

Considerations for Industrial Qualification of In-Process Phased Array Ultrasonics During High-Integrity Cladding

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A handwritten signature in dark ink, appearing to be 'Alan', with a long horizontal stroke extending to the right.

Signed:

Date:

01/06/2026

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Abstract

The nuclear industry has always had a turbulent time in terms of public support and funding within the UK, albeit is now seeing a resurgence in both civil and nuclear applications to ensure energy security and to keep our country safe from foreign aggressors. This has led to a demand for better value for money from nuclear projects, which have consistently seen cost overruns on projects; requiring modernisation of manufacturing processes to deliver high integrity components more efficiently with scheduled certainty at increased quality metrics of 'right first time'.

In the manufacture of high integrity welded pressure vessels, required within the nuclear industry, a great deal of cost and programme delays are accrued through the traditional sequential of manufacturing operations e.g. welding, machining, Non-Destructive Evaluation (NDE), dressing/machining of defects, repair, machining, NDE etc.

By implementing a method of assessing the weld integrity during the welding process, both reduces the manufacturing cycle time and environmental impact of the manufacturing processes through reduced weld pre-heating gas requirements and time on machine, with increased knowledge of the welding process through real-time data capture driving further efficiency advancements through better manufacturing controls.

This thesis presents significant advancements in the pursuit of real-time in-series phased array ultrasonic inspection of high integrity weld cladding. The challenges associated with deploying an in-series inspection are non-trivial in a highly regulated industry with technology far exceeding current codes and standards guidance. Considerable research has been undertaken to close these gaps and enable methodologies to address and overcome them.

The work in this thesis introduces a method of quantifying and improving the ultrasonic transmission through as-welded complex geometries in a ‘multi-beam’ method with experimental proof on varying surfaces showing an order of magnitude improvement in signal variability on reference reflectors. Furthermore, a calibration compensation algorithm is developed and justified on elevated temperature ranges found during industrial pre-heated Cold Metal Transfer (CMT) cladding operations to justify compensations in material velocity, reflector amplitude, position and size.

The accumulation of this work is demonstrated on a full-size industrial vessel inspected robotically, during a weld cladding operation with seeded defects in a blind trial format. Demonstrating a front wall tracking algorithm to aid inspector interpretation and validation of the method through conventional Phased Array Ultrasonic Testing and macrographs. This work sets the foundation for industrial adoption of the in-series cladding inspection and provides evidence in criterion that cannot be met in current conventional UT codes and standard requirements.

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Abbreviations

ASME	American Society of Mechanical Engineers
AWESIM	Automated Welding Equipment System Inspection and Monitoring
BINDT	British Institute of NDT
BS	British Standard
CASD	Continuous at Sea Deterrent
CMT	Cold Metal Transfer
DAC	Distance Amplitude Correction
DPI	Dye Penetrant Inspection
ECT	Eddy Current Testing
ENIQ	European Network for Inspection and Qualification
EN	Europäische Norm or 'European Standard'
FCAW	Flux Core Arc Welding
FBH	Flat Bottomed Hole
FMC	Full Matrix Capture
FSH	Full Screen Height
HAZ	Heat Affected Zone
GMAW	Gas Metal Arc Welding (MIG)
GPU	Graphic Processing Unit
GTAW	Gas Tungsten Arc Welding (TIG)
ISO	International Organisation for Standardisation
IQB	Inspection Qualification Body
MAG	Metal Active Gas
MIG	Metal Inert Gas
MMA	Manual Metal Arc
MPI	Magnetic Particle Inspection
MT	Magnetic Testing

NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
PAUT	Phased Array Ultrasonics
PCF	Phased Coherence Factor
PCI	Phased Coherence Imaging
POD	Probability of Detection
PT	Penetrant Testing
PWR	Pressurised Water Reactor
RPV	Reactor Pressure Vessel
RT	Radiographic Testing
SAFT	Synthetic Aperture Focusing Technique
SCR	Stress Corrosion Relief
SDH	Side Drilled Hole
SMAW	Shielded Metal Arc Welding
SMR	Small Modular Reactor
SNR	Signal to Noise Ratio
TFM	Total Focusing Method
TIG	Tungsten Inert Gas
TOFD	Time of Flight Diffraction
TRL	Transmit Receive Longitudinal
UT	Ultrasonic Testing
WAAM	Wire Arc Additive Manufacture

Chapter 1

Introduction

1.1. Industrial Motivation

The ability to join materials together was a key driver of the Industrial Revolution, driven by the demand for more efficient manufacturing processes [1]. The late 1800s saw the advent of arc welding [2], but is now demonstrably inefficient in time, money, and environmental impact [3, 4]. Weld flaws, require considerable work to locate, remove, and repair, with a potential for multiple repair cycles before a component meets the required standard. Increased pressure to reduce costs and environmental impacts requires the innovation of new technologies to reduce the inefficiencies and environmental effects in manufacturing across all sectors [5].

Weld cladding is an advancement of a traditional welding process in which dissimilar metals are metallurgically joined to achieve superior surface properties, including increased hardness, wear and/or corrosion resistance, electrical conductivity or ability to withstand hostile chemical environments [6]. This cladding process is commonly implemented through the deposition of specific alloys onto a lower-cost base substrate, therefore reducing raw material costs while significantly extending the service life of a

critical component and consequently maximising the economy of initial cost to service life [7]. Owing to the process advantages of weld cladding, it has become integral to high-performance and safety-critical industries such as oil and gas, power generation, nuclear energy and mining [6, 8]. A variety of welding-based techniques can be employed for the deposition cladding, including Gas Tungsten Arc Welding (GTAW) [9], Wire Additive Manufacturing (WAAM) [10], Shielded Metal Arc Welding (SMAW) [11] and Cold Metal Transfer (CMT) [12].

Weld cladding in high-integrity manufacture requires the structural integrity of the welded component to be demonstrated and justified before entering service. Precise inspections through Non-Destructive Evaluation (NDE) techniques are typically performed on the component at the final machined condition following welding or cladding operations. NDE is commonly used to justify the product integrity or conformance to international standards such as ASME pressure vessel requirements [13]. Nuclear industries within the UK specifically use the TAGSI (Technical Advisory Group on Structural Integrity) [14] ‘Four Legs’ methodology, which uses NDE extensively to inform two of the key structural integrity legs to ensure ‘Quality of Build’ and ‘Failure Analysis – demonstrating tolerance to structurally significant defects’.

Delayed defect mechanisms, such as hydrogen-induced cracking, require inspection after a defined cooling period in accordance with international NDE standards [15, 16]. For clad components, additional manufacturing operations such as surface machining are required to facilitate NDE methods such as ultrasonic testing [15] to reduce surface waviness and meet surface finish requirements, thereby increasing overall manufacturing

times and delaying the detection of structurally significant defects from the welding process where they were formed.

Development of in-process ultrasonic inspection provides a pivotal opportunity to streamline the weld cladding operation, reducing industrial inefficiencies and enabling defect detection at the point of origin. To realise this potential, the capability for detection of common weld cladding defects, including disbands, cracking [17], lack of fusion [18], pitting at the fusion interface [12], and dilution of the base metal alloy [11, 19] at elevated temperatures is a critical enabling technology. As such, key advancements for in-process ultrasonic inspection to date have centered around a thermally controlled RollerProbe design, allowing the ultrasonic probe to be maintained at a typical ambient inspection temperature [20].

Resultant facilitation of immediate identification and repair options through a robust real-time inspection method also enables enhanced process control and optimisation of weld parameters through the insertion of feedback loops within the cladding process. Additional benefits can then be realised through improved schedule certainty of components throughout the manufacturing process and a reduction in unplanned rework as a byproduct of the increased process reliability and efficacy of defect mitigation [21]. Now, exploration of strategies compensating for residual thermal effects within the component is conducted to further compound these benefits.

Ultrasonic wave propagation through non-planar surface topologies is challenging due to scattering, reflection, and attenuation at the interface [22]. As traditional arc-welded clad surfaces deposited during the welding process are non-planar, the provision of a topology

that optimizes the welded surface for ultrasonic waves to propagate and reflect consistently would be beneficial to an in-process inspection methodology.

Phased array ultrasonics, now seen as the industry norm, offers a higher degree of flexibility and efficiency over that of ultrasonic inspections with single crystal transducers [23]. A key advantage of phased array ultrasonics is the ability for the beam to be steered at varying angles, rather than the traditional fixed angles possible with traditional ultrasonic probes [24]. Various solutions have been proposed for testing through complex surfaces. Flexible ultrasonic arrays [25] that can conform to complex surfaces utilise profilometers to measure the surface geometry. Immersion inspections utilising hemispherical-omnidirectional ultrasonic probes with SAFT imaging [26] are then reconstructed with post-processing algorithms to define the curved surface profile. Full Matrix Capture-Total Focusing Method (FMC-TFM) techniques [27] have been developed to image curved surfaces as a replacement for radiographic inspections.

1.1.1. In-Process Inspection

Traditional NDE inspections have commonly been carried out far removed from the welding process due to multiple technological constraints. Ultrasonic probes rely upon the electronic excitation of piezoelectric crystals to transmit ultrasonic waves into a component under test. However, high-temperatures can cause common piezoelectric crystals to lose their ability to do this above the material's Curie point (150-250°C), with sustained exposure to high temperatures reducing the working life of the crystal, causing other probe internals to warp, de-bond, cause adhesive failure and reduce the life of the electronic components and therefore the ultrasonic probe [28].

A major challenge in the deployment of traditional NDE inspection in-series with the welding process is the hostile environment for human inspectors to operate within. Extended exposure to elevated temperatures can be detrimental to human health, necessitating automated deployment methods. However, the removal of the human and the ability to physically judge probe pose on the Phased Array Ultrasonic Testing (PAUT) probe through tactile feedback is impossible. Strategies have then had to be developed to ensure an automated deployment can compensate for the tactile pose correction effectively as a human inspector would.

Other major challenges of an in-series NDE deployment come from the electrical interference and noise created during the welding process, and in addition, noise from motors from automated welding equipment intended to remove the human from deposition process. This interference generates significant noise across the captured ultrasonic waveforms, potentially obscuring signals from defects within the component being inspected [29, 30].

Welding, by nature, commonly induces heat in metallic materials to fuse the individual components together into one homogeneous structure. As a byproduct, thermal gradients are induced into the part, as the part sees a non-uniform thermal distribution, creating variations in ultrasonic wave velocity. This variable wave velocity causes beam skewing, increased attenuation, and reduced SNR (signal-to-noise ratio) [21] which can lead to an ultrasonic inspection severely mis-plotting the position and/or size of a discontinuity [31].

Multiple strands of real-time inspection development have taken various approaches to tackle the issue; however, have all been very specific to the proposed problem. Another

approach taken to inspect wire arc additive manufacture (WAAM) metallic components has targeted a combined eddy current and ultrasonic inspection method [32]. Phased array ultrasonic (PAUT) approaches such as real-time weld pool monitoring [21], Thermal compensation strategies have been developed to deliver ultrasound at temperature and compensate for the thermal gradients and beam bending effects [31]. Advanced imaging algorithms of narrow gap welds [33] and dual tandem PAUT for imaging of near-vertical defects [34] have followed a more combined methodology built upon a PAUT roller probe capable of withstanding the challenging welding environment through a chilled internally pumped couplant [20].

Initial attempts have been made to tackle the complicated problem of calibrating and verifying an inspection system through embedding a single type of intentional defect into the weld process [35, 36]; however, prior results show a limited ability to overcome the range of defects commonly found in the welding process. Other approaches to in-process ultrasonic inspection have focused on the use of laser-induced phased arrays (LIPA), although this demands greater GPU power to process in real time and may not be suitable for a high-deposition-rate welding process [37, 38]. Some investigations into deploying laser ultrasonic inspections on WAAM components have employed mathematical models of known regular surfaces [39] and real samples with the surface averaged to give an RMS value [40], however none have tackled the issue of inspecting an irregular surface profile.

As such, the development of in-process NDE currently remains in its infancy, with each application specific to a manufacturing process or component. Drawing on the multiple use cases described above, developing a generic approach to weld inspection can only aid

the driver in reducing the bottleneck NDE has on manufacturing throughput. Combining the developments detailed for in-process NDE and the weld cladding processes would lead to a developed inspection method by which a single clad layer could be inspected and confirmed to be defect free at the time of weld deposition, reducing the rework-repair loop, increasing the efficiency of the manufacturing process in both time and energy resources whilst increasing the schedule certainty for the manufacturer.

1.1.2. In-Process Inspection of Cladding Calibration Challenges

Ultrasonic Testing (UT) and Phased Array Ultrasonic Testing (PAUT) are two of the principal NDE methods used for the detection and characterisation of internal discontinuities, not open to the surface of the part. Ultrasonic inspection is a highly sensitive defect detection technique; however, it is strongly influenced by environmental and operational parameters, which must all be accounted for by means of a calibration or reference block inspection. The calibration block can bound the inspection requirements by means of reference reflectors of a pre-determined size, bounding the inspection volume and is typically scanned both pre and post component inspection. Calibration of ultrasonic inspections typically accounts for the speed of sound (velocity) travelling through the reference block to enable a correct range or distance for geometric features, or defects to be determined and the amplitude of a reflector response. The amplitude response will be set from a known reflector size as agreed by the international code or standard relevant to the structural significance and defect tolerance of the component under test.

One of the key issues in defining an in-process based ultrasonic inspection is the effect temperature has on the propagation of ultrasonic waves. An increase in component temperature, as would be seen during the weld cladding process, reduces both longitudinal and shear wave velocity, primarily through a change in the material's Young's modulus and density [41]. Another key challenge encountered at elevated temperature is the increased sound attenuation arising through a progressive loss of signal amplitude due to enhanced material dislocation mobility and internal friction [42, 43]. Work undertaken on basic TIG welds [31] has shown compensation is possible using TFM and compensated time of flight maps; however, this approach would be impractical and challenging to deploy on as-welded geometry of thin cladding. Additional considerations must be given to balance the requirements of the inspection against the large data files created through the TFM method within security restrictive and data sensitive industries; where cloud storage is often not possible with air-gapped data storage expensive to develop and maintain.

Temperature-driven phenomena can cause substantial deviation in positional measurement accuracy and amplitude-based detection criteria under elevated temperature conditions. In relevant low-carbon steels, a decrease in ultrasonic signal amplitude has been reported by as much as 16.9dB from room temperature to 250 °C [44]. This increased attenuation is a direct consequence of increased temperature and dramatically reduces defect detection sensitivity, potentially resulting in underestimation of material thicknesses or non-detection of defects in safety-critical components. In response, related work in the power generation industry has also demonstrated ultrasonic measurements of

thermal distributions in solid materials [45] and assessment of time of flight data at elevated temperatures for plant life extensions [46]. Considerable work has also been undertaken in an adjacent industrial field to measure lubrication film thicknesses at temperature as an important metric for the behaviour of engine and gear oils [47, 48].

Ultimately, ultrasonic inspections are controlled and justified by the application of a national or international standard. BS EN ISO 17640:2018, the standard for manual ultrasonic testing of welds in metallic materials, specifies that an object under test must have a temperature between 0°C and 60°C, with the calibration block and component under test being within ± 15 °C of each other [15]. International standards such as ASME V require a maximum variance of ± 14 °C [13].

Work to justify an in-process inspection method must therefore overcome this current standard limitation by means of temperature compensations that correct for, as a minimum: the material velocity, material attenuation, signal amplitude of reflectors, position and sizing of indications at elevated temperatures. Inspection methods must also establish a link to a calibration block to ensure the inspection is appropriately conservative. Current attempts to define an in-process calibration method have focused on the embedding of intentionally seeded tungsten tubes within the welded volume [49], but this is non-preferable in high-integrity components and would undermine the structural integrity of components in many safety-critical industries. In addition to these requirements, an in-process inspection to determine the integrity of weld cladding must also take into account the dissimilar metals, which adds an additional challenge through acoustic mismatch, varying grain structures and differing material velocities.

1.2. Research Objectives

In-process inspection is notoriously difficult to achieve using standard ultrasonic or phased array ultrasonic techniques. Several key challenges must be considered to develop a reliable and robust in-process inspection methodology. The objectives of this research are outlined as follows:

- Verify performance and limitations of current in-process phased array ultrasonic imaging techniques with respect to cladding geometries.
- Investigate automated deployment of in-process phased array ultrasonic imaging techniques across a range of cladding processes.
- Investigate qualification approaches for in-process phased array ultrasonic imaging approaches during representative geometry cladding, taking account of applicable accepted standards and international processes.
- Assess the viability of providing a generalised pathway to certification of such inspection techniques in safety critical applications, including key generic steps required based on a range of product integrity standards, and a ready means of identifying the gap to approval and use of such emerging technology for a range of applications and modes of use.
- Develop suitable supporting evidence towards the qualification approach for in-process phased array ultrasonic imaging approaches during representative

geometry cladding, taking account of applicable accepted standards and international processes.

- Develop suitable verification approaches for approval of in-process phased array ultrasonic imaging approaches during representative geometry cladding, taking account of applicable accepted standards and international processes.
- Assess key weld cladding parameters to maximise compatibility with and optimise in-process phased array ultrasonic imaging, coverage and defect detection on components.

1.3. Contributions to Knowledge

Knowledge contributions produced as a result of the work of this engineering doctorate are outlined below:

- Development of a novel adaptive compensation for inspecting through an as-clad surface.
- Defining a calibration methodology for phased array ultrasonic inspections of cladding at temperatures up to and including 250°C.
- Defining a compensation methodology for sizing and positioning of known artificial ultrasonic reflectors in cladding at temperatures up to and including 250°C.
- Application of a multi-beam imaging algorithm and interface tracking on a robotically deployed blind trial phased array inspection of an internally clad vessel.

1.4. Thesis Structure

Chapter 2 introduces the relevant background theory which underpins this work, including a review of various welding and cladding methods and their uses. A thorough review is then presented of common defect types within weld cladding and various NDE techniques and methods with their aligned advantages and disadvantages with a particular emphasis on UT and advanced PAUT methods. Finally, an outline of high integrity NDE methods and qualification methods is presented.

Chapter 3 introduces the effects of varying clad surface finishes and quantifies its effect on a known reflector at the bond line between the weld cladding and parent metal substrate. Multiple samples are experimentally tested with an immersion system to quantify the maximum amplitude variation for a slot passing under multiple weld cladding surface peaks and troughs. The weld profiles are then mechanically profiled to define optimum ultrasonic beam angles for transmission through the surface and merged together in a multi-beam methodology. This multi-beam ultrasonic inspection is then used to remeasure the maximum amplitude variation from the slot reflector in both an immersion and roller-probe inspection set-up to define the improvement in amplitude variation through an as-clad surface.

Chapter 4 builds on this work in understanding and developing compensation strategies for the PAUT inspections to be calibrated at stable elevated temperatures as determined through weld modelling with industrially qualified welding parameters. Analysis is conducted to determine the effect of temperature against key ultrasonic input and output

parameters including material velocity and its effect on hole depth, reflector sizing and reflector amplitude to allow dynamic compensation curves from 25°C to 250°C. Significant benefits of this approach include the ability to link the calibration to a room temperature reference block and compensate during live in-process inspections or post-processing of the data, whilst maintaining the link to a code compliant calibration methodology.

Chapter 5 pulls together the developments from Chapters 3 and 4 to provide a robotically controlled in-series inspection of a vessel with internal cladding. The inspection is conducted in a blind trial format where the artificial reflectors were hidden from the inspectors to ensure a fair assessment of the inspection methodology was delivered. The inspections were then repeated from the opposing machined face external surface of the vessel with a code compliant PAUT inspection technique with a sample of the defects selected for confirmation through macrograph destructive testing. This approach showed a successful in-series welding inspection capable of finding structurally significant flaws at the weld bond line repeatably during the welding process.

Chapter 6 summarises the main findings and work conducted in the previous chapters of this thesis and documents the potential further work that has arisen during the research conducted to continue the development of an in-series weld cladding inspection system.

1.5. Journal Contribution

Lead author journal publications produced during this engineering doctorate are outlined below:

- **Thomas Leach**, Ewan Nicolson, Robert Watson, Charalampos Loukas, David Lines, S. Gareth Pierce, Charles N. MacLeod, “Adaptive compensation for in-process ultrasonic cladding inspection”, NDT & E International, 158 (103571), 2026
- **Thomas Leach**, Ewan Nicolson, Robert Watson, Charalampos Loukas, David Lines, S. Gareth Pierce, Charles N. Macleod, “Towards a calibration methodology for an in-series phased array ultrasonic inspection of weld cladding at elevated temperatures”, NDT & E International, 161 (103699), 2026
- **Thomas Leach**, Robert Watson, Ewan Nicolson, Charalampos Loukas, David Lines, S. Gareth Pierce, Charles N. Macleod, “Robotic-Controlled, In-Series Phased Array Ultrasonic Inspection of Industrial Vessel Internal Weld Cladding”, Insight – Non-Destructive Testing & Condition Monitoring (Submitted March 2026 – Under Review)

1.6. Conference Contributions

Lead-author conference contributions produced throughout work for this engineering doctorate are outlined below:

- Advanced Nuclear Research Centre (ANRC) - Enabling Global Nuclear Energy Renewal – 24-25th October 2024 – Lightning Talk: “Adaptative Compensation for In-Process Ultrasonic Clad Inspection Through Varying Surface Profiles”
- US/UK Advanced Technology Forum – NDE and Monitoring – 18th June 2025 – Rolls Royce Submarines - UK: In-Series NDE of Welding/Cladding

- UK Research and Innovation (UKRI) Doctoral Focal Awards (DFA) Interview for STAND-UP (Skills and Training driving availability of National Defence Assets UP skilling) – 13th January 2026

1.7. Industrial Partnership

The work throughout this Engineering Doctorate has been supported by Rolls Royce Submarines Ltd, with a focus on advanced NDE activities; specifically, in-process inspection of high integrity weld cladding operations.

Discussions with other adjacent nuclear manufacturers has allowed consistent engagement and collaboration on what an end goal solution would look like for the wider industry with organisations including:

- Rolls Royce SMR Ltd
- Babcock International Group
- BWXT

Chapter 2

Literature Review

2.1. Nuclear Power and it's Uses

The history of nuclear power has seen a shift from the years leading to and during World War II with focus primarily on the development and manufacture of weapons of mass destruction; to the years following the war where science broadened the development of nuclear technology to peaceful applications such as the provision of electricity generation, industrial & medical uses along with powering of space missions [50, 51].

Nuclear power has often been a controversial topic in the last few decades not only for the cost of building nuclear reactors but for the longer-term socio-economic implications and the drive for renewable energy. Renewable considerations are also given against a full life cycle – ‘Design to disposal’, applications and not just against initial development and construction impacts. Cost drivers in some countries such as the USA have led to the slowdown of investment in nuclear plant construction in the 2010’s and a greater push for the increase in production of natural gas due to its shorter-term cost benefit [52]. However, more recent developments have seen opinions change with nuclear energy being seen as

a key method of ensuring energy security and a step-change towards CO₂ reduction in energy and climate policies [53].

Nuclear power has key advantages in the provision of electricity generation, firstly in its power density. The European Nuclear Society [54] compares the power density of each fuel type: coal, mineral oil and uranium; comparing their like for like ability to provide power through combustion or fission in both heat output and electricity generation, with Uranium-235 containing two to three million times the energy equivalent of oil or coal. The World Nuclear Association [51] highlights the differing approaches around the world to nuclear reactors with 59 reactors under construction in contrast to 213 reactors currently shutdown and/or decommissioned. Various countries rely on nuclear power to supply a range from 10-50% of their electricity depending upon their countries attitude to nuclear power.

The use of nuclear power in civil electricity generation can be debated on its consideration as a green investment and is commonly compared to renewable energy sources such as solar, hydro, wind, tidal, biofuels and renewable waste[55, 56]. However [55] also highlights nuclear's role in supporting growth by enabling low carbon energy policies and aims to deliver a framework to explain the role nuclear has in the renewable mix as the second largest source of low carbon energy in 2019.

The use of civil nuclear power in the energy mix landscape can be questioned; however, in others are a binary decision due to power density requirements and space. Nuclear submarines have been a stalwart of the major naval powers since the commissioning of USS Nautilus in 1954 [57]. The United States realised the significant potential of nuclear-

powered submarines due to the nuclear plant being non-air breathing, increasing underwater endurance and speed with an unlimited range, without the need for support ships [58, 59].

The countries that operate nuclear submarines has always been limited with only 6 countries (USA, Russia, China, UK, France and India) operating nuclear powered submarines since the late 1980's: with some countries giving up during the development of an indigenous program. However, interest is building in the developing technological powers of Brazil, Turkey, South Korea, Australia and Iran all showing potential expansion into the ambition to develop nuclear powered submarines [60].

The drive for nuclear power not only makes sense for applications such as submarines with space constraints but in applications in civil power generation without the high construction costs traditionally associated with large scale civil nuclear plants. A novel approach to nuclear in the application of Small Modular Reactors (SMR) takes modern construction principles and manufacturing standardisation to maximise transportability of the reactor components through the available road networks and the removal of repeat design costs in the pursuit in reduction of construction costs[61].

Various nuclear reactor types have been put into practical use in the decades since the inception of civil nuclear plant usage with Light Water Reactors (LWR) being the most common with small modular reactors and Fast Neutron Reactor (FR's) being used in smaller quantities [62].

Novel reactor designs including traveling wave reactors, standing wave reactors, CANDU reactors, breed and burn concept [63], molten salt fast reactors [64], gas cooled reactor (A-GCR) [65] are being considered for the future Gen IV reactors to maximise safe usage and reliability and minimise waste generation.

The new concept reactor designs all have potential in the medium term to address the energy production mix in reducing the carbon footprint of the increasing population but cannot solve the issue in its entirety. Nuclear fission although capable of providing the energy for electricity production to the scale provided for global industrial growth is also limited by the reserves of uranium and concerns on radioactive contamination and release [66]. The dream of unlimited clean energy is often cited as the ability of nuclear fusion, the reaction occurring in stars, with the technical realisation of this on earth a combination of being able to control temperatures into the millions of degrees. Various technological approaches have been suggested to harness nuclear fusion [67] with major breakthroughs reported as recently as December 2022; with the fusion reaction releasing a greater quantity of energy than required to ignite the process [68]. Nevertheless, useable nuclear fusion reactors are still seen to be decades away unless major breakthroughs are forthcoming.

2.1.1. Nuclear Submarines

As previously discussed, the use of nuclear reactors in submarines is a necessity for sovereign states that require a continuous at sea deterrent (CASD) [69]; as it is the only power method that provides unlimited range without having to surface for refuelling or to take on air.

Nuclear power in an enclosed space does not come without challenges; with radiation in close proximity with the living quarters of the sailors that work within the confines of the submarine. This radiation also causes challenges as maintenance becomes a method of best endeavours of minimal invasiveness from external contact points due to the low levels of radiation dose humans can safely tolerate.

The immense cost of designing and maintaining the complex system of an underwater facility capable of powering itself for 25 years whilst making its own fresh air and water and enabling a liveable environment for the often 100+ sailors cannot be understated. All of these requirements; whilst containing a pressurised water reactor which is inaccessible during underwater manoeuvres, due to the radiation levels; whilst storing multiple nuclear warheads and their launch systems [70].

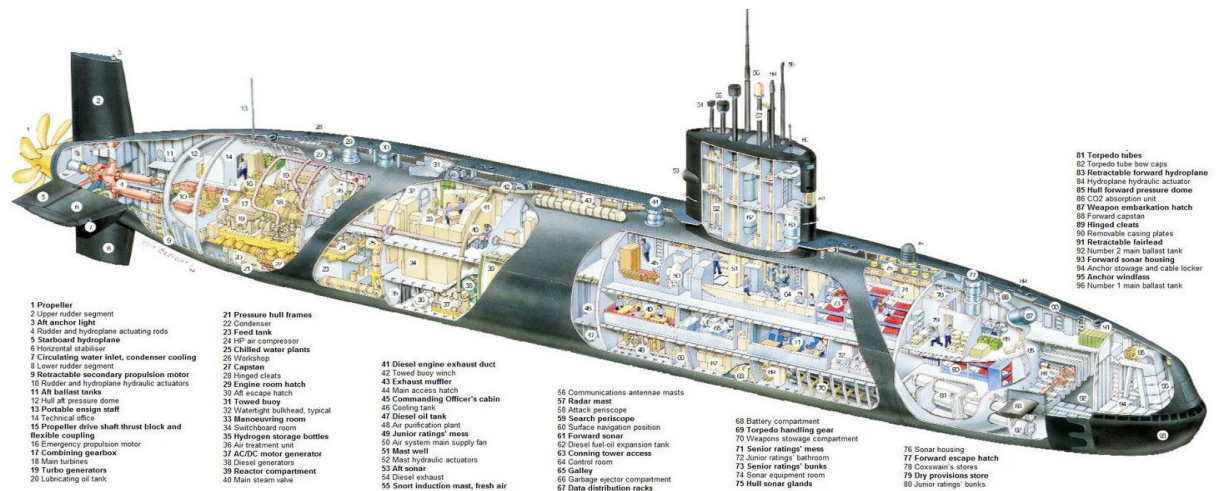


Figure 1 - UK Trafalgar Class Nuclear Submarine – Cut Away Image [71].

2.1.2. How does a Pressurised Water Reactor (PWR) Work?

All nuclear submarines in service today contain reactors called Pressurised Water Reactors (PWR) with over 160 ships containing more than 200 small reactors [71].

PWR's contain highly enriched uranium within a reactor pressure vessel (RPV) which under nuclear fission heats primary coolant (pressurised water) to high temperatures. This highly pressurised heated water then flows through a steam generator which transfers thermal energy to the secondary circuit through thin-walled tubes to maintain radioactive contaminants within the primary circuit. This secondary circuit heated steam then drives turbines in a similar manner to a conventional power station, which are then used to drive motor and turbo generators used to power the ship's functions and provide drive to a propulsor.

This enclosed system requires very little maintenance; especially within the primary circuit as most systems are designed with redundancy between the major systems. Maintenance within the secondary circuit is achievable even during sub-surface manoeuvres with primary circuit maintenance limited to the dock side, due to the high temperatures and radioactive dose present during reactor plant fissionable states.

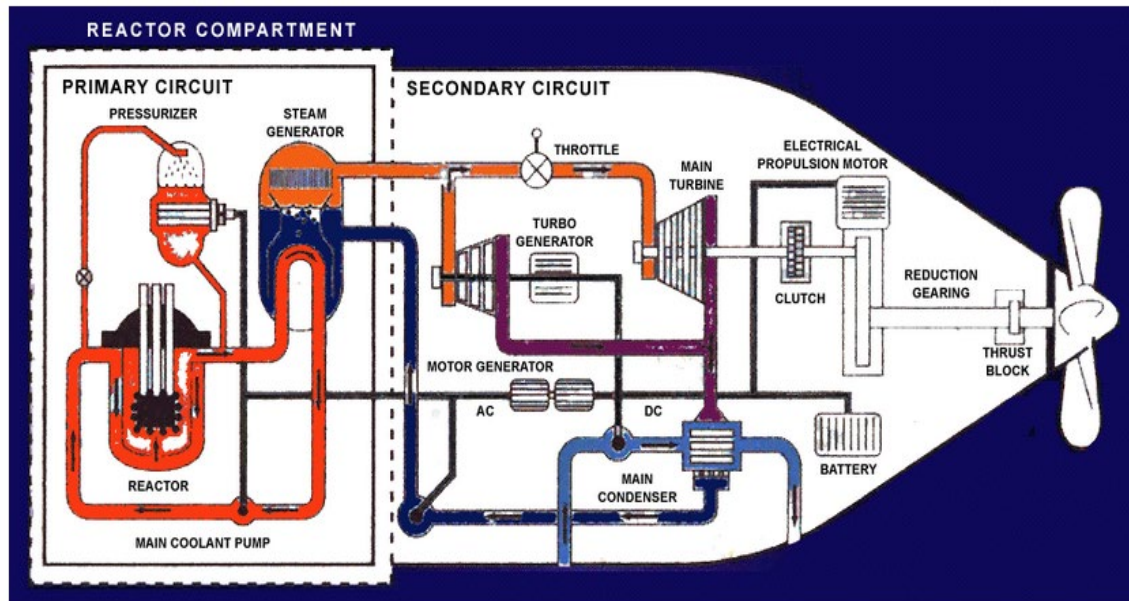


Figure 2- UK Submarine Major Components [71].

2.2. Pressure Vessels

Pressure vessels of various sizes and designs form the critical components in any nuclear reactor plant. Pressure vessel development throughout the 19th and the beginning of the 20th century featured numerous catastrophic failures and vessel failures [72]. These failures drove the requirement for the development of basic standards for the manufacturing of pressure vessels through codes and standards. The image below shows a steam drum failure during a final hydrostatic pressure cycle at Babcock and Wilcox Ltd in Glasgow which at that point in time considered a high-quality manufacturer as they welded vessels to one of the early standards: BS 113 (1958). The black tarnished areas of the image demonstrate cracking was already induced prior to final heat treatment and

although the failure was considerable, it was fortunate this failure happened before the vessel was put into service.

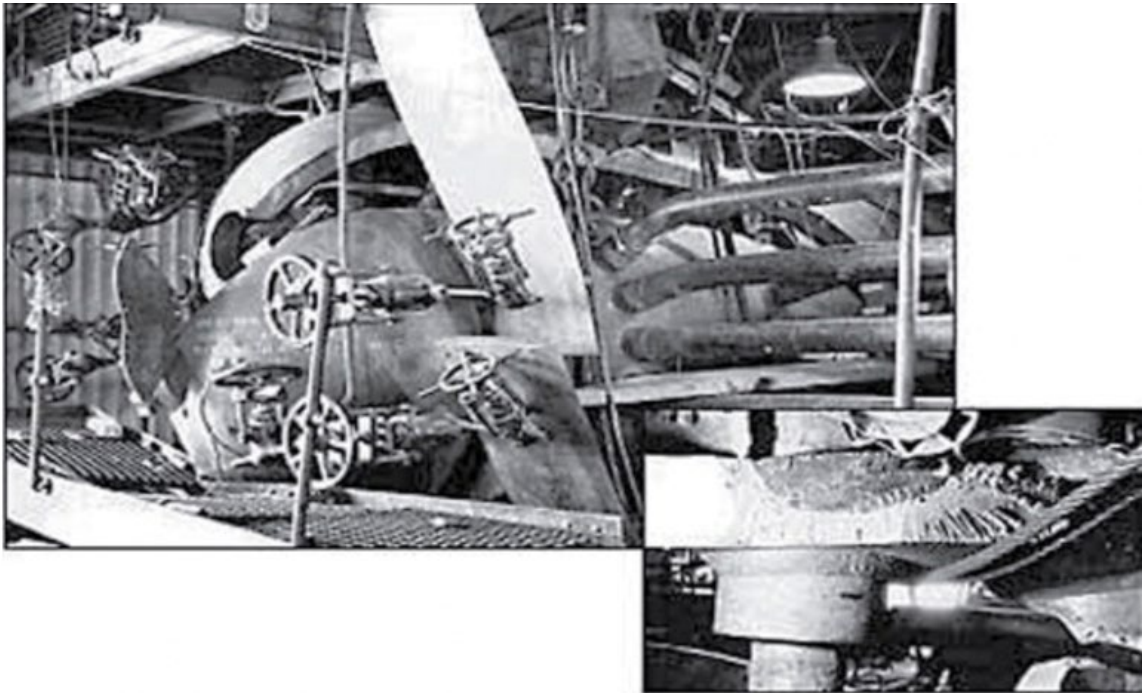


Figure 3- A failed vessel during hydrostatic testing [72].

The American Society of Mechanical Engineers (ASME) through the Boiler and Pressure Vessel Code [13] have continuously advanced modern standards and code cases since its first issue in 1914; in the pursuit of delivering a safe design, manufacture, and maintenance engineering specification.

Common pressure vessel materials such as carbon steel now have bespoke handbooks to cover the design and construction of pressure vessels in compliance with the ASME Boiler and Pressure codes [73]. Specific applications of pressure vessel construction and usage are covered in more detail for industries such as nuclear in Moss, D and Marshall, M [74] Design and practice publication.

Learning from failure is extremely important in pressure vessel manufacture and operation due to the high consequence of failure in both infrastructure and collateral damage; along with any potential fatalities from anyone unfortunate enough to be in close proximity to the failure. Design calculations are key in avoiding these catastrophic failures with case studies presented to optimise design parameters such as temperature, pressure, stress, corrosion and safety factors [75].

Another fundamental decision in the design and manufacture of pressure vessels is the correct choice of base materials. Materials selection is one of the major decisions to prevent the common failure mechanisms of pressure vessels; including but not limited to brittle fracture, hydrogen attack and stress corrosion cracking [76]. Depending upon the application of the intended vessel; the material can be selected based upon a large inventory of use cases and their performance. Knowledge of material performance is readily available and its susceptibility to failure mechanisms is now more widely recorded and understood [75]. The real issue for most pressure vessel designs is in how to appropriately join forged sections together to produce the finished vessel.

2.3. Welding Technology

Welding technology is both an art and science, in the modern era with extensive knowledge captured into codes and standards; from the basics in introductions on the principles and theory on arc welding processes [77] to more complex discussions on developing new welding processes and efficient designs and fabrication procedures [78].

Welding technology is such a broad function that it can encompass materials from basic steels to exotic titanium alloys and methods from traditional Shielded Metal Arc Welding (SMAW) to complex niche solutions such as underwater friction stir welding (UFSW) [79].

As noted previously, the consequences of failure in base material manufactured into pressure vessels, the need for the weldments deposited on or to join sections of the pressure vessel are equally as critical to prevent in-service failure. Welding technology has gone further in recent history to understand parameters such as weld residual stresses and how this affects fracture behaviours and mechanics, crack displacement calculations to assess leak and breakage scenarios prior to failure [80]. To fully understand the correct welding method and design; a clear set of design requirements are a must, ensuring the pressure vessels integrity through construction and through the full in-service life cycle of the vessel.

Common high integrity welds in pressure vessel manufacture often use traditional welding methods such as Gas Tungsten Arc Welding (GTAW); commonly referred to as TIG welding and Gas Metal Arc Welding (GMAW) more widely known as MIG welding [81]. These welding methods are both defined as arc welding; that are based on creating an arc between a consumable or non-consumable electrode and the workpiece. GTAW and GMAW are very similar processes in many aspects, and both use shielding gases but differ in the use of electrodes. GTAW uses a non-consumable electrode in the form of a tungsten with a manually added filler rod whereas GMAW uses a solid wire machine fed into the weld pool [82].

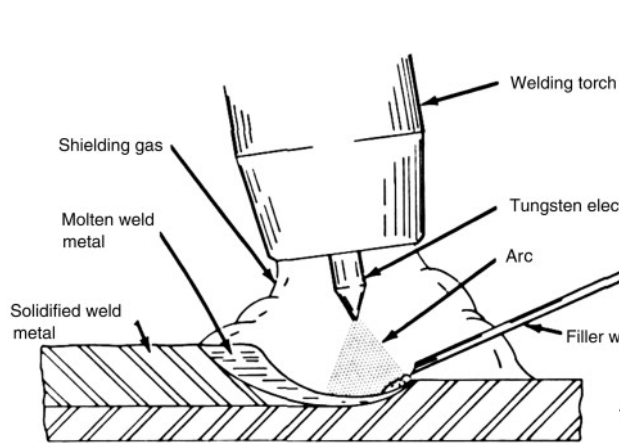


Figure 4- (Left) Gas Tungsten Arc Welding (GTAW)

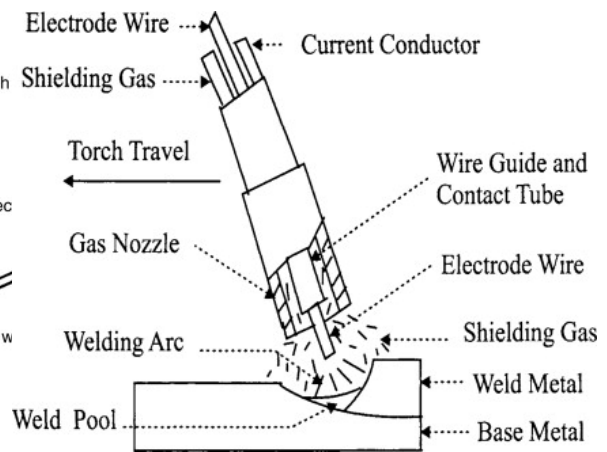


Figure 5- (Right) Gas Metal Arc Welding (GMAW)

GMAW welding is quicker than GTAW welding due to the automated filler wire application and is generally considered cheaper, quicker, and easier to learn however is not as precise, strong and aesthetically pleasing [82].

Other arc welding processes such as FCAW (Flux Core Arc Welding) are a more recent development from the 1950's developed as an alternative to MMA (Manual Metal Arc) more commonly termed as 'stick welding'. Flux Core arc welding can be performed in both a shielded or unshielded gas environment and overcomes MMA limitations through the use of a continuously fed consumable wire electrode [83]. Advantages of FCAW in the context of welding pressure vessels are the ability to weld outdoors and for joining thicker materials. The shielding provided by the filler wire can endure outdoor wind conditions, high deposition rates are available, and arc stability can be improved compared to MAG (Manual Active Gas) welding. The key drawback of FCAW is the slag formation from the flux; if not appropriately removed prior to subsequent weld layers can in turn become an embedded volumetric defect.

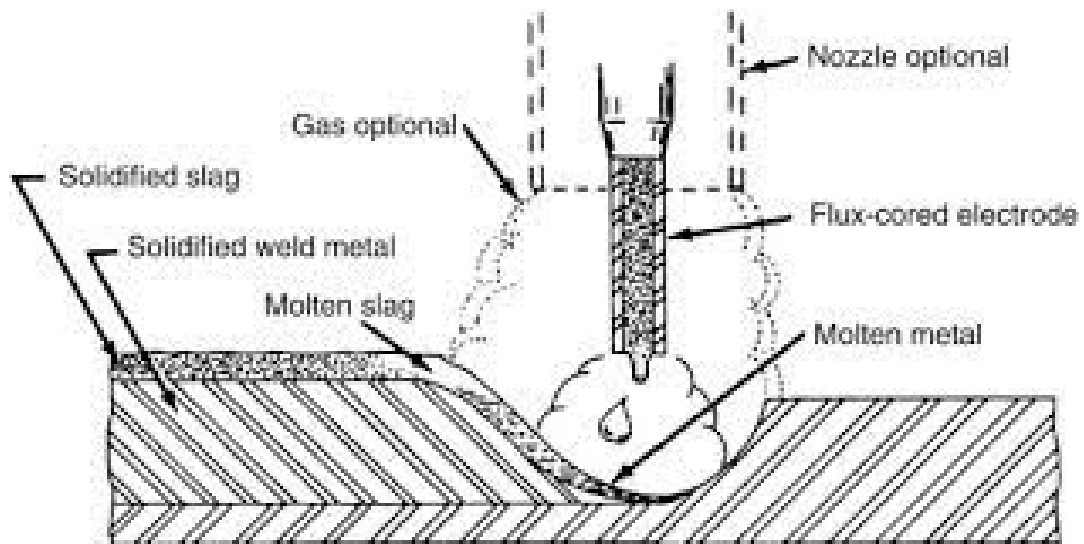


Figure 6 - Flux Cored Arc Welding[84].

All arc welding methods have advantages and disadvantages in terms of weld microstructure and metallurgical benefits, and the choice of the welding process is key to the overall pressure vessel manufacture. By having a pressure vessel design requirement, the appropriate welding method can be determined, and a balance of weld integrity can be delivered to ensure the structural integrity of the weld in service.

2.4. Weld Cladding (Purpose and Applications)

Pressure vessels in nuclear environments are subject to additional ageing affects during service conditions such as irradiation embrittlement, thermal ageing, fatigue, and corrosion. Due to these additional negative in-service conditions designers now cover nearly all RPV's (Reactor Pressure Vessels) with a weld cladding layer on the internal faces. Although weld cladding has major advantages in terms of enhancing corrosion

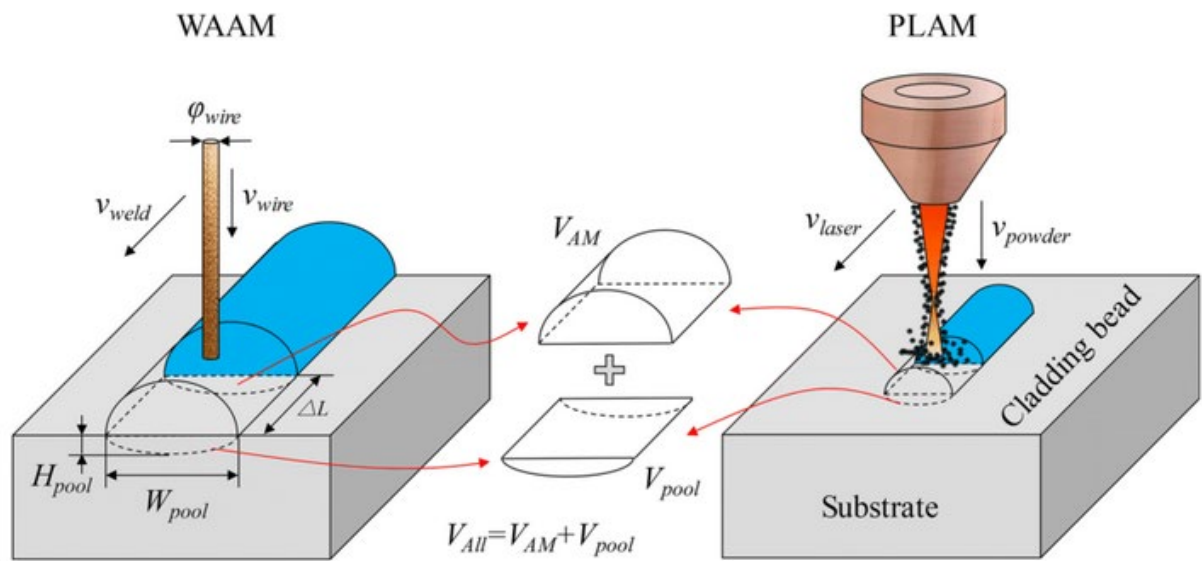
resistance it should be noted that the weld cladding can, if done incorrectly, increase residual stresses within the vessel [85]. The use of cladding in the RPV then becomes an integral part of the component and its metallurgical performance is then inherently linked to the performance of the RPV over life. Luo, Y., et al [7] argues the importance of the cladding and the stress/strain profile is an important consideration in the overall sealing performance of the RPV further emphasising the requirement for high integrity cladding in nuclear applications.

The use of nickel alloys such as Inconel 625 are highly utilised in internal weld cladding due to the ability to weld relatively thin layers of cladding for corrosion resistance whilst also ensuring low dilution of parent metal alloying elements [19]. The use of corrosion resistant alloys saves a great deal of cost to the pressure vessel method of manufacture, as the whole vessel doesn't need to be made from the selected material; however, the trade off's have to be managed by welding engineering. The root and hot pass of the wire for the welds in the components must be compatible with the clad material, limiting the options for the welding engineer [29].

The history of underclad cracking in reactor pressure vessels is a re-occurring problem due to the long life of nuclear plants and the repeated attempts to justify their use for longer periods beyond their original design life. Underclad cracking although first discovered as an issue in the 1970 was soon justified by Westinghouse [86] for a 40-year design life; noted as reheat cracking in the base metal directly below the deposited cladding. The issue re-surfaced in 1979 as 'cold cracking' with fracture evaluations again being justified for the 40-year design life. However, in the early 2000's with a push to

justify a 60-year design life a further assessment of the issue was required with the importance of Non-Destructive Testing (NDT) and accurate sizing of the underclad cracks justifying the plants continued use through fatigue crack growth assessments.

New welding techniques such as cold wire MIG (Metal Inert Gas) welding have come to fruition in the past few years to enable better control of the welding process in the pursuit of additive manufacture. The development of Wire Arc Additive Manufacturing (WAAM) provides a high deposition rate and the ability to customise complex geometries [10]. The author's findings suggested a direct relationship between arc power, weld penetration and dilution of the clad which should be considered when designing the appropriate welding strategy for the reactor pressure vessel cladding.



Schematic diagram of cladding AM processes for WAAM and PLAM

Figure 7- WAAM and PLAM (Powder Laser Additive Manufacturing)[87].

Other cladding welding methods include the use of GTAW stainless steel or nickel-based alloys deposited onto carbon steel substrates. [9] noted in the cladding of Inconel 825 various processing conditions correlated highly with the visual condition of the single clad layer tracks suggesting the parameters were key to acceptable weld quality. The trials noted by [11] concerning SMAW (Shielded Metal Arc Welding) of Inconel 625 cladding, showed that lower welding currents and a weaving technique led to deposits with greater width and reinforcement while still meeting low base metal dilution.

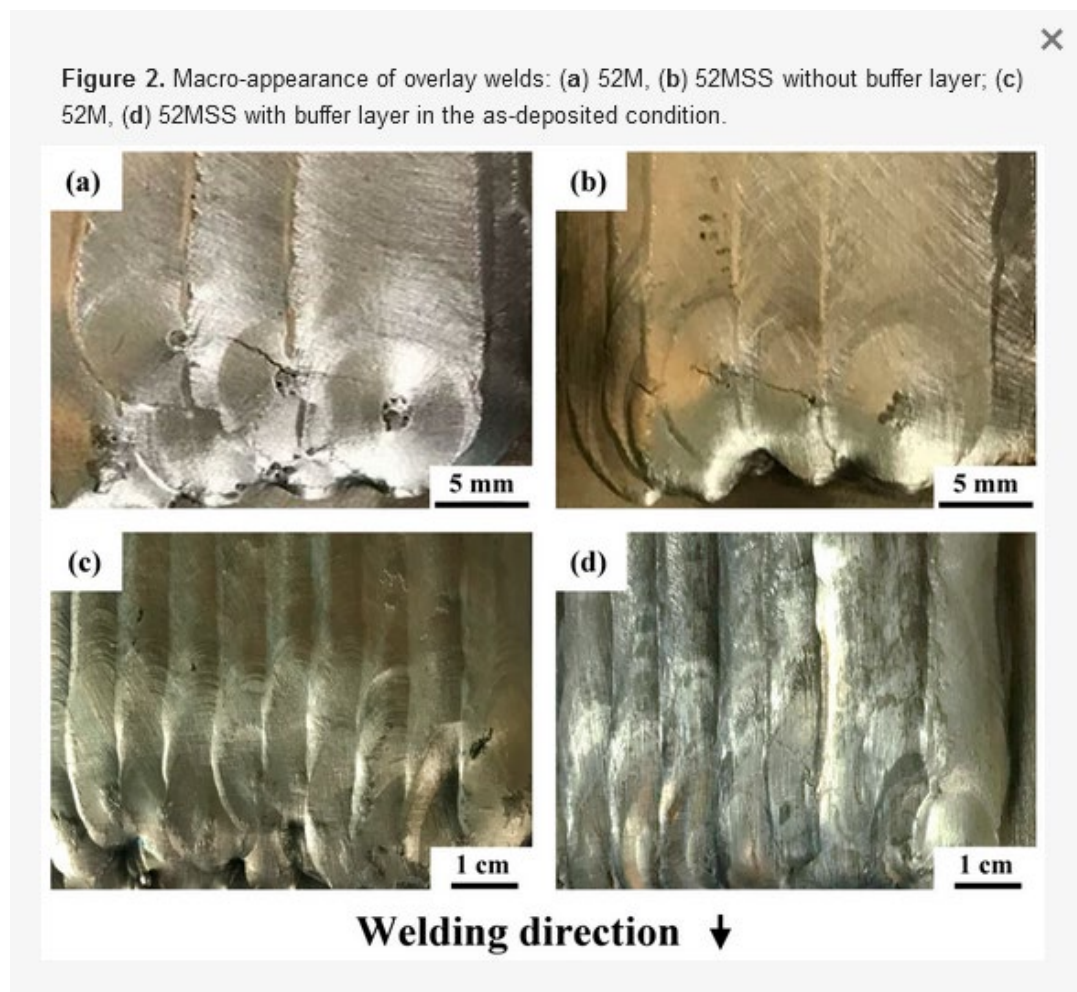


Figure 8- GTAW Cladding with Stop/Start Cracking [88].

Cold Metal Transfer (CMT) is also another modern approach to weld cladding application. [12] showed in trials that corrosion resistance was increased in CMT cladding in comparison to GTAW cladding; however, noted texture strength in opposing orientations between the welding methods. The study also highlighted the CMT had a higher pitting tendency at fusion boundaries. CMT however shows in Figure 9 its ability to provide a creatively parallel clad surface both on the external surface and the cladding to parent material transition. This parallel face then lends itself to the ultrasonic inspection methods allowing for any unbonded areas of the cladding to be detected through conventional 0-degree UT.

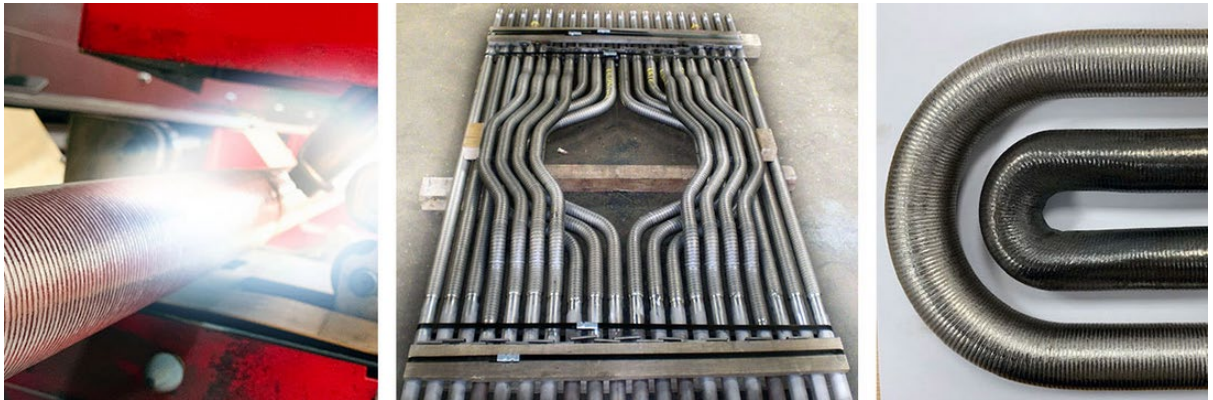


Figure 9- CMT Overlay Cladding of a 360-degree Spiral Wound [89].

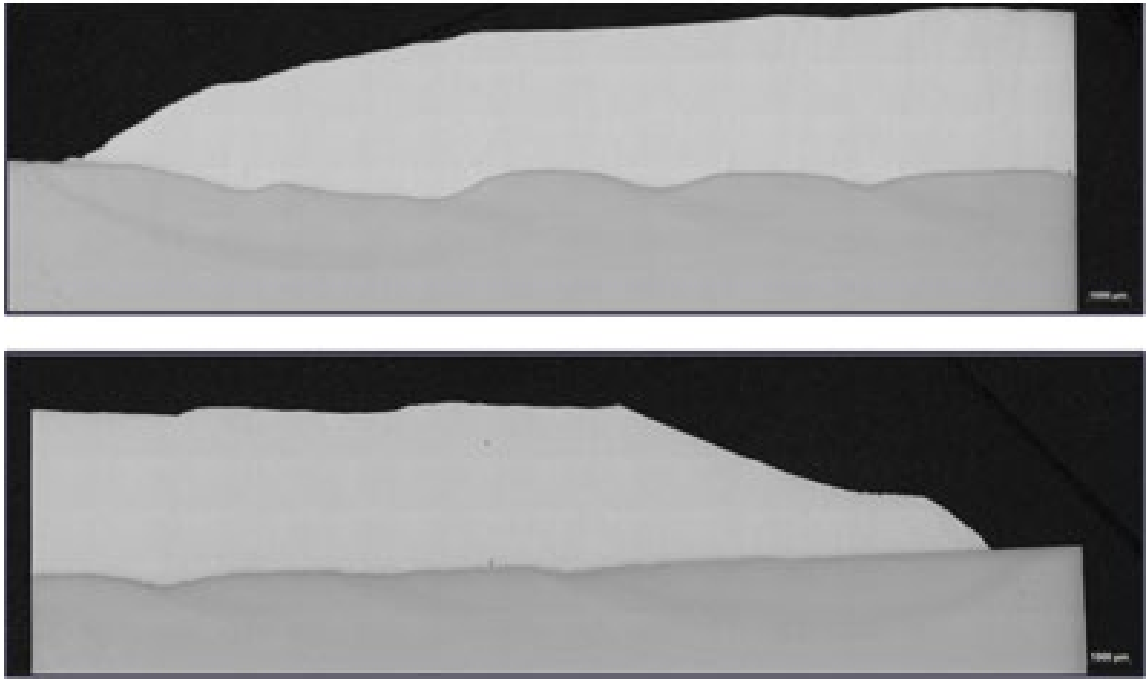


Figure 10- CMT Cladding (82H) onto S275 Steel – Macro Cross Sections

It can be shown that although there are multiple ways to appropriately apply weld cladding to reactor pressure vessels; again, the design intent and material requirements to justify the structural integrity all play a key role in deciding on the appropriate weld method and material for the vessel. The requirements for each vessel may differ very slightly in one parameter and lead to a completely different choice of welding process, cladding material, and base metal substrate to suit the application.

2.5. Weld Defects and their Formation

A key condition of cladding requirements is the structural integrity and bonding of the cladding to the parent material of the vessel. Cladding is typically tested to ensure no major defects have been implemented during the welding process and the clad layer is

fully bonded to the parent metal. Due to the nature of the cladding being a parallel surface, this lends itself to UT. The key disadvantage to this is the additional work required to machine the surface to make the surface finish appropriate for UT, a time consuming and costly process.

Pressure vessels and their cladding nearly always undergo post weld heat treatment to optimise the grain structure of the material for better through life properties. The author [90] noted during the 1970's during the stainless-steel cladding on low alloy steel substrate that the dissimilar materials were prone to underclad cracking. Although in SMAW, through trial and error the author managed to eliminate underclad cracking without a fundamental understanding of the cracking mechanisms.

Figure 11 below shows an example of incorrect welding heat input affecting the microstructure and formation of SRC (Stress Relief Cracking) during post weld heat treatment under restraint.

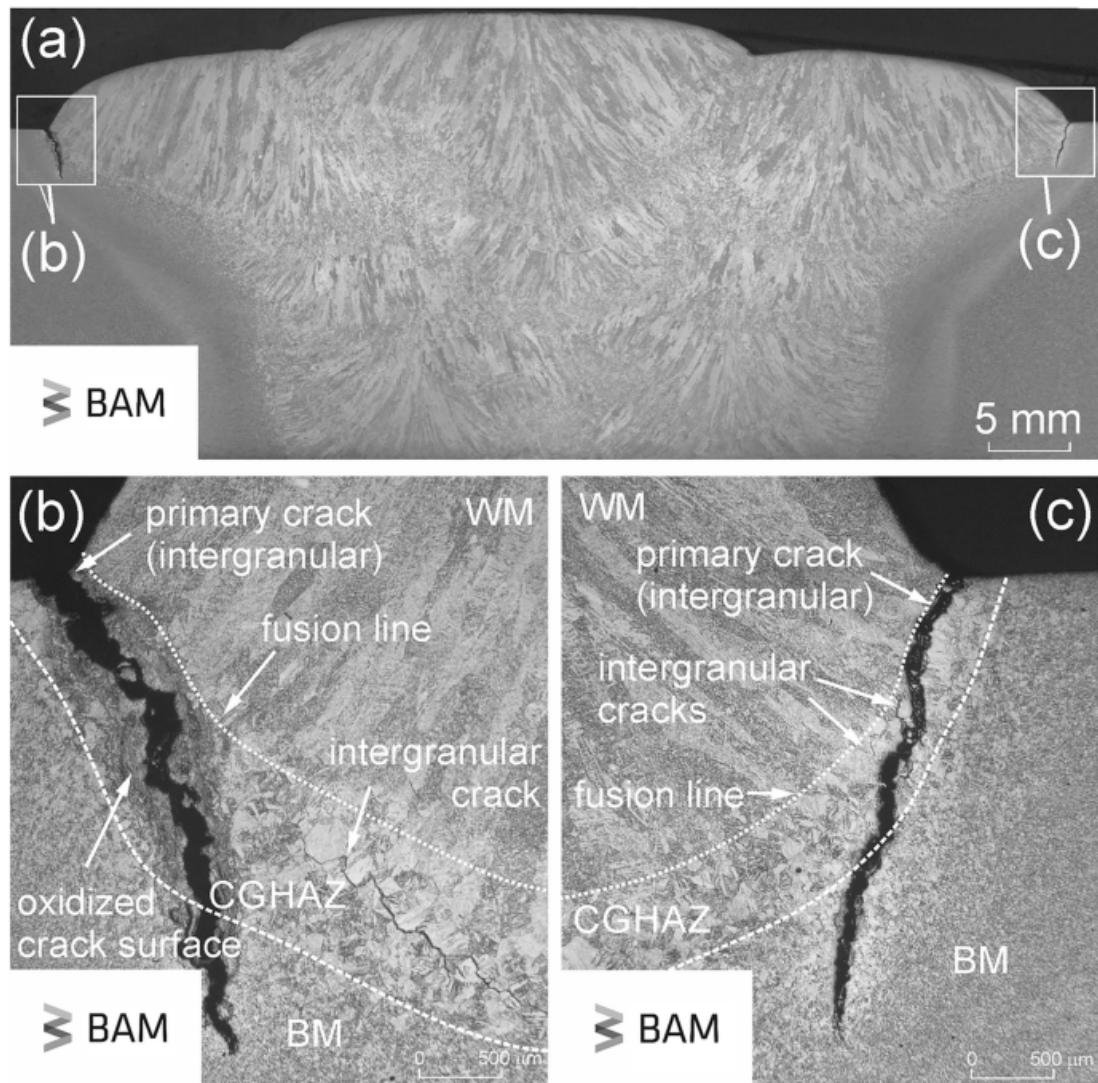


Figure 11- Macrograph of Weld Cracking during Post Weld Heat Treatment[18]

CMT in recent years has also shown great promise in development from a traditional GMAW process; with increased performance in welding of dissimilar metals, controlled metal deposition rates whilst maintaining a low heat input and creating an aesthetically pleasing weld bead [18].

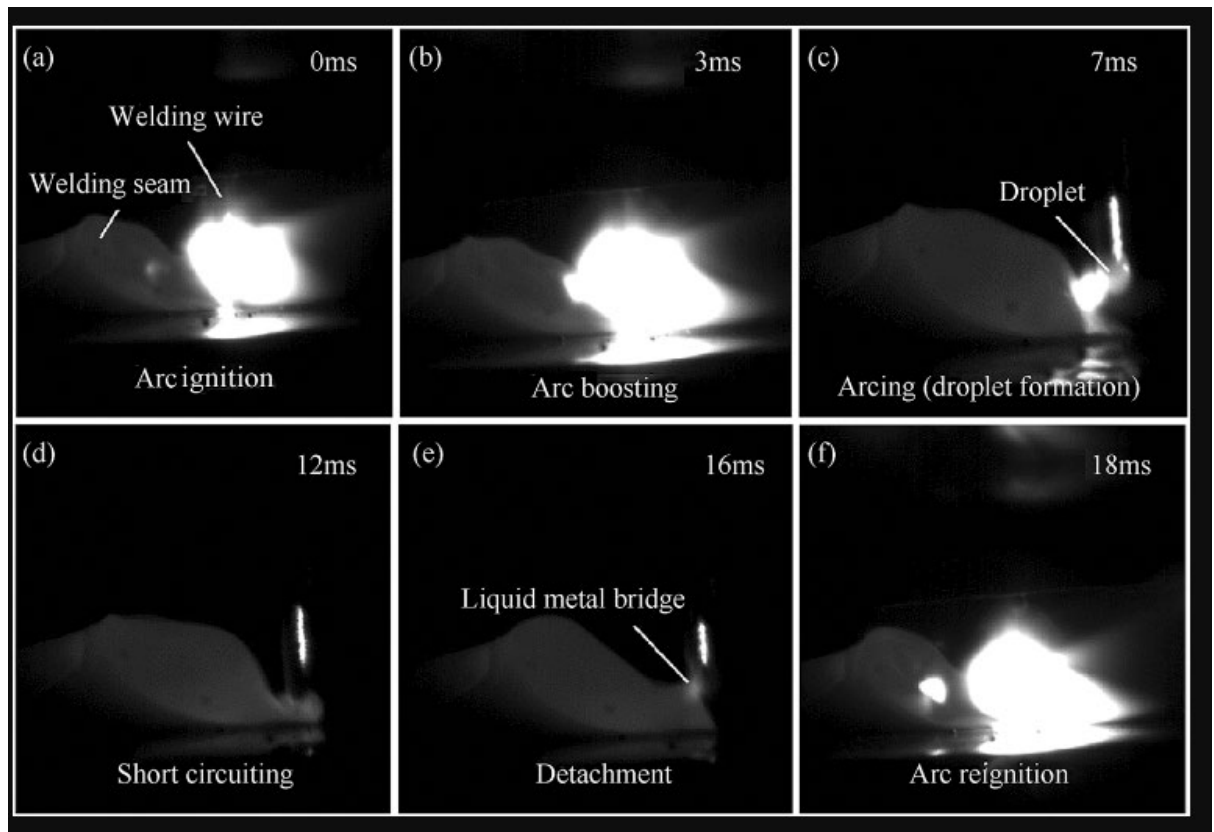


Figure 12- CMT Cladding Process [18].

However, the author notes the downsides of CMT as a process are a by-product of the process's advantages. The increased risk in lack of or incomplete fusion was a key defect type to control, however the author noted positive results in resolving this through increasing the arc length [18]. Defect free cladding was presented by [91] using CMT in the application of Inconel 718 with the work concentrating on the contact angle and its ability to add successive passes successfully. The author noted results where lower wire feed speeds, resulted in lower heat inputs and produced less dilution in the cladding.

Other CMT studies in aluminium welding; a commonly troublesome material to weld due to oxide layers, showed a relationship between feed rates and the ratio of dilution [92]. The study noted a wider process window was available with CMT than traditional pulse methods and dilution rates of up to 20% lower, resulting in greater control of the clad composition which if used correctly minimises chances of crack propagation.

A CMT cladding of Inconel onto a generic base steel (316L) was shown to be porosity and crack free in the overlay region with complete fusion at the bond line [93]. Again, CMT showed reduced dilution in the cladding to steel substrate Fe element levels, maintaining the corrosion resistance of the clad [94]. The study in [93] also maintained a defect free cladding with complete bond to the substrate; however only used destructive testing in the form of micrographs suggesting a sample inspection methodology at best. The key highlights to their results were the cross-sectional micrographs showing a minimal/ non observable HAZ (Heat Affected Zone) in comparison to a GTAW sample showing a considerable fusion zone, highlighting the strength of CMT in use of low dilution nickel-based alloy cladding for components requiring corrosion resistant properties.

2.6. Non-Destructive Evaluation (NDE)

2.6.1. NDE Methods (Uses and Limitations)

NDE or NDT is the name of a branch of materials sciences often applied in engineering industries, whereby a multitude of processes and techniques are applied to a variety of manufactured components; to determine their structural integrity prior to and/or during

the service life of the component. NDT is concerned with the uniformity, quality and serviceability of materials and structures [95] and is a broad subject with a variety of applied methods to assess significant properties and identifying unwanted discontinuities. This section aims to introduce a range of common NDT methods that have been used to identify, position, size and characterise internal discontinuities and assess their advantages and limitations in their application against weld cladding and its common defect forms.

Radiography is one of the main volumetric methods deployed in NDT; since it's early commercial applications during World War II [96]. X-Rays and Gamma Rays utilised by radiography are a proven method in locating internal discontinuities in castings, welds and forgings however has potential serious limitations in detecting defects in the parallel plane. Careful consideration on the defect orientations typical of the welding process and set-up is required to ensure the detection of the required defect morphology including skew angles, rake angles, tilt angles and defect gape / volumetric area. Serious shortfalls in the detection of defects normal to the angle of radiation in the form of defects such as laminations is widely reported due to the insignificant lack of radiographic contrast the defect type causes. However, crack like defects in-line with angle of radiographic incidence are highly suited to detection even with considerably tight crack gapes as discussed by [97] and his formula in the detectability of radiographic defect types by their key variables.

$$d = AF \frac{(W \cos \theta + U_T)}{(W - AF \sin \theta)}$$

Equation 1 - Detectability of radiographic defect types by their key variables

Where:

d = Crack Through Wall Extent (mm)

A = Minimum Thickness Change that can be Detected

F = Empirical Form Factor

W = Crack Gape (mm)

U_T = Total Radiographic Unsharpness

θ = Angle

Experiments have shown high reliability in the application of radiography to find defects perpendicular to the plate surface of cracks under weld cladding [98]. However, searches for the application of radiography both conventional and digital in detecting defects parallel to the clad application show little to no experimental data; due to the unsuited nature of this NDT technique to find defects in that plane.

Eddy Current Testing (ECT) is an NDT method generally considered a surface/ near surface technique based upon electromagnetic induction, where circular currents are used to induce opposing eddy currents into a conductive test component through the application of an AC current through a coil. The eddy current field induced into the component under test will then see a change in impedance if a defect exists under the coil as a by-product of opposing magnetic fields [99].

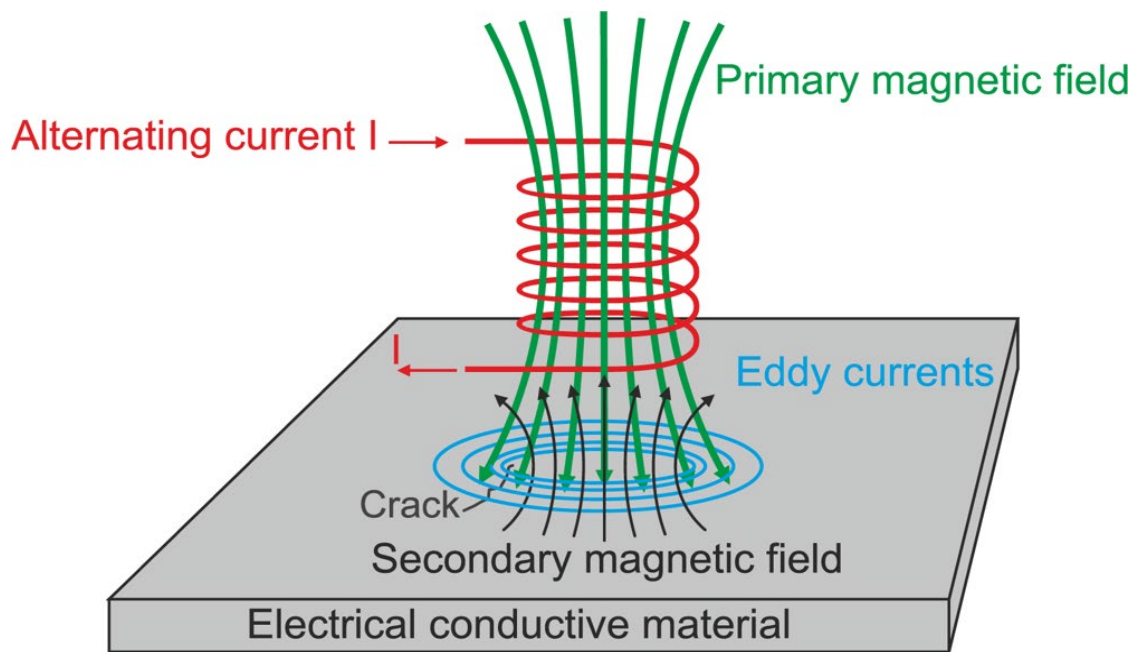


Figure 13- Magnetic Fields (Primary & Secondary) with Induced Eddy Currents within a Test Piece [99].

More modern applications of Eddy Current technologies have merged the method with thermographic imaging; for condition-based monitoring of offshore overlay weld clad components for real time structural health monitoring [100]. Challenges were however noted at interface regions due to the differing material structures as a by-product of the welding processes.

Quantitative experiments as far back as 1989 have shown the strengths of eddy current techniques in the use of crack depth measurements in overlay clad welded pressure vessels [101]. As discussed previously the justification that a crack is confined to a certain region for example the parent material directly below the clad layer or wholly contained within the clad layer can be crucial in the fatigue assessments to validate the vessel for a defined

service life. Eddy current showed the most reliable measurements for crack depth when compared to potential drop and ultrasonic time of flight techniques in overlay material.

Although eddy current techniques may show promising results for sizing crack depths in weld cladding applications consideration must be given to its application and the potential scenarios/ bounding considerations it may be best suited to. The use of eddy current inspection at temperature brings significant challenges; with ECT sensors extremely sensitive to ambient temperatures due to the change in coil impedance and material conductivity [102]. Developments have shown promise in using high temperature resistant ECT probes to monitor material microstructures during heat treatment [103] however literature on its use in testing weld cladding at temperature on as welded surfaces is non-existent.

Other NDE surface methods include Dye Penetrant (DPI) and Magnetic Particle (MPI) inspections. Dye penetrant or liquid penetrant testing is defined as a physical and chemical NDT testing procedure designed to detect and visualise surface connected discontinuities [104].

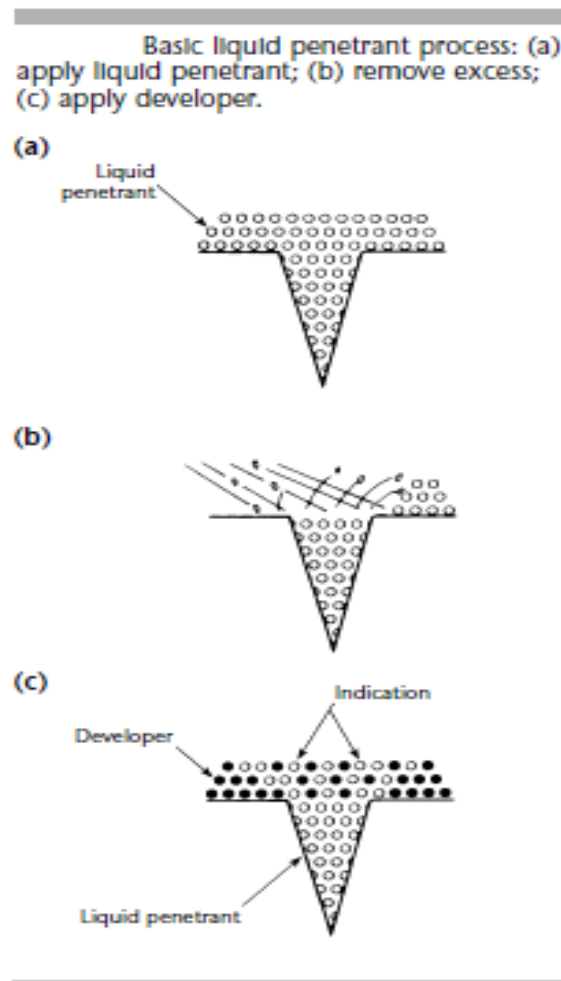


Figure 14- Basic Liquid Penetrant Process [104].

DPI relies on capillary action which allows the dye to enter the opening of a defect and remain in the defect until the application of a developer to the surface to draw the dye back out, creating a visual indication of the defect opening.

Dye penetrant is a simple inspection to deploy, however is better suited to machined surfaces to reduce false calls associated with dye trapping between weld runs, it's limited to surface inspections only, which reduces its ability for weld clad inspections due to

parent metal cracking and weld clad cracking being non-surface breaking. The main drawback to DPI would be the use of flammable chemicals ruling it's use out for inspection during welding processes.

MPI is a method that is used for detection of surface and 'near-surface' flaws in ferromagnetic materials only. The component under test is magnetised either in a local area or overall, as a component to induce magnetic flux within the test component, in the presence of a surface breaking flaw the magnetic field then becomes distorted causing a local area of magnetic flux leakage around the flaw [105]. This magnetic flux leakage is visually represented usually through the application of an ink with fine iron particles which accumulate at the region of flux leakage representing the crack on the surface [106].

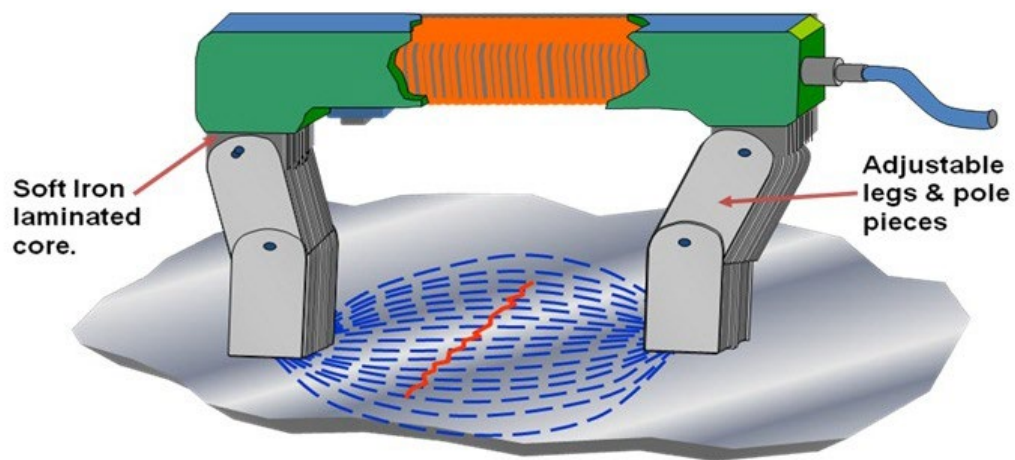


Figure 15- Magnetic Particle Inspection using a removeable AC yoke [107].

MPI disadvantages include the use of inks with fine magnetic particles suspended in high flash point kerosene. The process is considered quite messy; however, its key drawback

is the flammability of the majority of MPI chemicals containing kerosene ruling out its use during weld cladding application due to the temperatures far exceeding the flash point of the kerosene.

The other main NDT volumetric technique rather than the use of radiography is by means of ultrasonic inspection.

2.6.2. Fundamentals of Ultrasonic Inspection

Ultrasonic testing is considered a volumetric inspection that's easily portable, has a low cost to deploy, is safer than alternative volumetric inspections due to the absence of radiation (radiography) and is considered highly sensitive if deployed by trained technicians. Ultrasonic testing is considered a broad NDE method applicable for the detection of internal discontinuities, cross section evaluation (thickness testing) and bond testing. Thicknesses from a micrometer to a meter can be tested with accuracies of better than 1% [24].

Ultrasonic wave frequencies in industrial testing are commonly conducted with a central frequency between the 1 and 15 MHz range, however frequencies above the 20 kHz range are considered ultrasonic [24]. Higher frequencies are typically utilised for testing metallic components as the shorter wavelength of the higher frequency allows the detection of smaller defects. This is traded against higher frequency ultrasonic waves suffering from increased attenuation losses reducing the depth of penetration into the component under test.

Lower frequencies (usually within the kilohertz range) are better suited to inspections that require more penetration are now being used to conduct NDT in concrete structures [108]. Concrete suffers from a coarse granular structure due to it being a multi-phase material consisting of coarse aggregate particles leading to acoustic scattering increasing attenuation during ultrasonic inspection.

Further issues are noted in the testing of austenitic stainless welds due to the elastic anisotropy in the weld structure affecting the ultrasonic propagation [109]. The columnar grain structure of austenitic stainless steels in similar terms to concrete gives rise to increase scattering and attenuation. However, in contrast to testing concrete using lower frequencies the requirement for finding small defects in austenitic stainless welds prevents this approach. The use of compression wave [110] angled probes is used to mitigate the columnar grain structure due to the compression wave type providing higher penetration as a by-product of the higher velocity compared to shear wave angled probes.

2.6.2.1. Ultrasonic Wave Modes

Ultrasonic waves are a mechanical vibration/displacement of a material away from an equilibrium position. Ultrasonic waves have four dispersion types [111].

1. Longitudinal (Compression) waves where the waves oscillate the particles parallel to the propagation direction.
2. Transverse (Shear) waves where the waves oscillate the particles perpendicular to the direction of the wave propagation. Shear waves have shorter wavelengths and spread slower than compression waves.
3. Surface/Raleigh waves where the wave travels along the flat or curved surface to approximately 1 wavelength depth without influencing the bulk material below. Surface waves move the particles in an elliptical orbit while the wavefront propagates along the surface of the test component.
4. Lamb/Plate waves are produced in thin metal where the metal thickness is comparable to one wavelength of the ultrasonic wave. Lamb waves have

multiple or varied wave velocities depending upon the material thickness and its frequency with the particles moving either symmetrically or asymmetrically.

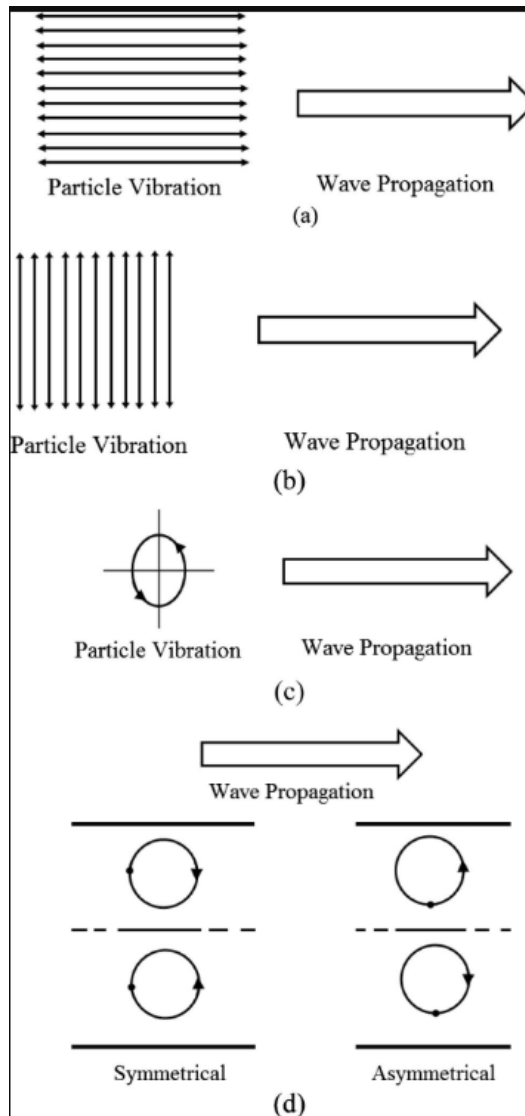


Figure 16- a) Longitudinal, (b) shear (transverse), (c) Rayleigh, and (d) Lamb waves and the direction of particle vibration [111].

Longitudinal waves can propagate through all mediums: solids, gases, and liquids whereas a limitation of shear waves is its ability to only be used in solids due to gases and liquids

not being able to propagate shear waves as a by-product of not having the shear strength to facilitate.

2.6.2.2. Acoustic Impedance

Acoustic impedance (Z) is a property for characterising the effect that occurs when the ultrasonic wave meets the boundary between two phases (material boundaries). A portion of this sound wave is transmitted into the component, whilst the rest of the wave is reflected away from the boundary.

Acoustic Impedance (Z) is measured in pascal seconds per metre (Rayl) and is given by the equation:

$$z = \rho \cdot v$$

Equation 2: Acoustic Impedance (Z)

Where:

ρ = Material Density (kg/m^3)

v = Velocity of sound in the material under test (m/s)

The impedance mismatch or transmission/reflection ratio of the ultrasonic wave can then be calculated by:

$$\text{Reflected Sound Coefficient} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2$$

Equation 3: Transmission/Reflection Ratio

Where:

Z_1 and Z_2 are the acoustic impedance of the first and second material.

2.6.2.3. Wave Refraction and Mode Conversion

As the ultrasonic wave reaches a phase boundary where the two materials have differing velocities, refraction occurs from the interface. The larger delta in material velocities between the two materials leads to higher refraction angles. Refraction angles are calculated using Snell's law:

$$\frac{\sin(\theta_i)}{v_1} = \frac{\sin(\theta_r)}{v_2}$$

Equation 4: Snell's Law

$\sin(\theta_i)$ = Angle of Incidence ($^\circ$)

$\sin(\theta_r)$ = Angle of Refraction ($^\circ$)

v_1 = Velocity of first medium (m/s)

v_2 = Velocity of second medium (m/s)

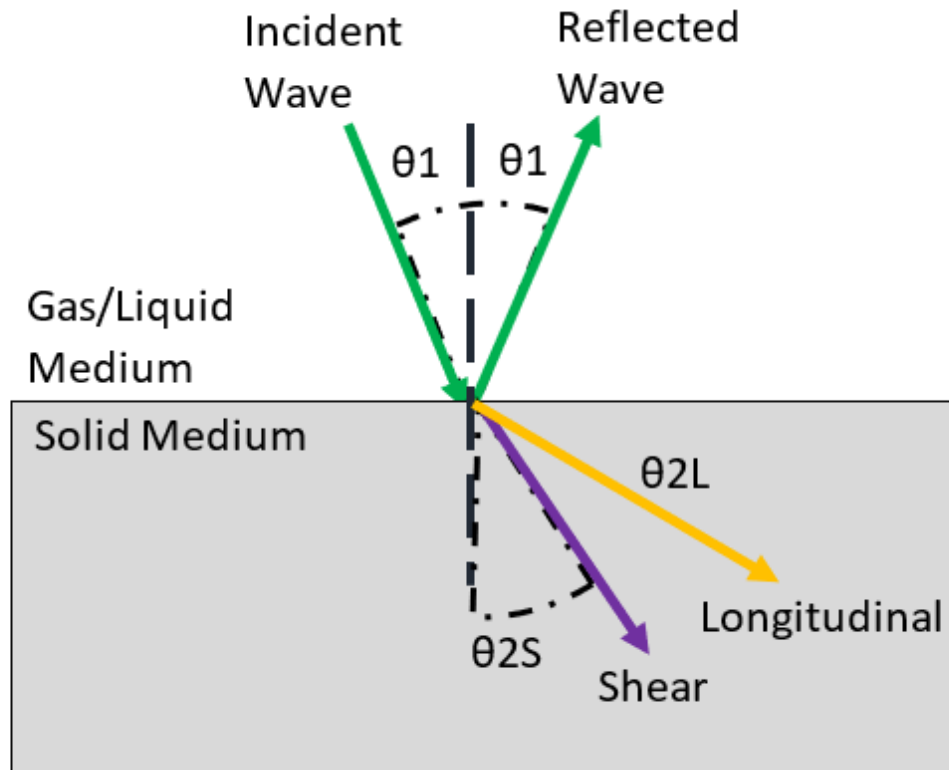


Figure 17- Wave Refraction at a Boundary

Mode conversion is the ability of an ultrasonic wave to convert from a wave mode to a differing wave mode, when refracting at a material interface where the two materials have different acoustic velocities e.g., usually from a longitudinal wave refracting to a shear wave.

The figure above shows a longitudinal wave at an angle θ_1 (greater than 0 degrees incident) is refracted at the interface into two wave fronts: θ_{2s} as a shear wave and θ_{2l} as a longitudinal wave. The first critical angle is a point beyond this whereby the refracted compression mode refracts to 90 degrees. When θ_{2s} reaches 90 degrees at the second critical angle, the shear wave is no longer refracted into the material but is converted to a

Rayleigh wave. If θ then reaches 90 degrees, no significant bulk energy is transmitted into the component.

2.6.3. Conventional Ultrasonic Inspection

Conventional or traditional Ultrasonic NDT is performed with a probe/transducer in direct contact with a component through a coupling medium placed between the probe and the component; often coupling mediums include water or glycerol-based fluids.

Commercial UT probes are constructed to contain a piezoelectric ceramic crystal in a protective housing. An ultrasonic wave is created by charging a capacitor in the ultrasonic flaw detector then quickly releasing this charge into the probe. The electrical energy released into the probe then causes the piezo electrical crystal to convert this energy into a mechanical vibration [112], whereby the crystal collapses in a similar method to the behaviour of a spring. The crystal then expands and contracts to form the ultrasonic pulse until it usually comes to rest in its original state noting that overdriving crystals can cause damage over periods of time.

Various damping materials are used within the probes to prevent unwanted signal reflections on the interior of the probe and to optimise performance for the required inspection methodology. The liquid couplant layer between the probe and component under test maximises the energy transmission of the crystal into the component by removing the air gap which has a high attenuation to ultrasonic waves.

Figure 18 below shows a simple pulse-echo single crystal ultrasonic configuration. Sound energy is transmitted from the probe into the test specimen at surface 'A' producing an echo at A1. Noting the echo at A1 is a result of sound reflecting of the front surface of the component combined with the inherent ringing of the crystal/initial pulse combining into a wider signal envelope. Signal B1 shows an area of the component where a perpendicular defect 'B' to the front surface is obscuring the sound from transmitting to the back wall and causing a reflection prior to penetrating the full component thickness. The remaining sound adjacent to this travels the full distance to the back wall 'C' providing an echo at 'C1' at a further distance than 'B1'.

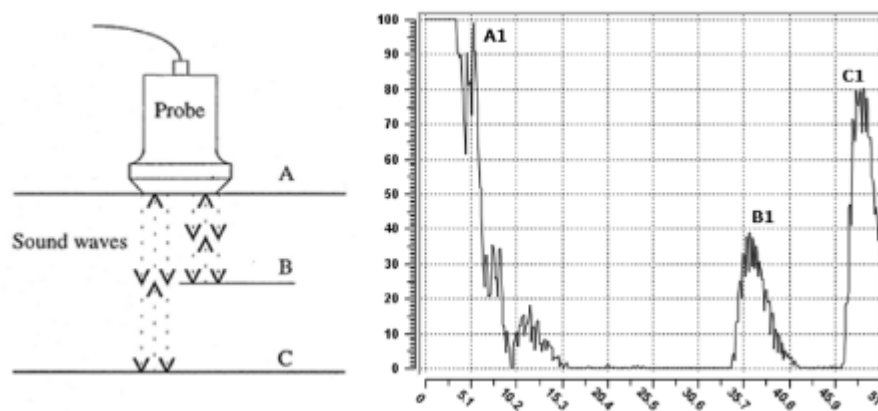


Figure 18- Basic pulse echo configuration demonstrating signals received from a perpendicular defect and a back wall response.

Using known properties within the material such as the materials acoustic velocity and calibrating the ultrasonic flaw detector by appropriate means allows accurate depth sizing of defects within the component. Further, more complex pulse echo alternatives can be used to optimise inspections on more challenging geometries as this thesis intends to

exploit; through inspection of as clad surfaces rather than the diagrammatic view above which demonstrates the inspection of a machined flat surface.

Alternative inspection configurations are available when access to both sides of the component is available. The use of dual transducers on opposing sides of the component commonly known as the 'Through Transmission' or 'Pitch Catch' method with one transducer acting as the transmitter and the second as a receiver. Figure 19 below shows the signal level on a defect free area and then in the right-hand view shows the position whereby half of the beam is now obscured from the receiver by the mid wall defect reducing the signal level amplitude received.

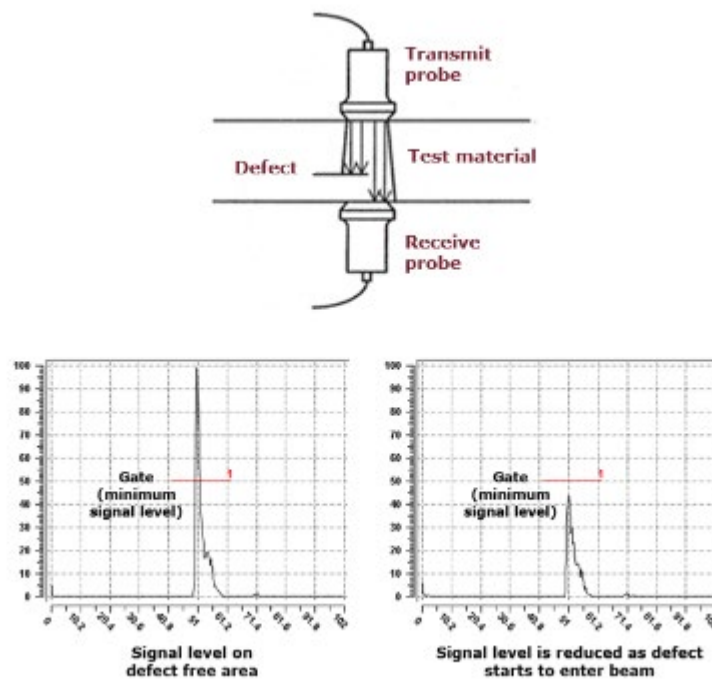


Figure 19 - Through transmission ultrasonic configuration and signal response from a defect free area and partially over a defect.

The two above scenarios utilise basic 0-degree transmissions for detecting defects parallel to the surface however in weld inspection this is not always possible due to the various angle of defects that can occur due to weld preparation angles and multi pass weld designs [109].

Figure 20 below demonstrates one of the major complexities of ultrasonic weld inspection and interpretation of an 'A scan' image whereby understanding the angle of the ultrasonic wave used to inspect the component and how this interacts with the defect orientation can lead to large amplitude differences or even completely missing a large defect within a component. Probe A below shows a scenario whereby the defect is in a non-optimum angle for this angled ultrasonic inspection, and this signal gets merged with the root signal due mode conversion as the angle of the beam being inadequate to provide a reflection to the probe from the defect alone. Probe B shows the large amplitude response from hitting the defect on a 'full skip' which approaches the defect at an optimum angle providing a good reflection signal optimum amplitude response.

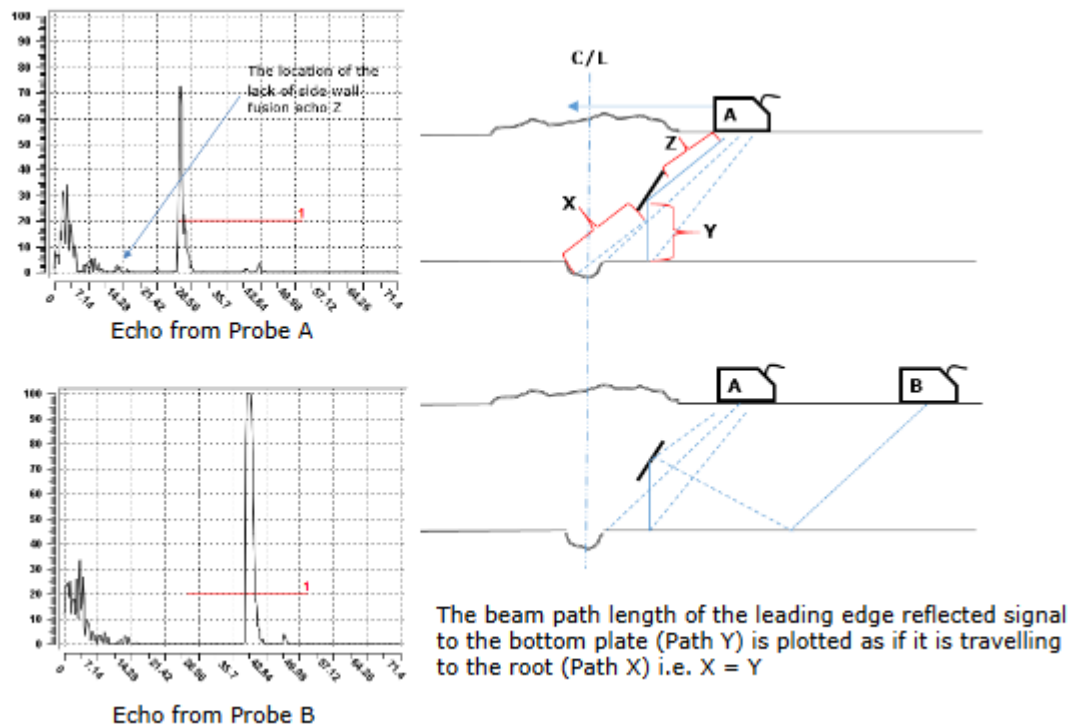


Figure 20- Angled ultrasonic weld inspection and mode conversion.

Various methods of setting sensitivity for ultrasonic inspection are commonly deployed within industry, and careful choices are required to ensure these are appropriate for the inspection methodology. Although too numerous to list, all methods of conventional ultrasonics rely upon reference reflectors of both SDH (Side Drilled Holes) and FBH (Flat Bottom Holes) to replicate simulated defects. Figure 21 below shows a method of setting sensitivity known as DAC (Distance Amplitude Correction) where a block with structurally similar material is constructed with reference holes. The probe is then scanned over these holes and the response maximised and plotted compensating for amplitude decreasing as depth increases as a by-product of material attenuation and increased beam divergence.

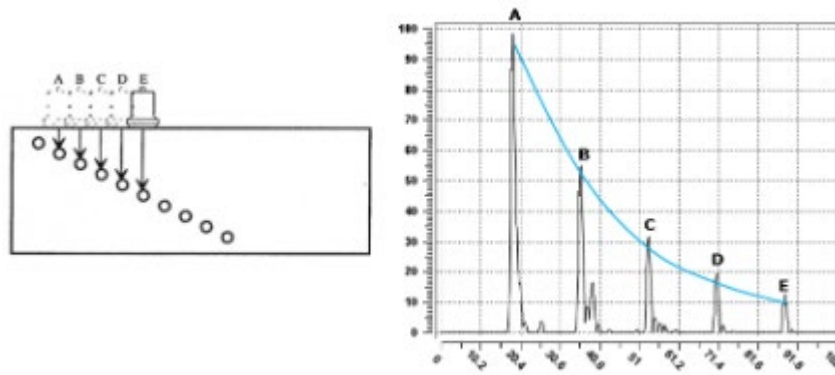


Figure 21- Distance Amplitude Correction

2.6.4. Phased Array Ultrasonic Inspection (PAUT)

Phased Array transducers are commercially manufactured for various purposes within industry and now offer a higher degree of flexibility and efficiency than single crystal transducers. Phased array transducers are probes that now routinely contain 32 – 128 independent piezoelectric crystals (elements) housed in a casing in either a linear (1D) or 2D Matrix configuration [23]. The increased flexibility in inspection methodology is enabled by utilising a combination of multiple elements for transmission or reception along with the ability to control voltage, delay or pulse width individually between elements.

This additional control that PAUT transducers enable allows sub-apertures of elements to perform different inspection modes simultaneously in ‘groups’. Phased array flaw detectors pulse each individual crystal within the transducer with various delay times to generate small waves that interact with each other to form a wave front. This can be

exploited to obtain beam focussing and steering as shown in Figure 22(left) below. This focusing can then be optimised to meet various weld inspection applications to optimise probability of detection from defects at optimum angles to the focusing method as shown in Figure 23 (right).

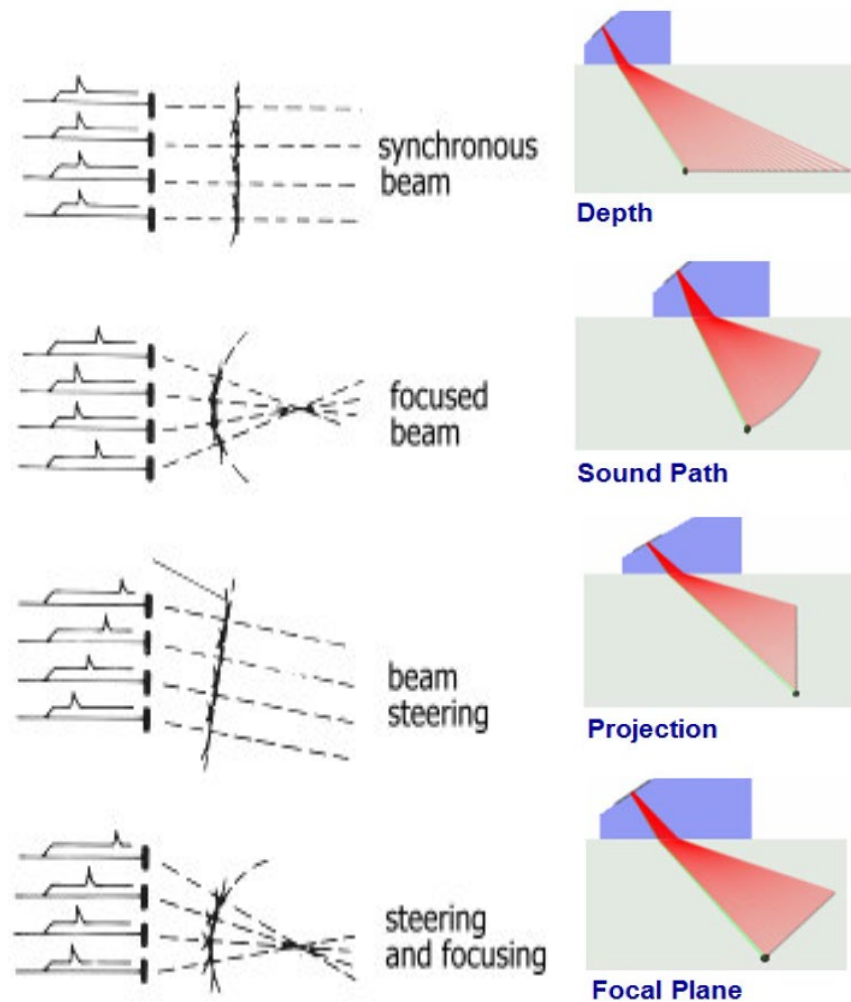


Figure 22- Beam Steering and Focusing (Left).

Figure 23- Beam Focusing Strategies (Right).

These additional beam steering and focusing strategies also require additional imaging methods to effectively display the increased amount of ultrasonic data available.

Figure 24 below shows the various commonly displayed ultrasonic imaging methods [113] all displaying the received signals by different properties. The A scan provides an amplitude response as a function of time as per the previous examples in section 2.6.3. The B scan then builds on this by merging multiple A Scans and plotting them on a 2-dimensional image as a side view; to visualise the interior of the component as a function of depth (time).

The C scan provides a 2-dimensional image from a plan view whereby the encoded B scans have been stacked on-top of each other, an extremely useful imaging method for encoded inspections of large areas. A 'D scan' is akin to a B scan view but at a right angle and is useful during weld inspection when transverse defects are suspected.

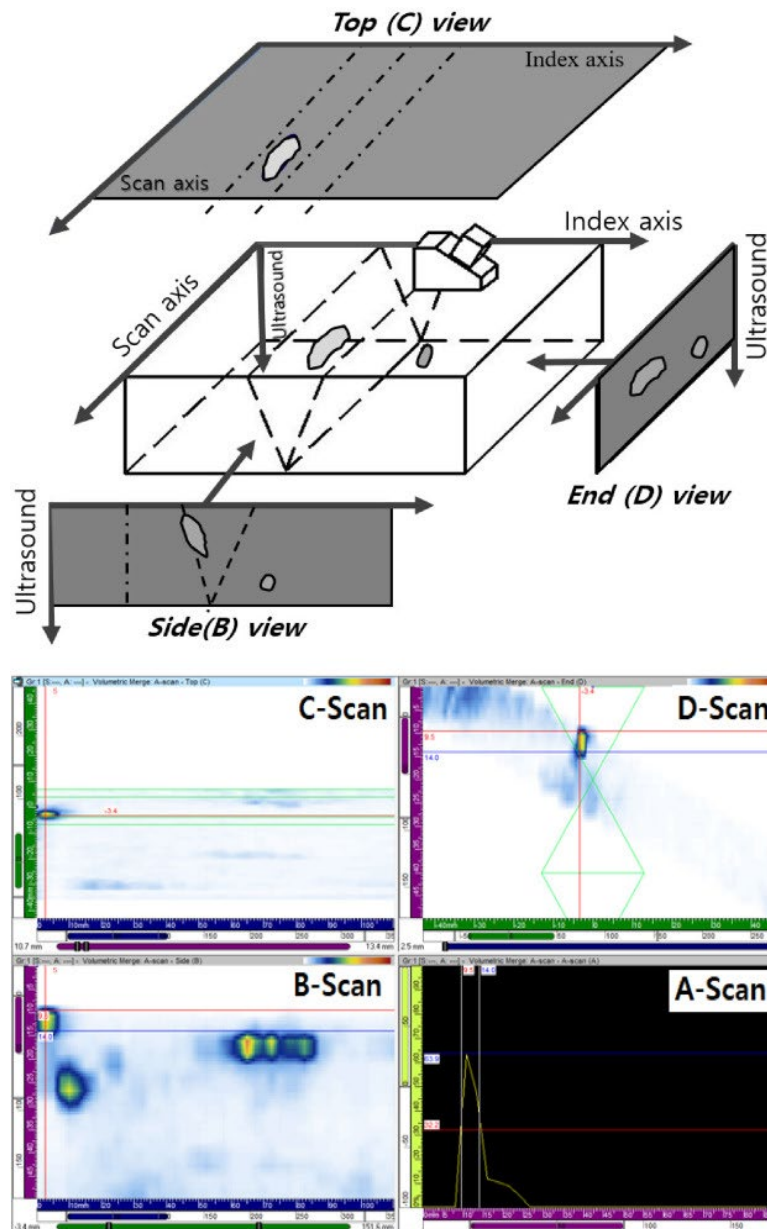


Figure 24- Ultrasonic Imaging Methods (A, B, C, D Scans) [113].

2.6.5. Advanced Ultrasonic Imaging & Post Processing Data Algorithms

As previously explored; the ability of Phased Array technology to individually activate and drive elements or in groups provides a flexibility unknown during the original pulse

echo technology era. Further advanced ultrasonic imaging processes are now accessible due to increased computer power such as FMC (Full Matrix Capture).

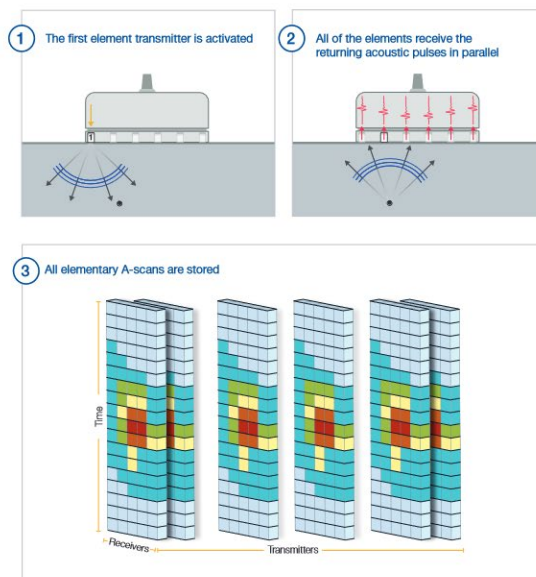
FMC as a process is conducted by firing the first element with the remaining elements/aperture set to receive within the transducer [114]. The process is then repeated cycling through the firing elements with the FMC dataset stored as a N^2 matrix of A scans with transmitters and receivers plotted against time [115].

How it Works

Full Matrix Capture (FMC) and the Total Focusing Method (TFM)

FMC uses phased array probes, but fires and receives information in a different way than standard PA. The TFM is used to reconstruct the data.

FMC—An Acquisition Strategy



TFM—Image Reconstruction

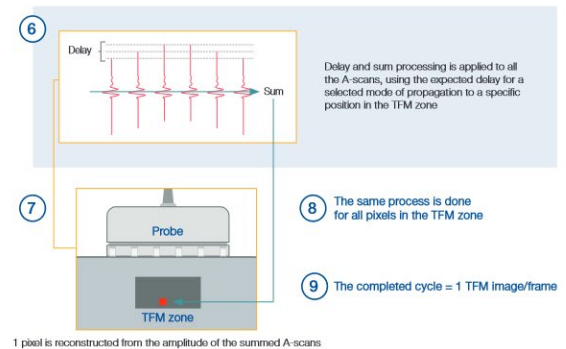


Figure 25- Full Matrix Capture and Total Focusing Method Post Processing [115]

FMC although positive in the ability to capture and save all of the raw data, the file sizes for large components can get increasingly larger requiring more time to capture and

slowing inspection times only counteracted by supplementing inspection equipment with more computational power.

For some high integrity inspections, the slow data acquisition rate of FMC outweighs the greater inspection times because the data can be post processed by various algorithms to present high resolution volumetric inspection displays.

One of the currently most highly utilised post processing algorithms is called Total Focusing Method (TFM). TFM conducts image reconstruction retrospectively by summing amplitudes from the each of the transmitting and receiving elements to every pixel within the inspection volume. This is enacted by taking the delay from the Time of Flight (ToF) data from the firing element to the pixel being processed back to the receiving element with the amplitude from this summed into the other elements to form a final summed image [115]. The advantages of TFM are the image of the full inspection volume has effectively been focused at each pixel enabling higher resolution and sensitivity to small point like reflectors and defects compared to conventional phased array beam forming and focusing [114].

Other post processing algorithms have now been developed but are less widely used in industry such as SAFT (Synthetic Aperture Focusing Technique), PCI (Phased Coherence Imaging) and Phased Weighted Amplitude algorithms such as PCF (Phased Coherence Factor) [116]. Various algorithms will be explored further in this thesis to assess the suitability of each method against the test cases.

2.7. Automated NDE

As can be shown by the developments listed above: the technological advances in ultrasonic technology from basic pulse echo inspections to Full Matrix Capture (FMC) shows the NDE industry not only wants more data but also require increased inspection accuracy and automated deployment.

Manipulators and semi-automated NDE tools are now commonly deployed to reduce manual deployment of NDE enabling higher scanning speeds and increased inspection accuracy/positioning with encoded data now readily accepted as the minimum standard.

In manufacturing areas such as welding and large-scale manufacture, axial or pipe manipulators are typically deployed to assist the operator as shown below [117, 118]. These devices most often provide magnets or positioning features to repeatably datum NDE Inspections with basic X, Y or Circumferential co-ordinate systems.

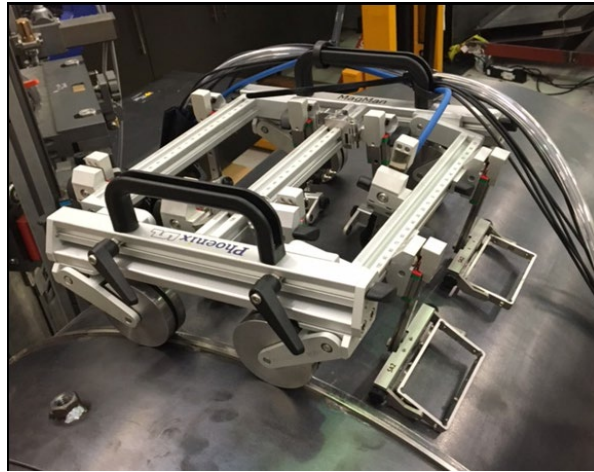


Figure 26- NDE Weld Pipe Scanner and X-Y Scanner [117, 118].

More recent advances now include robotic arms that can deliver the NDE sensor/transducer within a spherical working envelope with 6 degrees of freedom. Figure 27 below shows two robotic arms on a track system allowing full flexibility to inspect complex fan blade geometries from opposing sides with a considerable reach. The robotic arms are widely used due to their ability to be flexible whilst programmed for multiple inspection purposes, maintain a precise and repeatable location with high up times.

Additionally, safety features are programmed to enable safe human interactions within an inspection cell and can be routinely operated from a camera remotely.



Figure 27- Robotic Arms Conducting Fan Blade Inspection [119].

2.7.1. In-Process Inspection

Traditionally component manufacture such as the welding process and the subsequent inspection by means of NDE are separate operations with multiple intermediate processes to enable the latter. Surfaces are most commonly machined prior to any NDE operations and in real terms can see lead times on the scale of weeks between welds produced, welds ground and/or machined before a weld integrity can be assessed by NDE.

Recent advances in additive manufacture with technologies such as WAAM (Wire and Arc Additive Manufacture) have shown great promise in ultrasonic imaging of the metallic components as they are built layer by layer [120]. Using a conformable ultrasonic transducer allows the as-deposited layers to be inspected in between layers; albeit not

purely in-process and adding time to the manufacturing process. However, this technology shows promise in overcoming the lag time between a weld being produced and machined and getting a result on the component integrity closer to the manufacturing process. This approach, overcoming surface variation, also shows promise in ultrasonic imaging at temperature; another key barrier to in-process inspection.

High integrity welds can often have complex geometries and require multiple ultrasonic inspection angles to demonstrate adequate coverage of large weld thicknesses. FMC acquisition of a full weld in various thicknesses as the welds are laid upon each other utilising a tandem configuration from probes adjacent to each side of the weld shows promise in inspecting partially completed welds, providing the groundwork for complex in-process inspections [34]. The key difference in this study is using standard PAUT transducers that wouldn't be suitable for elevated temperatures above 60 degrees Celsius and as a by-product of the angled inspection methodology not required to interact with inspecting through an as-welded surface.

Combining the ability to deal with both elevated temperatures and the variation in surface flatness due to multiple weld deposits is a key challenge in deploying truly in-process NDE. Uncertainty on weld integrity causes many issues for industries such as nuclear, where manufacturing throughput and schedule certainty are key requirements in a cost driven society. The ability to detect any weld flaws during manufacture unlocks cost efficiencies that traditional NDE methods were incapable of with the additional benefit of schedule certainty achieving higher throughputs without having to extend costly facilities.

Work on a novel high-temperature roller probe encompassing a PAUT transducer [20] with the ability to work up to 350 degrees Celsius with a conformable surface, showed the ability to detect calibration side drilled holes and intentionally embedded defects [121].

As can be shown in Figure 28 below the multiple interfaces between the probe and the internal couplant, the couplant and the rubber wheel and then the rubber wheel and the sample interface with subsequent repeats leaves a small inspection window. This would require assessment to ensure inspections on thicker components weren't detrimentally impacted by repeat echoes obscuration or falsely flagging indications that could confuse the NDE inspector.

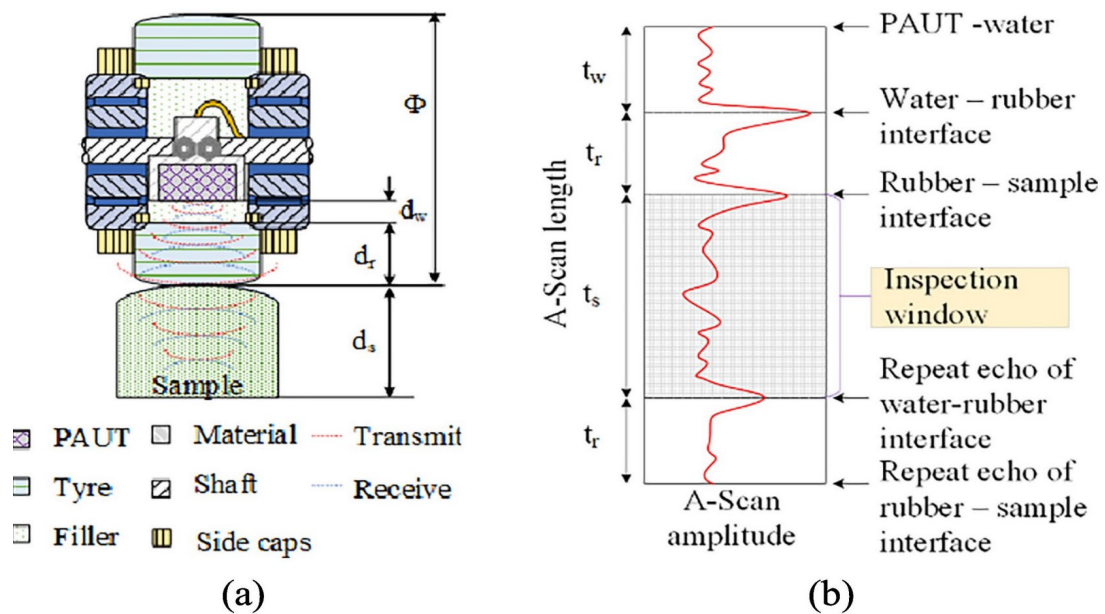


Figure 28- Roller Probe Schematic and A-Scan Signal from Probe Design [121].

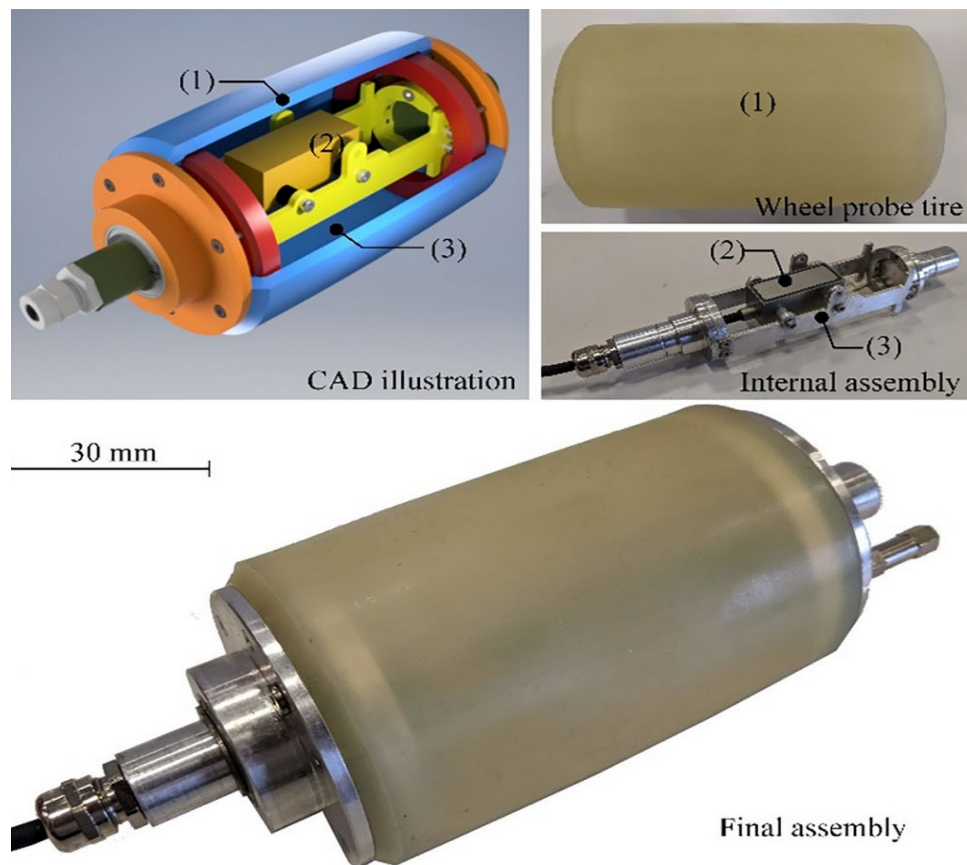


Figure 29- Roller Probe Internal Assembly and Image of Final Assembly [121].

The use of the dry-coupled phased array wheel probe with internal couplant actively cooled by a chiller could allow faster ultrasonic inspection in-process during the weld deposition in an automated deployment. Consideration needs to be given to potential increased dead zone of the roller probe setup due to the rubber tyre acting as a medium to conduct the ultrasonic waves into the component and the conformability of the probe into increased surface finish variation of high deposition welds. Other considerations required for utilising this technology in industry would be the ability to conform to inspection code

requirements and the ability to conduct various probe checks without access to the internals of the roller probe.

Considering the capabilities of each NDE technique, the proposed welding process and subsequent defect morphology, ultrasonic techniques offer strong potential for the use of in-series volumetric inspection of weld cladding at temperature and therefore form the core research subject of this thesis. However, challenges remain in mitigating the surface profile of as deposited weld cladding and subsequent ultrasonic beam scattering, proving calibration and repeatability of the inspection technique at elevated temperatures, and qualifying the technique to stringent NDE standards such as ASME V and European Network for Inspection and Qualification (ENIQ) qualification guidelines.

2.8. Qualification of NDE Inspections

2.8.1. Code Compliant NDE

NDE is conducted in multiple industries at varying levels of increased scrutiny, for a multitude of applications, component and geometries. NDE is usually conducted in accordance with a relevant standard or code which brings rise to the term ‘code compliant’ inspections. Industry, regulators, insurance companies and customers take credit from the fact the inspection was conducted in accordance with a standard and its performance as a minimum meets the level prescribed.

As previously discussed in this chapter; ASME [13] is the most common design practice followed in the manufacture and testing of pressure vessels worldwide. In the UK the most

cited standards are published by BSI (British Standard Institution) and cover in detail most usual applications of an ultrasonic inspection, acceptance standards or calibration requirements and performance checks necessary to maintain the requirements of the code. Most standards are prefixed by the acronyms 'BS EN ISO' demonstrating the standard is a 'British Standard' [122] compliant with the 'Europäische Norm' or 'European Standard' [123] and ISO 'International organisation for Standardisation' [124]. Industry then writes inspection techniques and procedures that follow the requirements of the standard in the inspections conducted to test.

Issues arise when new technologies are adopted, and standards have not caught up with the new approach or development. In this case or in industries or components that require increased scrutiny such as the nuclear industry being code compliant isn't often enough to satisfy a regulator and enhanced controls and measures have to be taken to justify a component into service.

2.8.2. ENIQ Guidelines for High Integrity NDE Component Qualification

The ENIQ is a committee that detail a framework for inspection qualification for justifying inspection methodologies in high integrity industries such as nuclear.

The ENIQ guidelines [125] deliver a qualification that consists of a technical justification that details all evidence on the effectiveness of an inspection including but not limited to previous experience, laboratory trials, mathematical modelling and physical reasoning. This, along with practical trials that can be conducted either in a blind or open manner on

representative test pieces with simulated worst-case defects combine to become a technical justification in support of an inspection qualification.

Technical justifications cover all aspects of the NDE inspection including the qualification of the personnel either by national certification scheme or by successful completion of a blind exam along with full equipment details notwithstanding all possible equipment parameters, a justification for their use and an inspection procedure that details the full working envelope of all key parameters.

Evidence from the practical trials will present worst case defects often in terms of defect size, morphology, position and tilt/skew deviation and the ability of the inspector to reliably find the proposed defects with a level of margin.

This body of evidence is then collaborated into a full technical justification which can be designed for different inspection levels that demonstrate varying probabilities of detection (POD) and is then submitted to an IQB (Inspection Qualification Body) for review, critique and assessment.

NDE technique qualification is often a time consuming and costly endeavour; only usually cost effective for justifying the use of complex nuclear vessels in service for extended periods of time. The approach can be used to justify inspection methods; however, that aren't covered by NDE codes and standards, or to fill gaps where standards can't fully be achieved due to the adaptive nature of new technologies.

This thesis aims to deliver trials that provide supporting evidence to overcome the gaps in standards for the implementation of In-Series NDE for welds within the nuclear industry

using the methods demonstrated in the ENIQ guidelines to design worst case defect trials to begin to qualify the use of the dry coupled roller probe for high integrity welds.

Chapter 3

Adaptive Compensation of PAUT through an as-clad surface

Chapter 3 explores the effects of varying clad surface finishes and quantifies its effect on a known reflector at the bond line between the weld cladding and parent metal substrate. Multiple samples were experimentally tested with an immersion system to quantify the maximum amplitude variation for a slot passing under multiple weld cladding surface peaks and troughs. The weld profiles were then mechanically profiled to define optimum ultrasonic beam angles for transmission through the surface and merged together in a multi-beam methodology. This multi-beam ultrasonic inspection was then used to remeasure the maximum amplitude variation from the slot reflector in both an immersion and roller-probe inspection set-up to define the improvement in amplitude variation through an as-clad surface.

3.1. In-Process Inspection Cladding Challenges

The key issues in deploying in-process inspection on a weld cladding during deposition was the varying geometry of the surface, causing non-planar scatter reflection, and the

increased attenuation due to elevated temperatures [44]. Additional challenges include the effects of heat on the ultrasonic probe crystals and potential for damage, the change in ultrasonic propagation and velocity, and electrical noise from the welding process.

The requirement for code-compliant PAUT inspections requires a weld surface preparation where a surface must be machined flat to a respective Ra (Roughness Average) value, with a gap of no more than 0.5mm to be present between the contact point of the probe [15] to the surface. These requirements ensure both probe contact and coupling are within known limits to adequately transmit the ultrasound into the component under test. Deploying this inspection on an as-welded surface means these requirements will not be achievable, and therefore, another approach must be developed. Previous work has demonstrated that complex front wall geometry interfacing with the ultrasonic probe face can cause issues with ultrasound beam divergence, leading to amplitude variation of up to 10dB [126].

This section proposes a novel methodology for in-process ultrasonic inspection of weld cladding deposition of complex nickel-based alloys through an as-clad surface.

3.2. Proposed Methodology & Technical Approach

This chapter addresses the limitation of inspecting through varying clad surfaces through the development of a simultaneous multi-beam steering method, matched to the deposited clad geometry, which attempts to minimise scatter and energy losses.

This process is then quantified experimentally to determine the effect of varying weld cladding surface profiles on localised ultrasonic defect sensitivity, by placing machined

reflectors under the clad surface at locations under both the peak and trough of the irregular clad surface. To achieve the varying surface profile, the overlap parameter of adjacent weld passes will be varied to arbitrarily create different surface profiles of weld clad layers that could be created in production, utilising a robotic welding process. Surface profiles are then generated for each test sample to establish the proposed optimum angle over the clad geometry to adjust the ultrasonic beam steering through the clad surface, as shown Figure 30. Targeting the dominant angles of the weld passes on either side matches and optimises the ultrasonic steered beam to enter the surface at a perpendicular attitude, increasing ultrasound transmission and reducing scattering at the front wall.

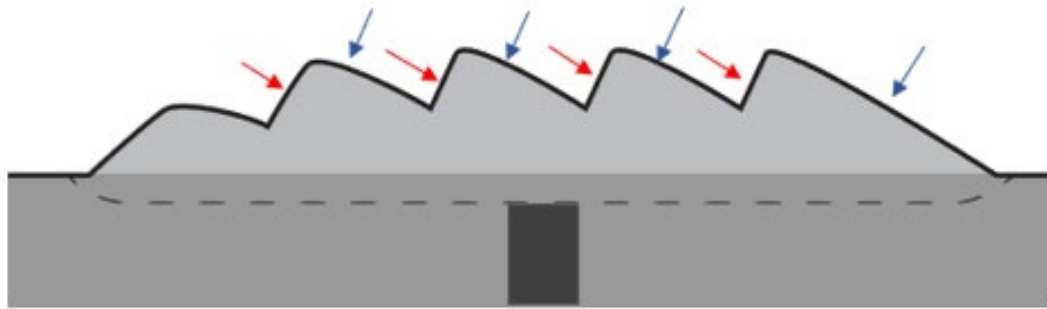


Figure 30- Typical weld cladding geometry with arrows showing perpendicular optimum ultrasonic beam (Red & Blue denoting + and – orientation), dotted line denoting weld bond line and dark rectangle denoting slot type defect.

The immersion ultrasonic was used to initially prove out this method due to the optimum coupling afforded with water flooding the full clad surface, removing front surface coupling as a dominant variable during the experimental trials. Although it is noted that this approach has inherent deployment limitations for application during the welding process, due to the nature of the uncontained couplant.

By firing multiple steered beams and combining the signals, a multibeam steering method can be achieved to handle the complex as-welded surface geometry. This can be demonstrated by presenting the variation in amplitude of a known reflector slot, firing multiple beam angles optimised to the surface profile and merging the images of each discrete angle beam together focusing on the highest amplitude response to demonstrate a reduction in amplitude variation. The experimental trials will then demonstrate the multibeam steering, with the novel roller probe developed by the University of Strathclyde, to show the feasibility of an in-process inspection methodology.

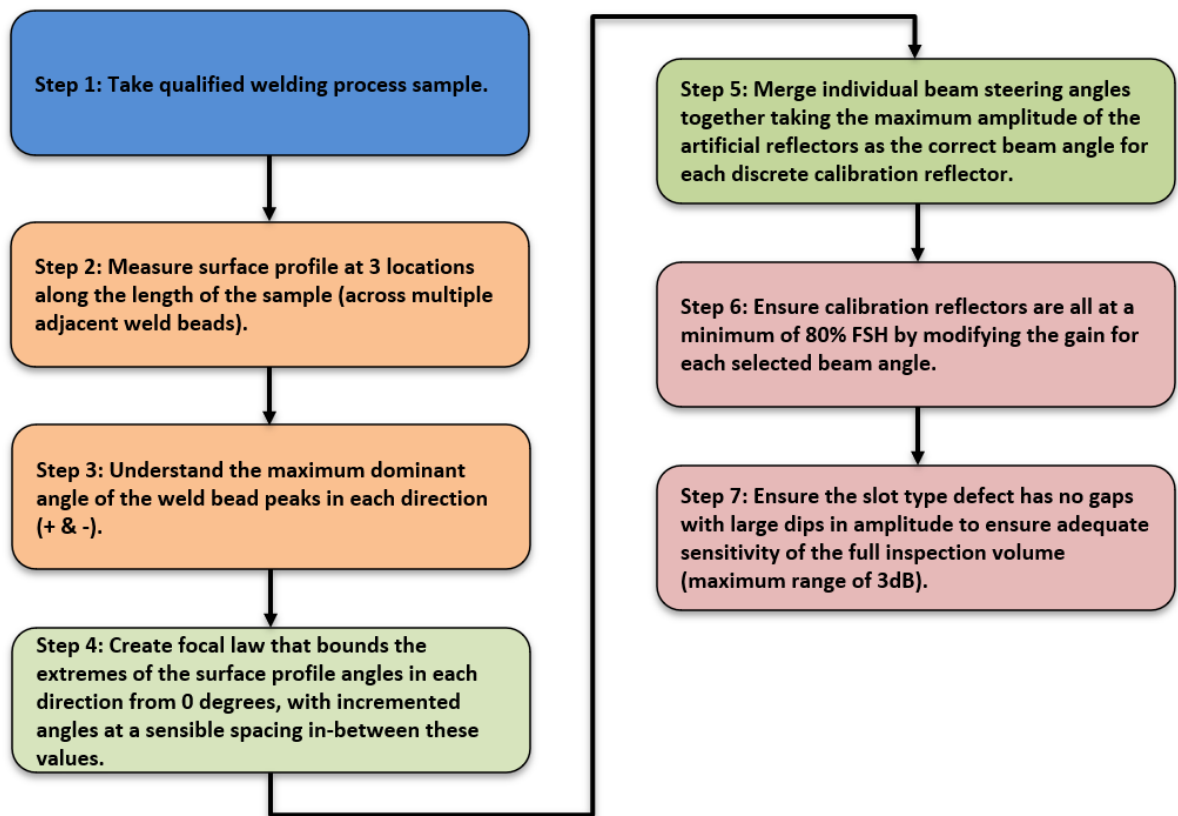


Figure 31: Proposed Inspection Methodology for Complex Surfaces

The remainder of the chapter is structured as follows: Section 3.3 to 3.6 details the reference sample preparation and experimental methodology used to investigate and characterise the issues associated with inspection of as-clad surfaces alongside the proposed strategy for their mitigation. Section 3.7 to 3.11 then presents the results of its empirical assessment and discusses findings in the context of industrial deployment, and Section 3.13 concludes the outputs of this chapter.

3.3. Reference Sample Preparation

Five cladding samples were created to provide a range of surface profiles to inspect ultrasonically with varying weld bead overlap parameters. Five samples were deemed sufficient to represent a typical industrial range of weld overlaps, as excessive spacing leads to gaps between the welds and insufficient spacing leads to the welds stacking on top of each other, both inefficient for providing a layer of weld cladding. To artificially create varying surface profiles by adjusting a single welding parameter, two approaches were possible: modifying the welding torch angle to the surface or changing the increment of the overlap parameter between welding beads. As in industry, the welding torch angle is usually a fixed parameter; bead placement was chosen as the method for creating the varied surface profiles required. To create the five samples, a base metal plate of carbon steel S275 was chosen as a generic ferritic steel with the addition of a nickel-based alloy EN82H as the clad substrate, providing a consistent substrate and cladding for all samples under test. A Fronius CMT TPS 400i [127] was selected as the welding equipment using Argon Helium C02 H2 (Cronigon Ni 10) gas [128] following industry best practice, laying a single layer of EN82H cladding on a 300 x 300 x 50mm S275 plate.

A single clad layer was selected as the worst case for ultrasonic inspection due to the recognised limitation of the dead zone inherent in standard pulse echo ultrasonic testing near surface [129]. A typical range of weld bead placements was selected with a range from 4.5 mm to 6.5 mm in increments of 0.5 mm to display a full range of overlaps possible to provide consistent cladding, as shown in Figure 32.

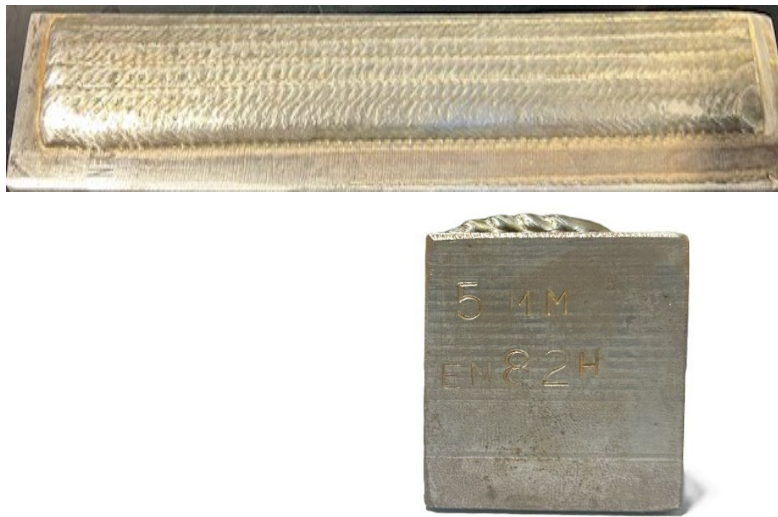


Figure 32: S275 Carbon Steel Sample – Example of 5mm Overlap (Plan & Side View).

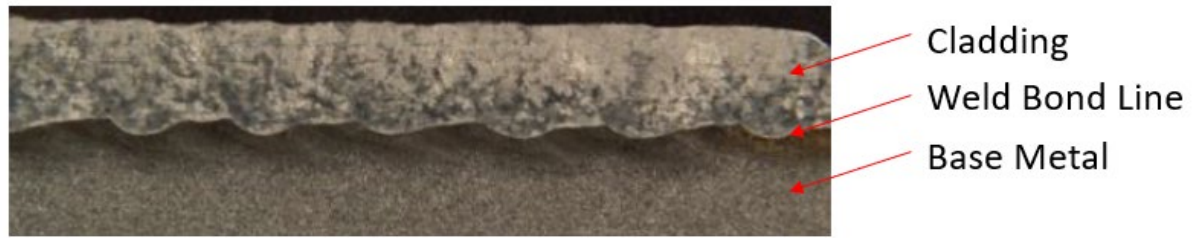


Figure 34: Weld cladding macro showing the weld bond line interface between the two dissimilar materials

The 3.0 mm diameter flat-bottomed slot was again machined to the weld bond line. The key parameter for the slot was the diagonal orientation of the reflector to represent a representative un-bond/ lack of fusion defect under the full weld profile, whereby the slot could be imaged through the peak and the valley of the surface profile on the front face of the test piece. By utilising this defect type, full coverage of the bond line can be shown and the influence of the surface finish on the ultrasonic inspection sensitivity.

3.4. Mechanical Surface Measurement

Surface profiles were gathered with a mechanical surface roughness instrument (Mitutoyo Surftest) with measurement conditions including max height range of 800 μm , speed of 0.1 mm/s, and pitch of 5 μm . The surface measurements were taken normal to the direction of welding across the adjacent weld beads at 3 discrete locations along the weld length pictured in Figure 32.

Each sample was measured for multiple surface roughness parameters: Min and Max Z, Ra, Rq, Rsk, Rku, Rt and Rz as described in Table 1 [131].

• Surface Roughness Parameters	• Descriptor
Z (Min & Max)	• Height of variation
Rz	• Average of consecutive highest peaks and valleys
Ra	• Numerical average of all peaks and valleys
Rq	• Root-mean-square roughness
Rsk	• Skewness
Rku	• Kurtosis Value – Tip geometry of the surface peaks to analyse contact points
Rt	• Total Height of the roughness profile

Table 1: Surface Roughness Parameters to JIS B 060.

3.5. Surface Finish - R Values

Of all the surface roughness parameters measured, the author proposes that there is no single parameter that can be controlled to maximise ultrasonic inspection compatibility.

However, a combination of the most influential parameters can be defined to choose a weld parameter to maximise the compatibility with In-Process NDE.

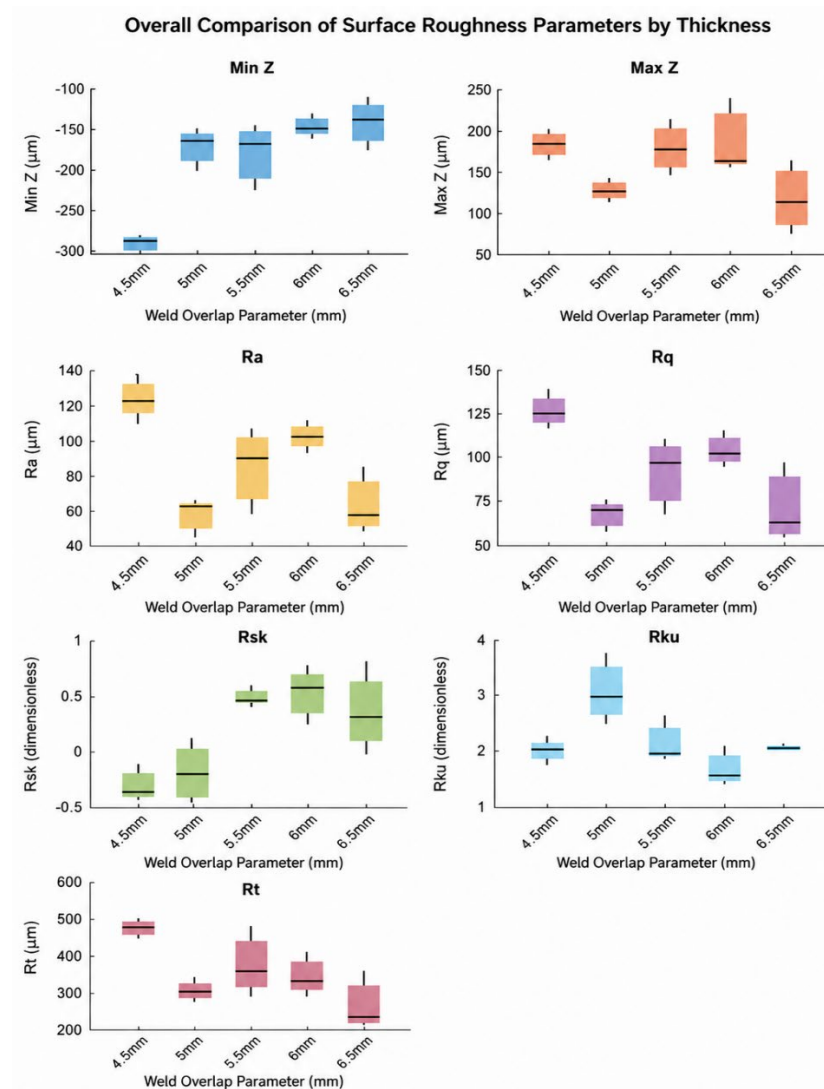


Figure 35: Box Plot of Surface Profile Parameters

Figure 35 above visualises the surface profile parameters in terms of each line sample taken perpendicular to the weld across multiple passes, with the 3 repeats defined within the box plot for each parameter. It can be noted that the predicted optimum sample based on the surface profile would be the 5.0 mm sample.

The 5mm sample's smoother surface (lower Ra and Rq), balanced skewness (Rsk closest to zero), moderate kurtosis (Rku), and lower total roughness (Rt and Rz) theoretically optimise the welded surface for ultrasonic waves to propagate and reflect consistently. These characteristics reduce scattering and attenuation of ultrasonic waves, leading to clearer and more reliable inspection results.

This theory can be tested through the application of a 0° ultrasonic scan over the slot region, without any compensation for the rough welded surface, determining if the surface profile does have a link to ultrasonic transmission and therefore inspection sensitivity, as shown later in Figure 39.

The surface profile data was then processed with MATLAB [132] to visualise the surface of each sample. From this profile, the dominant angle of the peak, trough, and overall surface skew can be defined to determine the range of angles selected for the ultrasonic inspection, noting the line of best fit is focused on the central peak or steepest surface angle of a full weld bead. Figure 36 below shows an example of the measured surface profile on the 5.0 mm overlap sample with

Table 2 providing the line of best fit equation and the resultant angle of the peak face.

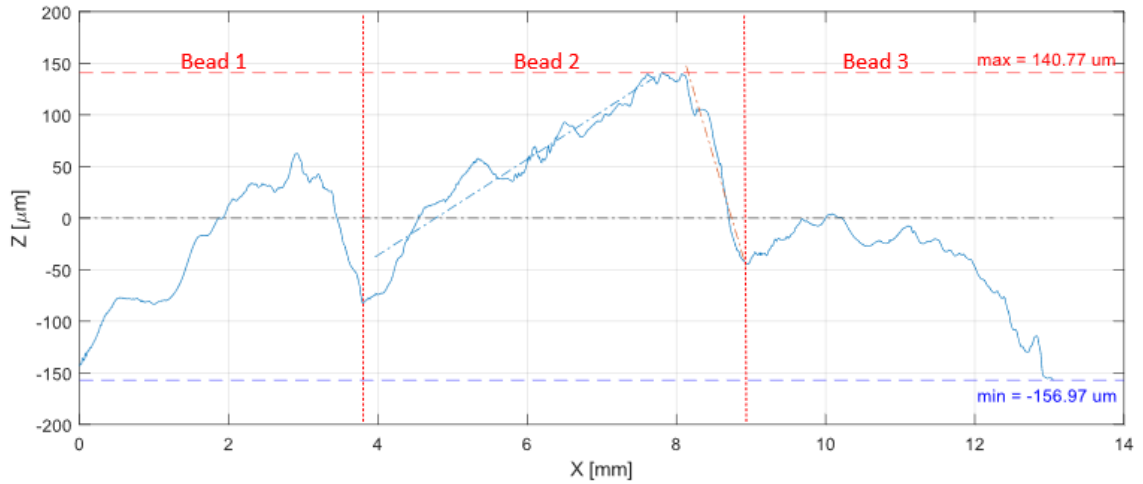


Figure 36: 5mm Overlap Sample Surface Profile with Peak Angle Measurements.

X Position	Angle
3.96 to 7.77mm	2.657°
8.13 to 8.93mm	-13.62°
Global	Negligible (-6.1e-16°)

Table 2: 5mm Overlap Sample - Angle of Peaks

These angle values will set the proposed optimum angle for inspection to aid in the ultrasonic inspection to optimise coverage through the complex geometry of an unmachined weld surface. Multiple measurements will then be taken to attribute the range of angles over the surface and define a surface area percentage requiring that angle at a discrete position. Defining the percentage contribution of a particular angle and assessing this against the ultrasonic inspection amplitude at a discrete position will then define if a generic approach can be found to ultrasonically inspect as-welded clad geometry without surface machining.

3.6. Surface Finish – Optimum Angle for Inspection

Taking the surface profile measurements and analysing them through a MATLAB-based script allowed for the dominant angles of the surface finish to be measured.

With the welded samples encompassing multiple weld passes, and robotically controlled offset values between the passes, the measurement of the peak angle travelling up and back down again to the valley contributes the majority of the surface area of the weld. By defining the angle of the peak on both faces, the ultrasonic inspection technique can be adjusted to approach this angle at the normal and therefore maximise ultrasound transmission into the sample.

Table 5 below demonstrates the predominant angle of both faces of the peak, setting the main range of ultrasonic inspection angles. It should be noted that a larger range than is attributed to the surface measurements below will be tested to affirm the theorem, along with quantifying whether angles outside of this range contribute to ultrasonic sensitivity in the smaller unmeasured regions on the irregular surface.

Sample	Rising Angle (1)	Falling Angle (2)
4.5mm	8.83°	13.81°
5mm	2.66°	13.62°
5.5mm	3.326°	20.52°
6mm	3.38°	11.24°
6.5mm	7.986°	2.461°

Table 3: Surface Finish Predominant Angle

3.7. Immersion Ultrasonic Inspection - 0°

To understand the relationship between the surface finish parameters, angle of the subsequent weld beads, and the ultrasonic sensitivity, an immersion ultrasonic inspection was chosen as the initial methodology, as the water within the immersion tank enables stable and optimum coupling when inspecting a rough surface [26].

A Peak-NDT MicroPulse LTPA [133] phased array controller was selected to drive an Imasonic 5 MHz PAUT probe with a 0.5mm element pitch (Reference 14814) driven by bespoke University of Strathclyde LabVIEW-based software. Focal laws were generated by Array Gen software designed by Peak NDT [134] to focus at the weld bond line 3.0 mm below the front surface, as defined by the macro image in Figure 34. The Immersion probe was held by a bespoke 3D printed holder driven by a Kuka KR10 R1000-2 [135].



Figure 37 - Immersion Ultrasonic Equipment Set-Up

To demonstrate the effect of the surface profile on the ultrasonic sensitivity, an initial scan was taken over each sample where the three FBHs are located, ensuring all holes are a minimum of 80% full screen height. By setting the sensitivity on the central sample (5.5 mm overlap) and then utilising the same parameters (Table 4) for each subsequent sample, the surface profile effect can be shown as in Figure 38.

Parameter	Value
Sensitivity	<i>80% Full Screen Height on Central FBH (5.5mm sample).</i>
Gain	<i>33.5 dB</i>
Material Velocity (Steel)	<i>5930 m/s (Longitudinal)</i>
Velocity (Water)	<i>1430 m/s (Longitudinal)</i>
Elements	<i>128</i>
Aperture	<i>32 elements</i>
Focus Depth	<i>3mm</i>
Range	<i>0.1 to 30mm</i>
Scan Speed	<i>5 mm/s</i>

Table 4: Immersion UT Parameters for FBH location

Figure 38 clearly demonstrates the significant issue in effectively ultrasonically inspecting an as-welded cladding layer through multiple adjacent weld beads. The peaks and valleys of the irregular surface act as a concave and convex lens, focusing or defocusing the longitudinal wave. Not compensating for this during an in-process NDE inspection would lead to mispositioning, mis-sizing, or missing defects altogether, rendering the inspection untrustworthy and unusable.

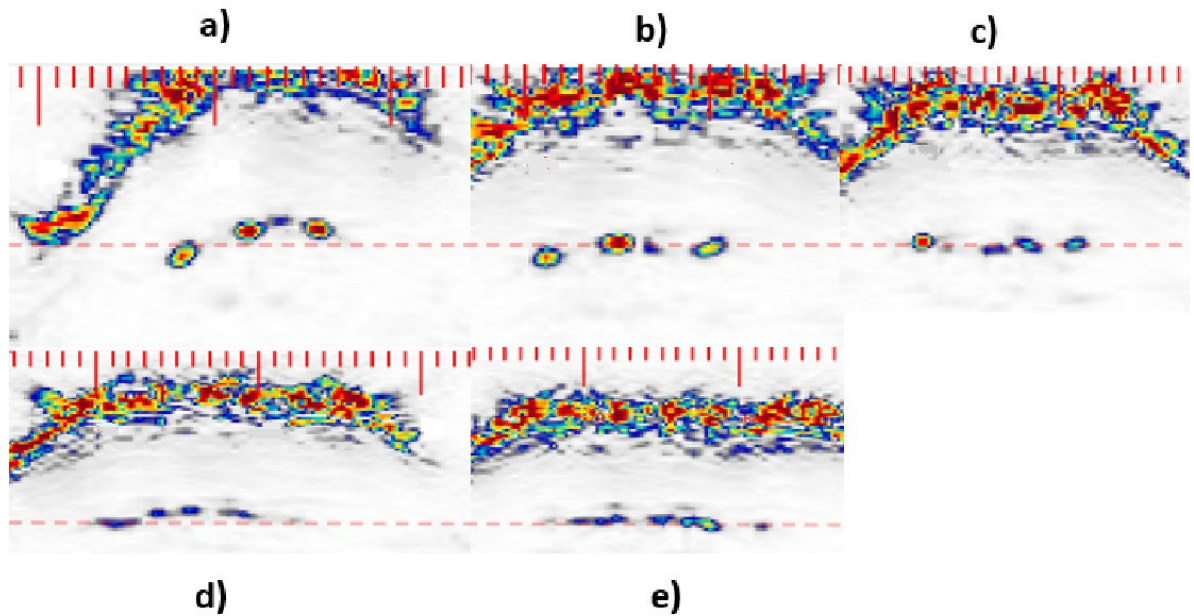


Figure 38: Immersion UT Scan of FBH Locations with Fixed Parameter on a) 4.5mm, b) 5mm, c) 5.5mm, d) 6mm and e) 6.5mm samples (Red dashed line denoting the weld bond line)

The array of images in Figure 38 highlights that an approach to in-process clad inspection requires more than a 0° longitudinal wave inspection as required by industrial standards for machined clad ultrasonic inspection, due to the absence of two parallel inspection surfaces. Using a linear 0° longitudinal wave inspection, through the varying surface clearly distorts known reflectors, defocusing, mispositioning, and displaying a reduction in inspection sensitivity.

By understanding the surface topology, the optimum angles can be selected to maximise transmission of the ultrasound into the sample.

3.8. Immersion Ultrasonic Inspection – Angled Scans

Through the surface profile measurements, a range of optimum angles was defined for each sample by establishing the angle that approaches the varying clad topology perpendicular to the surface to maximise ultrasonic transmission. However, small regions in between both peak and valley sections may have more extreme angle requirements for optimum ultrasonic transmission and subsequent amplitude response. To ensure this theory is fully investigated, the angular range will be extended to demonstrate the amplitude response of each angle indexed in 5° increments.

To achieve this, a maximum angled range was defined as 30° to incorporate the maximum dominant angle from the surface profiles of 20.52° as per Table 3, in both the positive and negative orientation from the normal (0°). Additional angles above 20.52° were used to prove the beam steering had a negligible effect past this point, leading to a range of 13 discrete positions from 0° to ±30° in 5° increments, utilising the equipment displayed in Figure 37.

This range of angled scans would then be repeated across all 5 samples to build up 65 data sets to fully explore the theory.

Each dataset would then be processed through a MATLAB-based imaging processor to display the B, C, and D scans of each scan angle. By then measuring the amplitude of the slot type defect along its length, which passes under the varied front wall clad surface due to its diagonal orientation, an amplitude response can then be plotted, demonstrating the transmission of the ultrasound into the irregular front wall of the sample. These plots will

then define a position on the Y axis (along the length of the slot) that shows the reduced amplitude due to the valley within the front wall surface, as shown in Figure 39.

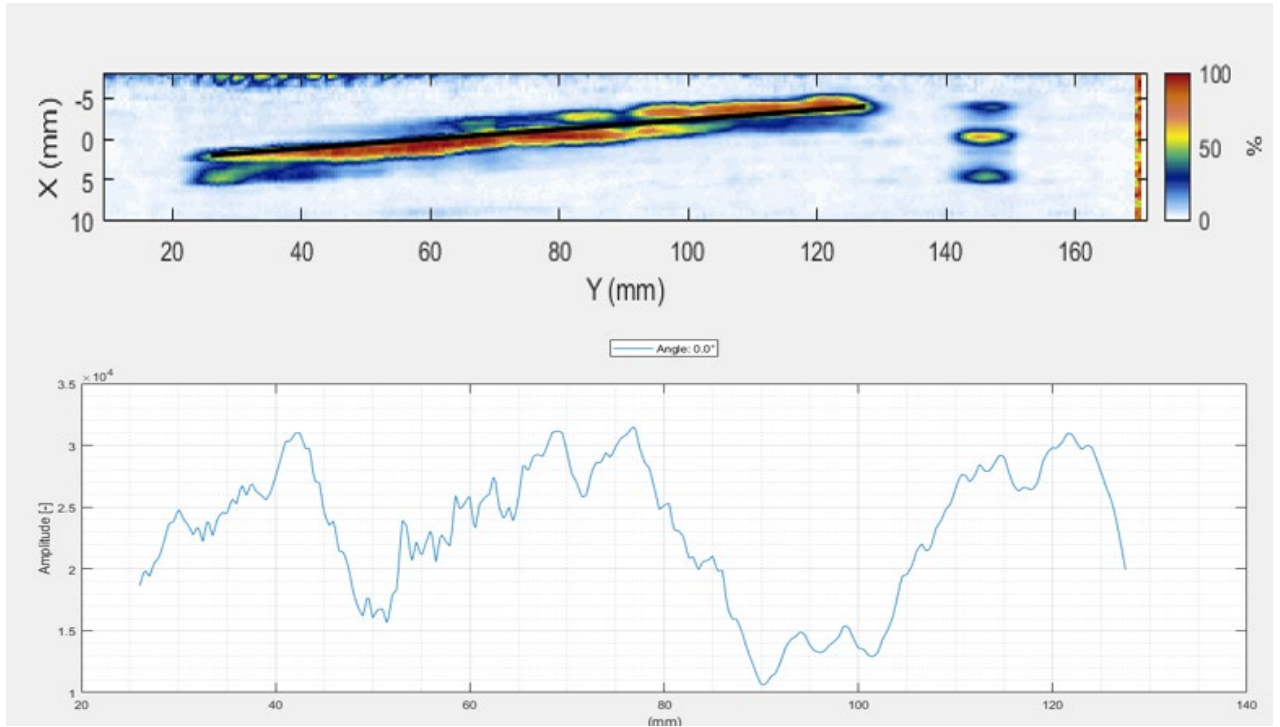


Figure 39: 5mm Sample - Slot C-Scan & Amplitude Graph

The variation in amplitude shows a key issue in setting ultrasonic sensitivity through the rough surface. The amplitude was normalised to the features maximum amplitude with the minimum amplitude recorded at $x = 90.07\text{mm}$ at 1.0624 relative amplitude with the maximum at $x = 76.65\text{mm}$ at 3.1373 relative amplitude.

Calculating the dB difference between these amplitudes taken from Figure 39 is undertaken by:

$$dB \text{ difference} = 20 \log_{10} \left(\frac{H1}{H2} \right) \quad \text{Eq. (5)}$$

Equation 5: dB Difference

Whereby:

$H1$ = minimum amplitude

$H2$ = maximum amplitude

$$20 \log_{10} \left(\frac{1.0624}{3.1373} \right) = -9.4db$$

This shows a typical as-welded surface without any other inspection uncertainty applied, such as coupling/water path tolerance, re-calibration tolerance, amplifier linearity, or initial calibration error adds an additional 9.42 dB variation into the inspection.

By optimising which ultrasonic angle is used for each discrete position along the slot feature, a reduction in amplitude variation to a level associated with a typical machined surface inspection can be targeted.

The selected angled scans, along with the 0° scan, can then be compounded into a merged image, whereby the contribution of each angle can be assessed against the amplitude it delivers towards the ultrasonic sensitivity. This can then be analysed to determine the contribution factor of each angle to the overall inspection, and at which position over the slot defect, optimising the ultrasonic firings for the surface finish under inspection.

3.9. Immersion Ultrasonic Results

Taking the 0° inspection of each overlap sample and plotting the amplitude of the slot region across multiple weld passes demonstrates the amplitude loss through the weld pass surface variation to provide baseline results for sensitivity losses.

Table 5 below demonstrates the large effect the surface profile has on the ultrasonic technique through increased variation/uncertainty far above a reasonable level used in a typical ultrasonic inspection. By calculating the dB loss taken from a line profile over the slot feature, from this 0° scan any improvements to the ultrasonic technique can be quantified.

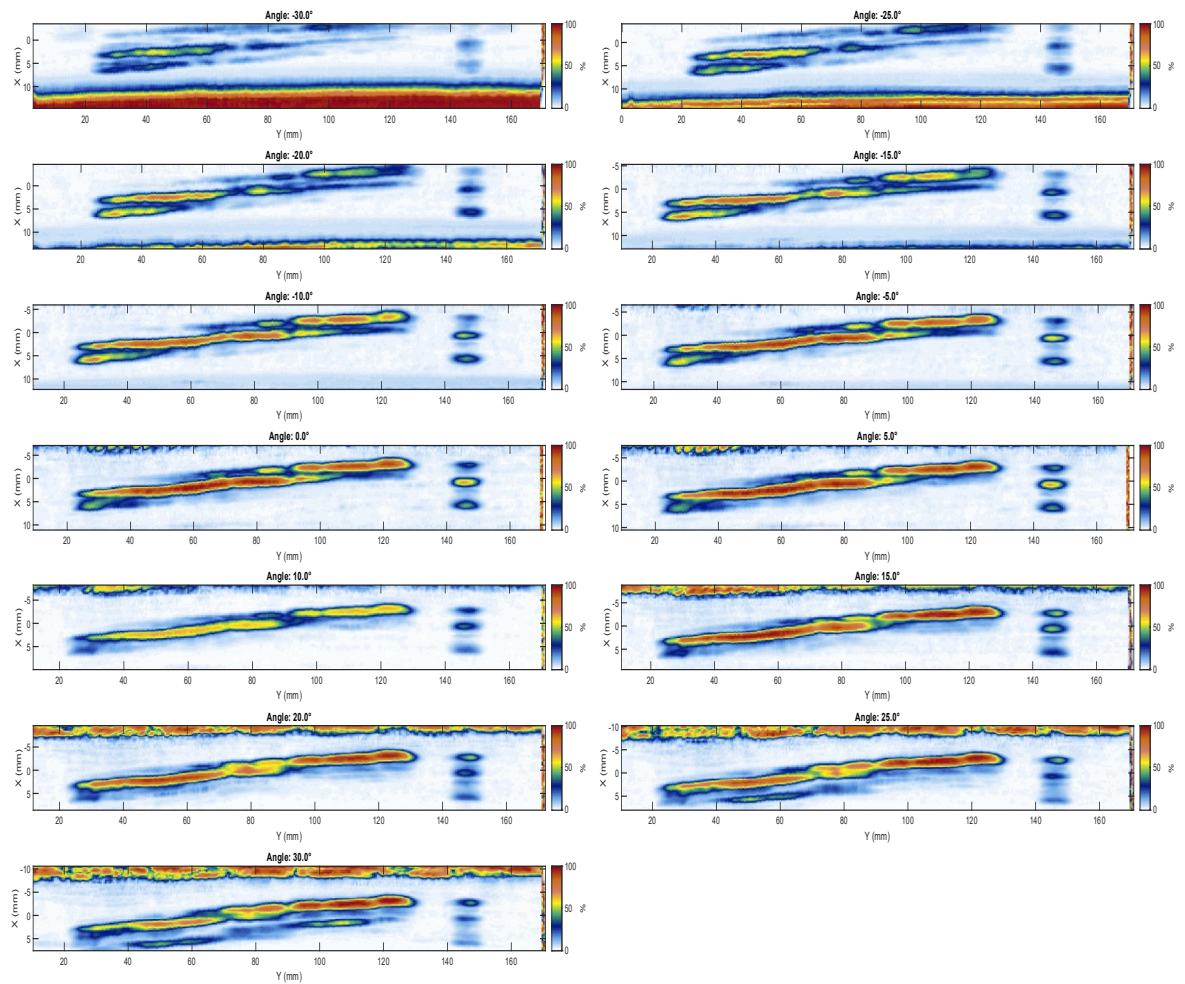
Sample	X Positions	Amplitude	dB Variation within Slot
4.5 mm	85.67mm, 114.23mm	3.37, 0.80	-12.55dB
5.0 mm	76.65mm, 90.07mm	3.14, 1.06	-9.42dB
5.5 mm	59.40mm, 93.29mm	0.70, 3.47	-13.95dB
6.0 mm	60.53mm, 113.47mm	1.75, 3.58	-6.23dB
6.5 mm	67.15mm, 96.21mm	0.75, 3.56	-13.56dB

Table 5: dB loss attributed to Surface Profile in each Overlap Sample

A range of angles was selected to bound the full range shown by the surface profile measurements with an additional range in each direction. Angles of 0° ±30° were selected as the proposed inspection angular range, with a 5° increment to reduce the quantity of data to assess.

As Figure 40 below shows; there is a much higher amplitude response in the positively steered beam angles than the negative steer, generally following the higher angles of the angle peak (2) from the surface profiling results. Beyond negative 15° and above positive

25°, the higher angles provided very little sound transmission and subsequent ultrasonic inspection efficiency, again in general agreement with the surface profiling results. These higher angles were included to demonstrate that the technique had a bounding limit and to see where the performance of the technique degraded.



0

Figure 40: Array of 5mm Overlap Sample Angle Inspection C Scan Images in 5° Increments from +30° to -30°

Other interesting observations from the scans are the breaks within the slot (within the Y-axis) align dimensionally with the valley of the surface weld bead, defining this as the

hardest area to insonify effectively. It can be noted that generally different angles struggle with the valley regions at different X-axis regions along the slot. Another observation of note is the more extreme angles displaying a double image of the slot which is proposed as the effect of mode conversion within the feature.

This variation in amplitude position along the slot can be counteracted by using the angle that is more effective in this region and building a compound image of the multiple angled scans. By compounding or merging the images together a reduction in amplitude variation can be achieved.

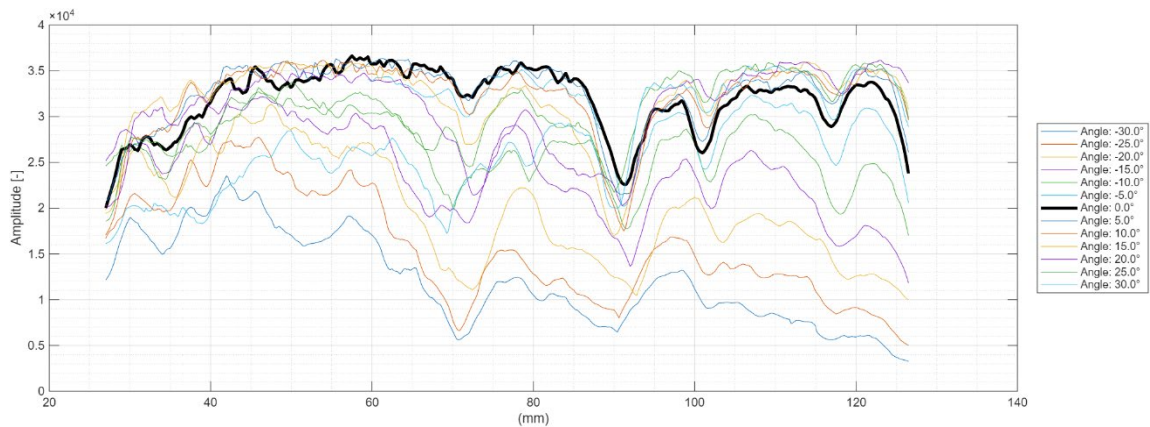


Figure 41: Amplitude Variation of Individual Angled Scans over the Slot Region (5mm Sample)

Plotting the amplitude from the ultrasonic inspection of the slot region under the 5.0 mm overlap sample surface demonstrates a wide range of variation in ultrasonic response throughout the feature. This variation fluctuates along the length of the slot, often crossing over other angled scan amplitudes, showing that a simple approach of applying a discrete angle or set of angles to a particular surface finish wouldn't give the optimum ultrasonic response.

The most interesting observation that can be made of Figure 41 is the distinct valley at the 90mm position along the slot. Apart from this discrete region, taking the optimum angle at any individual position along the slot provides a uniform ultrasonic response, suggesting another variable affecting the ability of the ultrasound to reflect with as much efficiency. Interpretation of Figure 40 is challenging with multiple overlapped and condensed regions, making the choice of the optimum angle difficult to achieve.

Figure 42 gives each discrete angle set a percentage improvement from the 0° inspection angle. Angles such as -30°, -25°, and -20° displaying a -100% value show that at no point over the slot region does the amplitude response from these angles provide a greater response than the 0° inspection value. However, improvement begins with the -15°, -10° and -5° group of angles showing contribution towards an increased amplitude response somewhere within the slot feature. Greater success is then shown in the 5° to 20° inspection angles, where there is always a position in the slot that attributes a higher ultrasonic amplitude in comparison to the 0° default inspection angle. The final two inspection values, 25° and 30°, then show reduced amplitude contribution to the slot region however, still show much better responses than the corresponding negative inspection angles.

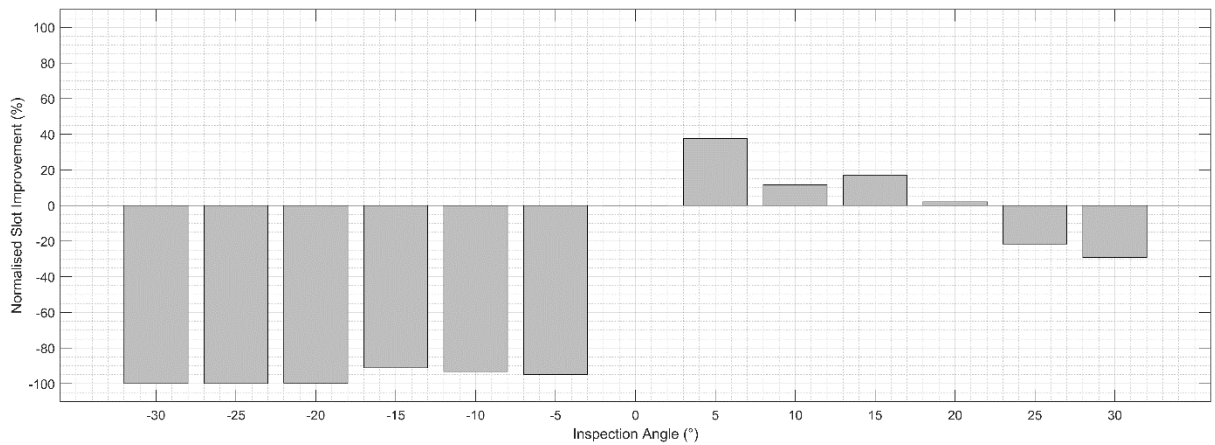


Figure 42: Normalised Slot Improvement by Angle to 0°.

It can be shown that this normalised response of inspection angles displayed in Figure 42 is in general agreement with the surface profile measurements displayed in Table 3 and the predominant surface weld bead angles. The angle of Peak (1) on the 5.0 mm overlap sample in the minus inspection direction of 2.66° shows agreement with the slight positive contribution of the -5° inspection angle along with the Peak (2) angle of 13.62°, in general agreement with the 15° inspection angle bar showing an increased contribution. Figure 43 provides an easy visual representation and tool to define if an inspection angle provides a positive contribution to the slot reflector and therefore if a useful inspection angle to contribute to an inspection of this fixed welding parameter.

Combining these two approaches a more useful visual representation would be a combined amplitude response from the slot, demonstrating which inspection angle contributed in that position to the maximum amplitude.

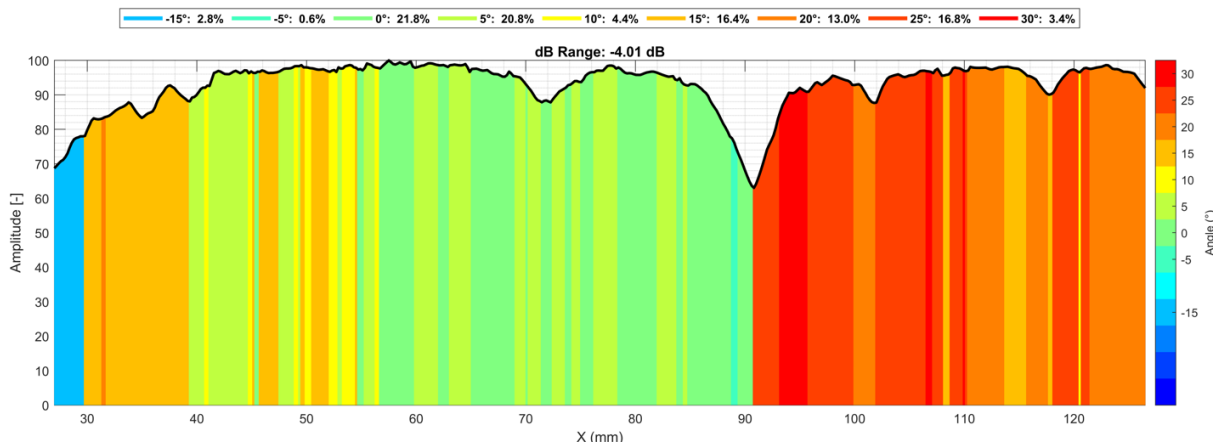


Figure 43: Slot Amplitude Response with Corresponding Inspection Angle of 5mm Overlap Sample

Figure 43 above shows the 5 mm sample with the contribution of -15° to 30° inspection angles, assisting the overall slot amplitude response in varying locations along the length of the slot. Visually, groupings of similar angles can be seen in sections along the slot length suggesting the surface profile of the sample is best insonified by the surface profile of the bead above this slot position, with the slot passing under 3 weld beads.

The key data that can be visually demonstrated by Figure 43 is the distinctive V-shaped valley centered at the 90 mm position along the slot with an approximate 6mm width, contributing the largest amplitude drop profiled along the full slot feature. This single position shows a -4.01 dB response to the overall slot feature. However, what can be noted is from the original approach of a 0° inspection, which demonstrated a -9.42 dB range in Table 5 the combined inspection angles have reduced the variation to -4.01 dB. If possible, by taking out the individual low spot, this would then reduce the amplitude variation to -1.0 dB, which will be investigated in further sections of this chapter.

The other key item of note is the optimum angles around the region showing the valley. The optimum angle on each side of the valley jumps from -5° to 25° & 30° on the other side. This suggests a very sharp trough in between the two adjacent weld beads, potentially acting as an ultrasound sharp corner feature, as the optimum angle changes at the discrete point that forms the bottom of the valley.

A combined C scan of the range of inspection angles can then be produced and compared to the original 0° only inspection to demonstrate the difference in imaging through the complex weld surface. Figure 44 below displays a few observations of note. There is a distinct gap at the 90mm region, where little to no amplitude of the slot region leaves an area that has limited inspection coverage. The amplitude of the slot varies greatly along the length, which, as a feature of constant depth and width, shows the effect the surface profile has on the ultrasonic transmission.

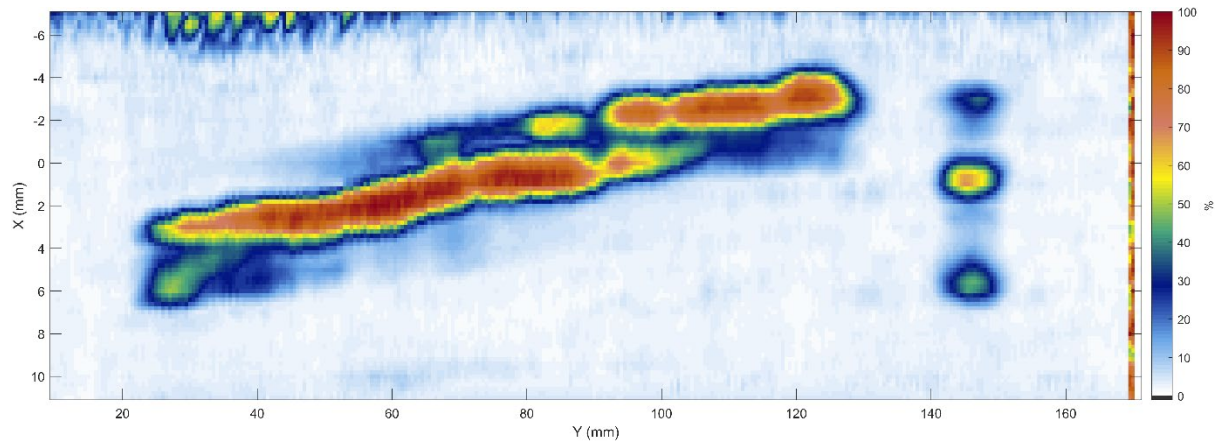


Figure 44: 0° Inspection C-Scan of the Slot and Holes of the 5mm Overlap Sample

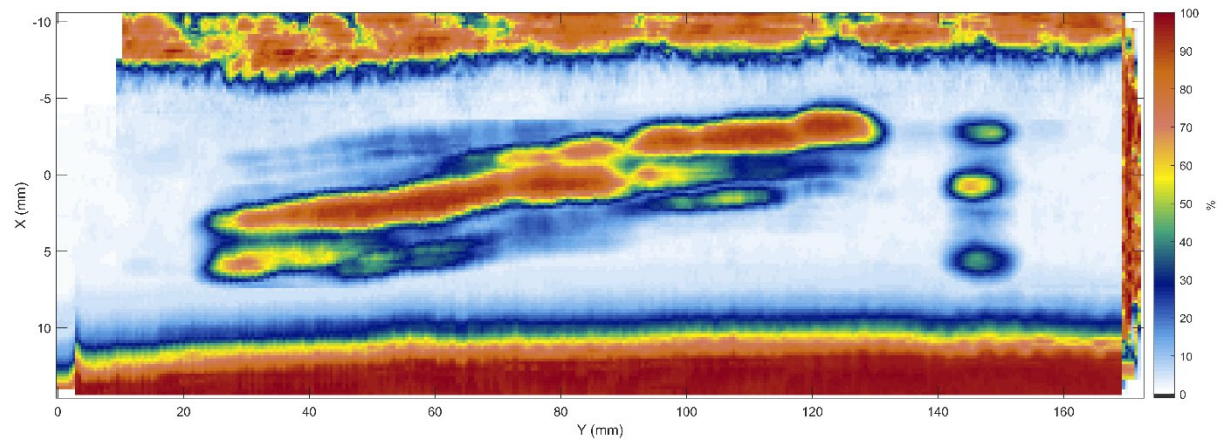


Figure 45: Combined Angles Scan of the Slot and Holes of the 5mm Overlap Sample

Figure 45 above shows the C-Scan image of the merged discrete angles with a reduced gap at the 90mm region, demonstrating that the challenging weld geometry at this position is better inspected with one of the other angles in the range selected. The amplitude of the slot is more uniform along the length of the slot, and the holes show reduced amplitude variation between the individual holes. Figure 45 aims to demonstrate the merged image with the more uniform velocity enables an inspection to justify reduced inspection limitations whereby a defect can not be readily missed in areas of reduced sensitivity.

Applying the same approach to the two adjacent samples, 4.5 mm and 5.5 mm weld overlap, gives a comparable result in terms of slot amplitude response. Visually, the 4.5 mm overlap sample is shown to have two discrete, sharp valley regions along the slot length, which could be attributed to the weld passes being tighter together, giving exaggerated peak and valley regions. The 5.5 mm sample showed comparable results to the 5.0 mm sample with a single valley region.

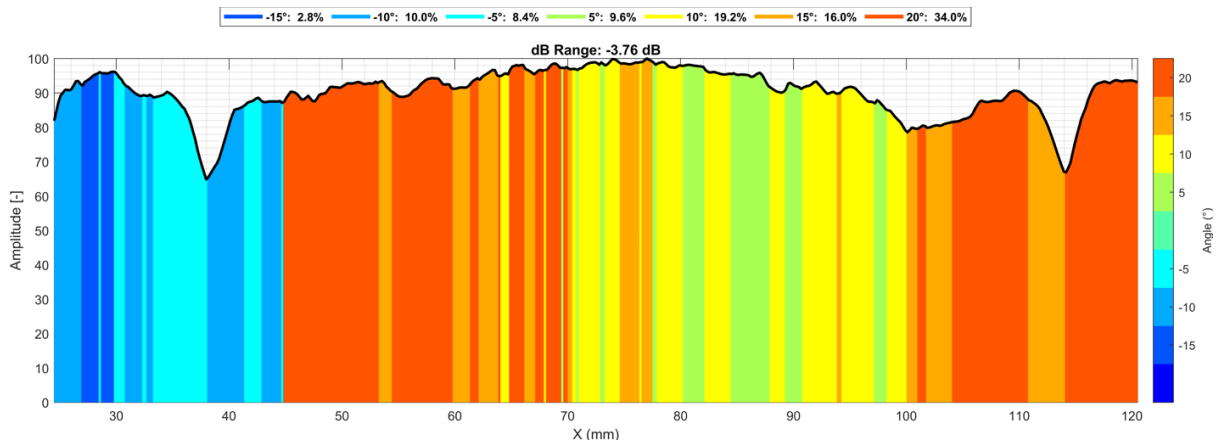


Figure 46: 4.5mm Overlap Sample (Slot Amplitude of Combined Angles)

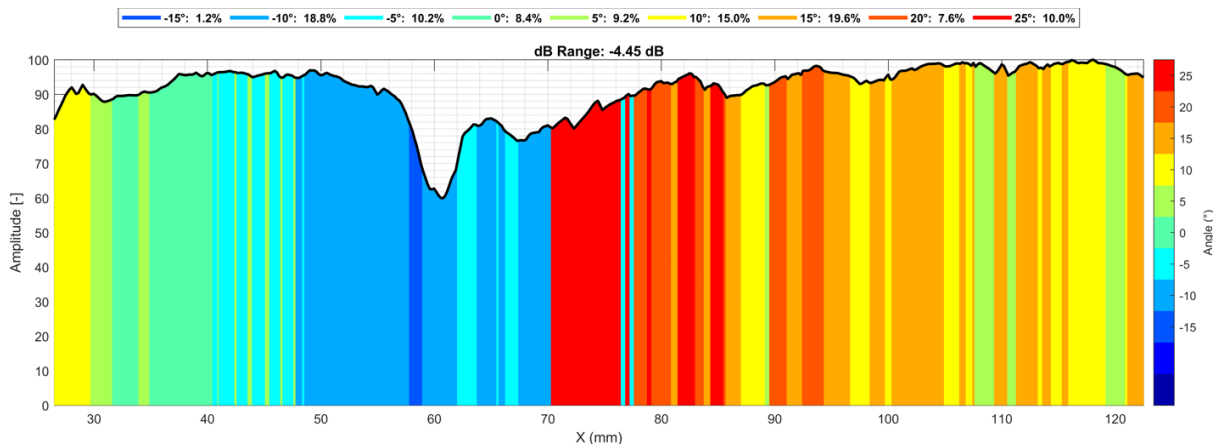


Figure 47: 5.5mm Overlap Sample (Slot Amplitude of Combined Angles)

The key output the three samples demonstrate is the angles used to enhance the ultrasonic transmission which vary between samples and in their contribution along the length of the slot feature. By applying inspection angles relative to the dominant surface profile angles, with sufficient latitude to include the extremity of any valley regions, an ultrasonic technique agnostic of location can be deployed to reduce the amplitude variation attributable to the varying weld surface.

Repeating this process for all five weld overlap samples shows a marked decrease in amplitude variation attributable to the weld surface condition, as shown in Table 6. A

reduction in variation from a worst-case variation of 13.95 dB to a range of 3.74dB to 4.45dB from a varied range of surface profiles.

Table 6: Weld Overlap Samples Slot Variation (0° compared to Compound Angles)

Sample	dB Variation (0° Scan)	dB Variation (0 ± 30° Scan)
4.5 mm	-12.55 dB	-3.76 dB
5.0 mm	-9.42 dB	-4.01 dB
5.5 mm	-13.95 dB	-4.45 dB
6.0 mm	-6.23 dB	-4.30 dB
6.5 mm	-13.56 dB	-3.74 dB

Using the compound of inspection angles reduces the variation of amplitude due to surface profiles to an average of 4.05 dB. Combined equipment checks to measure probe characteristic values are a common attribute of qualified automated and encoded ultrasonic inspections that are accounted for by means of standard tests with an example in accordance with BS EN ISO 22232-3 [136] including:

- Calibration variance +- 1db
- Re-calibration tolerance +- 1db
- Amplifier Linearity + 1.2db/ - 1.4dB at recording threshold
- Water path tolerance + 0db/ - 0.5db

By then applying BS EN ISO 16269-6 [137] methodology to the probe variables, a one-sided 95% confidence level due to sensitivity uncertainty is 2.2 dB. A rounding up policy is typical within industry to ensure conservatism in high-integrity inspections, by applying 3 dB, a conservative up-gain is included, allowing for 0.8 dB to account for less dominant sensitivity errors. The application of a 4.05 dB uncertainty to provide a means of

normalising the extreme valley of a varying weld surface is not largely disproportionate to uncertainties applied to enhanced manufacturing inspections conducted in high-integrity industries and is one possible method in application for In-process ultrasonic inspections during the welding process.

Other approaches could be to apply TVG retrospectively or scan certain inspection angles at varied gain to level the amplitude drop within the valley positions; however, understanding the root cause of these dips will determine the most appropriate approach for correction.

3.10. Valley Regions of the Weld Cladding Investigation

Understanding the distinct valley shown in Figure 43 and deriving a root cause is imperative to ensure the ultrasonic inspection methodology doesn't contain a systematic flaw in its approach. Reviewing both Figure 46 and Figure 47 clearly demonstrates that similar valley regions are present with identical geometries. A 6.0 mm wide feature with an amplitude drop of approximately 4 dB suggests a pattern in the data and either a systematic flaw in the methodology or a systematic flaw within the welded surfaces. Following a root cause analysis approach, defining physical causes is a key stage within the process, noting that the ultrasonic methodology is calibrated to appropriate standards, the logical place to investigate becomes the welded surface of the samples.

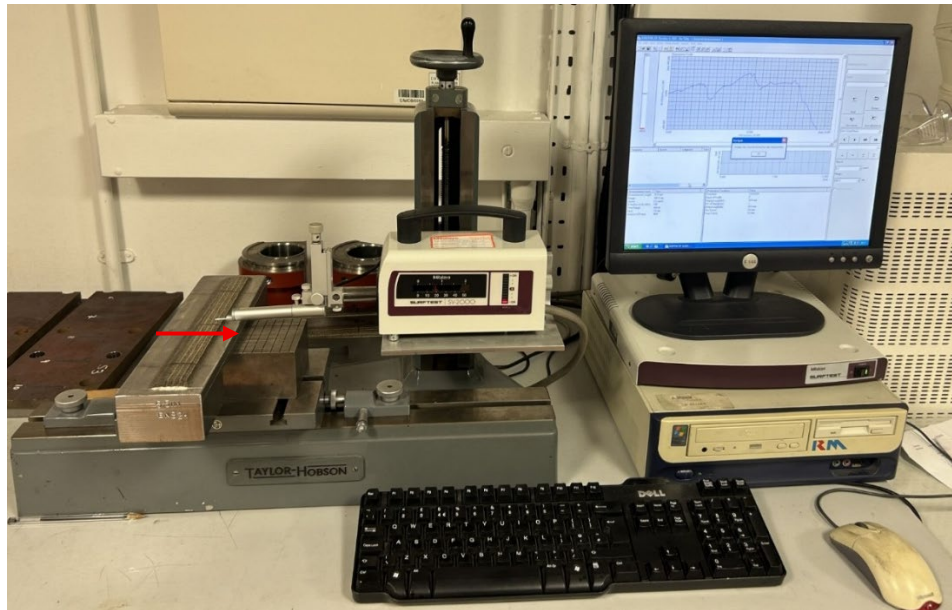
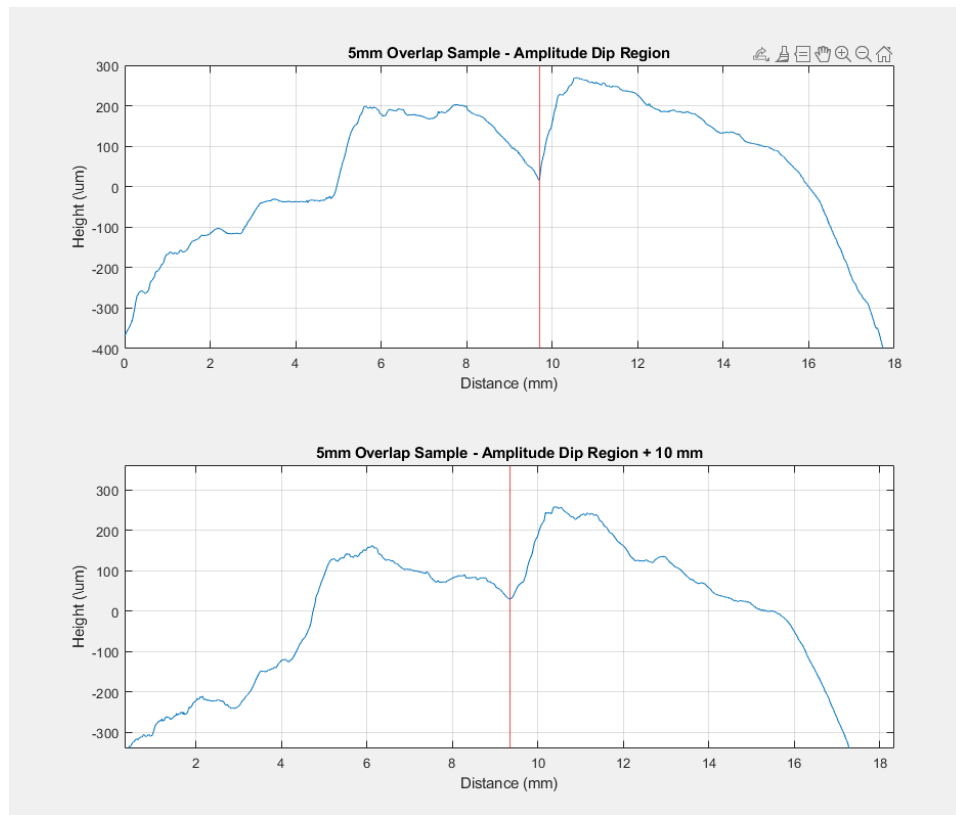


Figure 48: Surface Profile Data at Amplitude Dip Region and 10mm Offset on the 5mm Weld Overlap Sample (Red line denoting travel of surface profile stylus across adjacent weld beads)

Repeating the surface profile measurement of the 5mm at the valley region and 10mm adjacent to this region will then give a comparison outside of the 6mm feature shown in Figure 43. Noting the graphs in Figure 48 shows a clear difference in valley protrusion and sharpness between the two measured regions. The graph shown in the upper portion of Figure 48 clearly demonstrates a feature that is ultrasonically unoptimized in terms of geometry and will act as a smaller surface point to enable ultrasound transmission.

The corner trap mechanism [138] is an ultrasonic non-destructive testing method commonly used to detect planar flaws. The mechanism is most efficient when the crack is normal to the back wall of the component; in this case, however, the transmission surface presents itself as a corner, leading to reduced ultrasonic transmission and diffraction on the return sound path, leading to the reduction in amplitude. Noting the lower graph in Figure 48 that is 10.0 mm adjacent to this region, visual depicts a much more geometrically suitable surface for ultrasound transmission.

This method was repeated and correlated with the other valley regions in the other weld overlap samples and confirmed as the root cause in all cases. As there are limited options available to optimise the focal laws to overcome the weld geometry root cause with an immersion ultrasonic method, potential approaches left available are to optimise the welding method to smooth the surface and reduce sharp transitions, limiting the potential use cases to certain welding processes. Another approach is to amend the ultrasonic method to adapt more optimally to rough welded surface profiles.

3.11. In-Process NDE – RollerProbe Application of Methodology

The immersion ultrasonic method, although ideal for optimum coupling and for components that can be placed into an immersion tank, has limitations in the fact that this can't be deployed in-process, due to the elevated temperatures in the welding environment and on the component surface.

Repeating the proposed method of mapping the optimum ultrasonic transmission angles to the clad surface finish will be repeated with the novel RollerProbe method to prove that the method for an in-process welding inspection application is feasible [121].

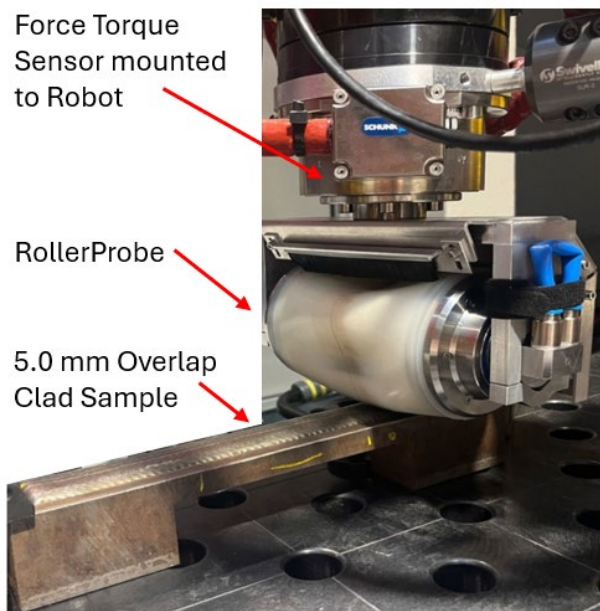


Figure 49: Fanuc Robot deployed In-Process NDE Ultrasonic RollerProbe

Figure 49 above shows the experimental set-up (with 5.0 mm overlap sample) utilising a University of Strathclyde 0° RollerProbe deployed by a Fanuc M-710iC/50 robot [139], driven by a Peak NDT MP6 PAUT controller with parameters as listed in Table 7.

Table 7: Roller Probe Ultrasonic Parameters

Parameter	Value
Frequency	5Mhz
Gain	46 dB (with added TVG at bond line up to +8dB)
Material Velocity (Steel)	5930 m/s (Longitudinal)
Velocity (Coolant in Roller Probe)	1430 m/s (Longitudinal)
Material Velocity (Utem Wedge)	2470 m/s (Longitudinal)
Elements	64
Aperture	32 elements
Element Size	0.5mm pitch, 0.42mm width
Focus Depth	3mm
Range	0.1 to 20mm
Scan Speed	5 mm/s

Following the same MATLAB imaging process as the immersion scan method, then confirms the ability to apply the same methodology to an in-process application. Comparisons can then be drawn between the immersion water coupling and the conformable roller probe tyre with internal coolant to highlight any potential issues for in-process inspection deployment.

3.12. RollerProbe Ultrasonic Results

An immersion ultrasonic method was chosen to provide proof of concept for the method in resolving ultrasound through a complex welded surface; however, knowing this method would not be applicable to in-process inspection due to the requirement of component immersion. The use of a RollerProbe has both advantages and disadvantages for the ultrasonic inspection method. Disadvantages include the attenuation through the tyre material, driving the requirement for more gain in the inspection system and the strong repeat interface signals from the tyre on inspections with thick section component geometry. The RollerProbe also lacks adaptability with probe and water path changes, not currently available in the rigid chassis internally within the tyre.

A side benefit of this system is the tyres conformity to surface profiles, allowing the roller to conform to the sharper weld profile and optimise the transmission angle of the ultrasound.

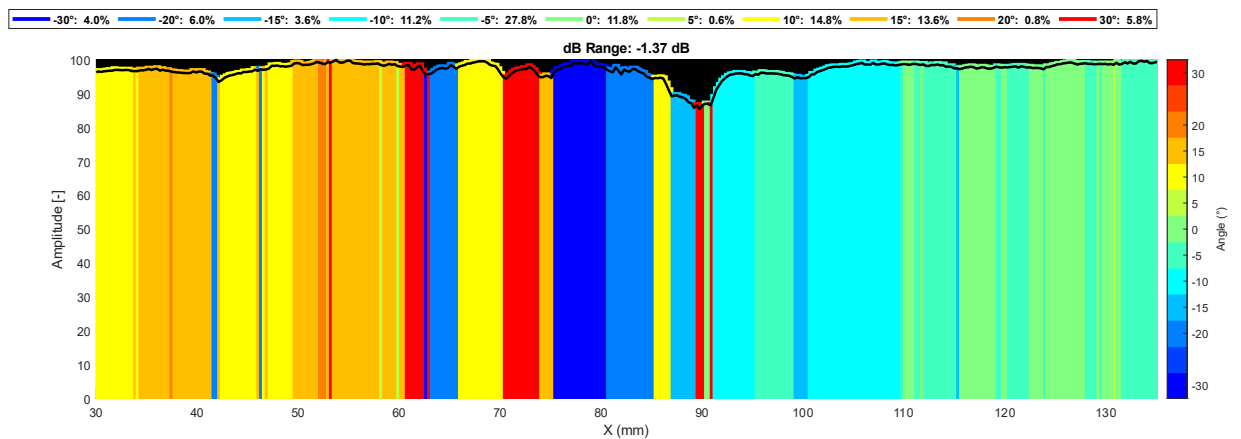


Figure 50: RollerProbe Combined Scan of 5.0 mm Overlap Sample over Slot Region

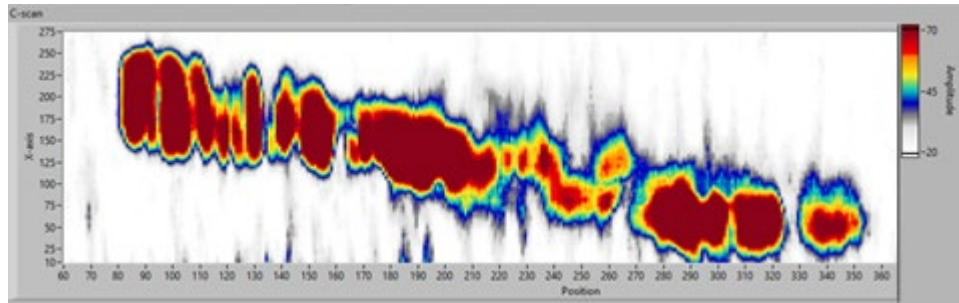


Figure 51: Merged C Scan of 5.0 mm Overlap Sample

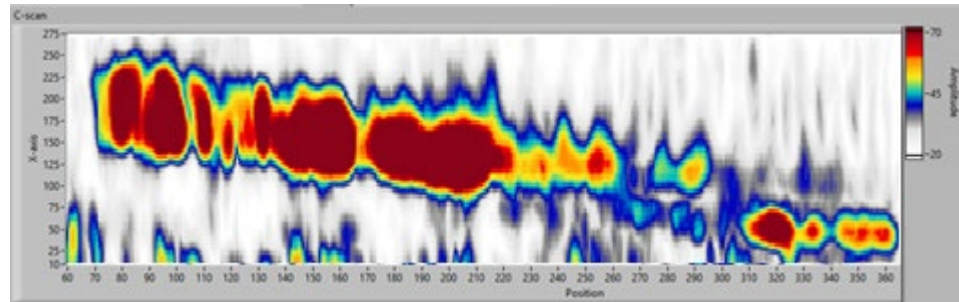


Figure 52: 0 Degree Scan of 5.0mm Sample

Again, the 5.0 mm welded overlap sample was chosen as the test for the RollerProbe inspection to provide a direct comparison between the immersion and roller probe scans over the slot region. Figure 50 shows the RollerProbe scan, and an interesting observation can be made whereby there is a reduction in the front wall surface amplitude relative to the immersion example, which is hypothesised to be due to the RollerProbe tyre conformability.

The RollerProbe application reduced the valley amplitude reduction from -4.01dB to -1.37dB a, threefold improvement. Interestingly, it can be noted that the RollerProbe still struggled with the valley region in some respects, as the width of the valley was comparable to the original from the immersion inspection, suggesting a limit to the RollerProbe's conformability. The addition of 1.37dB uncertainty into an ultrasonic

inspection system can be considered appropriate and within normal tolerances when considering variables such as amplifier linearity or recalibration tolerances, highlighting the potential of this method within welding and manufacturing.

The RollerProbe merged C-Scan shows a clear improvement in amplitude; in the region, the zero-degree scan shows limited ultrasound transmission. The merged C-Scan also shows a more consistent amplitude along the length of the slot. Further work is required to refine the multibeam steering method to filter out reflections from the side faces of the slot, to more accurately display and size the reflector to its known physical size.

3.13. Chapter Summary

This chapter has highlighted the challenges associated with inspecting through a variable as-clad surface which would be required to deploy an in-process PAUT Inspection.

A novel inspection methodology was developed and deployed showing a multi-beam approach can significantly reduce amplitude variation on a known surface reflector through multiple variable clad surfaces in both a proof-of-concept immersion UT method and a deployable Rollerprobe in-process methodology. The multibeam method can then be used to inspect in-process as-clad surfaces without the need for extensive surface preparation or machining to unlock real in-process inspection methods during the welding deposition of high integrity manufactured components.

Chapter 4

Defining a calibration methodology for PAUT inspections of weld cladding at elevated temperatures

Chapter 4 explores in depth the effects of temperature on ultrasonic inspections and developing compensation strategies for the PAUT inspections to be calibrated at stable elevated temperatures as determined through weld modelling with industrially qualified welding parameters. Analysis is conducted to determine the effect of temperature against key ultrasonic input and output parameters including material velocity and its effect on hole depth, reflector sizing and reflector amplitude to allow dynamic compensation curves from 25°C to 250°C. Significant benefits of this approach include the ability to link the calibration to a room temperature reference block and compensate during live in-process inspections or post-processing of the data, whilst maintaining the link to a code compliant calibration methodology.

4.1. In-Process Inspection of Cladding Calibration Challenges

Ultrasonic Testing (UT) and Phased Array Ultrasonic Testing (PAUT) are two of the principal NDE methods used for the detection and characterisation of internal discontinuities, not open to the surface of the part. Ultrasonic inspection is a highly sensitive defect detection technique; however, it is strongly influenced by environmental and operational parameters, which must all be accounted for by means of a calibration or reference block inspection. The calibration block can bound the inspection requirements by means of reference reflectors of a pre-determined size, bounding the inspection volume and is typically scanned both pre and post component inspection. Calibration of ultrasonic inspections typically accounts for the speed of sound (velocity) travelling through the reference block to enable a correct range or distance for geometric features, or defects to be determined and the amplitude of a reflector response. The amplitude response will be set from a known reflector size as agreed by the international code or standard relevant to the structural significance and defect tolerance of the component under test.

One of the key issues in defining an in-process based ultrasonic inspection is the effect temperature has on the propagation of ultrasonic waves. An increase in component temperature, as would be seen during the weld cladding process, reduces both longitudinal and shear wave velocity, primarily through a change in the material's Young's modulus and density [41]. Another key challenge encountered at elevated temperature is the increased sound attenuation arising through a progressive loss of signal amplitude due to

enhanced material dislocation mobility and internal friction [42, 43]. Work undertaken on basic TIG welds [31] has shown compensation is possible using TFM and compensated time of flight maps; however, this approach would be impractical and challenging to deploy on as-welded geometry of thin cladding.

Temperature-driven phenomena can cause substantial deviation in positional measurement accuracy and amplitude-based detection criteria under elevated temperature conditions. In relevant low-carbon steels, a decrease in ultrasonic signal amplitude has been reported by as much as 16.9dB from room temperature to 250 °C [44]. This increased attenuation is a direct consequence of increased temperature and dramatically reduces defect detection sensitivity, potentially resulting in underestimation of material thicknesses or non-detection of defects in safety-critical components. In response, related work in the power generation industry has also demonstrated ultrasonic measurements of thermal distributions in solid materials [45] and assessment of time of flight data at elevated temperatures for plant life extensions [46]. Considerable work has also been undertaken in an adjacent industrial field to measure lubrication film thicknesses at temperature as an important metric for the behaviour of engine and gear oils [47, 48].

Ultimately, ultrasonic inspections are controlled and justified by the application of a national or international standard. BS EN ISO 17640:2018, the standard for manual ultrasonic testing of welds in metallic materials, specifies that an object under test must have a temperature between 0°C and 60°C, with the calibration block and component under test being within ± 15 °C of each other [15]. International standards such as ASME V require a maximum variance of ± 14 °C [13].

Work to justify an in-process inspection method must therefore overcome this current standard limitation by means of temperature compensations that correct for, as a minimum: the material velocity, material attenuation, signal amplitude of reflectors, position and sizing of indications at elevated temperatures. Inspection methods must also establish a link to a calibration block to ensure the inspection is appropriately conservative. Current attempts to define an in-process calibration method have focused on the embedding of intentionally seeded tungsten tubes within the welded volume [49], but this is non-preferable in high-integrity components and would undermine the structural integrity of components in many safety-critical industries. In addition to these requirements, an in-process inspection to determine the integrity of weld cladding must also take into account the dissimilar metals, which adds an additional challenge through acoustic mismatch, varying grain structures and differing material velocities.

This study introduces a novel approach to calibrating in-process ultrasonic inspection of weld-cladding deposition, combining a modelled heat-profile typical of cladding operations with an experimentally derived temperature-based compensation strategy. This study first examines the temperature field during welding by means of simulated weld modelling of a CMT cladding process incorporating material preheating. It then evaluates the specific effects of this temperature field on ultrasonic testing and subsequently develops a compensation model to improve inspection accuracy, validated through experimental trials.

4.2. Characterisation of Temperature Influence on In-process UT Inspection

4.2.1. Weld Modelling

Three discrete weld models were run for the CMT weld cladding process, with minimum and maximum inter-pass temperatures of 110°C and 175 C based on current weld approaches, to bound the potential range of temperatures the ultrasonic probe would experience during the in-process inspection. Fixed parameters as per Table 8 were selected including the weld velocity of 8.33 mm/second were selected based upon typically selected industrial WPS (Welding Procedure Specifications) for a weld cladding GMAW-based process.

A fixed position for the ultrasonic probe of 300 mm behind the weld head was selected based upon typical accessibility constraints posed by the geometry and dynamic motion requirements of both the welding equipment and in-process PAUT sensor, within a 1.5 m diameter vessel without risk of equipment clashes. An efficiency of 0.8 is commonly used for arc-based welding process modelling [140, 141].

Fixed Parameter	Value	Provenance
Weld Velocity	8.33 mm/second	Extracted from WPS
Position Behind Weld Head	300 mm	From the Geometric Model
Weld Width	5 mm	Extracted from WPS
Weld Penetration	3 mm	Extracted from WPS/Macro
Energy/Unit Length	430 J/mm	Extracted from WPS
Efficiency	0.8 (Unitless)	Value commonly used for arc weld processes

Table 8: Weld process modelling fixed parameters and provenance.

The simulation (see Figure 53) aimed to understand bulk temperature characteristics only. Therefore, a sensitivity study was not undertaken to understand CMT weld bead geometry, residual stress distributions, or microstructure evolution as the scope for this investigation focuses purely on the primary effects of temperature on ultrasonic propagation. The pre-heat temperature of the model was bound by the WPS values, and the air temperature was modelled to understand its effect on the bulk component temperature.

Model	Pre-Heat Temp (°C)	Air Temp (°C)	Material Temp (°C)
1	110	110	165
2	175	20	222
3	175	110	227

Table 9: Weld cladding pre-heat model defined temperatures.

Table 9 shows that the air temperature had a negligible effect on the bulk temperature characteristics of the component, with the pre-heat temperature being the primary driver of the component's bulk temperature, as may be expected in consideration of the relative specific heat capacity and thermal conductivity of steel.

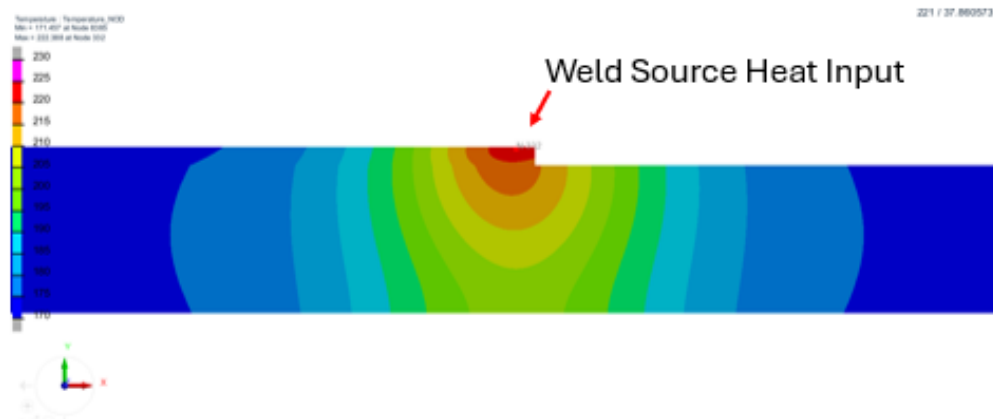


Figure 53: Weld model 2 heat distribution at the point of inspection in °C.

Taking the two extreme pre-heat values gives the maximum range foreseeable during the in-process ultrasonic inspection. Plotting the cooling rate of the weld (see Figure 54) shows that at a position 300 mm behind the weld torch, reached 32 seconds after cladding deposition, the PAUT probe effectively avoids the steep transient regions of weld cooling, reducing the variability of the temperature experienced by the ultrasonic probe and therefore variation in ultrasonic calibration compensation required.

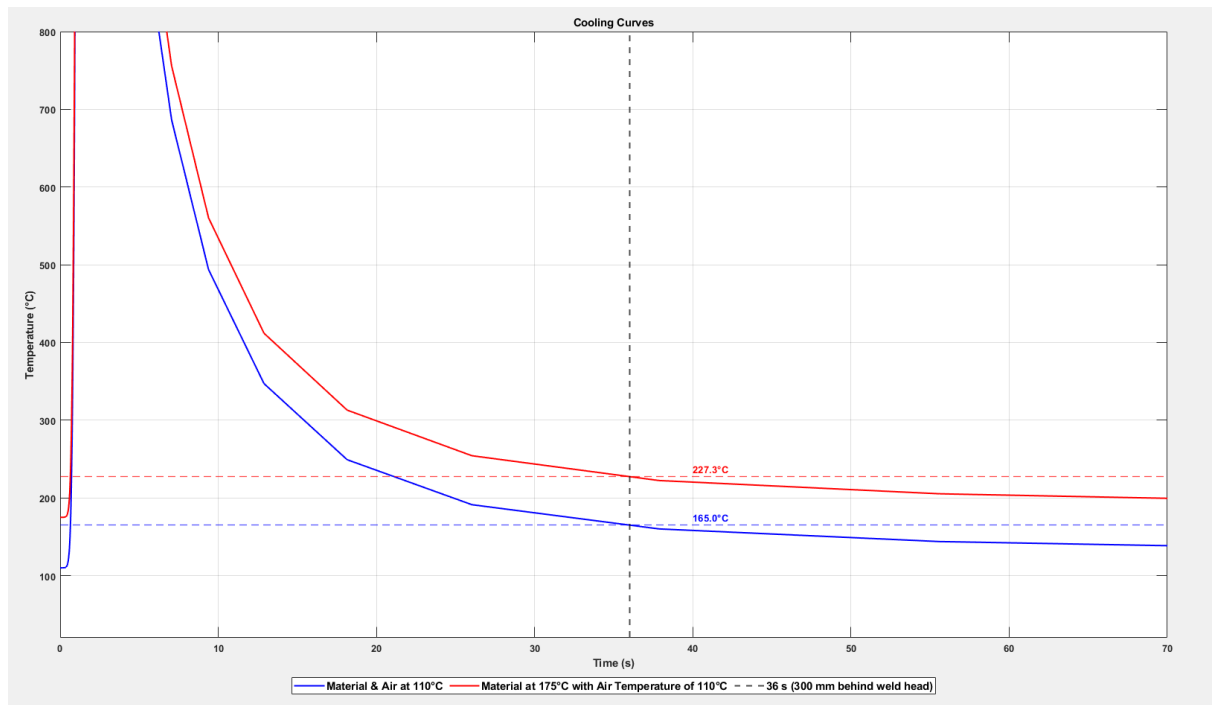


Figure 54: Cooling rates of weld models 1 and 3 (Bounding temperature cases)

During large-scale weld cladding operations on large components, the upper bounds are very unlikely to be reached due to the large surface area for heat loss through convection into the surrounding air, with the lower temperatures much more likely to be experienced as a bulk temperature during the in-process ultrasonic inspection. Theoretically, an

ultrasonic calibration compensation regime from room temperature to 227°C would fully define the weld cladding in-process inspection for this experimental design.

4.2.2. Reference Sample Preparation & Design

A weld clad reference block was prepared by depositing a nickel-based alloy EN82H as the clad substrate onto a carbon steel S275 base. A Fronius CMT TPS 400i [127] was selected as the welding equipment using an Argon Helium CO₂ H₂ (Cronigon Ni 10) gas mix [128] following industry best practice, laying 3 layers of cladding onto the base substrate (see Figure 55).

The non-planar, as-welded surface was then milled to provide a surface finish of 6.3 µm Ra or better as per industry standards [142] and to face off the calibration block to the appropriate length and width.

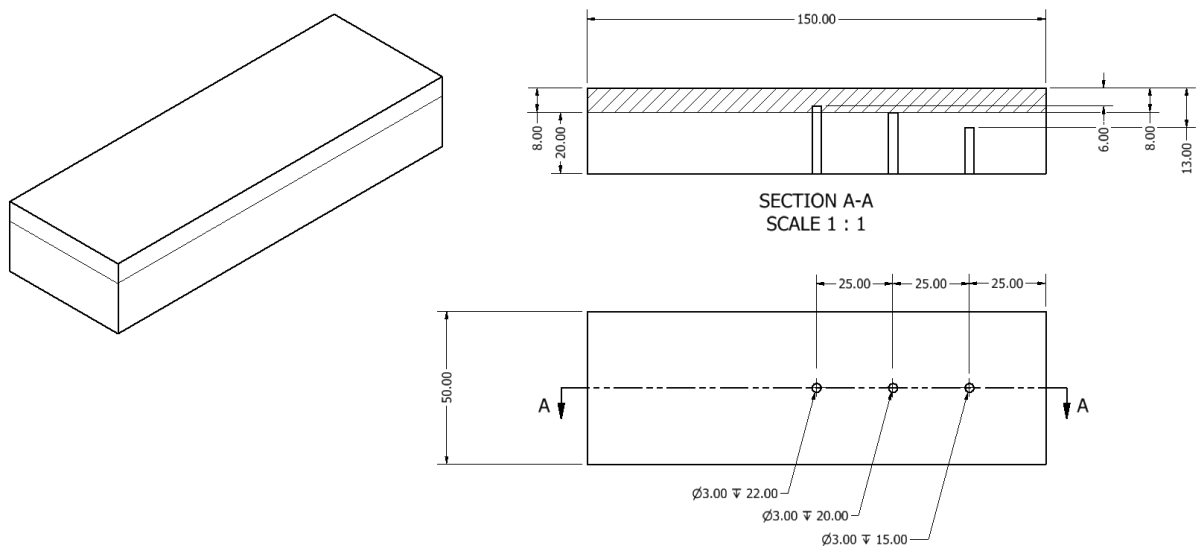


Figure 55: Engineering drawing showing clad thickness, hole position and hole size.

The flat-bottom holes (FBHs) were then precision drilled with a diameter of 3.0 mm as per the requirements of BS EN ISO 17640 [15] for reference reflectors, as used to set Distance Amplitude Curves (DACs) in line with current ultrasonic inspection specifications. Accordingly, precision tolerances of ± 0.1 mm for the hole diameter and ± 0.2 mm for the hole depth were specified.

A final clad thickness of 8.0 mm was selected in consideration of both industrial requirements for the weld cladding thickness necessary to providing the appropriate enhanced properties for the high integrity components, and the standards of BS EN ISO 17640 [15], applicable for material with a thickness of 8.0 mm or greater. By striking a balance between the industrial end user requirements and the worst-case inspection requirements of inspecting thinner material layers, a conservative approach to multi-layer weld cladding ultrasonic in-process inspections can be developed.



Figure 56: Completed weld cladding calibration block - showing the hole pattern and bond line between the dissimilar metals (Base metal shown as the top face, EN82H cladding below).

The hole depths were selected to provide a sensible range spanning the clad bond line in both directions across the two materials. Depths of 6.0 mm, 8.0 mm and 13.0 mm were selected.

- **FBH 1: 6.0 mm depth** – This depth was selected to be purely in the EN82H cladding to provide the elevated temperature experiment with a control value that ensured the ultrasonic waves had only passed through one material velocity.
- **FBH 2: 8.0 mm depth** – This depth was selected to represent the bond line depth of the material (the primary purpose of the inspection methodology – see Figure 34) and will also demonstrate the defect detection sensitivity at the crossover point between the two materials. This depth will also be in the crossover point between the two material grain structures.
- **FBH 3: 13.0 mm depth** – This depth was selected to be in the base metal region beyond both the clad interface and the Heat Affected Zone (HAZ). This will act as an additional data point during the experimental phase, as the velocity gradient should be different to Holes 1 and 2, and also covers the industrial requirement to detect defects below the bond line if induced through poor cladding operations [90].

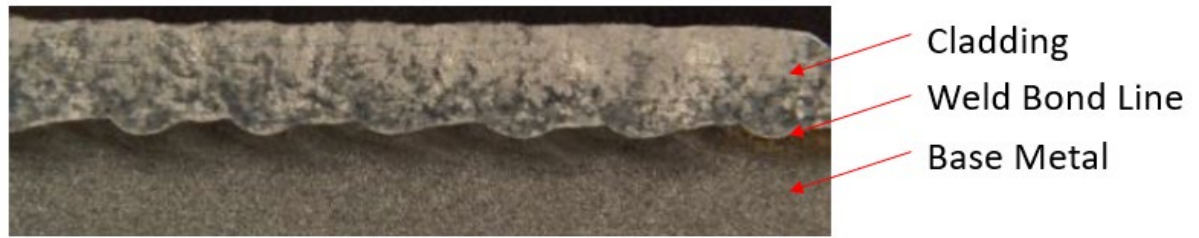


Figure 57: An example CMT weld cladding macro showing the weld bond line interface between the two dissimilar materials

4.3. Ultrasonic Inspection at Elevated Temperatures

4.3.1. Equipment

The reference block was to be heated in fixed increments to 25 °C, 50 °C, 100 °C, 150 °C, 200 °C and 250 °C, then inspected using a Kuka KR10 R1100 robot [135] with a mounted Schunk Delta IP65 force torque sensor to deploy the ultrasonic RollerProbe. A Peak-NDT MicroPulse LTPA [133] phased array controller was selected to pulse a 64-element 5 MHz Phased Array RollerProbe (see Figure 58) mounted to the force torque sensor within a heat-resistant tyre [20] and driven by bespoke LabVIEW[®]-based software designed by the University of Strathclyde.

An electrical inverter control unit was connected to a flexible, ceramic, resistance heater pad [143] positioned underneath the reference block to provide temperature control, utilising the feedback of two independent thermocouples on each side of the reference block. Thermal insulation wool [144] was used to isolate the heating element from the surrounding environment and to cover the setup during heating phases between discrete temperatures, ensuring an even temperature increase throughout the reference block.

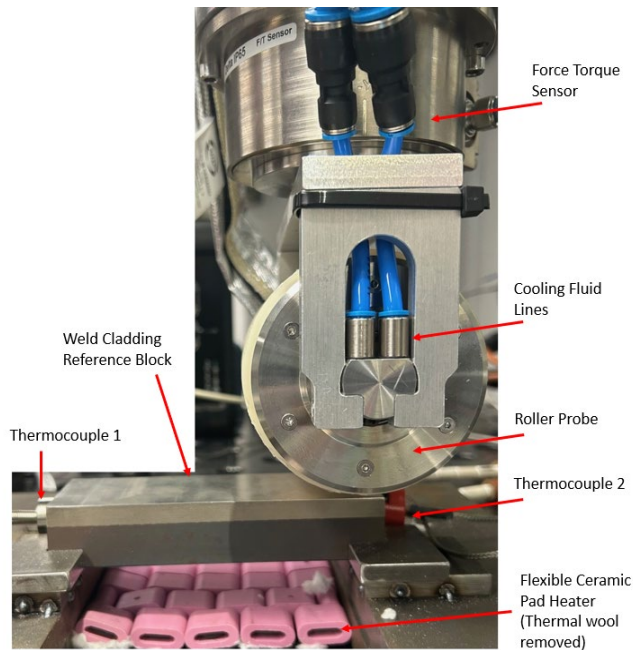


Figure 58: Roller probe heated calibration block scan set-up (Thermal insulation removed for set-up clarity – resistance heater would be pressed to the back of the block during the experimental phase)

The reference block was mounted in a steel fixture to allow the flexible ceramic pad to be placed behind the back face of the block and to heat from the bottom.

Parameter	Value
Probe Model	Imasonic
Centre Frequency	5 MHz
Effective Aperture/Active Elements	16 / 64
Transmit–Receive Law (Focal Law)	0° Longitudinal -Linear Scan - Unfocused
Step Size	0.5 mm
Scan Speed	5 mm/s
Sampling Rate	2170 Hz
Filtering Settings	4.0 MHz to 8.0 MHz
Gating Parameters	0.1 mm to 120 mm (Multiple Back Wall Repeats)
Couplant	Dry Coupled Externally
Tyre Material & Thickness	Silicone Rubber [20] & 3 mm
Front Wall Tracking	Disabled
6 dB Sizing Methodology	Maximum hole amplitude – 50% Full Screen Height

Table 10: Inspection Setup Parameters.

4.3.2. Experimental Set-Up

The experiment was set to utilise a 0° longitudinal wave inspection, which was chosen for a multitude of reasons: to include the ease of isolating variables, the ability to monitor a back wall response to understand velocity shifts as a by-product of temperature and being at the ideal incident angle for detection of planar lack-of-fusion (dis-bond) type defects within the cladding.

The ultrasonic focal laws and imaging configuration parameters were generated by ArrayGen software, designed by Peak NDT [134], to provide a linear scan using an unfocused beam using a velocity of 5820 m/s matching the EN82H Inconel velocity at room temperature [145]. By setting the material velocities to room temperature value, the effect of temperature can be quantified, and the time of flight from known values, such as the reference reflectors and the back wall of the reference block, can then be measured to quantify the change in velocity. The gain was set at room temperature to yield an 80% full screen height (FSH) signal from the hole at the bond line of the test piece (8.0 mm depth) so the effect of temperature on both amplitude and hole sizing could also be quantified as the temperature increases. The hole sizing was conducted by applying a 6 dB drop method as per the industry standard [146].

The reference test was then heated in fixed increments of an ambient temperature of 25°C, 50°C, 100°C, 150°C, 200°C and 250°C and monitored during the scan to ensure the thermocouples were within ± 1 °C around the set point. At the higher temperatures, this

included a soak time to ensure the thermocouples showed no drift during the scan time. The parameters were fixed, ensuring no change to the velocity or gain values during the experiment, and to enable plotting of the amplitude drop, back wall to back wall and front wall echo shifts as a function of temperature.

The RollerProbe array was actively cooled to 20 C from a controlled chiller and not placed on the reference block until the scan was initiated, ensuring the RollerProbe and tyre internals did not gain residual heat from contact with the heated reference block surface. The scans were independently repeated three times at each temperature interval to ensure repeatability and evaluate the variance of the process.

4.4. Results

4.4.1. Calculated Thermal Expansion

Thermal expansion is a known phenomenon at increased temperatures, which needs to be contextualised prior to understanding the effect of the measured ultrasonic reflector sizing. The known value of the three holes is a diameter of 3.0 mm. Taking the linear coefficient of thermal expansion (CTE) for each material:

- Inconel (typical, e.g. Inconel 718): $\alpha = 13.0 \times 10^{-6} /K$ [147].
- Steel (typical mild/carbon steel): $\alpha = 12.0 \times 10^{-6} /K$ [148].

Temperature (°C)	Δ (Inconel) (mm)	Final (Inconel) (mm)	Δ (Steel) (mm)	Final (Steel) (mm)
25	0.000000	3.00 mm	0.0000	3.00 mm
50	0.000975	3.000975 mm	0.0009	3.0009 mm
100	0.002925	3.002925 mm	0.0027	3.0027 mm

150	0.004875	3.004875 mm	0.0045	3.0045 mm
200	0.006825	3.006825 mm	0.0063	3.0063 mm
250	0.008775	3.008775 mm	0.0081	3.0081 mm

Table 11: Calculated CTE for Steel & Inconel from 25°C to 250°C.

As shown in Table 11, there is a negligible size difference associated with a maximum dimensional variance of 0.0088mm at 250°C; therefore, thermal expansion will be considered negligible in the reflector sizing during the amplitude/hole sizing experimentation stage.

4.4.2. C and D Scan Temperature Response – Visual Representation

Figure 59 shows the visual representation of the three FBHs at both room temperature and at 250°C. The key observation is that the elevated temperature scan shows a dramatic reduction in both amplitude and hole size, as expected with the increased attenuation at higher temperatures. An additional observation easily identifiable on the D scan shows a clear increase in apparent depth of the hole at the elevated temperature, as a byproduct of the reduced velocity at higher temperatures, leading to a longer time of flight and therefore a deeper reported depth of the holes.

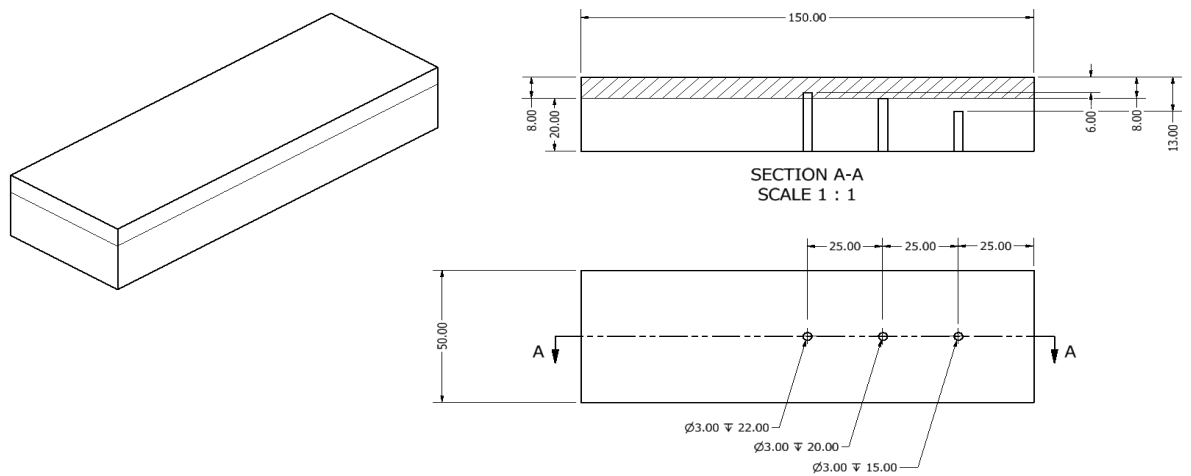
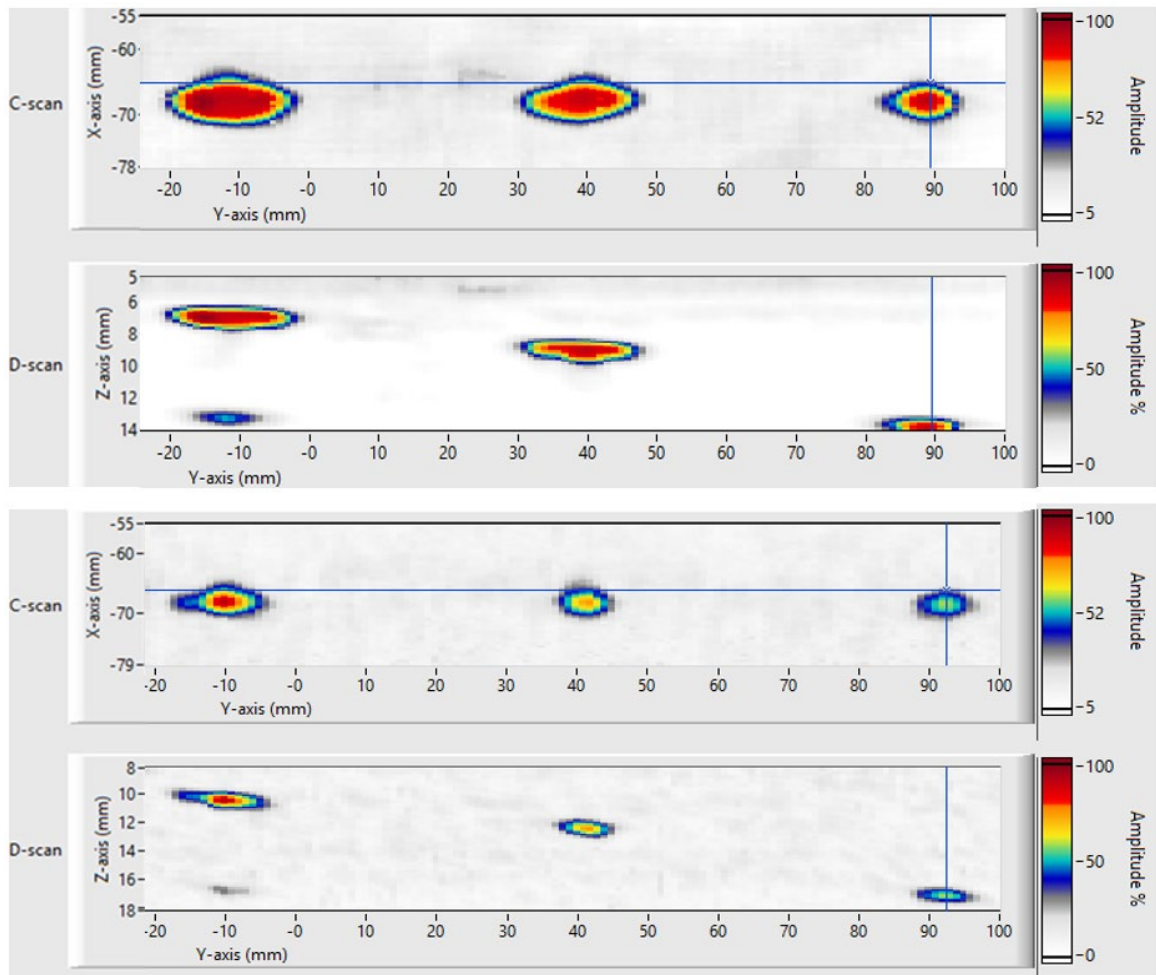


Figure 59: Visual Representation of Reference block response from 25°C (Top Image) to 250°C (Bottom Image) - C & D Scans).

4.4.3. Hole Depth & Back Wall Measurements at Elevated Temperatures

The three different depth holes (shown as an average of 3 independent ultrasonic scans) were plotted as a function of temperature to define the change in velocity against the known reflector depths. The results showed a strong correlation in R^2 values between 0.954 and 0.992, which is considered a strong agreement between the linear model and the data variability [149]. This means the variance in the dependant variable outside of the model is a maximum of 4.6%. Key observations show an extremely strong agreement in Holes 1 & 2, with a slightly lesser agreement in Hole 3, due to the slight mismatch in material velocity between Steel and Inconel values and the greater attenuation due to the increased hole depth.

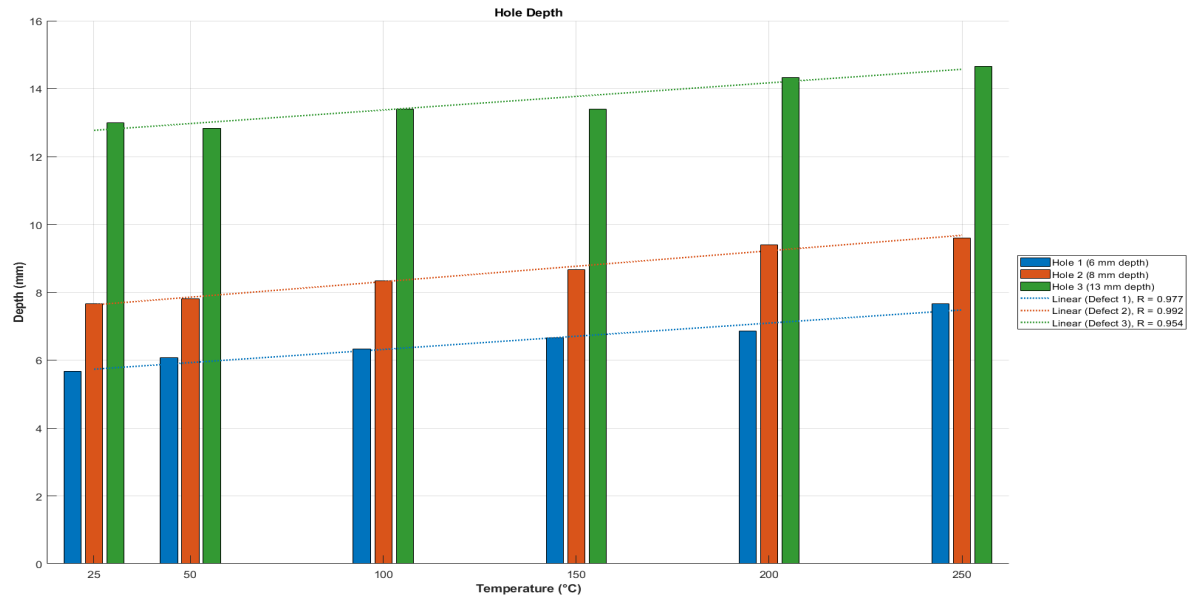


Figure 60: Hole depth shift at temperature with linear fit.

However, following this linear trend, an accurate velocity can be calculated from the time of flight from the front wall response to the response from the FBH to correct apparent reflector depth. Using this time of flight between the front-wall and hole signals isolates the effects of velocity changes in the component material from any occurring within in the RollerProbe itself.

Figure 61 shows another method of monitoring the velocity shift as an effect of temperature. The blue bars demonstrate the depth to the back wall, which increases marginally as the temperature increases, showing a combined velocity change through the Inconel and steel layers of the reference block. The orange bars then visualise the back wall to back wall repeat measurement, which is an industry standard technique for monitoring through wall thickness. One key observation of note is that the gradient of the

back wall measurement increases gradually, but the back wall to back wall measurement provides a steeper gradient. This is due to the inspection methodology using the velocity for the Inconel material rather than compensating for the steel velocity below, as the weld cladding defects are likely to be at the interface between the two materials or within the molten weld pool solidification in the Inconel layer.

This back wall monitoring provides a valuable tool used during in-process inspection if the weld and material thickness is a known value and used to infer the temperature of the welding process at the inspection point; however, greater confidence can be given to the reference reflectors in this experiment due to the precise nature of their manufacture and accurate positioning. For industrial deployment, the real-time correction should rely on backwall/known-thickness TOF to estimate the effective velocity and update depth calibration, taking account of any thermal gradients at that discrete inspection location in real time.

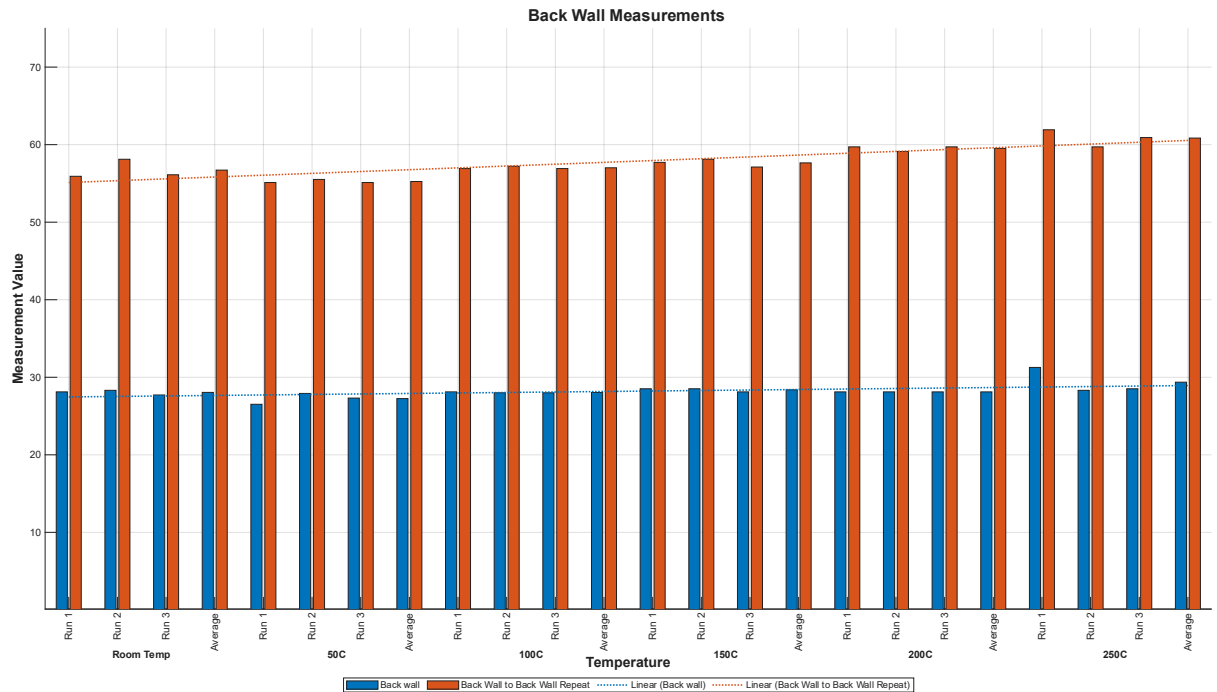


Figure 61: Back wall and back wall repeat measurements (mm) at elevated temperatures

4.4.4. Hole Amplitude Measurements at Elevated Temperatures

The ultrasonic signal amplitude from a discontinuity within a test piece is directly linked to factors specific to the individual probe and instrumentation hardware and so requires gain calibration to yield consistent results. Industry standards such as BS EN ISO 17640 – “Ultrasonic testing of welds” [15] and BS EN ISO 13588 – “Use of automated phased array technology” [142] control and mandate tolerances for a re-calibration at a maximum of every 4 hours during testing and after completion of the test. Further, BS EN ISO 13588 mandates that a deviation $\leq 4\text{dB}$ may be corrected by software, with anything above that requiring recalibration and re-inspection. Whereas BS EN ISO 17640 mandates:

- $\leq 2\text{dB}$ deviation requires no action.
- $2\text{dB} < \text{deviation} \leq 4\text{ dB}$, the setting shall be corrected before testing is continued.
- Sensitivity deviations of more than 4 dB require reinspection of the components.

Accordingly, Figure 62 plots the amplitude of each reference hole as a function of temperature when inspected with consistent settings alongside Upper and Lower Control limits (UCL & LCL) representing the boundaries for acceptable change.

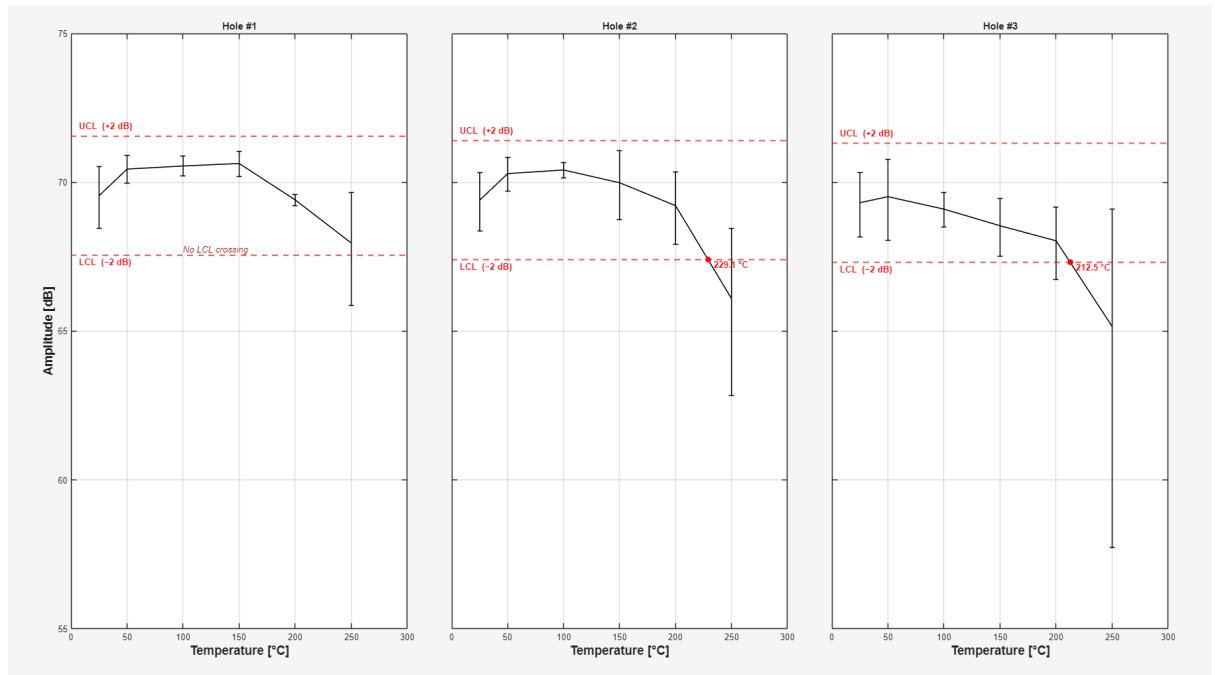


Figure 62: Hole amplitude at elevated temperatures (Hole 1: 6mm depth, Hole 2: 8mm depth, Hole 3: 13mm depth).

Taking the intent of both specifications, a $\pm 2\text{ dB}$ tolerance was applied as the UCL and LCL around the 80% FSH setting of Hole 2 to understand at what temperature amplitude must be compensated for outside of conventional re-calibration limits.

Taking the point on each graph where the curve passes the LCL line, outputs a temperature at which the -2 dB variation is exceeded. The key holes of interest for the cladding inspection, FBH 1 (6.0 mm depth) and FBH 2 (8.0 mm depth), show no crossing of the LCL and a crossing at 229.1 °C, respectively. Both values are above the 227.3 °C maximum process temperature demonstrated during the weld modelling of the GMAW process at the point of inspection, therefore allowing up to + 2dB gain to be applied to the inspection to conservatively bound the effect of temperature to a weld cladding bond line inspection.

For FBH 3 (13.0 mm depth) within the steel substrate, the 2 dB threshold is exceeded at a temperature of 212.5 °C, which does not fully bound the maximum foreseeable GMAW process temperature. Further mitigations would be required if inspections were to be focused at this depth within the substrate material, such as beam focusing or additional reference reflectors within the steel substrate to better characterise the temperature effects.

Figure 62 highlights the strong stability of the amplitude responses up to 150°C due to the coolant chilling system. Once past this point the stability decreases as the RollerProbe tyre collects more heat from the surface as it is not directly cooled, changing the attenuation of the tyre itself. Other factors at play are the elevated temperature shifts the near zone of the probe, as a result of the shortening wavelength.

4.4.5. Hole Sizing Measurements at Elevated Temperatures

Following the same methodology for the hole sizing and the data from the previous weld modelling in Section 4.2.1, a range of gain compensations can be calculated to compensate

for the apparent sizes of both Holes 1 & 2 across the range of temperatures examined (see Figure 56 and Table 12).

With the 165 °C component temperature being the most probable outcome during the CMT cladding process due to the heat losses involved with large surface areas, a small up-gain of 2.89 dB would adequately bound the calibration compensation to ensure weld defects weren't undersized during the inspection. If the welding process was deployed in a more extreme manner, utilising the full possible allowable heat input up to the maximum inter-pass temperature, the compensations would require a more extreme up-gain of 7.20 dB.

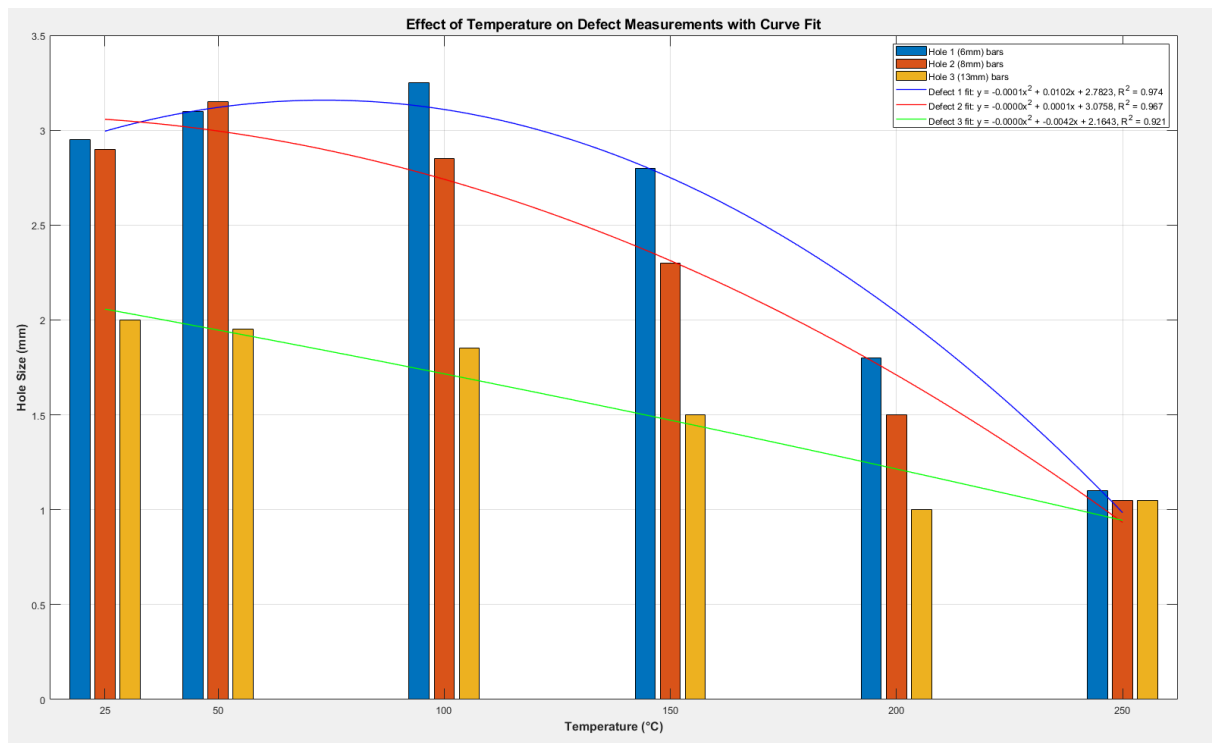


Figure 63: Effect of temperature on hole measurements (With 2nd order polynomial curved fit equations).

Key observations from Figure 63 show the relatively similar curved line fit of Holes 1 and 2 within the Inconel clad material, in contrast to the linear trend shown by Hole 3 in the steel substrate. Another significant observation can be seen that the curves follow a very similar trend to the amplitude curves, demonstrating that the known link between amplitude and size is not divorced during elevated temperature inspections. The amplitude and hole size both show a slight upward trend from room temperature to 100 °C, with a 1 dB increase in reflector response and corresponding size.

The values in Table 12 can then be used to calculate a depth and temperature-dependent compensation to create a hole sizing compensation methodology.

Table 12: Hole 1 & 2 Additional-Gain Required at 165°C and 227.3°C

Temperature (°C)	Hole Size (mm)	Reported Hole 1 Size (mm)	Reported Hole 2 Size (mm)	Up -Gain Required Hole 1 (dB)	Up -Gain Required Hole 2 (dB)
165	3mm	2.57mm	2.15 mm	1.34 dB	2.89 dB
227.3	3mm	1.51mm	1.31 mm	5.96 dB	7.20 dB

4.4.6. Front Wall Variation at Elevated Temperatures

Figure 64 displays the front wall average depth, which shows an expected trend whereby the front wall appears deeper as the velocity decreases because of the elevated temperatures. The interesting trend for the range of depths recorded between the repeat runs shows an increasing variance, showing that the repeatability decreases as the temperature increases. Mitigations for this phenomenon in process would require front wall interface tracking to remove this variation, allowing for the front wall position to be re-zeroed.

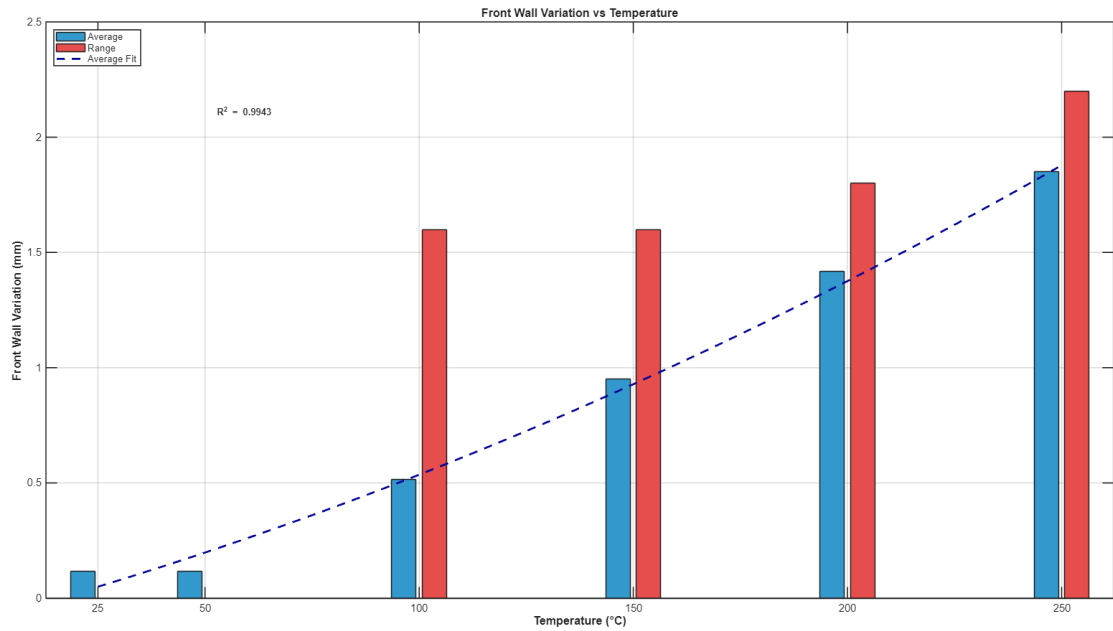


Figure 64: Monitoring of the front wall average and range at elevated temperatures

4.4.7. Material Effects

Weld cladding of corrosion-resistant alloys such as Inconel (EN82H), is known to cause non-ideal grain structures and conditions for the use of ultrasonic testing [150]. Nickel-based alloys are known to form columnar grains under welding cladding conditions, due to strong thermal gradients with intense heat near the bond line between the materials and cooler at the surfaces, resulting in elongated epitaxial grain growth perpendicular to the fusion boundary [151]. Multiple layers of cladding then cause re-heating and recrystallisation of the previous weld cladding layer to reduce dendritic segregation within the heat-affected zone. Figure 65 shows a macrograph from the EN82H weld cladding onto a steel substrate where the grain structure noticeably differs between the layers. The

Inconel cladding layer visually demonstrates the columnar grain structure generally found during the weld cladding process. The heat-affected zone formed in the unmelted base metal region shows a reworked layer with refined grains from the multiple weld passes thermal cycle. The substrate shows a typical coarse low-alloy steel grain structure. One key observation that can be noted from the macrograph is minimal dilution, typical of CMT at the fusion face due to the low heat input and fast cooling of the welding process, providing a sharp and consistent boundary between the material transitions.

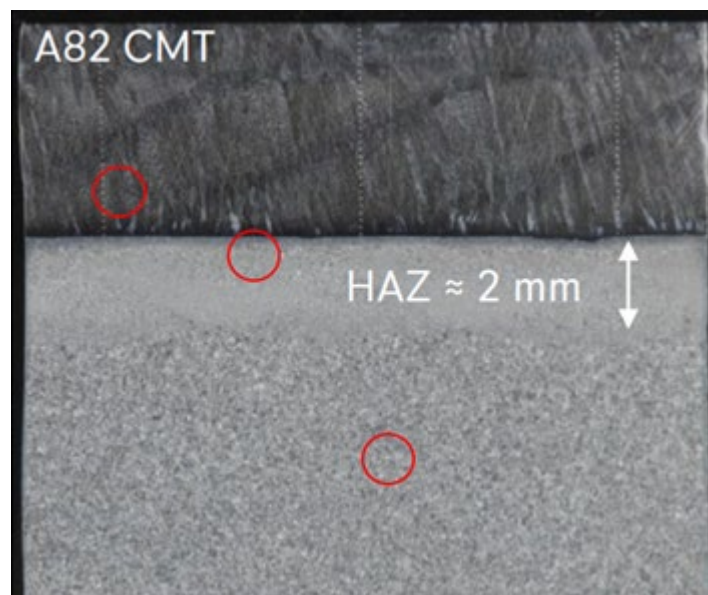


Figure 65: Macro of CMT Inconel Cladding on a steel substrate (Red circles denoting the approximate depth of the holes).

Another notable feature is that the gradients of the hole amplitude for the two holes in the Inconel clad layer both follow a similar shape when attenuation is factored, demonstrating the differing grain structure of the steel substrate line, which very clearly shows a linear gradient in hole amplitude response. A further observation that can be made from both Figure 62 and Figure 63 is a slight increase in amplitude and therefore hole size from the

inspections at room temperature up to 100°C of approximately 1 dB, as shown by the holes within the Inconel cladding.

Complex behaviours in ultrasonic wave propagation have been identified between anisotropic and isotropic grain structures and their propagation between boundaries [152]. Other observations have been noted in velocity measurements correlating to the equiaxed to columnar grain structures, with beam distortion demonstrated in longitudinal waves, resulting in an elliptical shape beam profile [153]. A combination of this beam divergence, higher residual stress between the two dissimilar metals, resulting in a change in velocity and greater coupling efficiency from the RollerProbe tyre, will have all contributed to the slight increase in amplitude response, albeit having a generally negligible effect towards the calibration compensation methodology.

4.4.8. Results – Key Findings

The heated reference block trial showed calculated values to demonstrate that the thermal expansion values of the flat bottom holes would be negligible to the overall methodology and proposed ultrasonic measurement prior to the experimental evidence and could be isolated from the results. Section 4.4.2 and 4.4.4 clearly demonstrated that the drop in amplitude with rising temperature is not a linear trend, with a slight increase from room temperature to approximately 100°C, with a steep fall, thereafter, demonstrating differing gradients based on the bulk material the ultrasonic wave had propagated through. Section 4.4.3 demonstrated the obvious potential for utilising back wall measurements to monitor and compensate for velocity in real time to aid accuracy in depth calculations, along with the potential to cope with thermal gradients. Section 4.4.5 visualised that sizing was

affected most readily by elevated temperatures, with a steep non-linear reduction in hole measured sizes compared to known physical values. With Section 4.4.6 and 4.4.7 consequently, demonstrating the effect of front wall variation in elevated inspection repeatability and the effects of dissimilar metals, respectively.

4.5. Temperature Compensation Algorithms

Through the experimental phase of this section the effects of elevated temperatures on all critical parameters of ultrasonic inspections have been identified with the goal to enable the use of a room-temperature reference scan as a baseline for in-process inspection. This approach allows in-process inspection data to be accurately interpreted and thermally compensated, precluding the need for repeated calibration scans at multiple elevated temperatures and enhancing overall measurement reliability. This section intends to provide simple compensation strategies that can be applied to a clad inspection to align the data to the known ambient temperature calibration scan.

For hole depth (Section 4.4.3), the cause of the incorrect depth is the reduced velocity at the elevated temperatures; however, for an inspector, a corrected depth of hole calculation would be of greater benefit and ease of use than a velocity compensation factor. Defining a depth correction factor per °C allows an inspector to determine the true hole defect depth either by reading the weld pre-heat thermocouples or by bounding the possible depths by taking the minimum and maximum required inter-pass temperatures, in addition to providing flexibility for multi-layer cladding weld compensations.

$$Depth_{Comp} = Depth_{Meas} - b(Temp_{Meas} - Temp_{Ref}) \quad Eq. (6)$$

Equation 6: Depth Correction factor per °C in mm

where:

- b = Depth temperature coefficient (from Figure 60, see Table 13).
- $Depth_{Comp}$ = Correction factor to minus from the inspection value.

Table 13: Depth Temperature Coefficient (mm/°C)

Hole Depth	Slope (b) (mm/°C)
6 mm	0.00777
8 mm	0.00911
13 mm	0.00799
Average	0.00829

A corrected amplitude value (Section 4.4.4) is more useful to set prior to the inspection being initiated, as the signal amplitude is optimised at source while minimising electronic noise, whereas applying post-gain increases both the noise and the reflector amplitude, potentially masking or creating false indications. Therefore, a corrected amplitude of +2 dB is recommended to be applied prior to inspection.

Hole sizing in Section 4.4.5 showed an increased detrimental link for correction of reflector size as the temperatures increased, suggesting the outer edges of the reflector presented an increased amplitude loss, therefore, under-sizing when performing a 6 dB drop measurement method.

Equation 7 expresses the additional gain (in dB) which is required to restore the ultrasonic signal to compensate for the corresponding true reflector size.

$$\text{Gain}_{\text{dB}} = 20 \cdot \log_{10} \left(\frac{\text{True Hole Size}}{\text{Reported Size}} \right) \quad \text{Eq. (7)}$$

Equation 7: Gain Compensation Correction Factor (in decibels)

where:

- True Hole Size = actual defect or calibration reflector diameter (mm)
- Reported Size = measured defect size at temperature T (mm)

From the experimental data, a linear relationship between the correction factor and temperature was obtained for each defect depth.

$$\text{CF}(T) = aT^2 + bT + c \quad \text{Eq. (8)}$$

Equation 8: Quadratic Equation for Temperature-Dependent Correction Factor in Inconel

where:

- CF = is the correction factor of true hole size divided by reported hole size.
- a = Quadratic coefficient of the curve.
- T = the inspection temperature in °C.
- b = Linear coefficient of the curve.
- c = Constant (y intercept)

Substituting

8 into Equation 7 provides a practical expression for the overall gain adjustment in dB required to compensate for temperature effects on hole sizing at a given defect depth:

$$\text{Gain}_{\text{dB}}(T) = 20 \cdot \log_{10}(aT^2 + bT + c) \quad \text{Eq. (9)}$$

Equation 9: Temperature-Dependent Gain Adjustment

Table 14: Quadratic component for each defect depth for elevated temperature compensation

Hole Depth	a (10^{-5})	b (10^{-3})	c
6 mm	3.78	-0.363	1.025
8 mm	4.67	-0.547	1.015
13 mm	3.93	-0.222	1.502
Average	3.78	-0.363	1.025

By inputting these values (see Equation 9: Temperature-Dependent Gain Adjustment

Table 14) back into Equation 9 a gain value in dB can be calculated to accurately compensate and re-size the FBH to the known cold reference scan true value. By following this method during an in-process inspection post-gain can be applied to calculate whether a defect detected breaches any acceptance criterion prior to the component leaving the weld cladding cell.

Table 15: Predicted defect sizes using the quadratic formula with error values to the measured values

Temperature (°C)	Hole 1 (mm)	Predicted 1 (mm)	Error 1 (mm)	Hole 2 (mm)	Predicted 2 (mm)	Error 2 (mm)	Hole 3 (mm)	Predicted 3 (mm)	Error 3 (mm)
25	2.95	2.89	-0.06	2.90	2.90	0	2.00	1.99	-0.01
50	3.10	3.02	-0.08	3.15	3.15	0	1.95	1.95	0
100	3.25	3.24	-0.01	2.85	2.85	0	1.85	1.85	0
150	2.80	2.80	0	2.30	2.30	0	1.50	1.50	0
200	1.80	1.80	0	1.50	1.50	0	1.00	1.00	0
250	1.10	1.10	0	1.05	1.05	0	1.05	1.05	0

Predicted sizes were calculated using the quadratic coefficients for each specific seeded defect. The errors are calculated as the difference between the predicted and measured values (see Table 15). The maximum absolute errors across the experimental temperature range (25–250 °C) are:

- Hole 1 – 0.082 mm
- Hole 2 – 0.005 mm
- Hole 3 – 0.007 mm

These results clearly show that a quadratic equation fit to define gain (dB) compensations provides an accurate reproduction of the experimental findings for use as a method within in-process inspections.

Table 16 shows the deviation of the hole at 8 mm depth in size, depth and amplitude, clearly highlighting the need for compensation factors.

Table 16: Error and compensation values for Hole 2 (3 mm diameter, 8 mm depth)

Temperature (°C)	Reported Hole Size Error (mm)	Reported Hole Depth Error (mm)	Amplitude Deviation – Up-Gain Required for Sizing (dB)
165	-0.85 mm	0.9 mm	2.89 dB
227.3	-1.69 mm	1.5 mm	7.20 dB

4.6. Experimental Verification

Experimental verification is challenging during a live welding and inspection process due to the inability to repeatedly manipulate the weld pool to create defects of known dimensions to verify the inspection methodology.

To experimentally verify the compensation strategies, a steel block was pre-drilled with two 3 mm diameter FBH's. One hole was offset 0.5 mm deeper to allow a machine skim to provide a flat surface post inspection, allowing the defects to be at the same final depth with one being under an as-clad surface and the other being under a flat surface at the same depth. By following this methodology and re-heating the plate to capture scanned data beneath the machined surface, a 6-way comparison can be made to include room temperature (machined and clad), 165 C uncompensated (machined and clad) and finally 165 C compensated (machined and clad).

The CMT welding process was followed in the same manner as the reference block, with a single layer of EN82H Inconel cladding deposited onto a steel substrate. Figure 66 demonstrates visually that the compensation strategies were very effective in making the in-process inspection more consistent between the two temperatures in both the clad and machined examples. Compensation for the clad surface vs the machined surface was taken

from work conducted previously to establish the link between varying surface profiles [154].

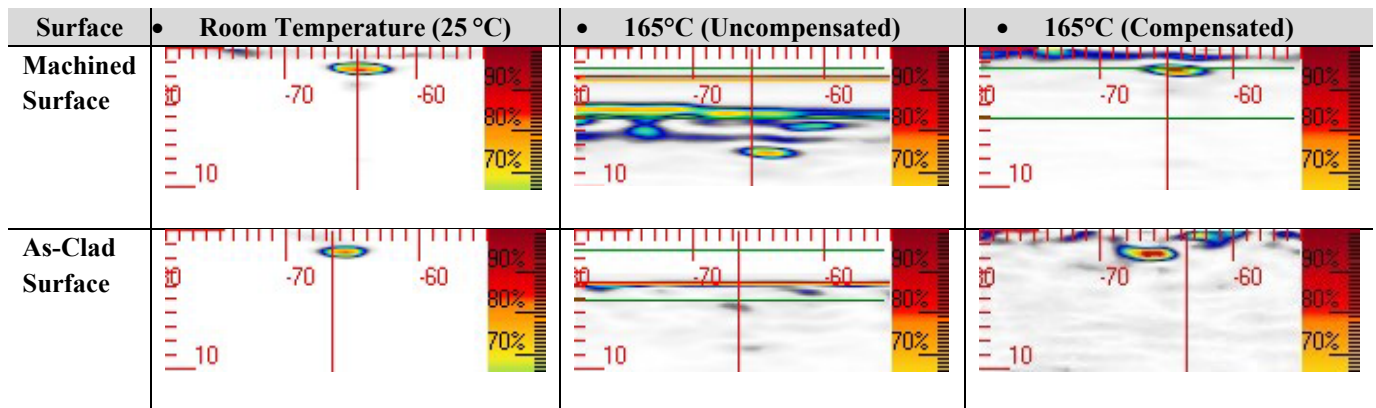


Figure 66: B Scans of machined and clad surfaces of a 3mm FBH compensated and uncompensated at both 25°C and 165°C.

The elevated temperature velocity/depth compensation effectively repositioned the reference reflectors to the appropriate depth, suggesting a front wall interface tracking method would be possible for in-process inspections to compensate in real time. The amplitude and gain sizing were also shown to be effective in visually representing the reference reflectors in both amplitude and size, as per the room temperature scans, bringing the hole amplitude within tolerance for recalibration tolerances cited in inspection specifications.

4.7. Chapter Summary

This chapter has highlighted the challenges associated with inspecting at elevated temperatures and its effect on decoupling from code compliant calibration methodologies which would be required to deploy an in-process PAUT Inspection.

A novel calibration compensation methodology has been developed and deployed for a typical CMT Inconel cladding process with a pre-heat and weld heat input of approximately 165 C to 227 C that can be readily inspected at the point of manufacture, with compensation applied to enable ultrasonic inspection for bond line defects and link the inspection output to a calibration block with code-compliant reference reflectors.

The approach developed within this chapter allows the ultrasonic inspection to be conducted during the welding process and links the pre- and post-calibration scans to the temperature range of a weld cladding process. The key advantage of the method developed is that the compensation strategies can be applied during the inspection parameter setup or retrospectively applied through post-gain and velocity adjustment.

Chapter 5

Robotic Controlled In-Process PAUT Inspection of an Industrial Internally Clad Vessel

Chapter 5 presents a case study of a robotically controlled in-series inspection of a vessel with internal cladding. The inspection is conducted in a blind trial format where the artificial reflectors were hidden from the inspectors to ensure a fair assessment of the inspection methodology was delivered. The inspections were then repeated from the opposing machined face external surface of the vessel with a code compliant PAUT inspection technique with a sample of the defects selected for confirmation through macrograph destructive testing. This approach showed a successful in-series welding inspection capable of finding structurally significant flaws at the weld bond line repeatably during the welding process.

5.1. Weld Cladding

Weld cladding for high-integrity manufacturing requires extensive justification of the structural integrity of the overall manufactured component, often by means of Inspection or NDE. Nuclear industries within the UK specifically use the TAGSI (Technical Advisory Group on Structural Integrity) [14] ‘Four Legs’ methodology, which uses NDE extensively to inform two of the key structural integrity legs to ensure ‘Quality of Build’ and ‘Failure Analysis – demonstrating tolerance to structurally significant defects’.

Traditionally, welding and non-destructive evaluation (NDE) of high-integrity joints are separate, manual, and sequential processes, reducing productivity and increasing re-work when defects are identified after subsequent manufacturing processes. Repair also increases commercial and environmental costs due to reheating requirements, while workforce shortages and safety concerns drive the need for automation. Automated in-process ultrasonic inspection integrates NDE closer to manufacture, enabling more efficient right-first-time production and overcoming access limitations of conventional ultrasonic inspection caused by obstructed inspection surfaces from features such as lifting lugs and ancillary equipment required for pre-heating (see Figure 67). In-Series NDE of cladding offers significant benefits to high integrity industries by allowing detection of discontinuities at source, reducing the burden in cost and time for welding repair processes and to increase the output of high value welding and manufacturing methods.

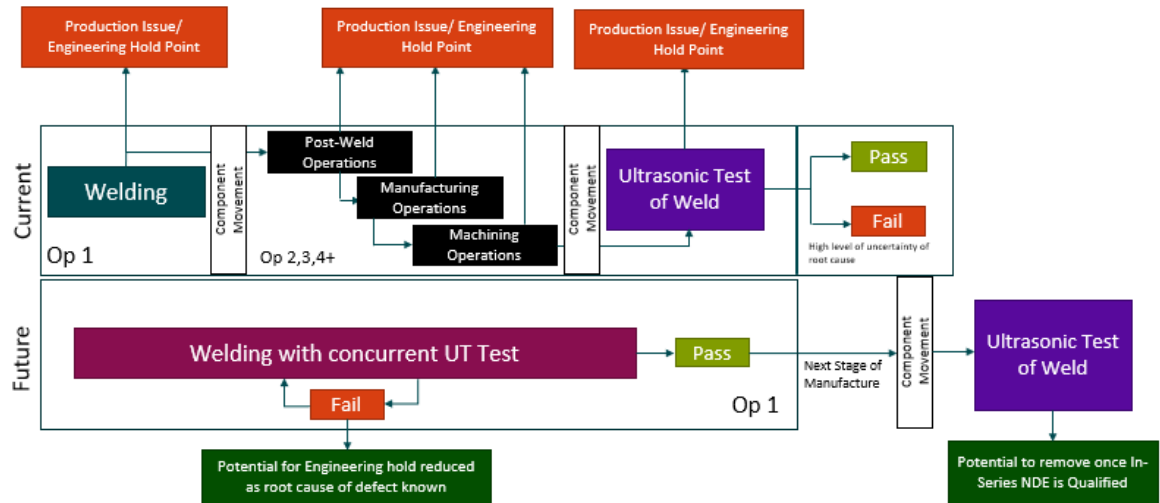


Figure 67: Current & proposed state for streamlining high-integrity welding with in-series inspection.

This chapter introduces the results of a study whereby a representative pressure vessel is inspected via the as-clad surface, directly during the weld cladding application, within the vessel for intentional artificially inserted flat bottom hole (FBH) reflectors to code compliant ISO standards, inserted from the outside diameter and in parallel unintentional indications. The results were then verified through conventional PAUT (Phased Array Ultrasonic Testing) inspection from the outside machined face of the vessel, and then specific defects verified through destructive macrograph sections, demonstrating a first of type in-series PAUT inspection of weld cladding for bond-line defects/lack of fusion.

5.2. In-Series NDE Challenges

Traditional NDE inspections have commonly been carried out far removed from the welding process due to multiple technological constraints. Ultrasonic probes rely upon the electronic excitation of piezoelectric crystals to transmit ultrasonic waves into a

component under test. However, high temperatures can cause common piezoelectric crystals to lose their ability to do this above the material's Curie point, with sustained exposure to high temperatures reducing the working life of the crystal and therefore the ultrasonic probe [28].

A major challenge in the deployment of traditional NDE inspection in-series with the welding process is the hostile environment for human inspectors to operate within. Extended exposure to elevated temperatures can be detrimental to human health, necessitating automated deployment methods. However, the removal of the human and the ability to physically judge probe pose on the PAUT probe through tactile feedback is impossible. Strategies have then had to be developed to ensure an automated deployment can compensate for the tactile pose correction effectively as a human inspector would.

Other major challenges of an in-series NDE deployment comes from the electrical interference and noise created during the welding process, and in addition, noise from motors from automated welding equipment intended to remove the human from deposition process. This interference generates significant noise across the captured ultrasonic waveforms, potentially obscuring signals from defects within the component being inspected [29, 30].

Welding induces non-uniform thermal gradients that alter ultrasonic wave velocity, causing beam skewing, attenuation, reduced signal-to-noise ratio (SNR), and potential mischaracterisation of discontinuities [21,31]. In-series NDE of as-deposited cladding further compounds these challenges, as irregular clad surfaces reduce ultrasound transmission and introduce additional beam distortion preventing accurate plotting and

characterisation of discontinuities [154]. Conventional phased array ultrasonic testing (PAUT) calibration methods are also unsuitable, since the thermal properties of the inspected component differ significantly from those of reference blocks in both bulk temperatures and gradients throughout the component [155].

5.3. Methodology

A manufacturing cell was designed to integrate fully automated robotic welding and inspection equipment together to perform weld cladding on cylindrical vessels and flat plates with an in-series PAUT inspection methodology.

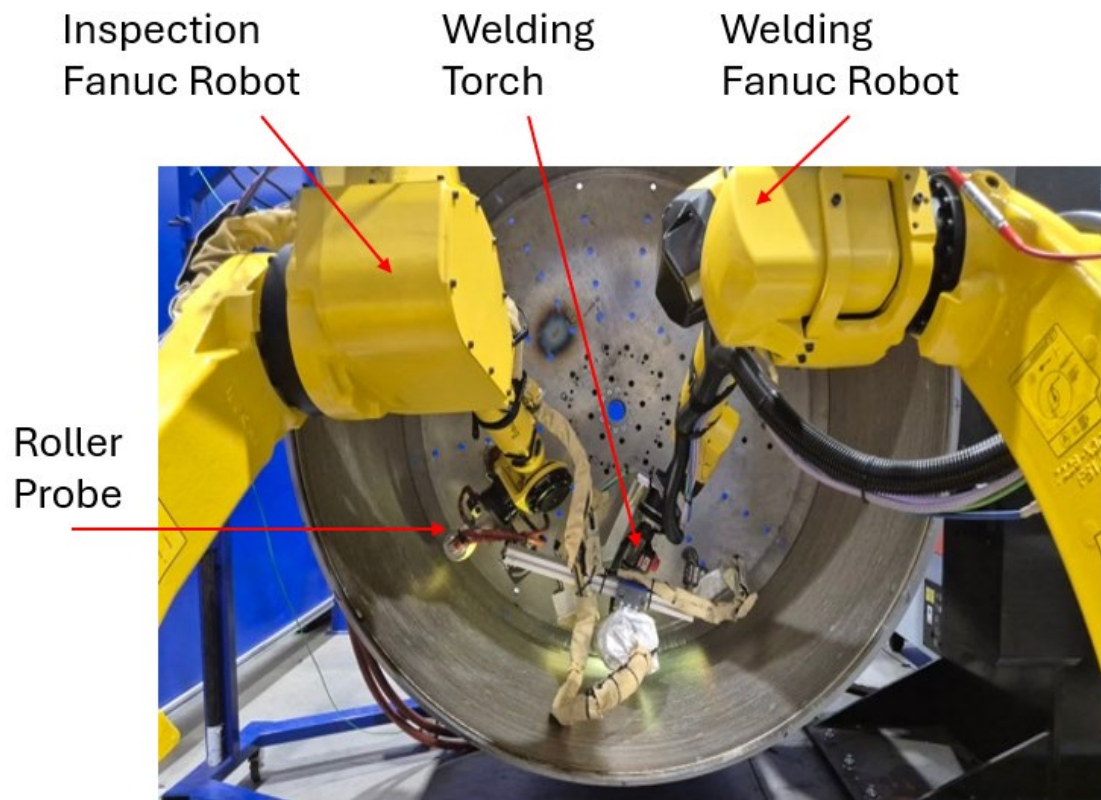


Figure 68: Robotic deployment of welding torch and PAUT RollerProbe

The weld cladding was monitored using an Xiris high dynamic range (HDR) thermal camera, enabling high contrast images of the welding arc alongside a thermal temperature map to monitor key weld zones [156]. Through a combination of the dual robotic control, thermal camera and temperature monitoring and in-series PAUT inspection through the RollerProbe, the weld cladding process can be evaluated during the deposition stage to ensure weld quality at the point of manufacture.

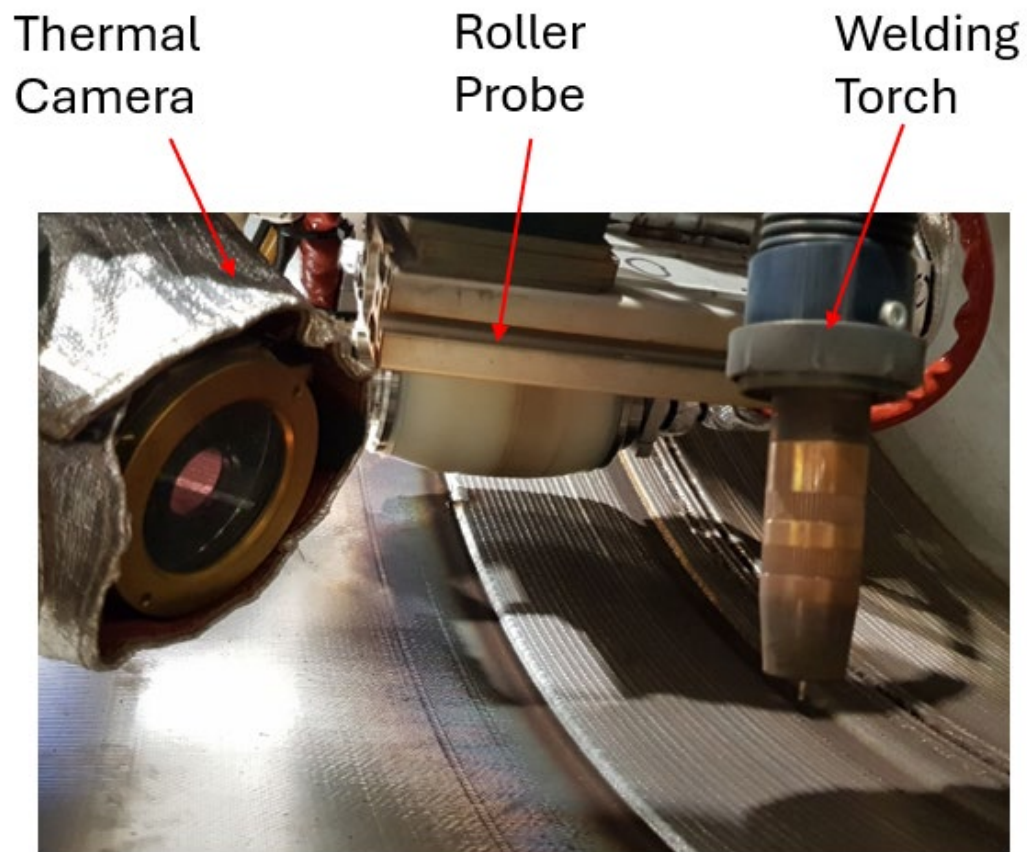


Figure 69 Weld cladding deposition with welding torch, weld camera and PAUT RollerProbe

5.3.1. Roller Probe

The RollerProbe [49] (see Figure 70) internals were optimised to increase ultrasonic sensitivity to the targeted lack-of-bond-line-fusion defect modes. Sufficient acoustic energy distribution is retained across the remainder of the cladding pass height to enable detection of other defect modes of interest within the cladding main body, whilst continuing to mitigate the near-surface dead-zone.

Utilising a TRL (Transmit Receive Longitudinal) probe methodology enables a reduction in the front-wall amplitude and corresponding dead-zone, highlighting the benefits of this probe for shallow near-surface weld cladding inspections, optimising coverage on a thin ligament weld deposition.

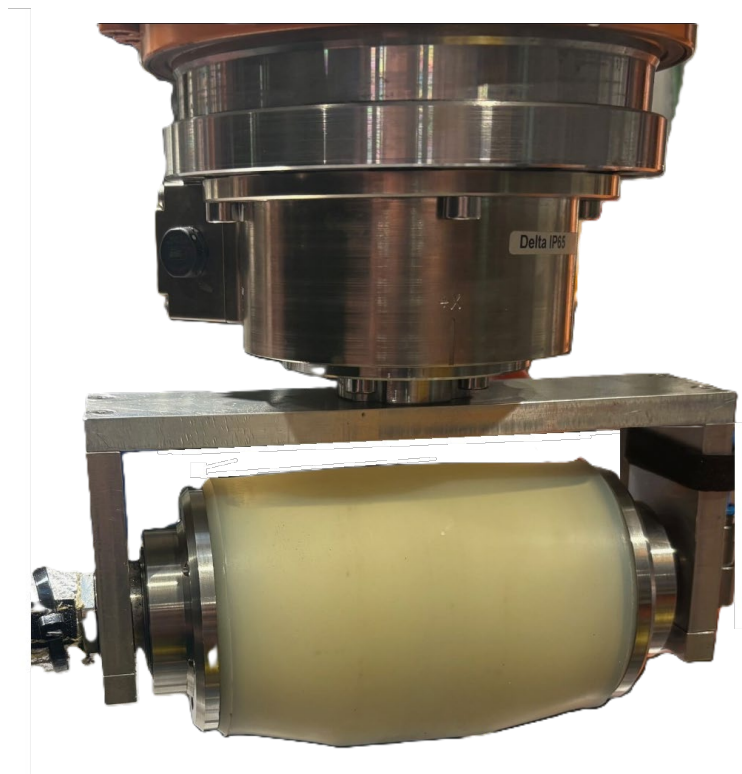


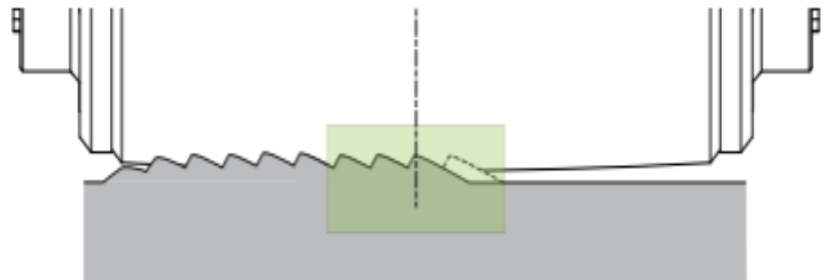
Figure 70: PAUT RollerProbe

Ultrasonic parameters are listed in Table 17 for both the probe and tyre hardware values and variable PAUT focal law settings. Additional settings are also provided to describe the robotic and automated deployment settings key to the deployment of this in-series PAUT inspection. Considerable development was required to model and refine the roof angle best suited to the TRL configuration for beam focusing through the variable cladding surface conducted on CIVA [157].

Interference suppression algorithms were applied during the welding/in-series inspection to reduce noise from the robotic deployment and from the weld process itself [158]. This is of critical importance to quality of the data the inspection outputs due to the potential for observable electrical noise.

Table 17: TRL probe ultrasonic parameters & Rollerprobe to weld scan-plan

Probe Hardware	
<i>Element Count</i>	64 + 64 (TRL)
<i>Frequency</i>	5 MHz
<i>Wave Mode</i>	Longitudinal
<i>Roof Angle</i>	16°
<i>Assembly Dimensions</i>	Array Separation 21.0 mm
	Wedge Path Length 24.0 mm
	Wedge Contact Width 52.0 mm
	Tyre Path Length 2.6 mm
<i>Propagation Velocities</i>	Wedge Velocity 2.44 mm/μs
	Tyre Velocity 0.95 mm/μs
Controller Settings	
<i>Excitation</i>	24 ns pulse @ 200 V
<i>Aperture</i>	16 elements
<i>Focal Depth</i>	5 mm
<i>Beam Angle(s)</i>	0°
<i>Filtering</i>	0.7 -> 6.0 MHz
<i>Gain</i>	74 dB
Robot & Automated Deployment Settings	
<i>Coupling Force</i>	250 N
<i>Scan Speed</i>	8.333 mm/s (matching deposition)
<i>Inspection Timing</i>	Simultaneous with deposition
<i>Coolant Flow Rate</i>	0.5 – 1.5 L/min
Scan Plan	Note: Green Box denoting area of Inspection



5.3.2. In-Series PAUT Reference Block

To provide a repeatable, benchmark for performance of the in-series PAUT system a reference block was designed specifically for the deposited weld cladding process. This was constructed using the identical weld cladding parameters to the vessel and therefore provides a prototypic reference by fully representing the materials and surface of the production parts.

Several machined features and specialised geometry, akin to standard ultrasonic calibration blocks [15], were introduced into the block, to act as controlled artificial defects which define the sensitivity and performance of the inspection. A dimensioned technical drawing for the reference block is given in Figure 71.

The reference block is divided into two sections, one where the surface remains as clad, and a second where the surface is machined flat to replicate current inspection methods. Multiple groups of features are replicated in each of these two sections, allowing comparative performance analysis between the as-clad inspection and a final inspection on a machined surface to quantify the performance and sensitivity of the inspection through the as-welded surface in comparison with a direct code compliant machined surface.

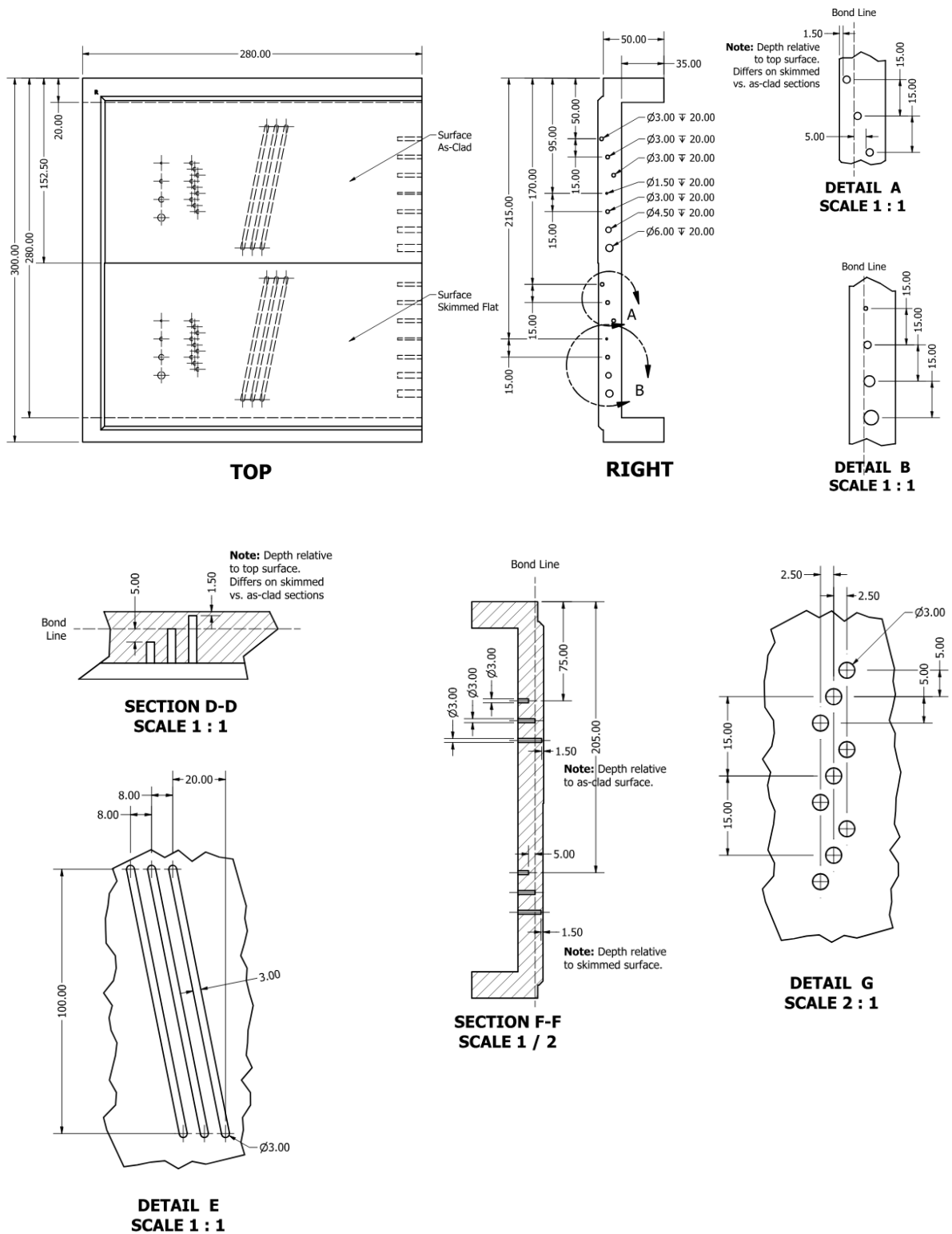


Figure 71 Design of in-series PAUT cladding reference block

The feature groups included in the block are as follows:

- **Bond-line flat bottom holes (FBH) at varying diameters:** These features enable the direct evaluation of the minimum detectable size of lack of bond-line fusion defect. Note that the hole diameters include diameters of 1.5 mm, 3.0 mm, 4.5 mm and 6.0 mm, corresponding to 0.5x to 2x the specified target defect size.
- **FBH pattern at varying depth:** As the TRL RollerProbe relies on the joint sensitivity of two arrays and is focused both electronically (in the direction across multiple cladding passes) and mechanically (along the direction of probe travel), its sensitivity profile differs from typical single phased array probe arrangements. These FBH features provide a means for direct empirical assessment of sensitivity as a function of depth. These are presented in groups of 3 holes to eliminate position beneath the cladding surface profile as a variable, selecting the maximum response for evaluation.
- **Slot pattern at varying depth:** Extending the depth-sensitivity characterisation capability, these features are designed to additionally pass under every point in the repeating cladding surface profile. This enables measurement of any variation in probe/beam skew sensitivity as a function of defect position beneath the as-clad cladding surface. Moreover, the indications will move across the full width of the B-scan frame during inspection, providing a means to confirm consistent response across array elements.
- **Side Drilled Holes (SDH) pattern varying depth & diameter:** In this case, the features emulate a different defect mode beyond the lack of bond-line fusion mode.

In providing cavities of varying size and depth beneath the surface with vertical flat faces, they may be used to examine sensitivity to lack of inter-pass fusion defects. Note that these are considered a secondary defect mode, less likely to occur in production and, in practice, are inspected using an alternative shear angle PAUT ultrasonic probe configuration.

- **Machined Surface:** The features above are all replicated beneath a section of the reference block that has been clad as normal, then subsequently had the surface skimmed flat using an end mill. The depth of the features set in relation to the surface is adjusted accordingly by the skim cut depth. This enables a direct evaluation of the effects of inspection through the as-clad surface against traditional, inspection approaches, while also aiding in the development of compensation strategies.

The block validates and confirms the equipment performance remains within specified ranges over the course of its utilisation within a manufacturing and inspection shift, with confirmation conducted at 4 hr intervals as per code-compliant inspections [142].

5.3.3. Test Vessel Design

The test vessel was selected to represent a full prototypic scale pressure vessel with a carbon-based steel substrate and a nickel-based alloy cladding commonly used to provide enhanced material capabilities to a pressure vessel surface, as described in Table 18. The

RollerProbe PAUT inspection system was then used to demonstrate the detection of representative artificial defects within the vessel during deposition of cladding material.

Table 18: Test Vessel Dimensions & Properties

Sample Properties	
Type	Cylinder
Dimensions	Nominal Outer Diameter: 1.5 m
	Wall thickness: 19.5 mm (nominal)
	Length: 1.0 m
Materials	
Base	S275 Low Carbon Steel
Cladding	Inconel (EN82H)
Welding Parameters	
Welding Mode	Cold Metal Transfer (GMAW)
Gas Mix	Ar, He, H ₂ mix
Gas Flow Rate	15-20 L/min
Linear Torch Speed	50 cm/min
Pass Pitch	5.0 mm
Preparation	Front & Rear surfaces skimmed by CNC mill. Degreasing with Isopropyl Alcohol and single-use lint-free wipe. Defect features seeded as detailed above in Figure 71.

Artificially created defects were used to assess the detection capability in dis-bonding or lack of fusion type defects between the cladding and base metal substrate, as shown in Figure 72. The design incorporates numerous 3.0 mm flat-bottom hole features in varying locations as per the requirements of BS EN ISO 17640:2018 - Non-destructive testing of welds - Ultrasonic testing: Techniques, testing levels, and assessment [15].

By locating artificial reflectors in four discrete locations around the circumference, multiple opportunities are provided to detect the discontinuities within a single pass, allowing the capability to quickly explore alternative inspection configurations or parameters should the need arise. To ensure inspection validity the welding/NDE was set in a blind trial format by which the inspector has no previous knowledge of the artificially created defects prior to the inspection in line with current PCN (Personal Certificate of NDT) inspection examinations. The precise location of these sites was, however, obscured from the inspectors by TIG welding a cap run over the drilled cavity where it is exposed to the outer diameter of the vessel and grinding flush the area to blend the cap with the surrounding material to provide a blind trial application of the inspection process.

In addition, the holes were placed at a nominal 8.0 mm pitch, causing them to appear under different regions of the clad profile, which was deposited at a 5.0 mm pitch, over the course of a single weld run. This provides the opportunity to evaluate the effect of the inter-weld pass locations on the detection of the defects using the inspection method. The start position of every other reflector group was also staggered along the cylinder axis. This ensures that each weld pass has at least 2 holes under its circumference, up to a maximum of 4 from the 12 offset holes, where the weld torch offset aligns. Accordingly, adjacent weld passes with no seeded defects are prevented, and margin is given to manufacturing tolerances, particularly useful given the size of the component versus that of available precision mills.

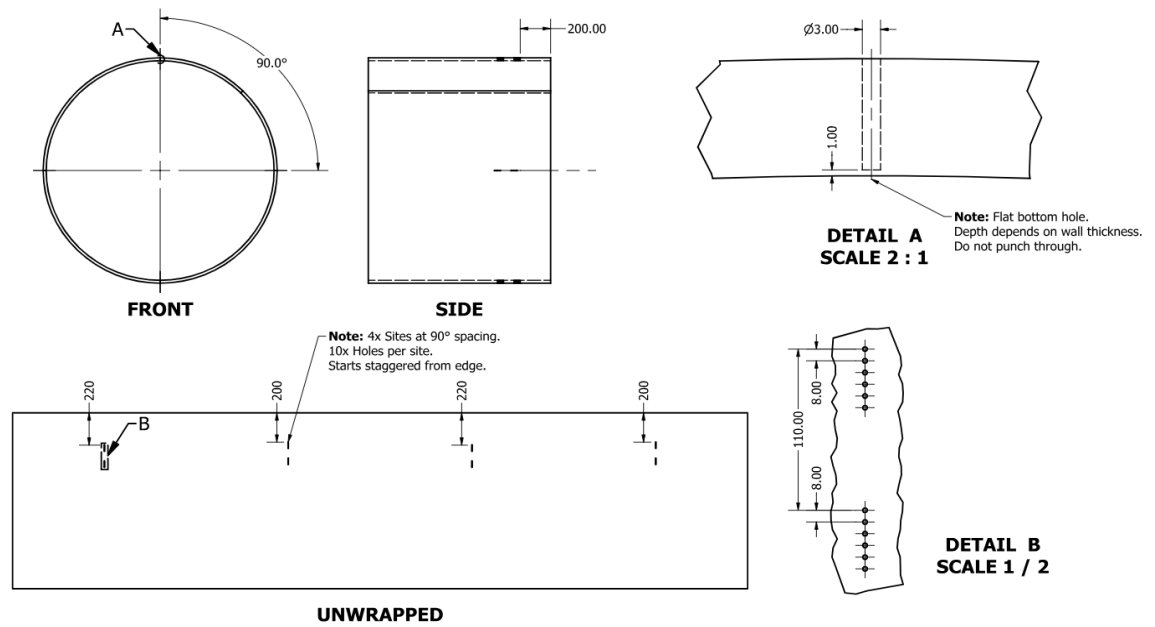


Figure 72 Design of a test vessel with flat bottom hole reflectors

Finally, the hole groups are split into two sections, placed at a pitch of 110 mm. This provides a duplicate of the above pattern spaced further along the vessel axis, intended to serve as a contingency to provide an alternative starting position or further supporting evidence for the inspection process.

5.3.4. Front Wall Interface Algorithm

One of the key challenges of inspecting an as-welded surface, not considered during the initial hardware design for the live weld inspection process (noting areas of electrical noise from initial hardware design in Figure 73 below), is that of effectively gating the varying front wall surface to make the inspector's interpretation clear and free from ambiguity. As Figure 73 shows, the front wall surface presents a challenge to gate-out effectively; with

a typical depth or time of flight linear gate showing the surface oscillating in and out of the gate through variation in clad height variation, triggering indications on the D Scan.

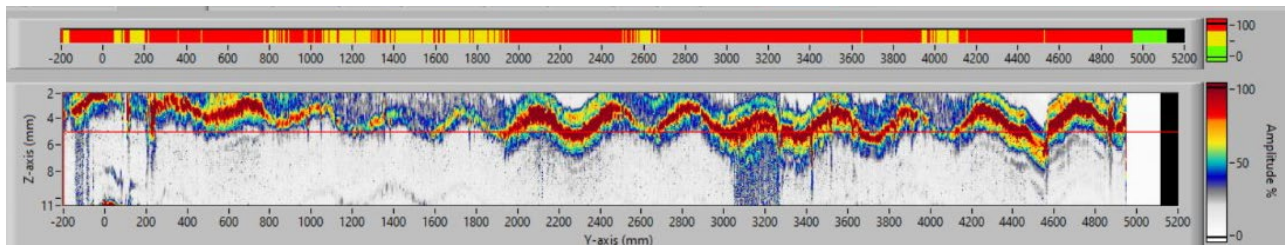


Figure 73: D Scan image without interface tracking for full cylinder weld pass

The algorithm processes unsaturated interface echoes with a detection gate and threshold by finding the maximum amplitude of the interface; whereas for saturated echoes, the first and last point of entering or leaving saturation are detected with a mid-point selected as the maximum amplitude location. Once the front wall interface is detected, the algorithm fits a polynomial fit to the detected interface points within the region of interest gated area, smoothly adjusting the front wall profile to track the weld undulations. This approach allows the C-Scan to be calculated without the extreme variations in front wall geometry triggering the gate, which could potentially obscure discontinuities, and aids the inspector in interpretation without anomalous indications.

5.4. Results & Discussion

5.4.1. Reference Block Results

The reference block was employed to validate and confirm that equipment performance remains within specified ranges over the course of its utilisation within a shift, with

confirmation conducted at 4 hr intervals as per code requirements. Images from reference scans of the relevant features of the Inconel calibration block are presented in Figure 74.

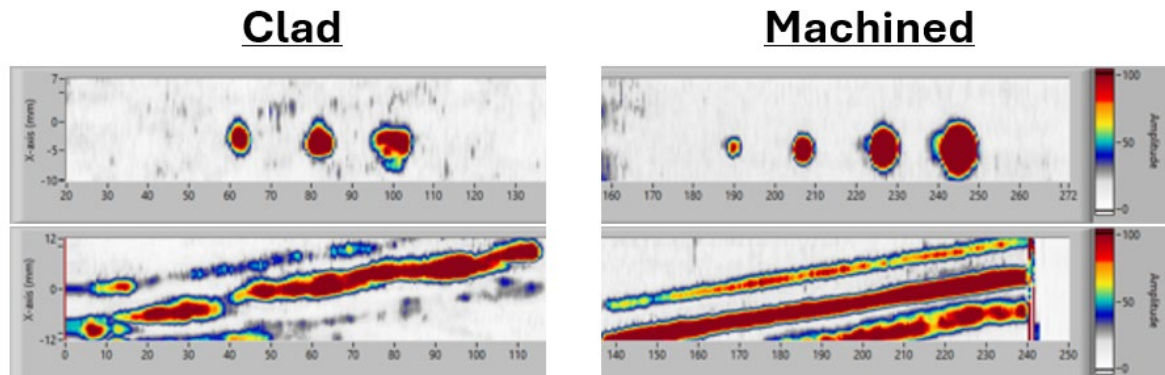


Figure 74: C Scan reference image of flat-bottom bond-line holes at diameters of 1.5 mm to 6.0 mm (Top Image), 3.0 mm wide slots at depth of 1.5 mm below the top surface, at the bond-line, and 5 mm below bond-line (Bottom Image) - As clad surface to the left, machined surface to the right on both images.

Key areas to note are that the TRL 0-degree longitudinal inspection is very obviously affected by the non-planar front surface, due to the scattering effects of the peaks and troughs of the individual weld passes deposited adjacent to each other. The 3 mm FBH and slot are both readily visible in both the areas under the as-clad welded and machined sections at the bond line depth; therefore, the sensitivity is adequate for the in-series inspection to relevant international codes [15]. It can be shown that the machined surface observed an additional hole than through the clad side inspection, a 1.5mm diameter FBH beyond the usual code and standard requirements; however, clearly visualises the impact a non-planar surface can have on defect detection sensitivity. This is also evident in the slot features with varying depths showing the uneven front wall surface effecting the slot

amplitude along its length, however noting a more consistent amplitude in slot 2 at the cladding bond line depth due to the TRL probe being designed to focus at this depth.

5.4.2. In-Series NDE – Front Wall Interface Algorithm

Results

One method to enable the C and D scans to work effectively during the in-series inspection is to apply an adaptive gating algorithm to adjust for the non-uniform weld pass front surface. The algorithm takes a two-stage approach, analysing the B scan data on a beam-by-beam basis to detect where the interface is located, and then the second stage defines how the interface is triggered for image analysis processing. As the inspection setup uses a TRL PAUT configuration, the interface echo is already reduced compared to a conventional 0-degree inspection; as a result, additional gain is required to clearly observe and detect the front wall.

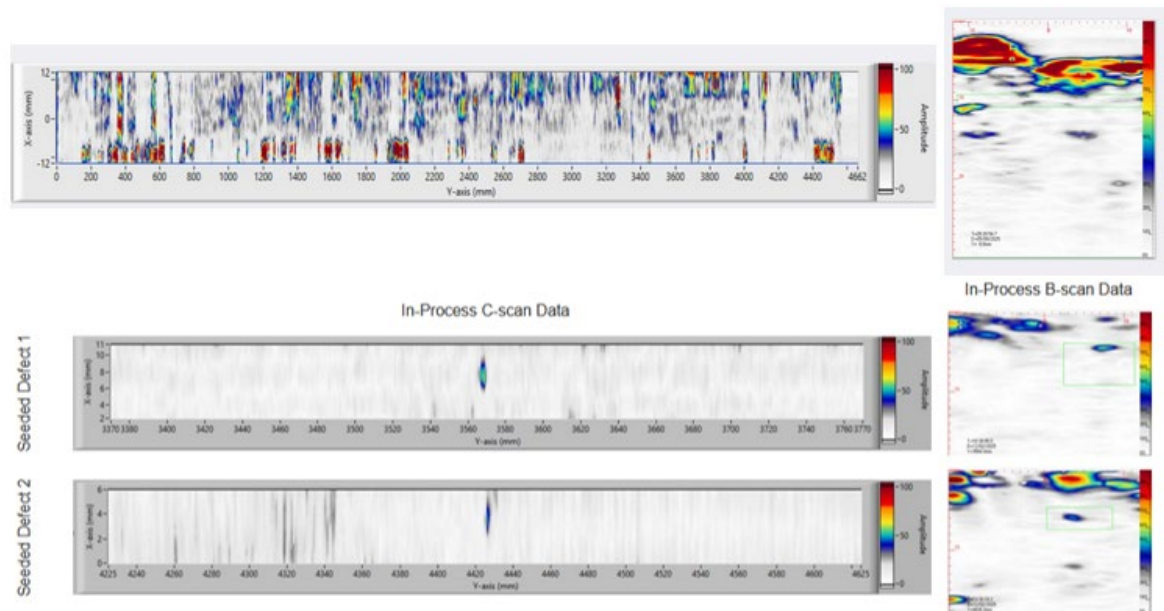


Figure 75: 3mm FBH seeded defects with a linear gate (Top), 3 mm FBH seeded defects detected and visible with C-scans and B-scans with Adaptive Gating (Bottom)

Figure 75 demonstrates both live in-series B and C scans of two 3 mm seeded FBH defects detected after the weld has passed over the defect locations. Key differences can be noted between Figure 73 and Figure 75 on the ease of spotting the defects with the aid of the interface tracking algorithm, even over a large weld area.

5.4.3. Seeded Defect Results

Detection of seeded defects with a novel inspection method must also be qualified through inspections with known capabilities to ensure the validity of the inspection methodology. In this section, this is conducted through two separate inspection methods, of which the

first is conventional PAUT post-welding from the outside machined diameter of the internally clad vessel, conducted as per

Table 19.

Table 19: Conventional PAUT parameters

Inspection Hardware	
<i>Array</i>	5 MHz – 64 elements
<i>Array Controller</i>	Peak MP6
<i>Wedge</i>	SA32-0-IHC
Controller Settings	
<i>Excitation</i>	100 ns pulse @ 200 V
<i>Aperture</i>	8 elements
<i>Focal Depth</i>	15 mm
<i>Beam Angle(s)</i>	0°
<i>Filtering</i>	0.7 -> 20.0 MHz
<i>Gain</i>	24.25 dB for 80% response
Procedure	
<i>Calibration</i>	Calibrate wedge velocity to give front-wall arrival at time of 0s Calibrate gain on 3 mm FBH at 15 mm depth for 80% screen height

Table 20 presents three of the indications detected during the in-series PAUT inspection during the welding process, against a conventional PAUT scan conducted after the welding process from the machined outer diameter location.

Key observations that can be noted are that the conventional UT also detected the holes but was conducted from the outside, once the component has cooled down to ambient temperature, the outer surface prepped as per inspection standards [15] and preheat equipment etc. has been removed. Therefore, the depth of the defect is further away from the surface the inspection is conducted from, aiding the interpretation as a greater distance

from the front wall surface is possible in comparison to during the in-series inspection over the as-clad surface as can be seen in Table 20. It can be noted that the indication amplitude is weaker in the in-series NDE due to the reduced transmission of sound through the as-clad surface noted in the images on the right-hand column of Table 20, in contrast to through the machined surface PAUT conventional inspection methodology.

Figure 76: Scan Plan to display the In-Series and Manual Coupled UT Scan Directions

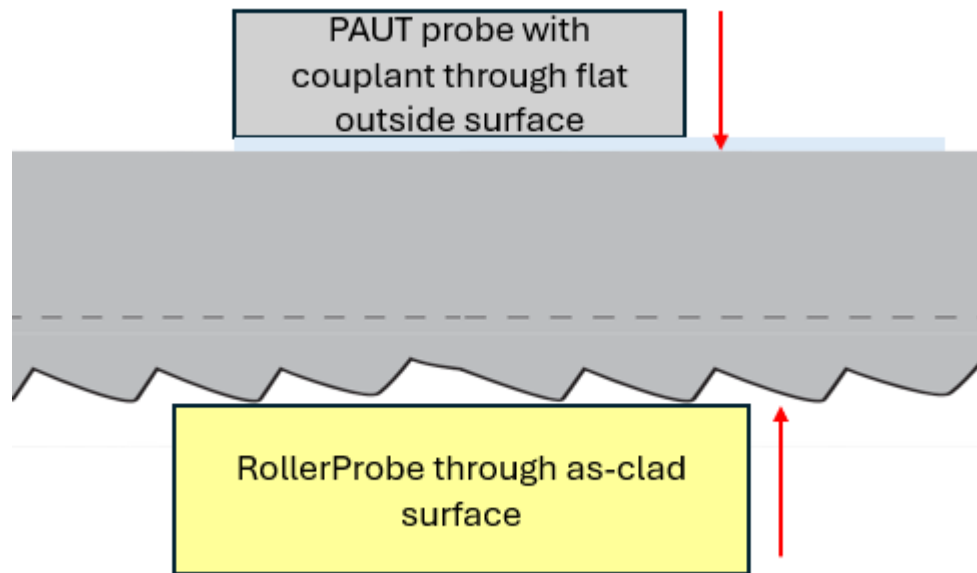
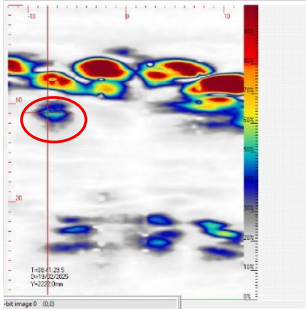
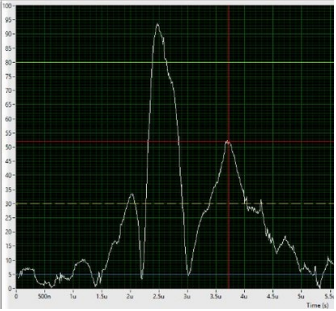
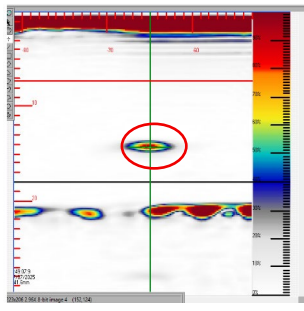
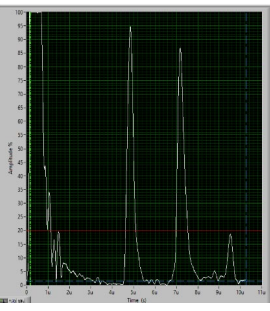
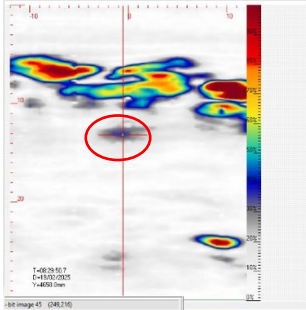
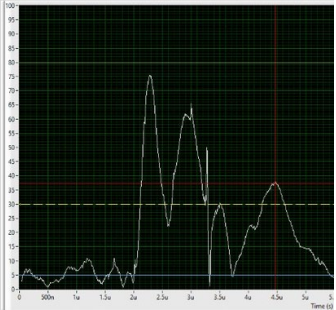
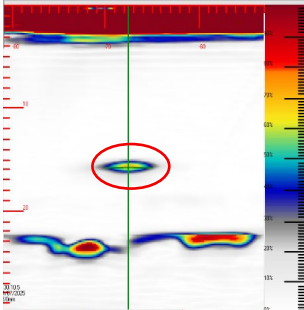
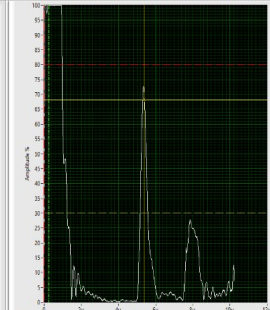
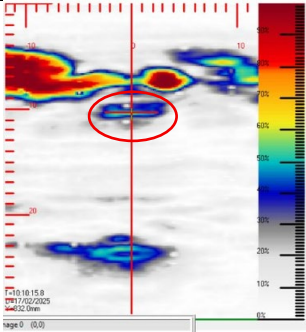
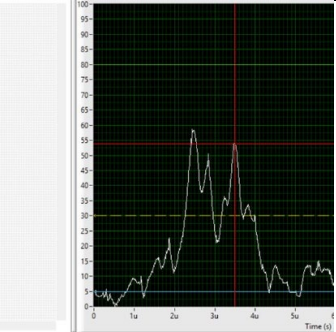
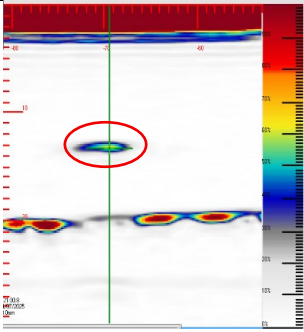
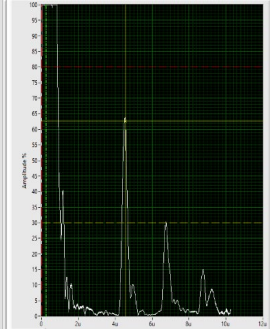


Table 20: Conventional PAUT from Machined Surface compared to In-Series RollerProbe PAUT (Red Circles Denote Indications)

Indication (Vessel 2.1) – Dimensions in mm			
In-Series RollerProbe UT		Manual Liquid Coupled UT from Back Face – Cold	
			
Indication (Vessel 2.3) – Dimensions in mm			
			
Indication (Vessel 2.7) – Dimensions in mm			
			

Non-destructive testing is extremely attractive to industrial manufacturers due to the ability to not detrimentally affect the component and allow it to enter service; however, destructive testing can be extremely useful in providing a ground truth to verify a new

non-destructive inspection method. Macrographs were prepared for these 3 indications to tie the ultrasonic results of both PAUT inspections to a physical defect through cutting the relevant section out of the vessel, etching and polishing the sample until the defect became visible and then a visual image was taken under a backlit microscope.

Table 21: Macrographs & magnified images of 3 PAUT indications

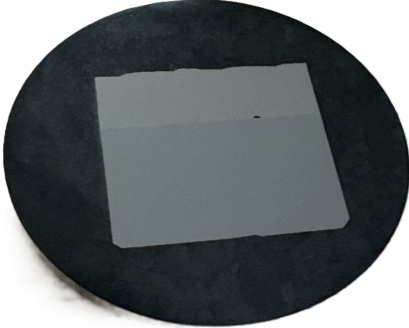
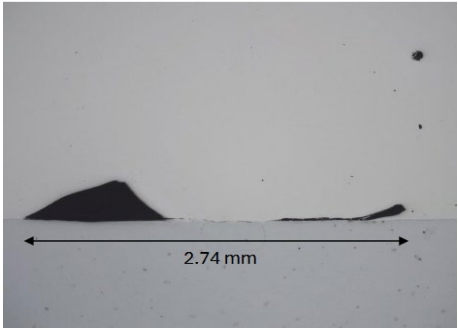
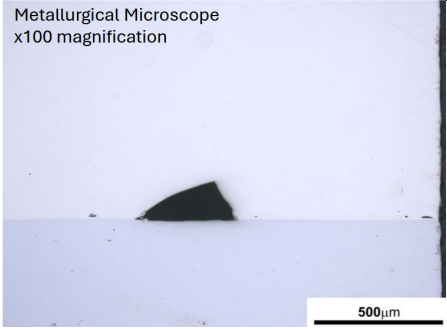
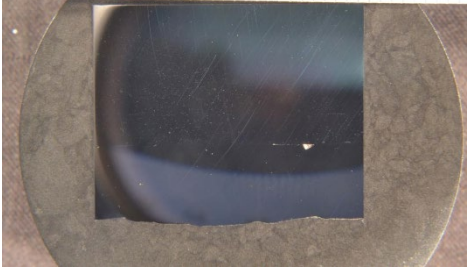
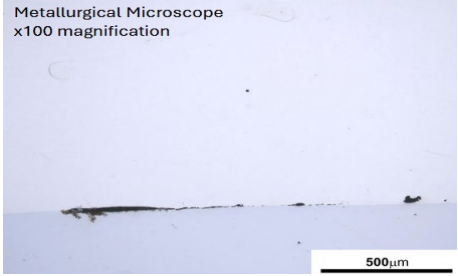
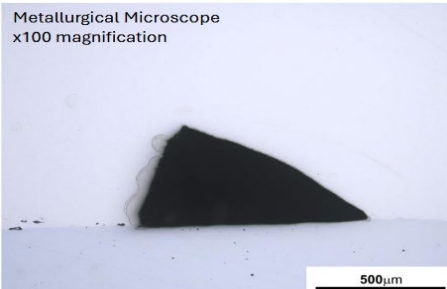
Indication (Vessel 2.1)	
	
Macro (x1 Magnification)	Metallurgical Microscope (x50 magnification)
Indication (Vessel 2.3)	
	
	Metallurgical Microscope x100 magnification
Indication (Vessel 2.7)	
	
	Metallurgical Microscope x100 magnification
	
	Metallurgical Microscope x100 magnification

Table 21 demonstrates the three defects on the bond line of the substrate to cladding weld location, validating the in-series PAUT inspection methodology through physical reasoning by means of destructive testing in addition to the code-compliant PAUT inspection depicted within Table 20.

5.5. Chapter Summary

Chapter 5 presents a case study demonstrating a successful in-series PAUT inspection of weld cladding robotically deployed matching the detection of a code compliant inspection methodology at point of manufacture. The results are verified through both traditional PAUT inspections from the opposing face of the industrial sized demonstrator vessel and further verified through the macrograph destructive analysis of multiple reflectors detected during inspection.

Chapter 6

Conclusion and Future Work

Chapter 6 summarises the main findings and work conducted in the previous chapters of this thesis and documents the potential further work that has arisen during the research conducted to continue the development of an in-series weld cladding inspection system.

6.1. Conclusion

Traditional ultrasonic inspections of welds are typically conducted after the component has completed production, downstream from the welding operation, necessitating multiple corrective inspect-repair cycles across key high-integrity manufacturing industries such as oil, gas and nuclear. This delayed feedback not only costs the industry through expensive rework processes but also misses out on the root cause information that may be used to control the welding process with greater accuracy and so provide a process with reduced defect quantity or formation.

An automated and robotically deployed in-series inspection method has been proposed as a solution to these downfalls and forms the basis of the work presented in this thesis. Enabling a truly real-time inspection of high integrity weld cladding will greatly improve manufacturing efficiency through reliable component output from a manufacturing

facility, reduced rework and repair time and costs and greater understanding of welding defect root causes feeding back into further improve the efficiency of the process.

However, a number of challenges stand in the way of an in-series weld cladding inspection. The first is the as welded surface presenting a complex geometry that both scatters and focuses the ultrasonic beam whereby a code compliant machined surface with a known surface profile is not feasible to produce by welding alone. A further key issue is in how the ultrasonic inspection is calibrated when both elevated temperatures and thermal gradients are present during the welding process and there being no link to a calibration block with reference reflectors within a temperature range allowable by international codes and standards. A further issue is presented in the variation of the front wall surface caused by multiple weld beads adjacent to each other with varying surface profiles and temperature profiles.

This thesis has sought to consider the application of an in-series weld inspection of high integrity corrosion resistant alloy cladding. The cladding is typically used in high integrity components in the nuclear and gas/oil industries which present the additional challenge of materials with different acoustic properties joined together requiring inspection.

Firstly, a multi-beam ultrasonic method was developed and tested through varying complex surface profiles with known manufactured slot and flat bottom hole reflectors. This allowed a direct comparison between a 0° inspection and the multi-beam method in demonstrating the variation in amplitude of the artificial reflectors. The developed approach has shown a typical 0° inspection through a complex surface has variability of up to 13.95 dB on this single variable alone. Combining appropriate angles to the

dominant surface profile angles along with the use of a conformable RollerProbe can reduce this to 1.37 dB. In the case of the key sample taken through all stages within this Chapter 3 (5.0 mm overlap sample) a reduction in variability from 9.42 dB to 1.37 dB was achieved. The approach developed allowed the ultrasonic inspection to be conducted during the welding process and negate the requirement for surface machining prior to inspection. The key advantage of the method developed is that the focal laws and ultrasound transmission are agnostic to the weld bead placement and can be used as a screening tool without complex ray-tracing computations.

Work was then undertaken to understand how to compensate for elevated temperatures during the in-series inspections as code-compliant ultrasonic and phased array ultrasonic inspections require a calibration pre- and post-inspection that must be conducted within a temperature range of 14-15°C if working to ASME or British standards, respectively. Calibration blocks with precision manufactured flat bottom holes at varying depths in the required inspection volume necessary to detect weld cladding defects were heated to a range of temperatures to define compensation algorithms for material velocity, reflector amplitude, position and sizing.

The approach developed within Chapter 4 allowed the ultrasonic inspection to be conducted during the welding process and links the pre- and post-calibration scans to the temperature range of a weld cladding process. The key advantage of the method developed is that the compensation strategies can be applied during the inspection parameter setup or retrospectively applied through post-gain and velocity adjustment.

The developed approach has shown that a typical CMT Inconel cladding process with a pre-heat and weld heat input of approximately 165 C to 227 C can be readily inspected at the point of manufacture, with compensation applied to enable ultrasonic inspection for bond line defects and link the inspection output to a calibration block with code-compliant reference reflectors.

The culmination of these methodologies was demonstrated through the ability to detect seeded defects in a vessel during the undertaking of weld cladding at elevated temperatures in a blind trial condition. A novel method of deploying a RollerProbe capable of withstanding the elevated welding temperatures was employed robotically to the internal as-clad surface of the vessel at the point of manufacture.

Advanced algorithms were employed to dynamically track the varying front wall surface of the weld cladding as deposited to allow for effective gating of the weld volume in pursuit of conventional B and C scan views that are easily interpretable without prior knowledge of the inspection setup.

The vessel was then tested with a conventional PAUT set-up from the machined outer face of the component to substantiate that the 3mm FBH defects detected were valid, with a selection of these chosen for destructive testing by means of macrograph, to qualify the inspection methodology as capable and feasible.

6.2. Future Work

In order to further progress the work outlined in this thesis, future work should be focused on the development of a fully automated inspection system that enables the real-time measurement of complex surface profiles and temperature ultrasonically. To an extent this work is underway, however a key number of challenges must still be addressed to realise this approach.

The future work will be separated into three distinct sections of surface profile measurement, additional calibration challenges for extended temperature ranges and shear wave inspections and further advancement of the in-series PAUT method for multiple clad layers and deployment of the multi-sweep method in real time.

6.2.1. Complex Surface Profiles

The ultrasound transmission through a surface is directly related to the surface profile of the inspection surface and it's angle relative to the ultrasonic beam angles. Therefore, future work in developing the in-process inspection approach for complex surface profiles will focus on the measurement of the surface profile ultrasonically or by an optical non-contact measurement, so it could be adapted online to different welding parameters live, rather than on a weld qualification and surface profile mechanical offline measurement-based approach. Combining the current compound angle inspection approach with a surface mapping algorithm and/or a laser scanner surface measurement would enhance the process adaptability to various welding processes and geometries.

Future investigation on deriving a link between the slot type defect and flat bottom holes in any location under a weld bead, although challenging, would allow the in-process inspection process to develop a calibration methodology in lieu of the current code case NDE. This future work would resolve the issue where international standards require machined surfaces on calibration blocks. The key challenge in this additional work is to ensure this approach is adaptable to any position under a 3-Dimensional varying surface, ensuring inspection sensitivity in any region after transmission through the varied front wall geometry.

Additional work would also benefit attempts to reduce the sharp valley features present during the CMT welding process to better optimise the surface for in-process ultrasonic inspections. Further work is also required to better filter the ultrasound response to more accurately size the known reflectors.

6.2.2. Calibration Methodology

The obvious step in improving elevated temperature calibrations is in developing a method of continually measuring the temperature and compensating in real-time. Key observations from the results in Chapter 4 show that past 220 C, the variation of the amplitude increases significantly. Further work should be taken to understand the cause of this variation, which would allow hotter welding processes, such as GTAW and/or the RollerProbe to be positioned closer to the welding torch to be considered.

Another key finding from the experimental data is that depth is very obviously a definitive factor shown by the variance in amplitude in Hole 3 (13 mm) as a byproduct of the greater

attenuation, combined with the elevated temperatures, meaning a considerable amount of additional gain is required to perform a meaningful inspection. The increased depth and attenuation provide greater variation in amplitude response, which further work would look to control in pursuit of a calibration methodology for thick-section welds, such as GTAW narrow gap welding processes.

This study could also be repeated to define calibration methodologies for shear wave inspections, quantifying how different angled beams are affected by the elevated temperatures, providing a code-compliant inspection methodology for inspecting with both longitudinal and shear wave modes. Further work could also be conducted to assess this methodology against other corrosion-resistant cladding alloys, such as stainless steel and to define a method to better define the two materials separately during the inspection.

Additional further work could investigate if a front wall or back wall interface tracking method could be used to define the component temperature at the point of inspection with enough accuracy to compensate for thermal effects in-process during the welding. This additional work would also allow the ability to monitor and compensate for thermal gradients in real time to further the accuracy of the inspection methodology.

6.2.3. Robotic Deployment of In-Series NDE in Real Time

The fully automated deployment of an inspection method during the welding process will unlock a new level of manufacturing control not seen previously. Future work for the advancement of the in-series PAUT inspection method shall include multiple

developments, which include quantifying the sensitivity of the inspection to different-sized FBH indications rather than the code-compliant 3 mm baseline value.

Additional work needs to be completed to investigate the sensitivity of the TRL inspection set-up to defects at different depths, potentially allowing inspection of multiple cladding layers simultaneously. This would then allow previously solidified weld passes and their heat-affected zones to be inspected for other defect mechanisms, such as hydrogen or underclad cracking. Conversely, fully defining the near zone resolution would also quantify the depth of the weld cladding that can be inspected for internal defects away from the bond line region, supporting additional verification of the cladding deposition quality.

One of the larger pieces of future work is to embed the multi-sweep ultrasonic method [154] into the in-series inspection method to reduce the variation seen when firing ultrasonic beams through the as-clad geometry and to better align the method to the conventional PAUT from the machined face of the vessel.

Other future work that would enhance the ability to deploy in-series inspection more widely would be to develop inspection set-ups for other geometries, such as vessel nozzles, dished ends and nodes, along with validating the method is capable with various other cladding materials and welding methods.

6.3. Final Summary

The work demonstrated in fulfilment of this Engineering Doctorate has shown developments in the in-series or real-time inspection of high integrity weld cladding and

developed compensation methodologies to overcome some of the key issues in its deployment. A new method of ultrasonic inspection has been developed by firing multiple beam angles through a complex surface and merging the beams back together in a 'multi-sweep' approach. Furthermore, calibration compensation algorithms have been developed for PAUT inspections at elevated temperatures to link room temperature reference block scans to compensate for temperature effects on amplitude, position and reflector sizing. Further work is underway in developing a fully automated robotic deployment of the technology in a welding development centre in pursuit of this being used during high integrity manufacturing.

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