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Towards Real-Time Quantitative Monitoring and Control of Weld Pool Dimensions using Phased Array Ultrasonics

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ABSTRACT

While ultrasonic NDT of welded joints is well understood and commercially undertaken at the end of the fabrication timeline, significant commercial benefits can be realised through the adoption of novel in-process inspection and monitoring techniques. This paper shows the use of phased array ultrasonics to monitor and analyse the molten weld pool live during weld deposition. The received ultrasonic signals are shown to contain information related to key physical transitions occurring within the welding process, namely the melting and solidification of the weldment. This preliminary work unlocks the potential for real-time monitoring and control of the welding process. The information stored within the ultrasonic signals can be directly related to quantitative information about the welding process providing means for anticipation of defect occurrence and preventative control.

Keywords: Weld Pool Monitoring, Phased Array Ultrasonics, In-Process, Welding, Non-Destructive Testing

INTRODUCTION

Many industrial sectors, such as energy and defence, employ high-integrity welding processes for the manufacture of high-value, safety-critical components. Often, these welded components are composed of thick sections which necessitate the use of multi-pass welding schedules. Generally, the Non-Destructive Testing (NDT) of these components is performed at the end of the manufacturing process and once a specified time period has lapsed in which delayed defects may have formed to conform with international standards [1,2]. In recent times, there have been increasing economic and industrial drivers to reduce manufacturing costs and the development and deployment of novel in-process inspection and monitoring systems is one way in which the NDT sector can support the achievement of this. In-process inspection makes it possible to detect defect formation at the earliest possible point, enabling quicker and more cost-effective repair. Furthermore, data gathered through in-process monitoring can be used to inform control algorithms to optimise weld deposition and reduce the overall defect formation rate.

Ultrasonic monitoring of Resistive Spot Welding (RSW) has previously been deployed within commercial spot welding equipment successfully [3,4]. Air-coupled ultrasonics has been trialled for the in-situ screening of thin section butt welds through the use of guided Lamb waves [5]. Traditional single-element contact ultrasonic inspection has been investigated for real-time monitoring of root pass deposition [6]. The angled beam pitch-catch using longitudinal waves was shown to be effective in monitoring and characterising the molten weld pool whilst also providing reasonable indications of defects as they are formed through changes to the received signal. However, single-element probes have significant limitations due to their fixed physical characteristics, such as natural focus and beam spread, which constrain their operation. This is especially problematic when considering the monitoring of higher passes within a multi-pass weld.

In the preliminary studies reported here, phased array ultrasonic testing is deployed to monitor the formation of a molten weld pool in real-time. Through analysis of the signal responses, it has been determined that sufficient information can be extracted to isolate the molten weld pool and monitor any changes occurring. It is also reasoned that the information held within the ultrasonic signals is of sufficient quality to inform process control algorithms for future deployment systems.

EXPERIMENTAL PROCEDURE

Figure 1a shows the experimental hardware used. A robotically deployed Gas Tungsten Arc Welding (GTAW) process was used to generate a molten weld pool at the root of a common weld prep geometry, shown in Figure 1b. The ultrasonic setup was designed to provide focussed through transmission longitudinal ultrasonic waves through the root of the weld in a pitch-catch arrangement as shown in Figure 1c. As the probes are in contact with the surface, high-temperature wedges were used to protect the ultrasonic probes and to enable inspection up to 150 °C. High-temperature liquid coupling was used between the wedges and the surface to provide consistent and even coupling throughout.

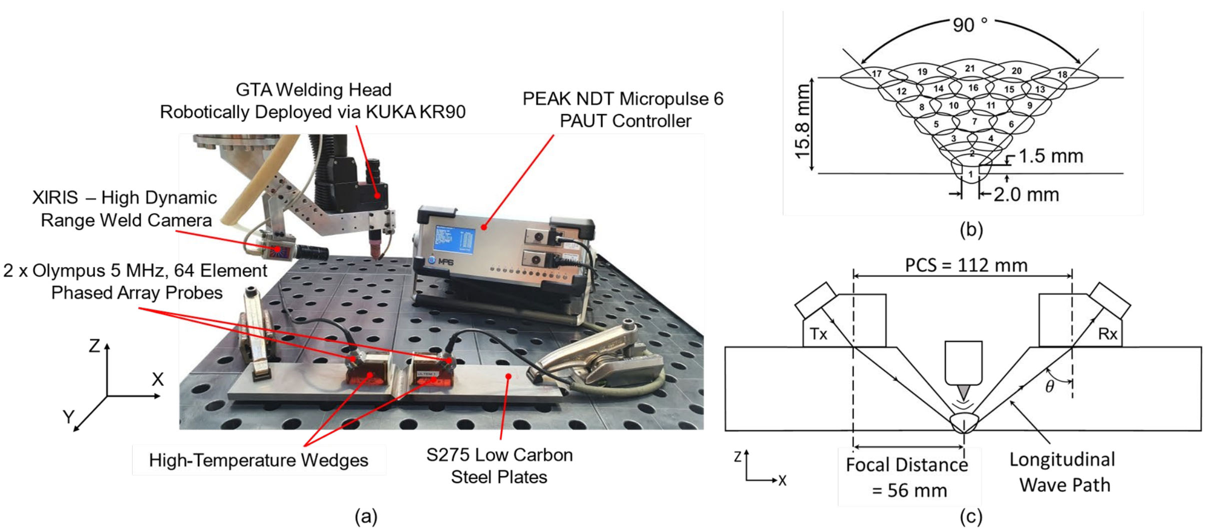

Figure 1: (a) Experimental hardware set-up, (b) weld preparation geometry showing individual weld passes indicating welding procedure and (c) ultrasonic hardware set-up showing transmission path and relevant measurements

In order to isolate the formation of the weld pool and observe the signal changes which occur through melting and solidification, the experiment began with a small solid tack weld placed between the two probes. The welding arc was then ignited on this tack weld allowing a large enough weld pool to form so that the ultrasonic transmission path is restricted to being purely through the molten material. A High Dynamic Range (HDR) camera was used to confirm visually that the tack weld was completely melted. A short weld was then performed with a length of 5 mm before the welding was stopped and the weld was allowed to solidify and cool. Ultrasonic control was provided by Peak NDT's Micropulse 6 controller interfaced through a bespoke LabVIEW suite.

RESULTS

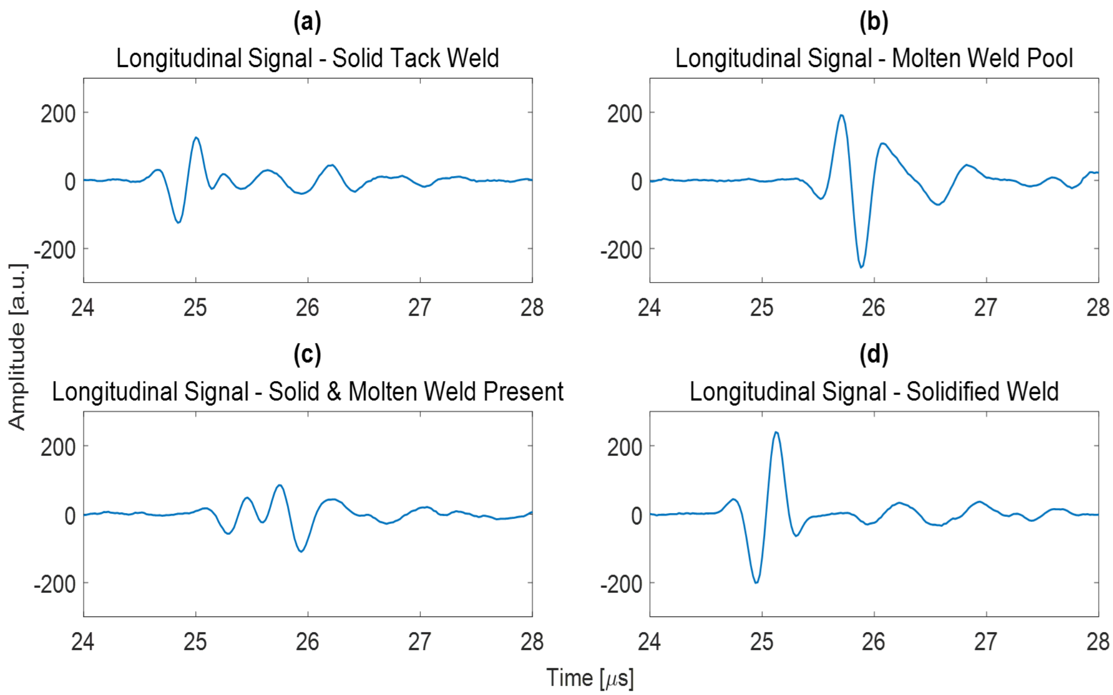

Figure 2: Received Longitudinal Through Transmission Signals for (a) Solid Tack Weld (b) Molten Weld Pool (c) Solid and Molten Weld Pool and (d) Solidified Weld

Figure 2 shows A-scans taken from key moments in time throughout the experiment. In Figure 2a, the ultrasonic beam is travelling through the solid tack weld at room temperature. The signal is seen to have a positive phase, with the phase being defined by the first peak amplitude of the signal, with a Time-of-Flight (TOF) of 24.7 μs. This TOF agrees with the theoretically calculated TOF for this case. Figure 2b shows the period where the weld pool is formed and the ultrasonic transmission path is restricted through the molten weld pool. There is a clear TOF shift which indicates the reduction in the speed of sound associated with ultrasound travelling through liquids and high temperatures [7]. The signal now exhibits a negative phase. Figure 2c shows the A-scan taken after the weld torch has begun its movement. An earlier arriving signal is now apparent, indicating two ultrasonic paths being present with differing TOF's. The ultrasonic transmission path is no longer restricted through the molten weld pool as there is now solidified material adjacent. The path through the solidified material will have a shorter TOF as both the path length is reduced and the speed of sound is increased. This is evident through the earlier arriving signal. This effect is shown visually in Figures 3a and 3b. Figure 2d show the A-scan taken after the arc has been extinguished and the weld has fully solidified and begun to cool. The TOF has reduced, which can be attributed to the cooling of the weld which results in an increase in ultrasonic wave velocity. The signal now returns to having a positive phase.

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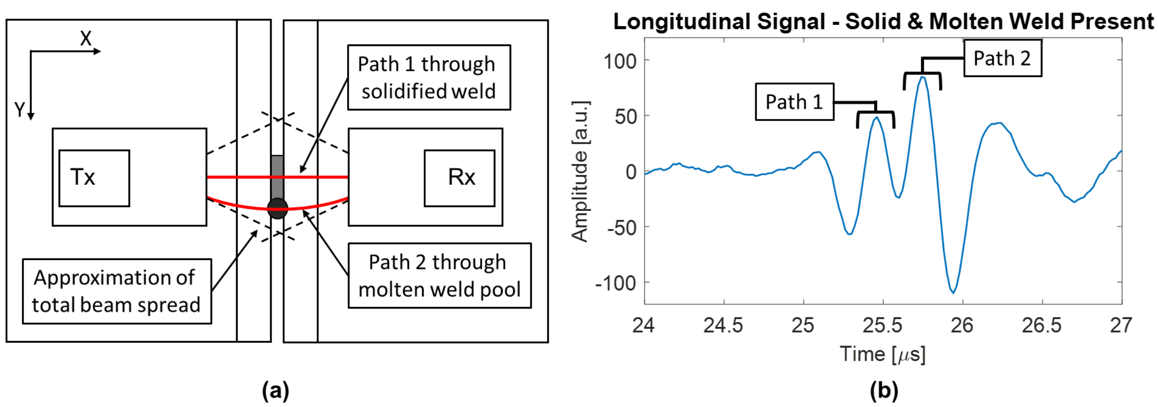

Figure 3: (a) Visual explanation of multiple ultrasonic paths present related to the resultant ultrasonic signals through (b)

CONCLUSIONS & FUTURE WORK

In-process phased array monitoring of welding processes offers significant technical and commercial benefits to the future of manufacturing. In the preliminary work reported here, focussed phased array pitch-catch inspection techniques have been implemented successfully to provide real-time ultrasonic monitoring of the molten weld pool during deposition. Despite the technical challenges anticipated due to the harsh welding environment, ultrasonic waves have been successfully propagated through the molten weld pool. It is believed that with further development, the resultant signals will be useful in determining a quantitative measurement of weld pool size and shape which offers considerable opportunity to form the basis of a closed-loop control system in the future.

REFERENCES

[1] The British Standards Limited 2019, 2019, *BS EN ISO 17640:2018: Non-Destructive Testing of Welds. Ultrasonic Testing. Techniques, Testing Levels, and Assessment*.

[2] The British Standards Limited 2017, 2017, *BS EN ISO 19285:2017: Non-Destructive Testing of Welds. Phased Array Ultrasonic Testing (PAUT). Acceptance Levels*.

[3] Maev, R., Chertov, A., Regalado, W., Karloff, A., Tchipilko, A., Lichaa, P., Clement, D., and Phan, T., 2014, "In-Line Inspection of Resistance Spot Welds for Sheet Metal Assembly," Welding journal, **93**, pp. 58–62.

[4] Maev, R. G., Chertov, A. M., Paille, J. M., and Ewasyshyn, F. J., 2017, "Ultrasonic In-Process Monitoring and Feedback of Resistance Spot Weld Quality."

[5] Vasilev, M., MacLeod, C., Galbraith, W., Javadi, Y., Foster, E., Dobie, G., Pierce, G., and Gachagan, A., 2021, "Non-Contact in-Process Ultrasonic Screening of Thin Fusion Welded Joints," Journal of Manufacturing Processes, **64**, pp. 445–454.

[6] Stares, I. J., Duffil, C., Ogilvy, J. A., and Scruby, C. B., 1990, "On-Line Weld Pool Monitoring and Defect Detection Using Ultrasonic," NDT International, **23**(4), pp. 195–200.

[7] Scruby, C. B., and Moss, B. C., 1993, "Non-Contact Ultrasonic Measurements on Steel at Elevated Temperatures," NDT & E International, **26**(4), pp. 177–188.