# Abstract for RCNDE Showcase Track

## Automated Multi-Modal In-Process Non-Destructive Evaluation of Wire + Arc Additive Manufacturing

Ehsan Mohseni[1], Rastislav Zimermann[1], Randika K.W. Vithanage[1], Euan Foster[1], Momchil Vasilev[1], Charalampos Loukas[1], Muhammad Khalid Rizwan[1], Charles Macleod[1], David Lines[1], Misael Pimentel[2], Stephen Fitzpatrick[2], Steven Halavage[2], Scott McKegney[2], Gareth Pierce[1], A. Gachagan[1], Stewart Williams[3], Jialuo Ding[3]

[1] *SEARCH: Sensor Enabled Automation, Robotics & Control Hub, Centre for Ultrasonic Engineering (CUE), Department of Electronic & Electrical Engineering, University of Strathclyde, Royal College Building, 204 George Street, Glasgow G1 1XW, Ehsan.mohseni@strath.ac.uk*

[2] *National Manufacturing Institute Scotland (NMIS), 85 Inchinnan Dr, Inchinnan, Renfrew PA4 9LJ*

[3] *Welding Engineering and Laser Processing Centre, Building 46, Cranfield University, Cranfield MK43 0AL, UK*

The scale of the global market size for metal Additive Manufacturing (AM) in recent years, at €2.02 billion in 2019, and predictions for the continuous growth up to 27.9% annually until 2024 highlight the key role that these processes will play in the future of high-value manufacturing. AM technology leverages the concepts of the latest industrial revolution, Industry 4.0, where the manufacturing is made more flexible and smarter capable of fabricating cost-effective high-quality customized products. Among the various AM technologies, only a few such as the Wire + Arc Additive Manufacturing (WAAM) process can meet some industries' demands for producing large components in a short time. The process typically involves industrial robots and arc-based welding performing layer-by-layer deposition on substrates and building up components to their final desired shape. The process is majorly used to manufacture low volume, high mix, critical components for applications in aerospace and nuclear industries. Therefore, the imposed inspection requirements demand very high detection sensitivities. Robotically-deployed Non-Destructive Evaluation (NDE) during the manufacturing process might just be the inspection process needed to ensure the component's integrity as it is being built, paving the way for an easier part certification process which is normally of concern to many end-users of the technology. In-process automated inspection of WAAM, deployed after deposition of every few layers, adds to the process cost-effectiveness as the early defect detection capability provides the opportunity for the process intervention and taking remedial rework actions reducing the time/material waste.

This work presents a demonstration of the concept of in-process NDE of WAAM using two different modalities: a) a high temperature phased array Ultrasound Testing (UT) roller-probe, and b) a high-temperature flexible Eddy Currents (EC) testing array. The automation cell is composed

of two robots, where one is dedicated to the WAAM deposition process and the other to NDE sensor delivery on the WAAM. A titanium WAAM component with a straight geometry was deposited using the plasma-arc process and oscillation strategy, where the deposition path and process parameters were controlled by software. Intentionally-embedded tungsten tube and ball reflectors of varying sizes/orientations were inserted in between different WAAM layers to assess the in-process detectability of each of the employed NDE modalities. Full external control of the sensor-enabled adaptive motion control for the NDE robot and the integrated UT and EC array controllers and array probes were achieved through a central program developed in the LabVIEW platform. Moreover, real-time robot motion corrections, driven by the Force-Torque sensor feedback, were established to adjust the contact force and orientation of the sensors to the component surface during the scan. The high-temperature (up to 350 °C), dry-coupled UT roller-probe inspection of WAAM was conducted in-process at the dwelling time between the layers while the surface was at a maximum temp of 130C. Subsequently, EC scan was also carried out in the dwell time at high temperature. The C-scans were produced live from both UT and EC arrays demonstrating the successful detection of embedded tungsten defects with high SNRs. The WAAM component was X-ray CT scanned after production to confirm the exact location if the defects and compare it against the other NDE findings.