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IN-PROCESS INSPECTION OF MULTI-PASS ROBOTIC WELDING

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

ABSTRACT

Traditionally fusion welding of manufactured components and quality control inspection of such welds are distinctly separate processes in the supply chain, which ultimately limit productivity, throughput and increase re-work. The concept of combining both of these practices directly at the point of manufacture offers the potential to produce superior, globally-efficient fabrications. This paper presents the results of a study investigating such a strategy, where a multi-pass weld is autonomously deposited and, in parallel, an autonomous inspection is deployed for real-time Non-Destructive Evaluation (NDE). A real-time sector scan is implemented after each of 21 weld passes and in three inspection positions, i.e., the first position is 50 mm from the weld start, the second being in the center of the weld length and the last is 50 mm distance to the weld endpoint. Only in the second position, anintentionally embedded defect, a tungsten rod, is introduced into the multi-pass weld to allow subsequent in-process calibration and verification. Based on the phased array inspection results, the tungsten rod is successfully detected in the real-time NDE of the deposited position. Furthermore, the reflection due to the partially filled groove is captured during the inspection of the filling passes.

Keywords: Weld Inspection; In-Process NDE; Real-time Inspection; Ultrasonic Phased Array.

1. INTRODUCTION

Traditionally fusion welding of manufactured components and quality control inspection of such welds are distinctly separate processes in the supply chain, which ultimately limit productivity, throughput and increase re-work. The opportunity exists to combine both of these practices directly at the point of manufacture through the use of new inspection, automation and control approaches, ultimately addressing the above challenges and producing superior, globally-efficient fabrications. This completely new and novel step-change approach to a well-established manufacturing principle has the potential to wholly reshape the approach, possibilities and direction of the global factories of the future [1].

The concept of inspecting the welding process in real-time offers the possibility to control, adapt and consistently ensure high-quality defect-free welding [2]. The use of modern automated welding strategies offers fundamental changes to the flexibility and range of possibilities, in terms of complexity and shape, of final fabrications. However, current industrial robotic welding solutions do not feature this flexibility, ultimately hindering uptake, especially within the flexible SME sector [3]. High-value thick complex welded components, typically feature multi-pass welds across multiple layers. Defects introduced in the lower layers which remain undetected until final completion, result in all remaining upper layers passes being mechanically removed to re-access the defecated lower layer. Early detection of such defects would result in reduced re-work requirements and hence improved component build time and overall cost. Inspection of each pass during the welding process would allow the early and efficient screening of each layer and detection of any flaws. Such a concept has clear benefits to industrial organizations in both the quality of the final product and major improvements in production throughput. This has clear applicability to many industrial sectors that feature safety critical multi-pass welds such as nuclear, energy (O&G, renewables) and defense. Non-destructive evaluation (NDE) in the form of Ultrasonic Testing (UT) allows for such welds to be tested in a safe, efficient and unobtrusive manner [4].

This paper presents the concept of a combined multi-pass welding and inspection strategy and the results of an industrially relevant proof-of-concept trial.

2. SYSTEM ARCHITECTURE

2.1. Hardware Configuration

The automated multi-pass welding and inspection system used in this study is shown in Figure 1. The Tungsten Inert Gas (TIG) welding process is deployed via a 6-axis KUKA robotic manipulator equipped with a TIG welding torch. The inspection process utilizes a separate 6-axis KUKA robot to

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[1] Contact author: yashar.javadi@strath.ac.uk

deploy an NDE end-effector (Figure 2) carrying a Phased Array Ultrasonic (PAUT) array and angled wedge for shear wave inspection. The NDE end-effector has three main parts: (I) ultrasonic array, (II) high-temperature compliant wedge and (III) thermocouples. The ultrasonic array is a 5 MHz, 64 elements, 0.5 mm pitch array. The angled wedge (55°) is manufactured in an amorphous thermoplastic polyetherimide resin called ULTEM™ and is capable of withstanding intermittent temperatures as high as 150° C. The wedge holder was also equipped with four spring-loaded thermocouples which first touch the specimen, before the wedge, in order to ensure the surface temperature is less than the wedge operational limit.

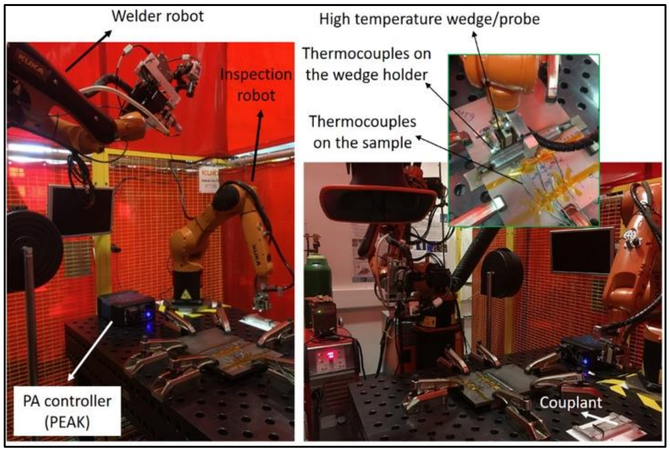


FIGURE 1: AUTOMATED MULTI-PASS WELDING AND INSPECTION SYSTEM

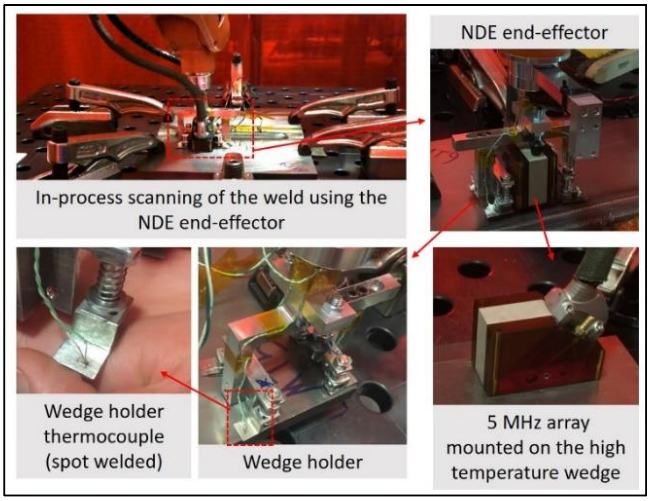


FIGURE 2: IN-PROCESS SCANNING OF THE WELD USING THE NDE END-EFFECTOR

High-temperature couplant is utilized between the wedge and the surface under inspection. A PEAK LTPA phased array controller was used for array control and signal acquisition with an active aperture of 64 elements. A National Instruments, Compact RIO 9038 real-time controller programmed in the LabView environment, is employed to control the TIG welding machine, welding robot, inspection robot, thermocouples and PAUT controller.

2.2. Inspection Methodology

The process first starts with the autonomous deposition of a welding pass by the welder robot, defined by the material, thickness and groove preparation. An integrated line laser scanner and High Dynamic Range (HDR) cameras provide real-time process information and control to optimize deposition parameters. Permanent thermocouples attached to the specimen plate being welded monitor the surface temperature for overall process control purposes. After the completion of a single welding pass and the specimen surface temperature drops to 150° C, the inspection robot initiates the NDE process (Figure 3).

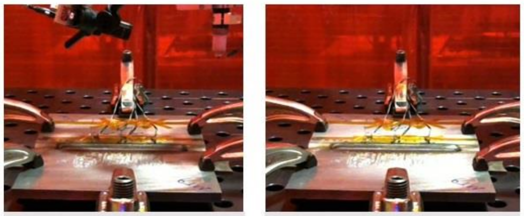
The inspection robot first introduces sufficient couplant to the wedge lower surface by bathing it in a couplant bath built for the purpose. The NDE effector is then deployed at multiple user-defined scanning positions along the welding axis. The four thermocouples attached to the NDE end-effector first contact the sample surface and verify that the temperature is below the 150 °C limit. If so, the end-effector is deployed downward and the wedge and couplant make contact with the surface specimen. The chosen array processing technique (FMC and/or Sectorial Scanning) is then generated and received data captured by the PA controller. The NDE process is repeated for each subsequent scanning position along the weld axis. Once all NDE scanning positions have been inspected, the welder robot begins the next welding pass and the outlined procedure is repeated for all the welding passes required to complete the multi-pass weld.

3. EXPERIMENTAL CONCEPT

An experiment was prepared to demonstrate the feasibility of the concept and validate the performance of the in-process inspection. The chosen specimen was a 15 mm thick structural steel (S275) plate of length 300 mm. In total, 21 weld passes were deposited in 7 distinct layers inside a 90° degree V-groove. Four thermocouples were attached to the surface in order to support the control process. Three distinct PAUT inspection positions were selected along the weld axis each with a wedge contact duration of 5 seconds, deemed sufficient to achieve the desired ultrasonic data transmission and reception. The first position was 50 mm from the weld start, the second being in the center of the weld length and the last was 50 mm distance to the weld endpoint. For calibration purposes, a ø2.6 mm tungsten rod of length 38 mm was intentionally embedded in the weld center, within pass 7 on layer 4, to provide calibration information, reference sizing indication and differentiate the center NDT results from those obtained from the start and end positions [5, 6]. The imaging approach selected was phased array sectorial scanning with a sweeping angle of 40-75° and step size of 0.5°. The horizontal distance (perpendicular axis to the weld length) between the wedge front face and the weld center is 23 mm so that there is no direct contact between the weld cap and the wedge, instead, the wedge is always sitting over the parent material. This necessitates the requirement for multi-skip inspection.

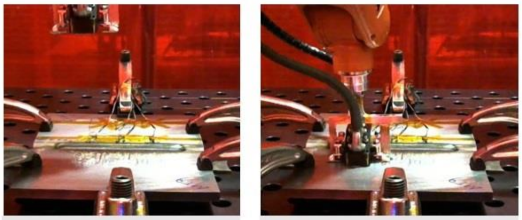
Time: 16s (start of welding)

Time: 120s (end of welding)



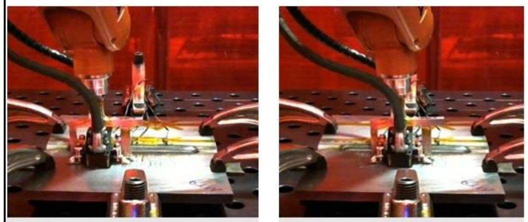
Time: 150s (welder robot in the safe position)

Time: 180s (waiting for the temperature < 150°C)



Time: 223s (inspection robot over the inspection position 1)

Time: 228s (NDE end-effector thermocouples touching the surface)



Time: 231s (NDE end-effector wedge/array touching the surface)

Time: 261s (scanning over the inspection position 2)

Time: 291s (scanning over the inspection position 3)

FIGURE 3: IN-PROCESS WELDING AND INSPECTION METHODOLOGY

4. RESULTS

Three distinct sector scans were acquired for each weld pass, giving a total of 63 distinct sectorial scans. The known size reference defect of the embedded tungsten rod was detected in the scan immediately following the pass in which it was embedded, and also in all subsequent layers. The tungsten rod was successfully detected in the deposited position while no lack of fusion defects at the start and end position were detected (Figure 4). However, a reflection from the partially filled groove is detected during the inspection of the filling passes (e.g., after Pass 16 as shown in Figure 4) which expectedly vanishes once the cap passes are deposited (e.g., inspection after Pass 21, the last cap pass, as shown in Figure 4).

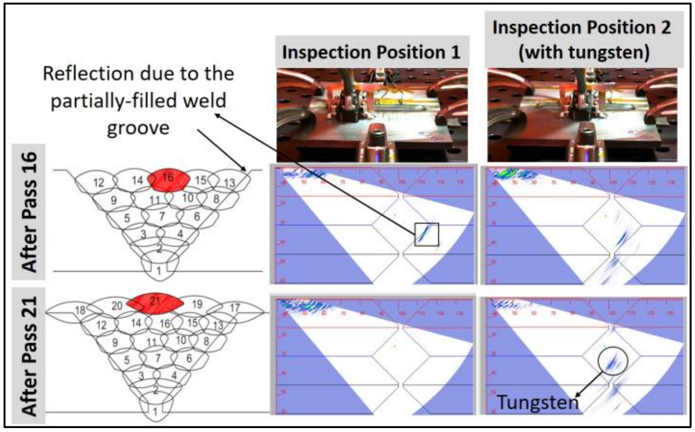


FIGURE 4: IN-PROCESS INSPECTION RESULTS

5. CONCLUSION

A combination of robotic multi-pass welding and automated phased array inspection is successfully implemented in this work. For calibration purposes, a tungsten rod was intentionally embedded in the weld center to differentiate the center NDT results from those obtained from the start and end positions. Based on the real-time sector scanning results, an embedded tungsten rod was successfully detected in the deposited position while also showing no lack of fusion defects at the start and end position. Furthermore, a reflection from the partially filled groove is detected during the inspection of the filling passes which vanishes once the cap passes are deposited.

REFERENCES

[1] Consonni, M., C. F. Wee, and C. Schneider. "Manufacturing of Welded Joints with Realistic Defects." Insight 54, no. 2 (Feb 2012): 76-+.

[2] Javadi, Y. , M. Vasilev, C. N. MacLeod, S. G. Pierce, R. Su, C. Mineo, J. Dziewierz, and A. Gachagan. "Intentional Weld Defect Process : From Manufacturing by Robotic Welding Machine to Inspection Using Tfm Phased Array." In 45th Annual Review of Progress in Quantitative Nondestructive Evaluation. Burlington, United States: AIP, 2018.

[3] Kah, P., B. Mvola, J. Martikainen, and R. Suoranta. "Real Time Non-Destructive Testing Methods of Welding ". Advanced Materials Research 933 (2014): 109-16.

[4] Sun, Y., P. Bai, H. Y. Sun, and P. Zhou. "Real-Time Automatic Detection of Weld Defects in Steel Pipe." Ndt & E International 38, no. 7 (Oct 2005): 522-28.

[5] Wang, G., and T. W. Liao. "Automatic Identification of Different Types of Welding Defects in Radiographic Images." Ndt & E International 35, no. 8 (Dec 2002): 519-28.

[6] Zou, Y. R., D. Du, B. H. Chang, L. H. Ji, and J. L. Pan. "Automatic Weld Defect Detection Method Based on Kalman Filtering for Real-Time Radiographic Inspection of Spiral Pipe." [In English]. Ndt & E International 72 (Jun 2015): 1-9.