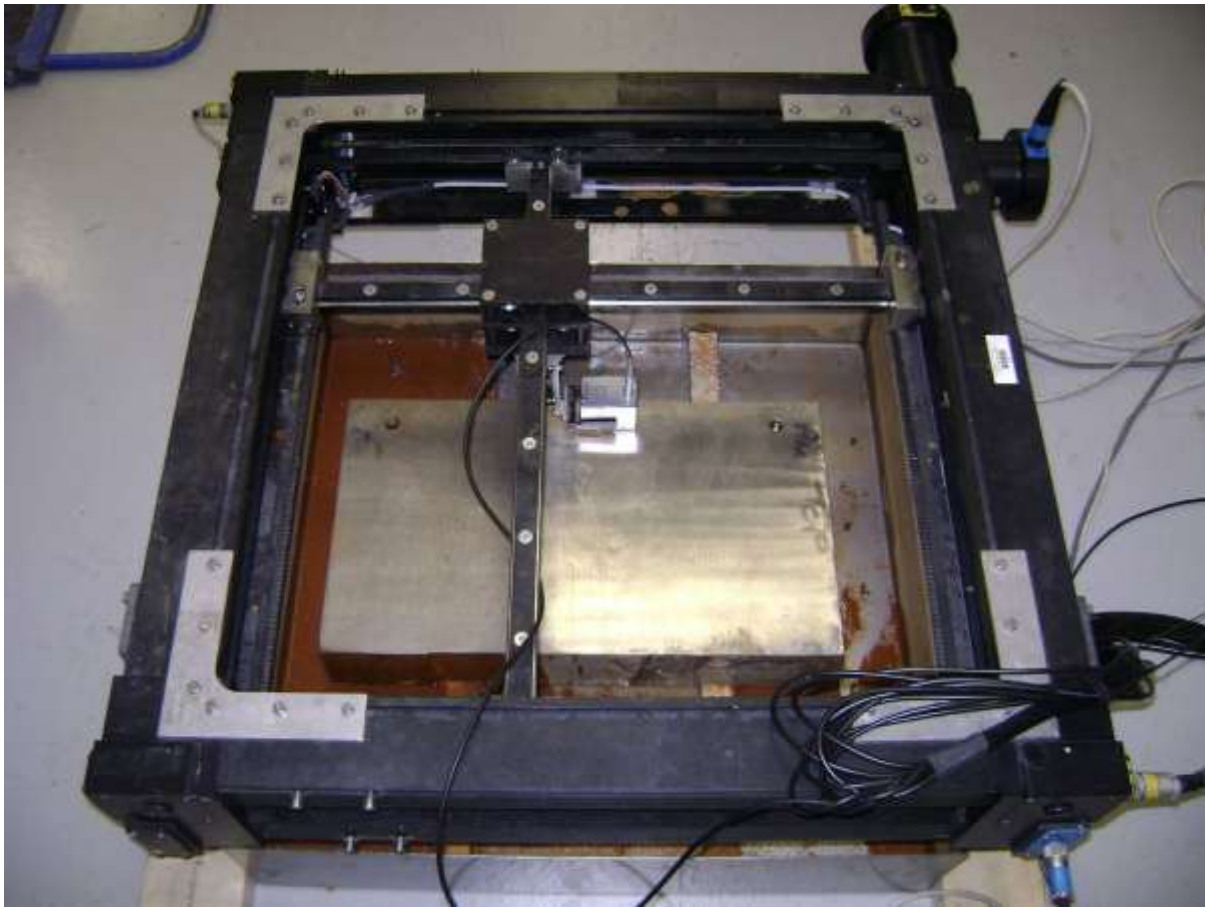
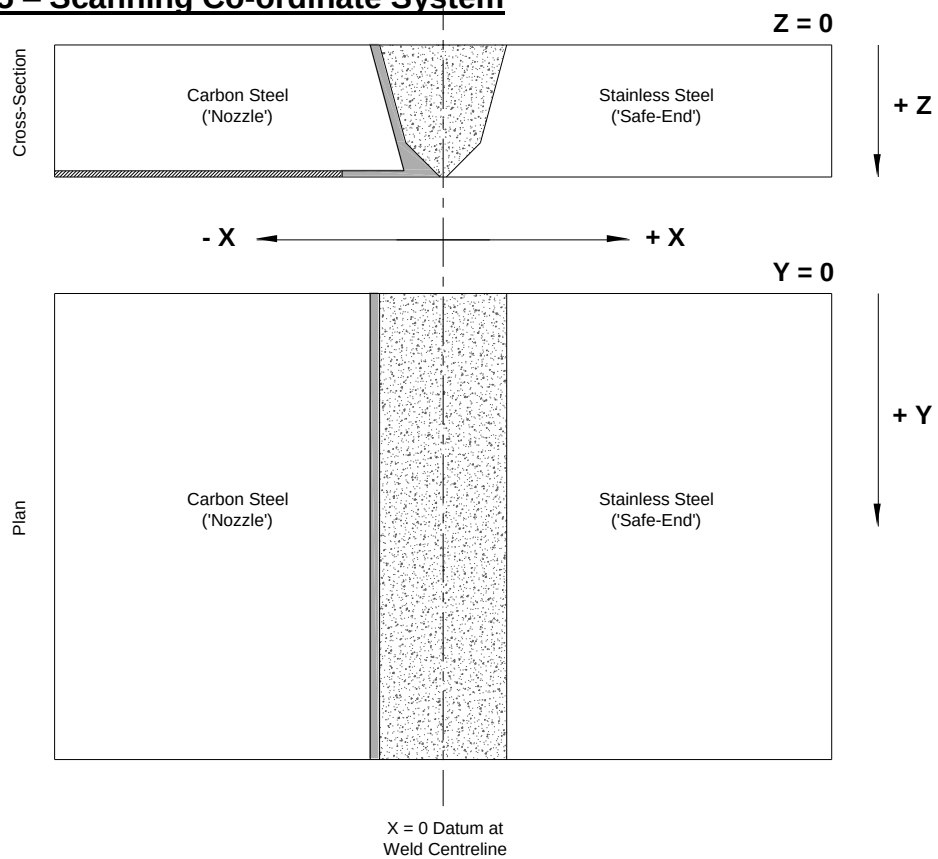
FIGURE 4 – Scanning Setup - XY Scanning Frame and Immersion Tank**FIGURE 5 – Scanning Co-ordinate System**

FIGURE 6 – Fine-grain forged austenitic stainless steel calibration blocks

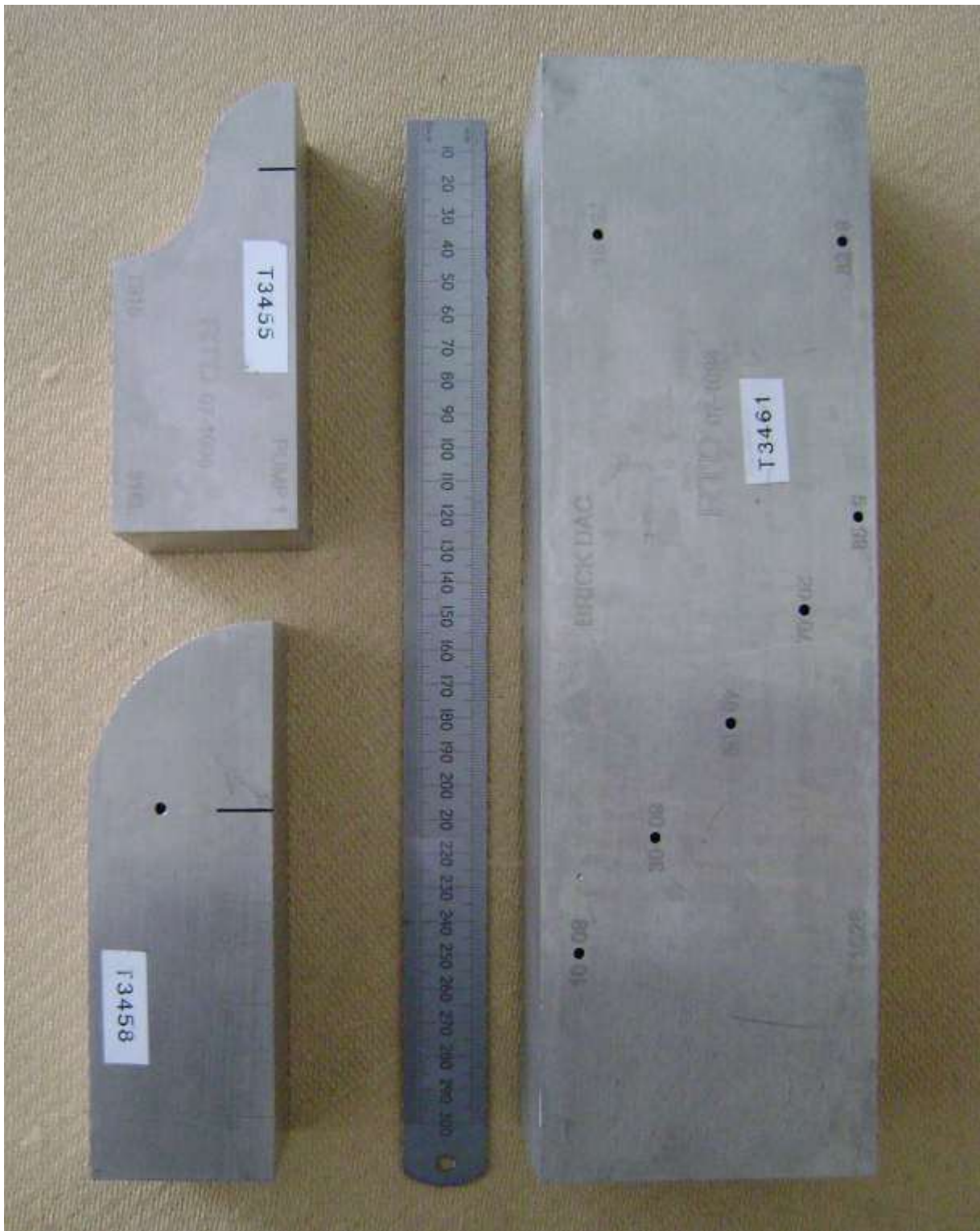


FIGURE 7 – Inspection Volume

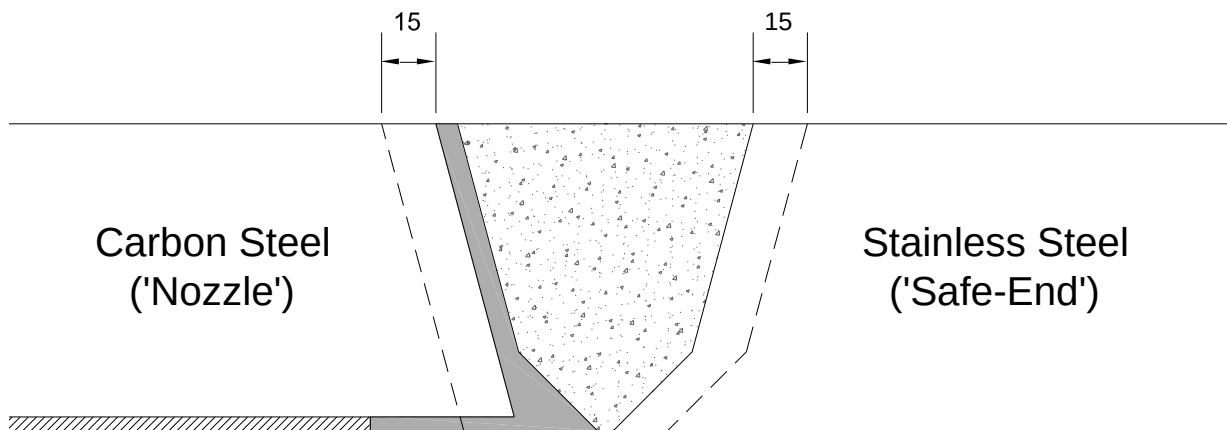


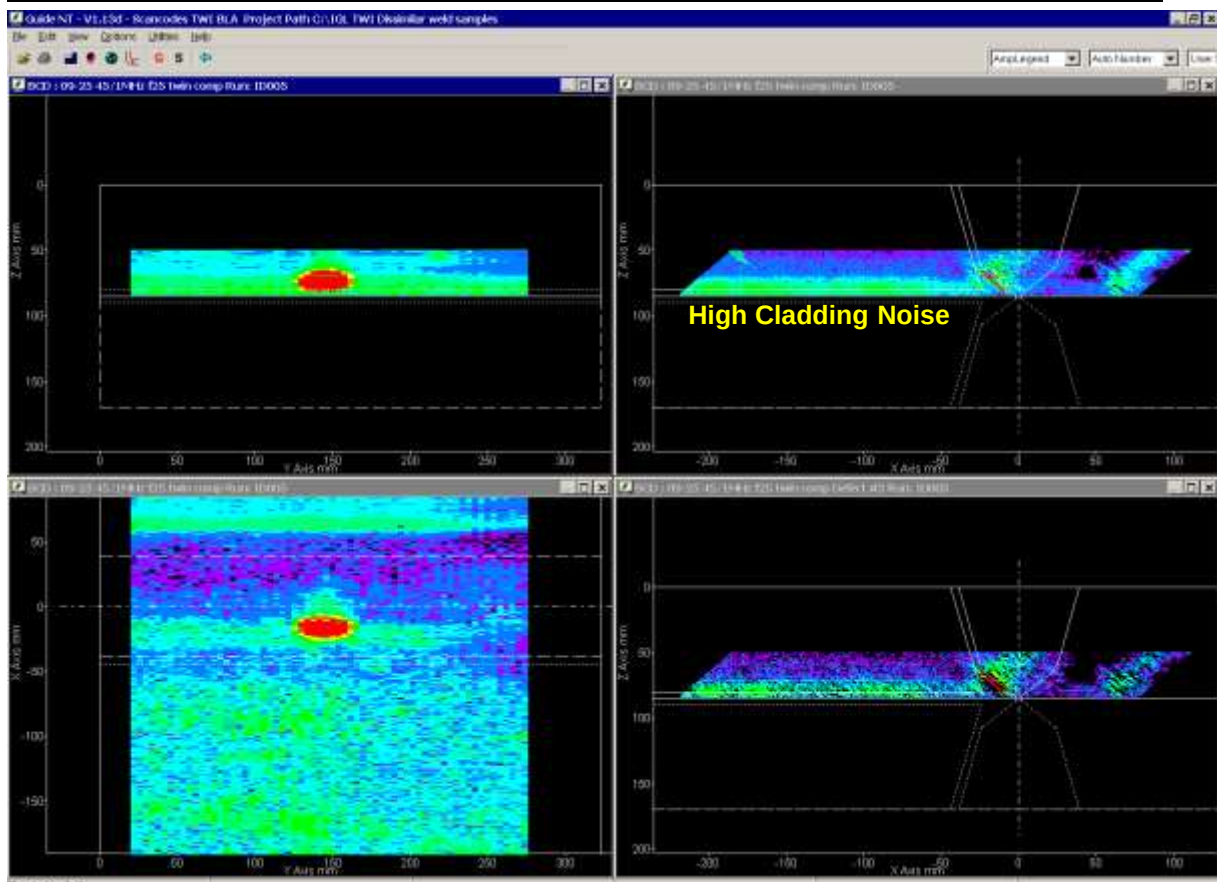
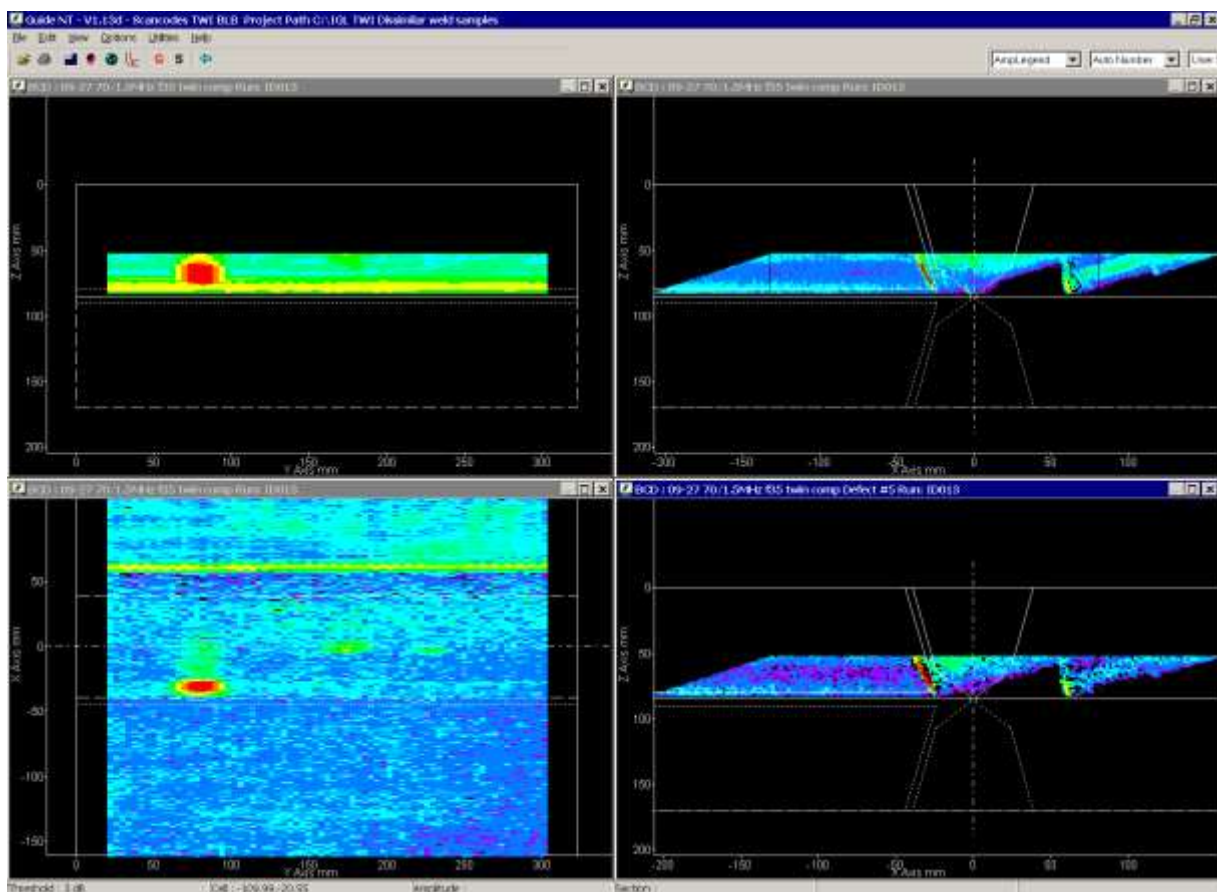
FIGURE 8 – Example GUIDE Image – Defect #3 – 1 MHz 45° TRL1 f25 – ID005**FIGURE 9 – Example GUIDE Image – Defect #5 – 1.5 MHz 70° TRL1.5 f35 – ID013**

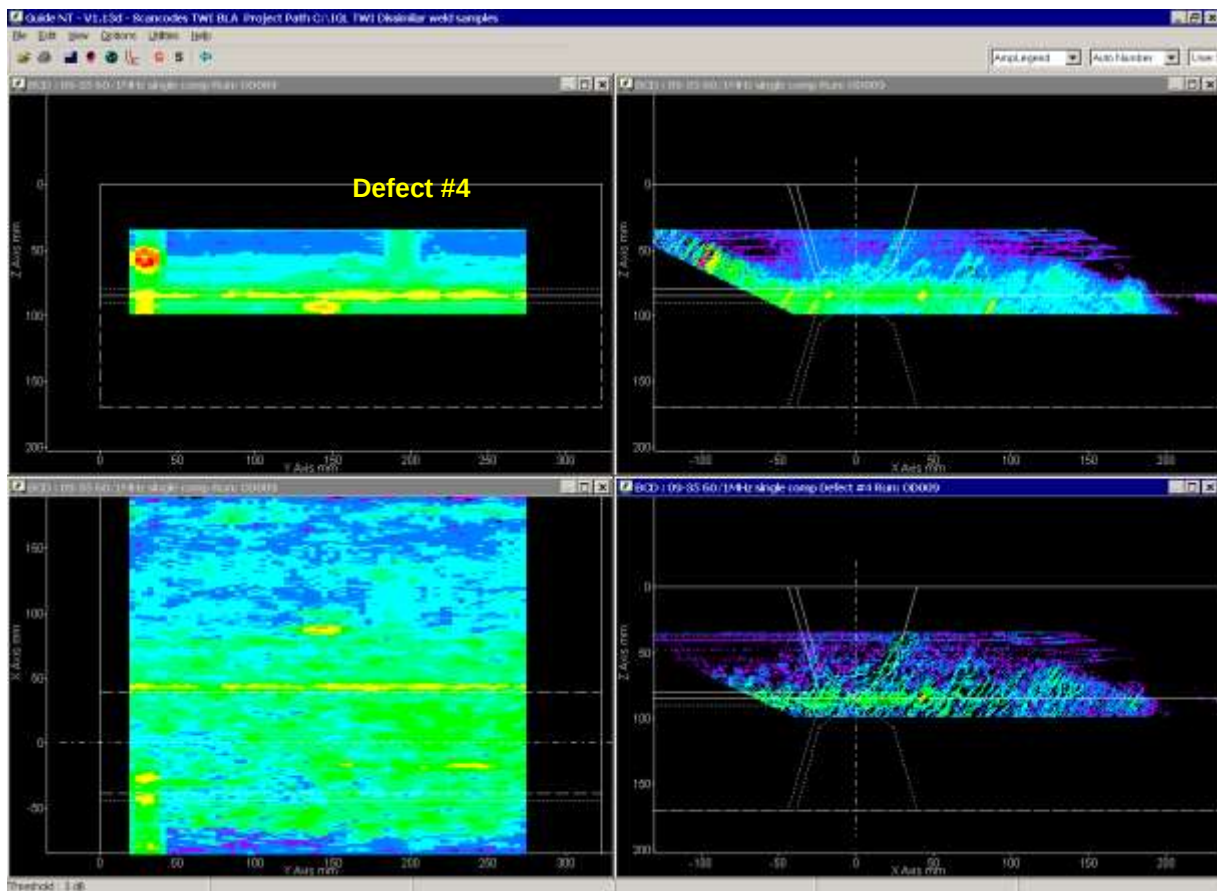
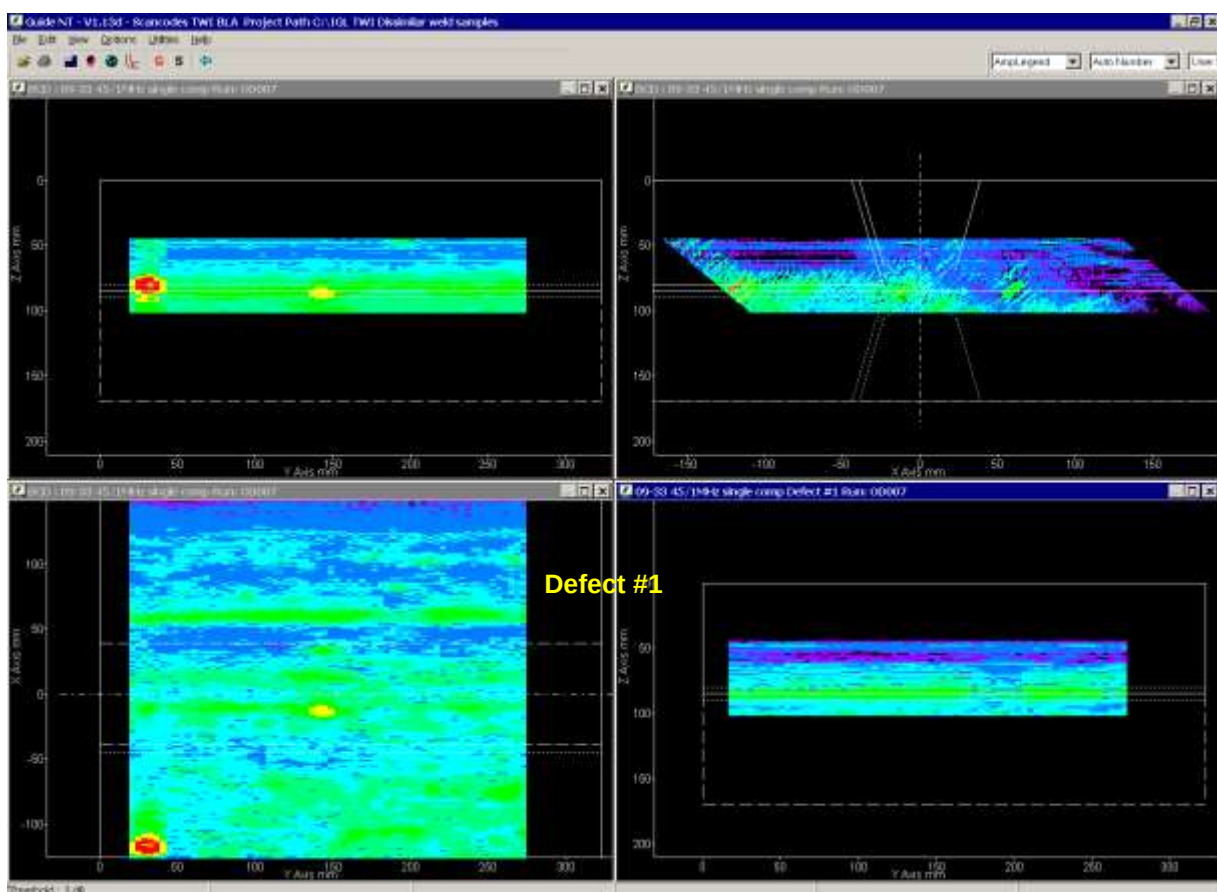
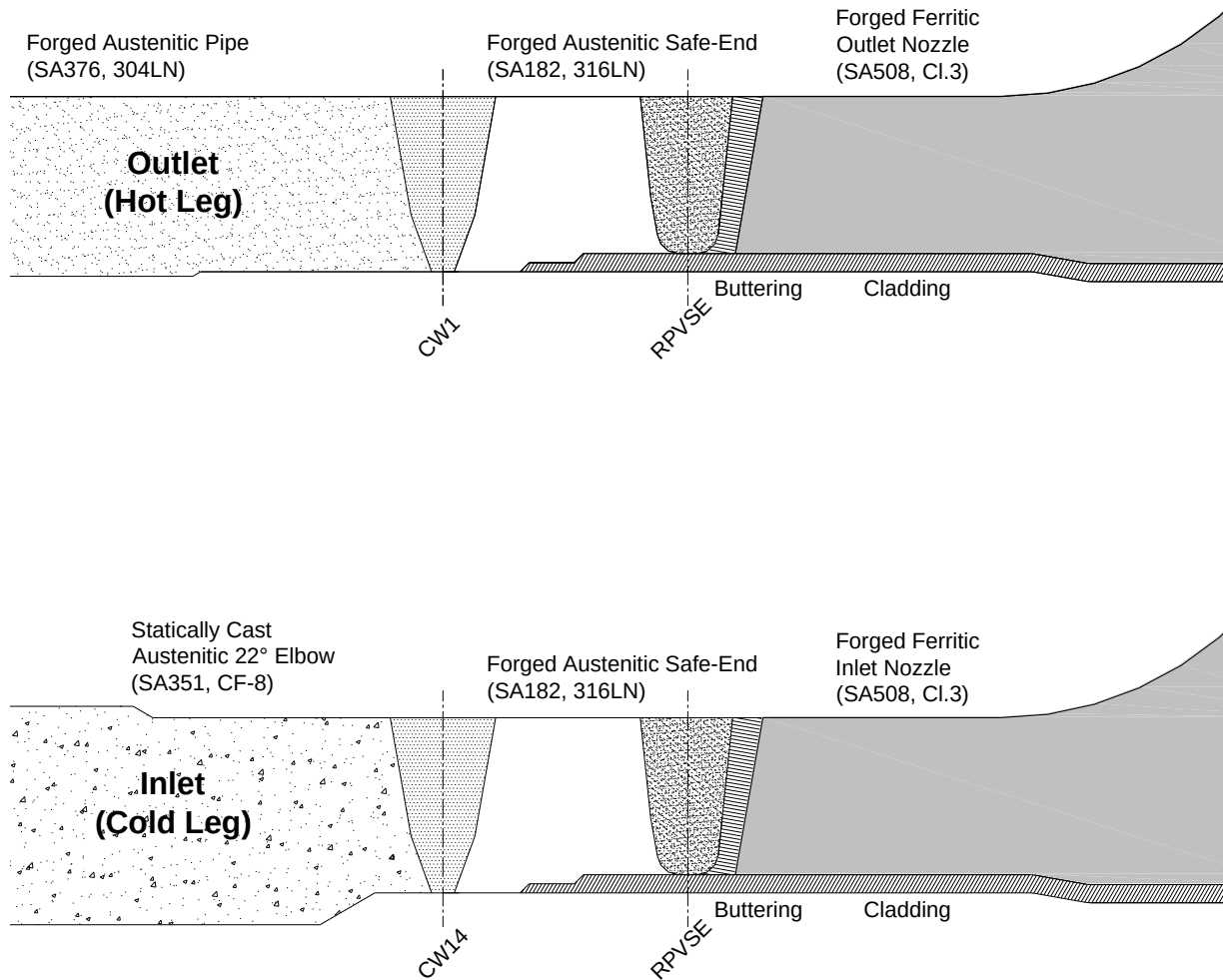
FIGURE 10 – Example GUIDE Image – Defect #4 – 1 MHz 60° L1 – OD009**FIGURE 11 – Example GUIDE Image – Defect #1 – 1 MHz 45° L1 – OD007**

FIGURE 12 – Typical PWR RPV Nozzle Safe-End Weld Design

Note: 1) short length of safe-end and consequent proximity of pipework welds
2) limited flat on nozzle side outer surface, before blend radius

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TABLE 1 – List of Probes / Beams applied to DISSIMILAR Test Specimen Weld Blocks

Number	Make	Angle/°	Freq/MHz	Single/ Twin	Focus/mm	Crystal(s)/mm	Casing/mm (LxWxH)	Scans
1	Applus-RTD	0	2.5	Twin	12	2(½ Ø10) Composite	40x40x35	Search
2	Applus-RTD	0	1	Single	--	Ø25 Composite	40x40x35	Search
3	Applus-RTD	70	1.5	Twin	35	2(15x25) Composite	40x40x35	Search
4	Phoenix ISL	70	2.5	Single	--	Ell(25x43) PZT ¼λ	60x40x40	Search
5	Applus-RTD	65	1	Single	--	Ell(25x43) Composite	60x40x45	Search
6	Applus-RTD	60	1	Single	--	Ell(25x43) Composite	60x40x45	Search
7	RTD	60	2	Twin	35	2(15x25) PZT	40x40x35	Search
8	RTD	60	2	Twin	65	2(15x25) PZT	40x40x35	Search
9	Applus-RTD	45	1	Single	--	Ell(25x34) Composite	60x40x45	Search
10	Applus-RTD	45	1	Twin	25	2(15x25) Composite	40x40x35	Search
11	RTD	45	2	Twin	50	2(15x25) PZT ¼λ	40x40x30	Sizing
12	RTD	45	2	Twin	25	2(10x18) PZT	40x40x35	Sizing

All compression wave probes

TABLE 2 – Detection and Signal-to-Noise Ratios for Defects in Blocks ‘A’ and ‘B’

BEAM	SURFACE	DIRECTION	DEFECTS								
			BOTH	BLOCK A				BLOCK B			
				1	2	3	4	5	6	7	8
1.5 MHz 70° f35	OD	Aust→Ferr	NB	OD014 30	NB	OD014 6	NB	NB	NB	NB	
1.5 MHz 70° f35	OD	Ferr→Aust	NB	OD013 12	NB	OD013 10	NB	OD013 6	NB	NB	
1.5 MHz 70° f35	ID	Aust→Ferr	ID014 22+	NB	ND	ID014 16	ID014 6	ID014 20	ND	ID014 9	
1.5 MHz 70° f35	ID	Ferr→Aust	ID013 20+	NB	ID013 18	ID013 6	ID013 20+	ND	ID013 12	ID013 17	
2 MHz 60° f35	OD	Aust→Ferr	NB	OD016 14	NB	ND	NB	ND	ND	NB	
2 MHz 60° f35	OD	Ferr→Aust	NB	OD015 6	NB	ND	NB	ND	ND	NB	
2 MHz 60° f35	ID	Aust→Ferr	ID016 12	NB	ID016 8	NB	ND	ND	ND	ID016 19	
2 MHz 60° f35	ID	Ferr→Aust	ID015 10	NB	ID015 20+	NB	ID015 19+	ND	ID015 10+	ID015 16+	
1 MHz 45° f25	OD	Aust→Ferr	NB	OD006 14+	NB	ND	NB	ND	ND	NB	
1 MHz 45° f25	OD	Ferr→Aust	NB	OD005 6	NB	ND	NB	ND	ND	NB	
1 MHz 45° f25	ID	Aust→Ferr	ID006 12	NB	ID006 6	ID006 6	ID006 9	NB	ND	ID006 15	
1 MHz 45° f25	ID	Ferr→Aust	ID005 12	NB	ID005 24+	NB	ID005 12	NB	ID005 18	ID005 14	
1 MHz 45° Single	OD	Aust→Ferr	OD008 24	NB	OD008 15	OD008 6	OD008 8+	OD008 10	OD008 10	ND	
1 MHz 45° Single	OD	Ferr→Aust	OD007 9	NB	OD007 8	OD007 9	OD007 6	OD007 8	ND	ND	
1 MHz 45° Single	ID	Aust→Ferr	NB	ND	NB	ND	NB	ND	ND	NB	
1 MHz 45° Single	ID	Ferr→Aust	NB	ID007 6 *	NB	ND	NB	ND	ID007 8	NB	
2 MHz 60° f65	OD	Aust→Ferr	NB	OD018 22	OD018 15	ND	OD018 9+	OD018 6	OD018 12	NB	

BEAM	SURFACE	DIRECTION	DEFECTS								
			BOTH	BLOCK A				BLOCK B			
			1	2	3	4	5	6	7	8	
2 MHz 60° f65	OD	Ferr→Aust	NB	OD017 10	ND	ND	ND	ND	OD017 6+	ND	NB
2 MHz 60° f65	ID	Aust→Ferr	NB	ND	ND	ID018 24	ND	ID018 24	ID018 8	NB	
2 MHz 60° f65	ID	Ferr→Aust	NB	ID017 12	ID017 15	ND	ID017 20+	ND	ID017 22	NB	
1 MHz 60° Single	OD	Aust→Ferr	OD010 20	NB	OD010 9	OD010 12 *	OD010 8+	OD010 8+ *	OD010 8+	ND	
1 MHz 60° Single	OD	Ferr→Aust	OD009 10	NB	OD009 10*	OD009 10	ND	OD009 8+	ND	ND	
1 MHz 60° Single	ID	Aust→Ferr	NB	ND	NB	ID010 20+	NB	ID010 21	ND	NB	
1 MHz 60° Single	ID	Ferr→Aust	NB	ID009 12 *	NB	ND	NB	ND	ID009 12 *	NB	
1 MHz 65° Single	OD	Aust→Ferr	OD012 16	NB	OD012 10	OD012 10	OD012 12 *	OD012 12 *	OD012 14	ND	
1 MHz 65° Single	OD	Ferr→Aust	OD011 14	NB	OD011 8	OD011 10 *	ND	OD011 8	ND	ND	
1 MHz 65° Single	ID	Aust→Ferr	NB	ND	NB	ID012 28	NB	ID012 23	ID012 20 *	NB	
1 MHz 65° Single	ID	Ferr→Aust	NB	ID011 10 *	NB	ND	NB	ND	ID011 15	NB	
2.5 MHz 70° Single	OD	Aust→Ferr	NB	NB	ND	OD020 14 *	OD020 15	OD020 7 *	OD020 12	OD020 9	
2.5 MHz 70° Single	OD	Ferr→Aust	NB	OD019 10	ND	ND	NB	OD019 6 *	ND	ND	
2.5 MHz 70° Single	ID	Aust→Ferr	NB	ND	NB	ID020 36+	NB	ID020 35 *	ID020 6 *	NB	
2.5 MHz 70° Single	ID	Ferr→Aust	NB	ID019 8	NB	ND	ID019 18	ND	ID019 15	NB	

Key: NB – Beam does not sweep defect depth, or beam not gated for this depth / range

ND – Defect not detected

* – higher amplitude signal also present from associated mechanism, e.g. self-tandem

TABLE 3 – Positioning and Sizing Measurements – Defect #2 Block 'A'

BLOCK A - DEFECT 2	DEFECT THROUGHWALL EXTENT (mm)				DEFECT LENGTH (mm)		
Scan / Surface	Top	Bottom	Height	Ligament	Start	End	Length
IDS21 2 MHz 45° f50 ID - Ferr→Aust	10.3	19.2	8.9	10.3 mm to OD	83.6	103.1	19.5
	Maximum Amplitude sizing used				6 dB sizing used		
IDS22 2 MHz 60° f65 ID - Ferr→Aust	3.9	14.9	11	3.9 mm to OD	84	104	20
	6 dB sizing used, no tip arc evident. Sizing errors probably due to proximity of backwall and beam passing through cladding.				6 dB sizing used		
ODS21 2 MHz 45° f25 OD - Ferr→Aust	8.6	20.1	11.5	8.6 mm to OD	79.5	102.5	23
	Maximum Amplitude sizing used				6 dB sizing used		
ODS22 2 MHz 45° f25 OD - Aust→Ferr	8.9	22.4	13.5	8.9 mm to OD	81	106.5	25.5
	Maximum Amplitude sizing used				6 dB sizing used		
ODS23 2 MHz 60° f35 OD - Ferr→Aust	11	19	8	11 mm to OD	81	102.5	21.5
	Maximum Amplitude sizing used				6 dB sizing used		
ODS24 2 MHz 60° f35 OD - Aust→Ferr	8	20	12	8 mm to OD	80.5	106	25.5
	Maximum Amplitude sizing used				6 dB sizing used		

TABLE 4 – Positioning and Sizing Measurements – Defect #3 Block 'A'

BLOCK A - DEFECT 3	DEFECT THROUGHWALL EXTENT(mm)				DEFECT LENGTH (mm)		
Scan / Surface	Top	Bottom	Height	Ligament	Start	End	Length
IDS25 2 MHz 45° f25 ID - Ferr→Aust	66.9	75.9	9	66.9 mm to OD	130.5	156	25.5
	Maximum Amplitude sizing used				6 dB sizing used		
IDS26 2 MHz 60° f35 ID - Ferr→Aust	69.8	80.3	10.5	69.8 mm to OD	131	154.5	23.5
	Maximum Amplitude sizing used				6 dB sizing used		
ODS27 2 MHz 45° f50 OD - Aust→Ferr	64.5	77	12.5	64.5 mm to OD	130	153	23
	6 dB sizing used				6 dB sizing used		
ODS28 1 MHz 45° Single OD - Aust→Ferr	60.1	77.6	17.5	60.1 mm to OD	129.5	156.5	27
	6 dB sizing used				6 dB sizing used		

TABLE 5 – Positioning and Sizing Measurements – Defect #4 Block ‘A’

BLOCK A - DEFECT 4	DEFECT THROUGHWALL (mm)				DEFECT LENGTH (mm)		
Scan / Surface	Top	Bottom	Height	Ligament	Start	End	Length
IDS23 2 MHz 45° f50 ID - Aust→Ferr	33.6	50.6	17	33.6 mm to OD	184.5	203	18.5
	Maximum Amplitude sizing used. Beam partially obscured by Defect 1, resulting in probable mis-positioning of indication				6 dB sizing used		
IDS24 2 MHz 60° f65 ID - Aust→Ferr	20.5	38	19.5	20.5 mm to OD	182	198.5	16.5
	Throughwall extent greater than expected theoretical defect. Unable to define alternate signal mechanism for indication.				6 dB sizing used		
ODS25 2 MHz 45° f50 OD - Ferr→Aust	37.2	48.2	11	37.2 mm to OD	180	198	18
	Maximum Amplitude sizing used				6 dB sizing used		
ODS26 2 MHz 45° f50 OD - Aust→Ferr	39	52.6	13.6	39 mm to OD	NA	NA	NA
	Maximum Amplitude sizing used				Poor signal response, not able to assess length		

TABLE 6 – Positioning and Sizing Measurements – Defect #5 Block ‘B’

BLOCK B - DEFECT 5	DEFECT THROUGHWALL (mm)				DEFECT LENGTH (mm)		
Scan / Surface	Top	Bottom	Height	Ligament	Start	End	Length
IDS21 1.5 MHz 70° f35 ID - Ferr→Aust	58.8	75.8	17	58.8 mm to OD	68.5	91.5	23
	6 dB sizing used				6 dB sizing used		
IDS22 2 MHz 60° f35 ID - Ferr→Aust	61.6	74.1	12.5	61.6 mm to OD	67.5	91.5	24
	Maximum Amplitude sizing used				6 dB sizing used		
IDS23 2 MHz 45° f25 ID - Ferr→Aust	62	74	12	62 mm to OD	70.5	92	21.5

TABLE 7 – Positioning and Sizing Measurements – Defect #6 Block ‘B’

BLOCK B - DEFECT 6	DEFECT THROUGHWALL (mm)				DEFECT LENGTH (mm)		
Scan / Surface	Top	Bottom	Height	Ligament	Start	End	Length
IDS24 2 MHz 45° f50 ID - Aust→Ferr	41.8	54.8	13	41.8 mm to OD	115	139.5	24.5
	Maximum Amplitude sizing used. Beam obscured by Defect 1 resulting in beam edge detection only, causing mis-positioning of indications				6 dB sizing used		
ODS25 2 MHz 45° f50 OD - Aust→Ferr	39.8	50.8	11	39.8 mm to OD	122.5	150.5	28
	Maximum Amplitude sizing used				6 dB sizing used		

TABLE 8 – Positioning and Sizing Measurements – Defect #7 Block ‘B’

BLOCK B - DEFECT 7	DEFECT THROUGHWALL (mm)				DEFECT LENGTH (mm)		
Scan / Surface	Top	Bottom	Height	Ligament	Start	End	Length
ODS26 2 MHz 45° f50 OD - Ferr→Aust	34.3	NA	NA	34.3 mm to OD	178	189.5	11.5
	Single arc, insufficient S/N to use 6dB sizing				6 dB sizing used		
ODS27 2 MHz 45° f50 OD - Aust→Ferr	42.5	47	4.5	42.5 mm to OD	175	190.5	15.5
	Maximum Amplitude sizing used				6 dB sizing used		
IDS28 2 MHz 45° f50 ID - Ferr→Aust	40.7	51.7	11	40.7 mm to OD	164	191	27
	Maximum Amplitude sizing used				6 dB sizing used		
IDS29 2 MHz 45° f50 ID - Aust→Ferr	38.2	48.2	10	38.2 mm to OD	169	192	23
	Maximum Amplitude sizing used				6 dB sizing used		

TABLE 9 – Positioning and Sizing Measurements – Defect #8 Block 'B'

BLOCK B - DEFECT 8	DEFECT THROUGHWALL (mm)				DEFECT LENGTH (mm)		
Scan / Surface	Top	Bottom	Height	Ligament	Start	End	Length
IDS30 1.5 MHz 70° f35 ID - Ferr→Aust	80	NA	5	80 mm to OD	219.5	238.5	19
	Single arc (truncated) Maximum Amplitude sizing used				6 dB sizing used		
IDS31 1.5 MHz 70° f35 ID - Aust→Ferr	77.5	NA	7.5	77.5 mm to OD	221.5	242	20.5
	Single arc (truncated) Maximum Amplitude sizing used				6 dB sizing used		
IDS32 2 MHz 60° f35 ID - Ferr→Aust	82.2	NA	2.8	82.2 mm to OD	218.8	240	21.5
	Single arc (truncated) Maximum Amplitude sizing used				6 dB sizing used		
IDS33 2 MHz 60° f35 ID - Aust→Ferr	79.1	NA	5.9	79.1 mm to OD	220.5	242.5	22.5
	Single arc (truncated) Maximum Amplitude sizing used				6 dB sizing used		
IDS34 2 MHz 45° f25 ID - Ferr→Aust	79.7	NA	5.3	79.7 mm to OD	217.5	239	21.5
	Maximum Amplitude sizing used				6 dB sizing used		
IDS35 2 MHz 45° f25 ID - Aust→Ferr	NA	NA	NA	NA	NA	NA`	NA
	Defect exhibits poor S/N unable to give accurate dimensions						

TABLE 10 – Best Estimate of Defect Positions and Extents

BLOCK	DEFECT NUMBER	NOMINAL / MEASURED	DEFECT LENGTH / mm			DEFECT THROUGHWALL EXTENT / mm			
			Start	End	Length	Top	Bottom	Height	Ligament
A	2	NOMINAL	85	110	25	10	18	8	10
		MEASURED	81	106	25	9	20	11	9
	3	NOMINAL	135	160	25	67	75	8	67
		MEASURED	129	155	26	67	78	11	67
	4	NOMINAL	185	210	25	38	48	10	38
		MEASURED	180	201	21	34*	49*	15*	34
B	5	NOMINAL	77	102	25	65	75	10	65
		MEASURED	69	92	23	62	74	12	62
	6	NOMINAL	126	151	25	40	45	5	40
		MEASURED	116	140	24	41*	51*	10*	41
	7	NOMINAL	176	201	25	37	49	12	37
		MEASURED	167	194	27	41	52	11	41
	8	NOMINAL	226	251	25	82	85	3	82
		MEASURED	219	240	21	80	85	5	80

* - Defects #4, #6 partly obscured by Defect #1 from austenitic side and some anomalous signals noted which were difficult to reconcile – see **Tables 5, 7**

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