46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-1234

DRY-COUPLED AUTOMATED INSPECTION FOR WIRE + ARC ADDITIVE MANUFACTURE

Charles Macleod[1], Zhen Qiu, Ehsan Mohseni, Randika Vithanage, Yashar Javadi, Rastislav Zimermann, Momchil Vasilev, David Lines, Gareth Pierce, Anthony Gachagan
Centre for Ultrasonic Engineering
Department of Electronics and Electrical Engineering,
University of Strathclyde
Glasgow, UK

Stewart Williams, Jialou Ding, Filomeno Martina
Welding Engineering and Laser Processing Centre, School of Aerospace Transport and Manufacturing, Cranefield University
Cranfield, UK

ABSTRACT

This paper presents the simulation and experimental results of the concept and validity of a dry-coupled roller probe inspection technique for in-process WAAM NDE. A parametric FEA simulation defined and optimised key probe inspection parameters such as coupling-medium thickness, surface contacting acoustic window and coupling medium depth. Experimental studies positively highlighted and demonstrated the feasibility of using surface profile and high-temperature compliant (< 250°C) silicone rubbers, with low attenuation (-0.8 dB/mm @ 5 MHz) for acoustic coupling through the as-built WAAM surface for representative defect detection and imaging of 3 mm side-drilled holes.

Keywords: WAAM, Additive Manufacture NDE

1. INTRODUCTION

Additive Manufacturing (AM) is the process of adding material layer-by-layer to produce a (near-)net shape component, thus promising reduction in material waste, lead times, design constraints and ultimately in the total cost of the finished product.

Due to this, there is considerable worldwide industrial interest in AM and it is predicted to have a major impact on the production of innovative high performance future components across multiple sectors such as aerospace, energy (O&G, renewables and nuclear), defence and construction [1,2].

There is a wide variety of metal AM processes currently being researched and commercially available, such as Powder Bed (PB) and Directed Energy Deposition (DED) approaches, each with their own distinct advantages and disadvantages. Directed Energy Deposition (DED) is where the material feedstock, in the form of a wire or powder, is directly fed into a heat source and moved to deposit molten metal in predetermined positions allowing the structure to be built up in repetitive layers. Wire based DED processes, such as Wire + Arc Additive Manufacturing (WAAM) are ideally suitable for large-area additive manufacture and have major inherent potential advantages including: very high build rates (over 10 kg/hr per deposition source possible), 100% utilisation of material, high quality feedstock and materials that can be deposited without defects, an unlimited build volume and, most importantly, low cost.

WAAM is seeing increasing popularity in industry by reducing material wastage and time to market, an increase in design freedom and weight saving, as well as manufacturing of complex single-part geometries rather than assemblies made of many subcomponents. The drive to reduced lead-times and material wastage is driving the exploration of utilising WAAM to replace traditional forging techniques, which are hindered by their long-lead time and raw material cost highlighted by their undesirably high Buy-To-Fly (BTF) ratio of between 10 to 40 [3-5], which represents the weight ratio between the raw material used for a component and the weight of the component itself. A shift from traditional materials such as aluminum to newer higher performance alloys such as titanium, further exacerbates these challenges and drives interest in WAAM.

Using robotically deployed arc based heat sources and wire feedstock, WAAM has been shown to allow complex shaped builds with BTF reductions of 25 and materials savings of 500 kg per part [3-5].

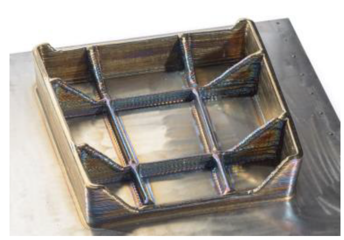

FIGURE 1: WAAM TITANIUM LANDING GEAR RIB [3]

[1] Contact author: ehsan.mohseni@strath.ac.uk

A major challenge facing all metal AM processes is how to qualify and verify the structural integrity of built components accurately and in a rapid and cost effective manner. This is deemed essential if metal AM is to move out of niche application areas and deliver on the step-change promise of replacing existing manufacturing processes and be utilised for structural engineering components over any scale. The current approach for qualification of parts is to qualify incoming material and finished components through extensive destructive and NDE and statistical analysis of the results, in order to provide design allowables that can be applied to a wide range of components.

Quality assurance requires development of in-process NDE techniques suitable for WAAM, to enable in-process inspection of every layer as it is built permitting optimum part building and process control and verification. Any potential defects can be identified as they are introduced and subsequently removed or repaired prior to subsequent layer builds, saving time, money and reducing potential part scrappage.

New in-process NDE approaches are required that are compatible with the WAAM process, namely the ability to have sufficient defect resolution, be rapidly and autonomously deployed, require no liquid coupling to avoid contamination, be deployable on profile varying and hot surfaces and permit in-process layer by layer inspection. Autonomously deployed ultrasonic NDE techniques have the potential to deliver on all of these key requirements and offer a solution to future in-process WAAM NDE.

This paper presents on the results of a study into optimum deployment considerations for WAAM NDE, specifically focusing on dry-coupled deployment at high temperature (<250°C) over surface varying profiles.

2. WAAM NDE CONCEPTS

Phased Array ultrasonic inspection strategies allow for improved imaging and detection of potential defects while permitting larger scanning areas and electronic steering and focusing of the beam at multiple specific points. Signal acquisition and processing such as the Full Matrix Capture (FMC) and Total Focusing Method (TFM) permit capture of all raw data combinations and subsequent post-processing of the data allows for focusing at all points of the image under a changing and non-planar surface [6-8]

Dry-coupled roller ultrasonic probes have shown strong promise and results when being deployed from industrial 6 Degree of Freedom Manipulators [9]. Permitting liquid-couplant free deployment and fast scanning speeds resonates strongly with WAAM NDE inspection requirements. Dry-coupled compliant coupling mediums such as rubbers, permit acoustic coupling between the transducer and part reducing the acoustic impedance and permit wave coupling transmission and reception [10] When considering WAAM NDE, the coupling medium such as rubber, must be acoustically suitable with low attenuation and optimally matched impedance, compliant to the varying and geometrically challenging surface profile and capable of withstanding the mechanical required layer inter-pass temperatures (< 250°C). This paper presents on the results of a detailed study into optimum design, manufacture and characterization of roller probes with acoustic coupling rubbers to meet these distinct requirements.

Furthermore, the physical design and deployment of PAUT roller probes for WAAM NDE requires consideration of inspection parameters such as depth of inspection, speed of inspection, WAAM surface profile variation, material under test and anticipated defect sensitivity requirement.

The design of roller probes for WAAM are presented, specifically looking at normal incidence pulse echo, angled wedge and transmit-receive concepts. A parametric simulation study of array and wheel probe parameters such as number of elements, pitch, wheel radius, wedge angle, tire thickness, coupling medium material and depth was run in parallel with experimental studies of coupling medium acoustic properties, thickness and hardness for optimum coupling.

3. RESULTS AND DISCUSSION

a. Roller Probe Simulation

Optimum wheel parameters, such as wheel radius, tire thickness and wheel circumference compliance to allow a wider surface coupling acoustic window, were parametrically optimized, within the PZFlex Finite Element Analysis (FEA) software package, for maximizing transmitted and received Signal to Noise Ratio (SNR)

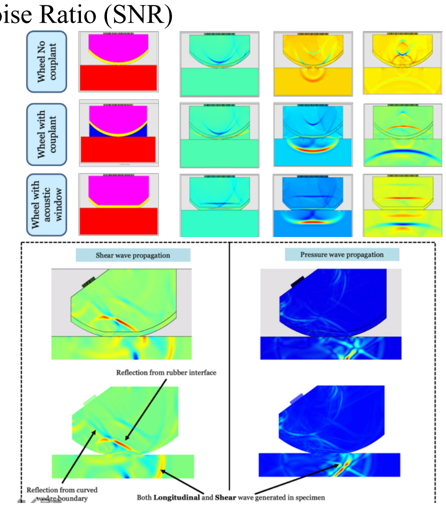

FIGURE 2: PZFlex PARAMETRIC WHEELPROBE PARAMETR FEA WAVE PROPAGATION SIMULATION RESULTS

b. Experimental Material Study

In conjunction and in parallel with the simulation studies an experimental analysis was undertaken on the acoustic transduction and material suitability of number of different high-temperature rubbers. 14 different rubbers with high-temperature compliance were designed and manufactured and subsequently investigated for acoustic properties such as acoustic impedance, longitudinal and shear velocity and attenuation at various operating temperatures between 20°C and 250°C.

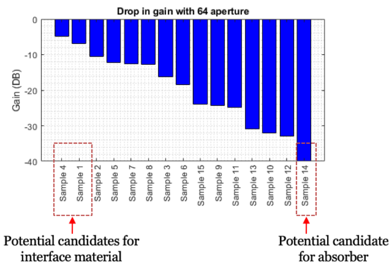

FIGURE 3: WAAM NDE SUITABLE ACOUSTIC COUPLING RUBBER ATTENUATION STUDY RESULTS

Two suitable silicone based rubbers were selected to be considered for WAAM NDE wheel probe deployment based on suitable longitudinal wave velocity (1001 - 1458 m/s), low acoustic attenuation (- 0.8– 2.5 dB/mm @ 5 MHz) and low shore hardness (10 – 25).

These rubbers were then suitably tested under realistic WAAM NDE inspection conditions. A 1D 64Element array of 5 MHz, with rexolite 20 mm stand-off was placed above two different rubber thickness (3 and 1 mm). Representative reflectors of 3 mm diameter side-drilled holes were machines into WAAM titanium walls 6 mm below the surface. FMC data capture and TFM was utilised for imaging purposes

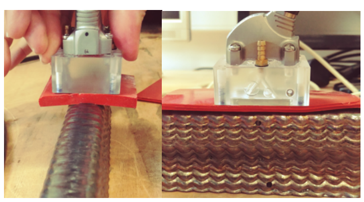

FIGURE 4: WAAM DRY-COUPLED ACOUSTIC COUPLING PHASED ARRAY ULTRASONIC INSPECTION

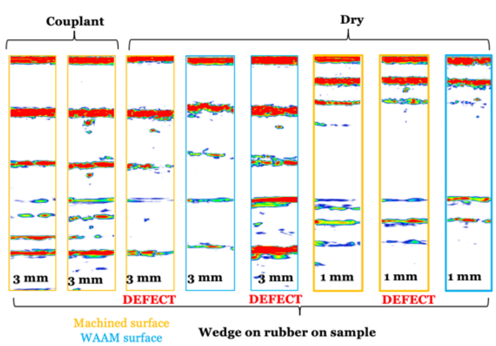

FIGURE 5: DRY-COUPLED WAAM PHASED ARRAY ULTRASONIC TFM INSPECTION REULTS

All defects were visibly detected with both 3 and 1 mm dry-coupled rubbers. Experimental results related to roller-probe inspection parameters such as wheel diameter, tire thickness and surface contacting acoustic window were found to agree strongly with the FEA simulations.

4. FUTURE WORK

A prototype dry-coupled roller probe has been designed and key design parameters verified through the above design and verification studies. Subsequent manufacture and testing of the roller probe will ultimately consider the automated deployment of the sensor within an in-process WAAM NDE context.

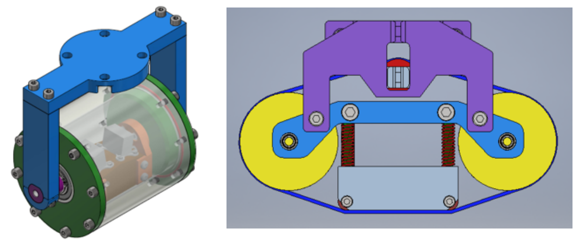

FIGURE 6: WAAM NDE TRANSMIT-RECEIVE AND ZERO INCIDENCE DRY-COUPLED PROBE CONCEPTS

5. CONCLUSIONS

This paper presents on the simulation and experimental results of the concept and validity of a dry-coupled roller probe inspection technique for in-process WAAM NDE. A parametric FEA simulation defined and optimises key probe inspection parameters such as coupling-medium thickness, surface contacting acoustic window and coupling medium depth. Experimental studies positively highlighted and demonstrated the feasibility of using surface profile and high-temperature compliant silicone rubbers for acoustic coupling through the as-built WAAM surface for representative defect detection and imaging.

REFERENCES

[1] J. Coykendall, M. Cotteleer, J. Holdowsky, M. Mahto, 3D opportunity in aerospace and defense: additive manufacturing takes flight, A Deloitte series on additive manufacturing, Deloitte University Press, Westlake, TX, 2014.
[2] W.E. Frazier, Metal Additive Manufacturing: A Review, Journal of Materials Engineering and Performance 23 (2014) 1917-1928.
[3] S.W. Williams, F. Martina, A.C. Addison, J. Ding, G. Pardal, P. Colegrove, Wire plus Arc Additive Manufacturing, Materials Science and Technology (2016)
[4] D.H. Ding, Z.X. Pan, D. Cuiuri, H.J. Li, Wire-feed additive manufacturing of metal components: technologies, developments and future interests, International Journal of Advanced Manufacturing Technology 81 2015)
[5] F.D. Wang, S. Williams, P. Colegrove, A.A. Antonysamy, Microstructure and Mechanical Properties of Wire and Arc Additive Manufactured Ti-6Al-4V, Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science 44A (2013) 968-977.
[6]B.W. Drinkwater, P.D. Wilcox, Ultrasonic arrays for non-destructive evaluation: A review, Ndt & E International 39 (2006) 525-541.
[7] C. Holmes, B.W. Drinkwater, P.D. Wilcox, Post-processing of the full matrix of ultrasonic transmit-receive array data for non-destructive evaluation, Ndt & E International 38 (2005) 701-711.
[8]J. Zhang, B. W. Drinkwater and P. D. Wilcox, "Efficient immersion imaging of components with nonplanar surfaces," in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 61, no. 8, pp. 1284-1295, 2014.
[9]C. Mineo *et al*., "Fast ultrasonic phased array inspection of complex geometries delivered through robotic manipulators and high speed data acquisition instrumentation," *2016 IEEE International Ultrasonics Symposium (IUS)*, Tours, 2016, pp. 1-4.
[10] B. W. Drinkwater and P. Cawley, "An Ultrasonic Wheel Probe Alternative to Liquid Coupling," Insight **36**, 430–433 (1994)

