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Dry-coupled ultrasound phased array inspection of as-built complex geometry metal additive manufactured components

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ABSTRACT

Growing demand for smart and flexible factories, producing high-value components cost-effectively has driven the development of large-scale metal Additive Manufacturing (AM) processes such as Wire+Arc Additive Manufacturing (WAAM). To match the strengths of metal AM, a novel high-temperature dry-coupled ultrasound roller-probe was developed to facilitate quality assurance, deployed in-process. In this work, the authors present novel work and research from the field of an automated dry-coupled ultrasound in-process NDE. During the experiments, a titanium complex-shaped WAAM, featuring characteristic geometries and a range of flat bottom holes in critical locations drives the development of an NDE strategy deployable on real as-built WAAM geometries. The outcome of this work demonstrates a novel knowledge applicable to path planning strategy for the best ultrasound wave propagation into critical locations within a specimen along with further enhancements applied to the existing robotic NDE system.

Keywords: metal additive manufacturing, automated in-process non-destructive evaluation, ultrasound phased array inspection

Introduction

Three-dimensional (3D) printing, also known as additive manufacturing (AM), is a method of creating objects layer by layer while using data from a digital 3D model to direct the deposition paths. The adoption of additive manufacturing (AM) is anticipated to rise as companies transition to Industry 4.0. This is due to the increasing desire to create intelligent production systems that can manufacture customized products with high quality and value. The aerospace, civil and automotive industries are a few examples of those where this technology is most in demand. This work is related to one such metal AM method called Wire+Arc Additive Manufacturing (WAAM) [1]. The objective of WAAM is to provide automated fabrication of highly valuable structurally complicated 3D near-net-shaped components. Moreover, given the need to produce a component using a minimum volume of feedstock material, superior cost-effectiveness to conventional subtractive manufacturing can be achieved [2].

In this paper, the authors intend to further enhance the overall benefits of WAAM by developing a novel NDE approach that can be deployed automatically and in process. This is accomplished using a bespoke ultrasound roller-probe that was developed to facilitate in-process inspection using dry-coupling and at elevated temperatures (up to 350°C) [3, 4]. The successful in-process inspection of WAAM was already demonstrated within a dedicated WAAM & in-process NDE cell, in which the titanium specimen with artificial defects was successfully inspected during a dwell time set for interlayer cooling [5]. The automated dynamic inspection was achieved using a sensor-enabled robotic system enabling real-time corrections via force-torque sensor input [6]. However, the experimental work was conducted on a straight wall and the approach's ability to detect defects within complex and challenging geometries was not yet analyzed and discussed.

Hence, in this work, an as-built complex geometry Ti-6Al-4V WAAM component was developed. The component was deposited to feature characteristic features commonly occurring in e.g. aerospace geometries [1], these were I) curved sections, II) t-joints and III) varying thicknesses. To analyze the results quantitatively and comparatively, the experimental WAAM featured a large variety of bottom-drilled holes located in critical locations within its volume. The hypothetical component was subsequently subjected to an experimental inspection intending to develop a most suitable inspection strategy for defect detection under conditions that significantly affect I) the automated NDE deployment (force-torque control and path planning) and II) ultrasound wave propagation through a dynamically changing as-built WAAM surface. During the inspection, the position-encoded ultrasound data were acquired to form a volumetric interior image of WAAM. The inspection was repeated by adjusting inspection parameters such as path planning, force applied on the specimen and ultrasound inspection parameters. The obtained results were analyzed through defect detection quality by measuring the Signal-to-Noise Ratio (SNR). Thus, the analysis of this work enabled the development of the most suitable approach for dry-coupled ultrasound in-process NDE of metal AM components.

Experimental method

Experimental specimen

The experimental work was conducted using an as-built WAAM specimen depicted in Figure 1 (a). The specimen was manufactured using Ti-6Al-4V wire on a 12 mm thick substrate plate. The layers were deposited using an oscillating deposition strategy to a height of approximately 21 mm. Individual features highlighted in the figure were chosen as characteristic bead shapes commonly found during deposition. These are I) curved section II) T-joint section and III) thickness-reducing section. A wide range of Bottom-Drilled Holes (BDH) was produced, representing defects such as keyholes. The holes were 2 mm in diameter and were reaching from 10 to 3 mm below the surface.

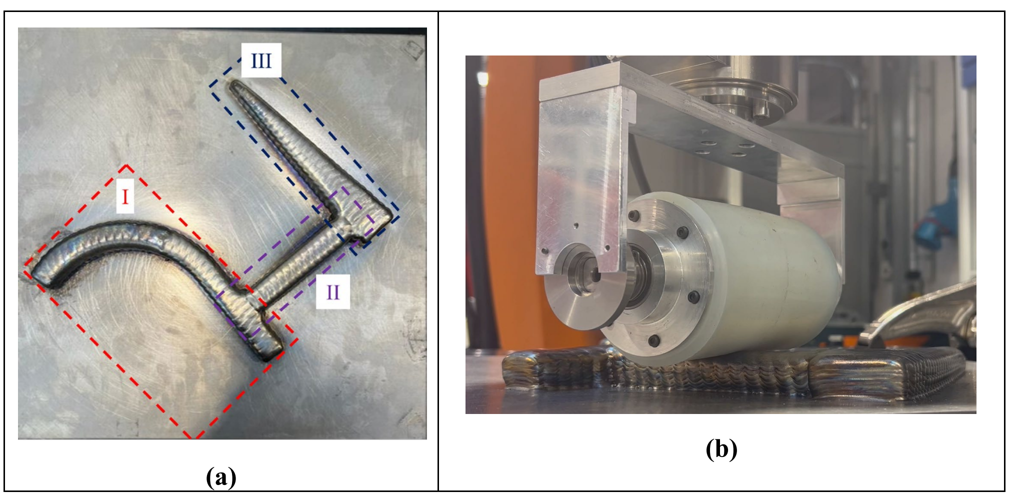

Figure 1: Experimental setup. (a) Experimental Specimen (b) Dry-coupled roller-probe setup inspecting an as-built WAAM specimen

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Ultrasound inspection Parameters

The ultrasound data were acquired using a roller-probe featuring a solid delay line housed in a rubber tyre. The PAUT, with specifications found in Table 1, was positioned to sit on the top of the delay line.

Table 1: Transducer Parameters

Array Parameters	Value
Element Count	32
Element Pitch	0.5 mm
Element Elevation	10 mm (unfocused)
Element Spacing	0.1 mm
Centre Frequency	5 MHz

The NDE was driven using LTPA phased array controller (Peak NDT, Derby, UK). The ultrasound data were acquired using ultrasound beamforming focused into the centre of the targeted volume. During the data acquisition, the 32-element sub aperture with 1-element shift was excited. The acquired B-scans were stored on a local hard drive for later post-processing and analysis.

Results and discussion

The result of this work shows the ability of the automated dry-coupled roller-probe NDE system to detect defects at critical locations within complex WAAM components. Figure 2 depicts inspection outcomes where the selected BDH were detected during dynamic scan while the dry-coupled roller-probe was transitioning on the top of the as-built WAAM surface of the curved section, the joint beads and bead with varying thickness. It is worth noting, a signal received from the WAAM surface along with the roller-probes tyre (on edges) were visible on every frame. The detected BDH, highlighted in yellow circles were detected with an SNR of up to 20 dB while the selected frames show a BDH located at A) centre and 5 mm depth, B) centre 3 mm depth and C) corner and 10 mm depth.

The results were achieved by adjusting path planning parameters and optimizing the direction when transitioning over joining beads. Further enhancements for sensor-enabled robotic package facilitated automated on-flight force changes. These changes enabled steady contact pressure between roller-probe and WAAM during continuously varying contact areas. Hence, steady compression of the rubber was achieved which assured accurate focal laws at all times and therefore accurate interior ultrasound imaging of WAAM.

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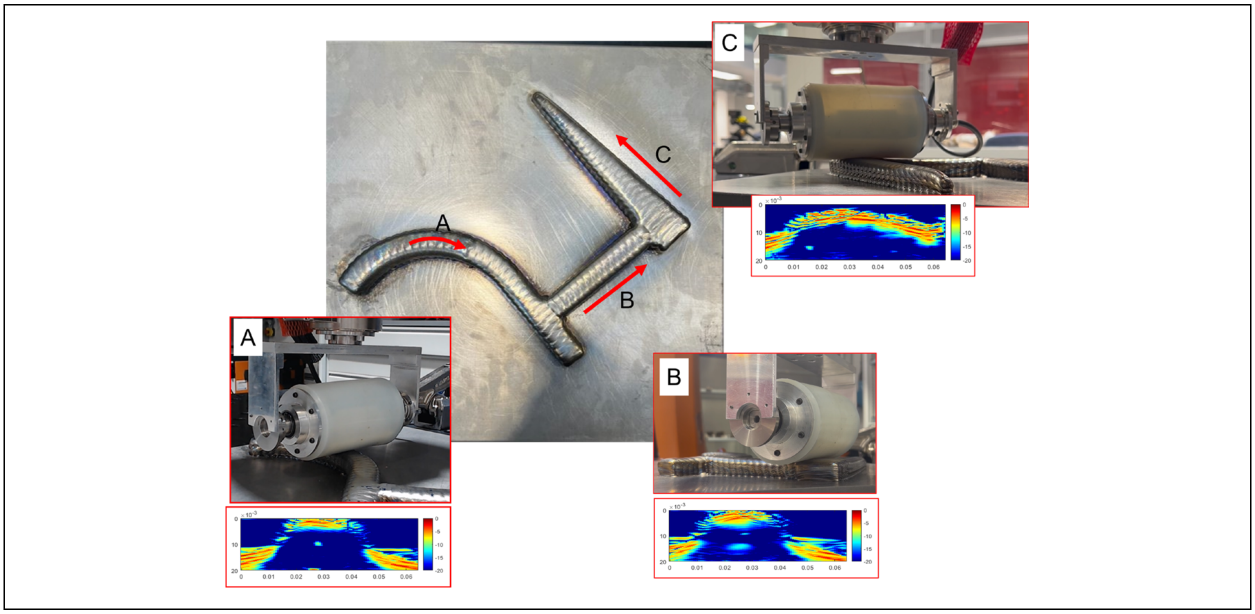

Figure 2: Results showing the detection of artificial defects (highlighted in yellow circle) at various locations during inspection of complex WAAM geometry.

Conclusions.

A dry-coupled roller-probe inspection of a complex WAAM geometry was demonstrated. During the dynamic inspection, a wide range of targeted BDH were detected and analyzed while inspecting through challenging coupling conditions created by complex geometry WAAM.

The developed inspection strategy along with further enhancements to the robotic package will be fed into future work intending to deploy this knowledge during the actual in-process inspection. Further ultrasound inspection optimization will be investigated to dynamically change the ultrasound imaging parameters according to sensor input which in future can enhance the sensitivity and accuracy of inspection results as well as influence the robotic control during the inspection.

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