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# IN-PROCESS ULTRASONIC INSPECTION OF THIN MILD STEEL PLATE GMAW BUTT WELDS USING NON-CONTACT GUIDED WAVES

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## ABSTRACT

*Welding plays an important role in our modern world, with safety critical welds of thin sheet metals being widely used in airplane fuselages, boilers and nuclear cannisters among others. A potential failure in such welds could prove to be catastrophic, hence the need for thorough inspection and testing. With the ever-increasing automation of welding operations, the manually deployed Non-destructive Evaluation (NDE) has become a major bottleneck in the supply chain. This paper presents a weld inspection approach deployed at the point of manufacture using air-coupled ultrasonic transducers and guided Lamb waves. 3mm thick mild steel plates are butt welded together using Gas Metal Arc Welding (GMAW) while a continuous inspection is performed on a section of the weld seam. Trials with varying levels of welding power and amplitude sizing of the received Lamb waves have revealed a correlation between signal amplitude and the penetration and quality of the welded joints. Advantages of the outlined method include higher production rates, reduced levels of scrap and higher production quality in regards to thin metal sheet welded components.*

Keywords: in-process inspection, welding, air-coupled ultrasound, Lamb wave, guided wave

## 1. INTRODUCTION

Welding is an important part of our modern world, being employed in numerous high-value manufacture industries. Many of the welded components serve a structural and safety role and hence their health and integrity is paramount. Non-destructive evaluation (NDE) in the form of Ultrasonic Testing (UT) allows for such welds to be tested, without the need of cutting or damaging them, and is for that reason widely utilised in practice. Safety critical welds in thin sheet metals are used in airplane fuselages, boilers, pipework and nuclear cannisters need to be thoroughly tested to ensure their safety and integrity, as a potential failure of these could be catastrophic.

In the dawn of Industry 4.0, sensor enabled robotic applications offer commercial and technical advantages in terms of quality and production efficiency of final product. With many high-value welding operations automated through the use of articulated robots, NDE has become a major bottleneck in the production process, as it is traditionally manually deployed post manufacture. Therefore, inspection at the point of manufacture, also known as in-process or on-line inspection, is sought after and brings forward many advantages over manual deployment such as, higher production rates, lower quantities of scrap and higher overall quality. The opportunity also exists to detect and repair weld flaws in-process as they develop using advanced imaging and fast low-latency control .

In [1] hyperspectral cameras were used during the welding process to identify welding current variations, protection gas shortages and changes in torch offset, however the developed system does not inspect the deposited weld. [2] and [3] show how passive and active imaging respectively can be applied to monitor the weld pool and predict the weld bead geometry, but as they use visual sensors only surface flaws could be detected. In [4] authors outline a system for inspecting partially filled welds using Electromagnetic Acoustic Transducers (EMATs) using surface waves. Although implementing a non-contact UT method this was only demonstrated to work off-line after the welding passes were completed.

Conventional UT requires that the transducer and material under test are in direct contact, with a thin layer of liquid couplant between the two facilitating the transmission of sound waves. This is fit for inspection of as-built components, however introducing such liquid compounds to a workpiece during welding could produce many flaws like porosity, lack of fusion and slag inclusion among others. Therefore an NDE approach that requires no couplant would be preferable for in-process inspection. Another key challenge introduced by the welding process are the extremely high temperatures (around 1500°C) that are required to melt and fuse the metals together. Traditional commercial contact transducers typically can only resist up to around 200°C for short periods of time. Furthermore, large amounts of wideband electromagnetic noise is broadcast from the welding machine during the welding process, so necessary filtering and signal processing needs to be employed to ensure an adequate signal to noise ratio (SNR) for defect detection.

Given the outlined challenges of in-process weld inspection, non-contact ultrasonic testing proves to be favourable. Laser Ultrasonic (LU) systems generate soundwaves through the impact of photons on the test surface, but are very expensive and cumbersome. Non-contact gas-coupled UT on the other hand is rather inexpensive to implement, using the air as the coupling medium between the transducer and test piece to transmit the sound waves. There is of course a distinct disadvantage to such a concept, as due to the acoustic impedance mismatch, air is not efficient as liquid couplant, resulting in a significant reduction in signal amplitude [5].

Lamb waves are guided ultrasonic plate waves which propagate through solids and have been used to inspect composites since the 1980s. Such waves are made up of longitudinal and transverse waves and can be induced through air-coupled transducers. Lamb waves can be used to detect discontinuities and flaws inside the material using amplitude, phase velocity and group velocity measurement [6].

This paper presents a novel in-process inspection approach for testing thin-plate (3 mm) mild steel Gas Metal Arc Welding (GMAW) butt welds using non-contact ultrasonic transducers. The developed method is suitable for other metals such as Stainless Steel and Aluminium and can be applied to different welding processes such as Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW).

## 2. MATERIALS AND METHODS

### 2.1 Experimental Set-up

A JÄCKLE ProPULS 400 power source and wire feeder unit and the GMAW process are used to butt weld two 3 mm thick S275 Steel plates. Automation of the welding process is provided through a KUKA KR5 Arc HW 6 Degree Of Freedom robotic manipulator, externally controlled in real-time using the Robotic Sensor Interface (RSI). Two non-contact air-coupled ultrasonic transducers with a 25mm element size and 520kHz centre frequency are positioned laterally on both sides of the weld interface in a pitch catch arrangement, as shown in Figure 1. The transducers are excited with a 200V 520kHz 5 Cycle tone burst and the received signal is hardware amplified (> 60 dB) through a frequency matched Low Noise Amplifier and filtered prior to being digitised by a PEAK LTPA ultrasonic controller. The full system is controlled and data captured by a National Instruments cRIO 9038 real-time embedded controller, which is programmed in the LabVIEW environment. Relevant welding parameters are logged, along with the transmit and receive signals which are encoded by the coordinates of the manipulator-held welding torch.

### 2.2 Method

A zeroth order asymmetric guided Lamb wave (A0) with a travel direction perpendicular to the weld interface is excited in one plate. This wave propagates to the weld interface, through any subsequent weld joint and received by the positionally aligned receiving transducer. The nature of the ultrasonic wave is such that reaching a flaw in the weld would result in reflection and scattering, lowering the amplitude of the received signal. Furthermore, if no weld is present between the two plates, the guided wave would not propagate across to the receiver. Hence, by monitoring the amplitude of the received ultrasonic waves it was found possible to corelate the level of weld penetration in the thin-walled joint as depicted in Figure 2.

Hardware and software bandpass filtering around the transducer's centre frequency was employed to remove the erroneous electromagnetic noise generated by the welding system. Envelope and peak detection was used to locate and size the received Lamb wave peaks.

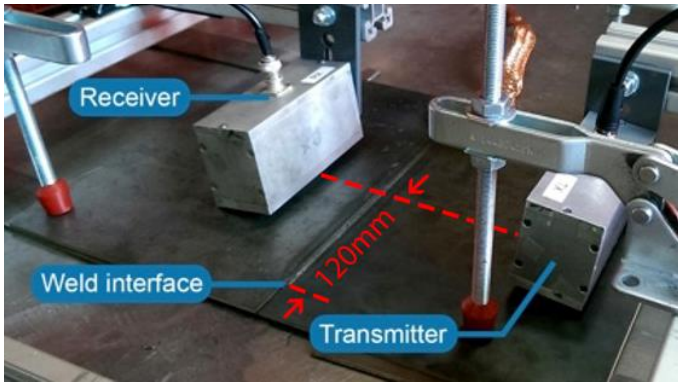

**FIGURE 1:** EXPERIMENTAL SETUP; TRANSMIT RECEIVE NON-CONTACT ULTRASONIC LAMB WAVE INPSECTION

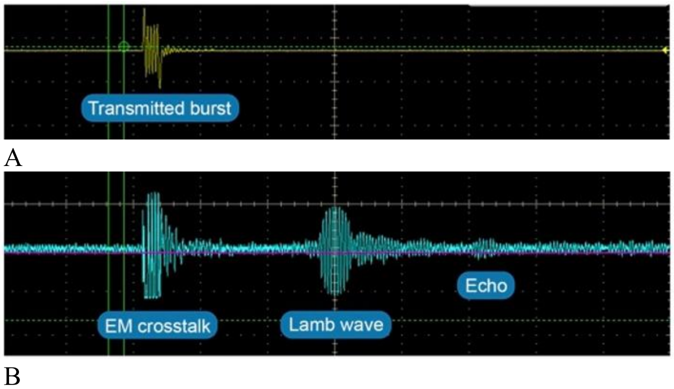

**FIGURE 2:** A- TRANSMITTED ULTRASONIC BURST, B- RECEIVED SIGNAL SHOWING, EM CROSSTALK, LAMB WAVE AND GEOMETRY ECHOS

A study corelating reduced arc power, and hence reduced weld penetration with received lamb wave amplitude was undertaken. As the transducers were statically positioned, relative to a moving GMAW torch head, arc power was decreased in the active inspection region between the aligned transmit and receive transducers to reduce weld penetration and allow positionally controllable studies. The transducers were placed at a distance of 120mm away from the weld start, meaning that no waves could propagate to the receiver before the welding torch reached the 120mm position along the weld.

## 3. RESULTS AND DISCUSSION

The system was configured for full penetration of the 3mm plates with 150 A of current, resultant Lamb waves were detected across the welded joint and utilised as the base reference. Figure 3 shows the effect of three varying levels of arc power reduction on the welding bead profile and level of penetration across and area of width 100 mm directly in-front of the transducers.

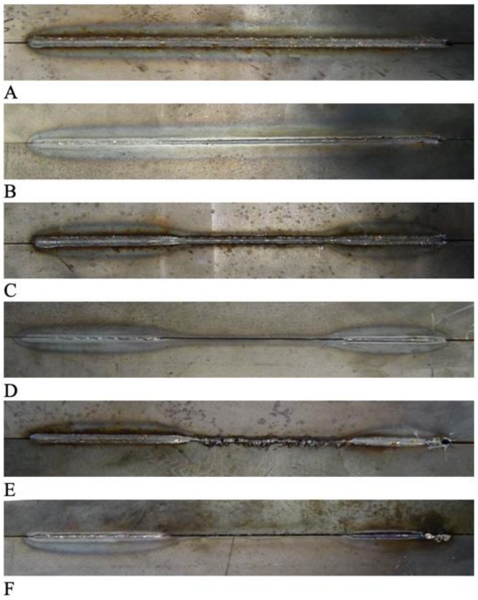

**FIGURE 3:** WELD PROFILES; A- 100% WELDING POWER TOP FACE, B- 100% WELDING POWER BOTTOM FACE, C- 50% WELDING POWER TOP FACE, D- 50% WELDING POWER BOTTOM FACE, E- 30% WELDING POWER TOP FACE, F- 30% WELDING POWER BOTTOM FACE

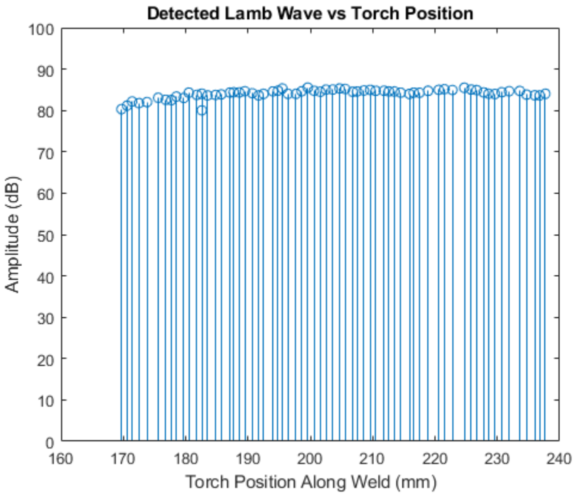

**FIGURE 4:** DETECTED LAMB WAVES ENCODED WITH WELDING TORCH POSITION

Lamb waves were detected when the welding torch was approximately 170mm along the seam, with the amplitude of the received waves increasing up to the 200mm mark. It is concluded that this increase in amplitude highlights and is due to the solidification of the weld pool, as Lamb waves cannot propagate through the liquid weld pool.

Furthermore, the 170mm mark, 20 mm across the width of the transducer, was found to be the point where the received signal rises sufficiently above the ambient background noise level to allow stable detection.

Ten subsequent studies with varied reduced arc power highlighted that the Lamb wave amplitude is non-linearly correlated to the arc power, and hence weld penetration and quality with amplitude reductions of approximately 25% with 50% reduction in arc power.

## 4. CONCLUSION

In-process ultrasonic inspection of thin-plate steel welds has been successfully demonstrated using non-contact air-coupled transducers. Trials with varying levels of arc power input have highlighted that received A0 Lamb wave amplitudes were directly correlated to the arc power, and hence weld penetration and overall weld quality.

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