New Wire Additive Manufacturing

Newsletter (2nd quarter, 2021)

Cranfield University

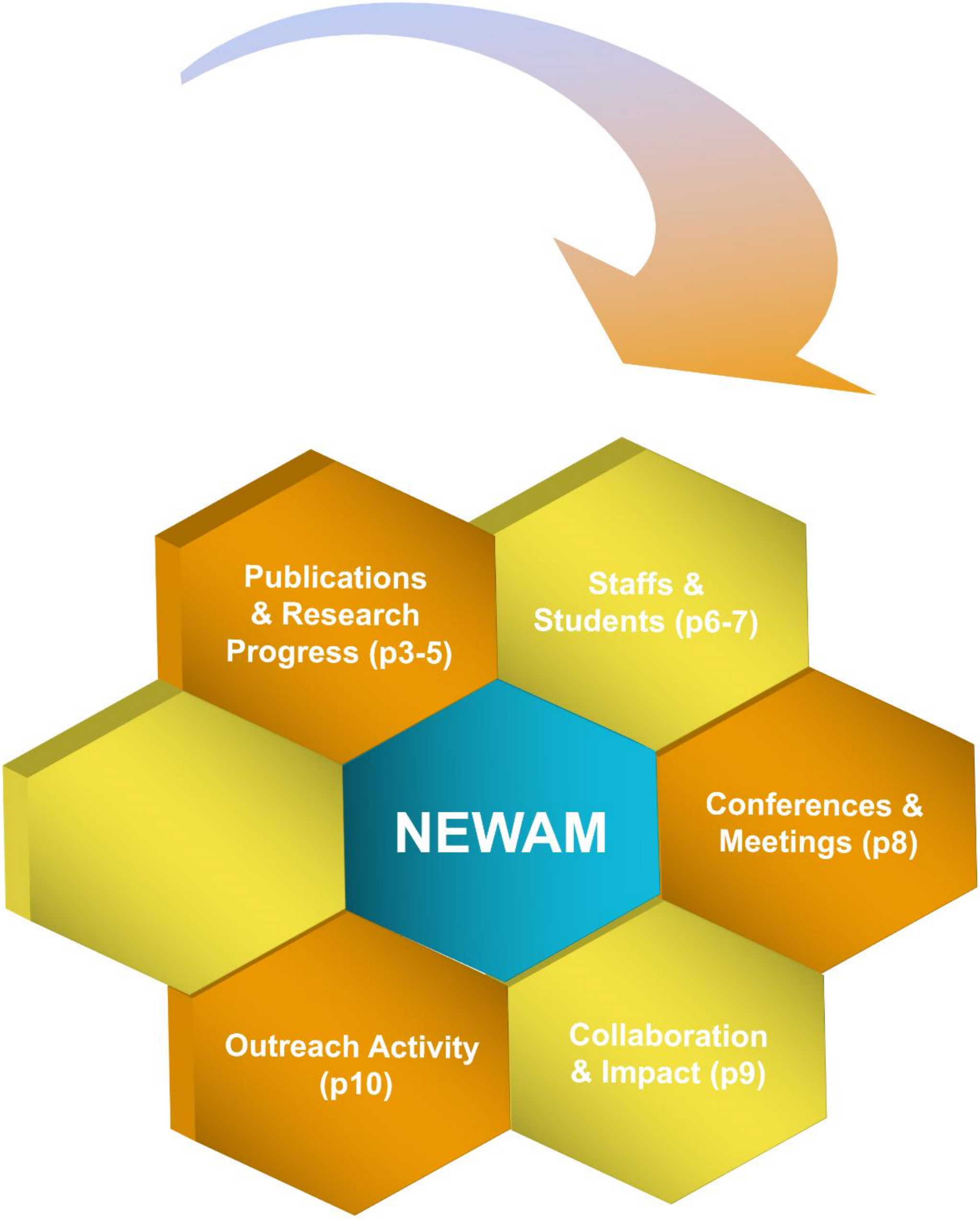
MANCHESTER 1824

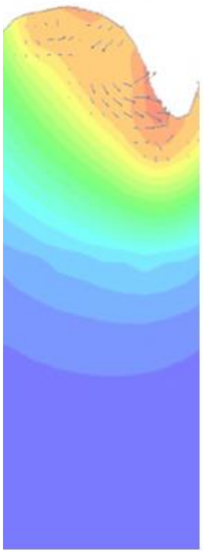
University of Strathclyde

Coventry University

Compiled by NEWAM dissemination committee and released on 1 July 2021

Your NEWAM in April – June 2021



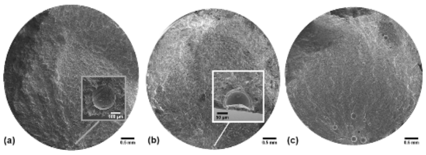


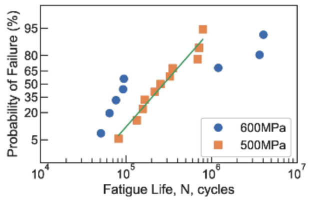
Publications & Research Progress

Coventry Team's new publication on fatigue of WAAM Ti64

- In this work, the team have studied the source of dispersion and the influence of pore size on fatigue life using samples from the standard processing route and samples with intentionally introduced porosity defects. According to the fracture surface study, contrary to the common belief, the source of dispersion is primarily the pore location, e.g. surface or embedded pore, rather than the pore size. In the case of embedded pores as the failure source, a threshold pore size of approximately 85 µm was observed, below which the wrought level fatigue performance was achieved.

For surface pores above the threshold size, fatigue life was reduced by two orders of magnitude, but remained unchanged, even though crack initiating pore size increased roughly by a factor of four. This experimental observation was supported by local elastic stress analysis, which indicated that pores above a certain size could behave like micro-notches suggesting the popular Kitagawa-Takahashi diagrams should be presented with a horizontal asymptote for this alloy.

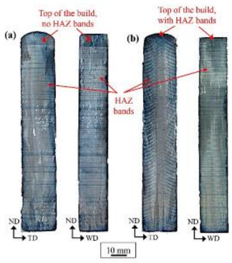




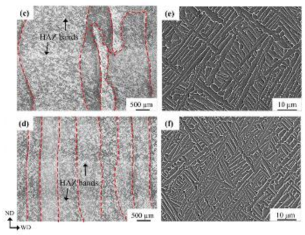
- Emre Akgun, Xiang Zhang, Romali Biswal, Yanhui Zhang, Matthew Doré; Fatigue of wire+arc additive manufactured Ti-6Al-4V in presence of process-induced porosity defects. International Journal of Fatigue (2021), 150, 106315.

Coventry Team's new publication on WAAM property correlation with deposition strategy

- This outcome is a collaborative effort from Coventry University and Cranfield University. This paper investigates the influence of two different deposition strategies, oscillation and parallel pass, on the tensile and high cycle fatigue properties of a wire + arc additive manufactured Ti-6Al-4V alloy in the as-built condition. Test specimens were manufactured in horizontal and vertical orientation with respect to the deposited layers. Compared with the parallel pass build, the oscillation build had lower static strength due to its coarser transformation microstructure. However, the elongation values were similar. The presence of columnar primary β grains has resulted in anisotropic elongation values. The vertical samples with loading axis parallel to the primary β grains showed 40% higher elongation than the horizontal samples. The fatigue strength was comparable with its wrought counterpart and greater than typical material by casting. At 10^7 cycles, fatigue strength of 600 MPa was achieved for the oscillation build vertical samples and the parallel pass build in both orientations. Only the oscillation build horizontal samples had lower fatigue strength of 500 MPa. Fractography analysis showed that most of the samples (about 70%) had crack initiation from pores, about 20% samples had crack initiated from microstructural features and the rest did not fail (runouts at 10^7 cycles).

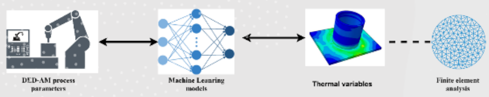


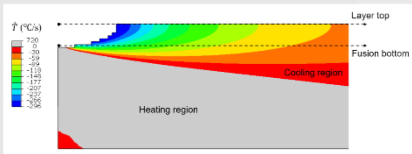
- Abdul Khadar Syed, Xiang Zhang, Armando Caballero, Muhammad Shamir, Stewart Williams; Influence of deposition strategies on tensile and fatigue properties in a wire + arc additive manufactured Ti-6Al-4V. International Journal of Fatigue (2021), 149, 106268.



Bi-directional machine learning and FEA modelling for DED process design

- Recently, the Cranfield digital modelling team has been working on proposing a bi-directional digital modelling approach for guiding and improving direct energy deposition (DED) based additive manufacturing (AM) process design. This approach integrates Machine Learning (ML) and Finite Element Analysis (FEA) techniques, which can discover the hidden patterns and relationship between the process parameters and resultant thermal variables.
- By using the proposed approach, DED process operators and researchers can predict the process parameters based on required thermal variables in real-time. In the meanwhile, for the process modeller, this approach can be used as an affordable alternative to FEA modelling to obtain the specific thermal variable efficiently. This approach has achieved reasonable results of prediction accuracy in both directions with over 90% accuracy and coefficient of determination.

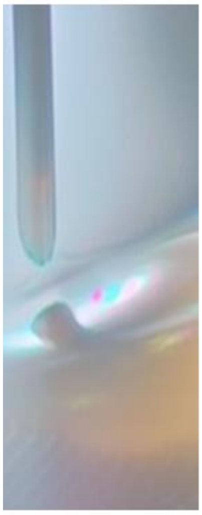


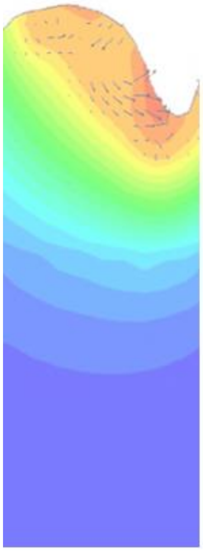


	Cooling rate	Fusion depth and length	Thermal gradient
RMSE	5.95 °C/s	0.810 mm	26.679 °C/cm
Accuracy	0.922	0.948	0.963
R2	0.930	0.927	0.826

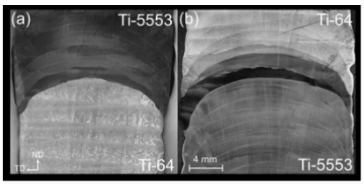
	Wire feed speed	Travel speed	Current
RMSE	7.069 mm/s	0.429 mm/s	14.457 Amp
Accuracy	0.918	0.933	0.947
R2	0.878	0.948	0.912

Publications & Research Progress



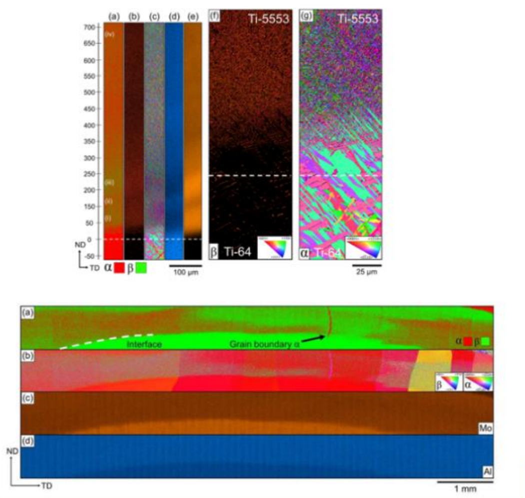


Manchester Team's research progress on WAAM materials characterisation (1)



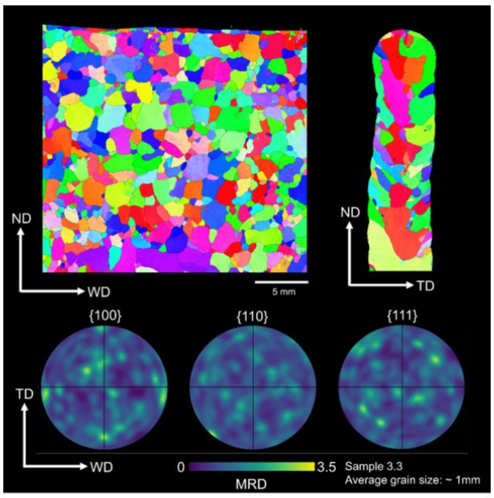
- At the University of Manchester during this last quarter, the focus has been on electron backscatter diffraction (EBSD) characterisation of many WAAM materials. The bulk of which has been conducted on dissimilar titanium alloy WAAM interfaces of Ti-6Al-4V (Ti64) and Ti-5Al-5V-5Mo-3Cr (Ti5553). These dissimilar alloy WAAM builds were deposited at Cranfield University, and consist of Ti64 deposited on a substrate, then the wire feed was switched to Ti5553 and more material was deposited, and finally the wire feed was switched back to Ti64. This allowed us to study the liquid alloy mixing that occurred during deposition, and the resultant microstructural impact, with both alloy deposition orders. Just from the etched sample optical images the impact of deposition order can be seen:

- The key findings of this research was that heterogeneous microstructures resulted from the incomplete mixing that occurred during deposition. The electron probe microanalysis results showed how the substrate alloy is diluted during deposition of each subsequent dissimilar alloy wire layer, and the alloying elements are carried through these layers in a stepwise fashion. However, especially in the first layer, the 'steps' are not chemically homogeneous, demonstrating the incomplete mixing of alloying elements. The resultant microstructure heterogeneities are shown below, and may be detrimental to mechanical properties of such components. In the near future, we will analyse exactly how these interfaces behave under loading conditions.



Manchester Team's research progress on WAAM materials characterisation (2)

- High resolution EBSD and chemical maps of the Ti64->Ti5553 interface going into the first Ti5553 deposited layer. (a) Ti alpha and beta phase EBSD map, (b) beta phase EBSD orientation map, (c) alpha phase EBSD orientation map, (d) Al EDS map, (e) Mo EDS map. (f) and (g) show (b) and (c) in higher magnification. The white dashed line is the dissimilar alloy interface.
- Low resolution EBSD and EDS chemical maps of the Ti5553->Ti64 interface going into the first Ti64 layer. (a) shows the EBSD phase map and how the incomplete chemical mixing creates a heterogeneous distribution of the these phases across the transverse cross section of the WAAM build, (b) is an orientation map of both phases, (c) Mo EDS map, (d) Al EDS map. Unfortunately, the EDS technique is not sensitive enough to resolve chemical variances across the interface.

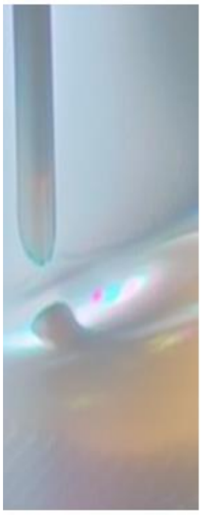


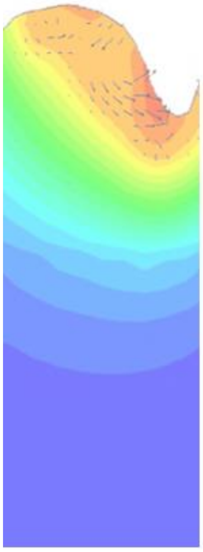
Manchester Team's research progress on WAAM materials characterisation (3)

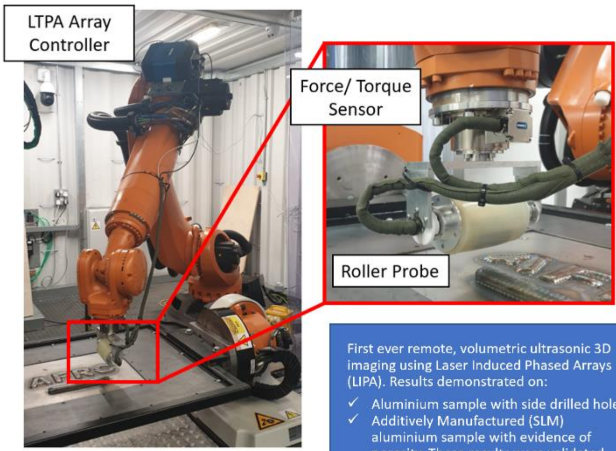
- The University of Manchester has also assisted Cranfield University with characterising beta grain refinement in Ti64 WAAM this last quarter. Test Ti64 WAAM walls were deposited using a faster and faster wire feed speed to reduce the energy density during deposition. The goal of this was to change the solidification conditions so that the columnar beta grains that are usually found in deposits of these kinds are avoided, and an equiaxed structure is achieved instead. This approach was successful in creating a homogeneous, equiaxed beta grain structure in Ti64, as can be seen by the EBSD maps below. The technique also helped to reduce the strong crystallographic textures found in typical Ti64 WAAM builds and is expected to improve the mechanical isotropy of the material.

New Wire Additive Manufacturing

Publications & Research Progress







First ever remote, volumetric ultrasonic 3D imaging using Laser Induced Phased Arrays (LIPA). Results demonstrated on:

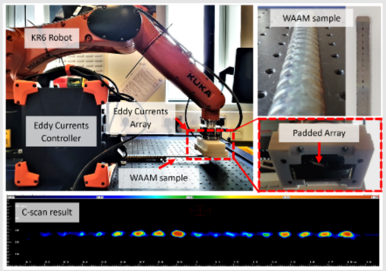
- ✓ Aluminium sample with side drilled holes
- ✓ Additively Manufactured (SLM) aluminium sample with evidence of porosity. These results were validated using XCT images of the sample.

Strathclyde Team's research progress

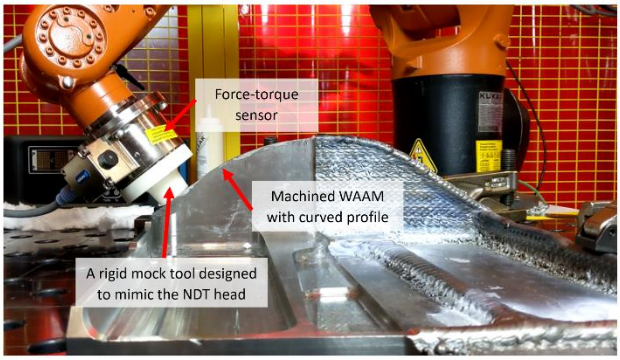
- The NDT team has begun first trials of an in-process NDT of as built WAAM. First steps included integration of the hardware within the cell. The grip brackets and the mounting plate were fabricated, and the array controller is now fixed directly on the robot. The cables coming from the roller-probe and the F/T sensor are now protected from the heat by a cable protector.
- The initial scans were performed on previously built titanium WAAM wall, testing, and calibrating the force/torque sensor driven motion with ultrasound data collection active. Additionally, from the week starting 28th of June, the deposition of the first test wall with in-process NDT was commenced. The wall built will contain artificial reflectors, in form of tungsten rods, and thermocouples, allowing to measure component's temperature during the inspection.

Strathclyde Team's Eddy Currents Testing Equipment Procurement and Preliminary Automated Tests

- A new Eddy Currents (EC) array controller was procured by Centre for Ultrasound Engineering (CUE), and a new custom-designed flexible eddy current array, capable of conforming to the complex surface of the as-built WAAM components and performing inspection at high temperature of 150 Celsius, was designed and manufactured. The array, connected to the EC controller, was delivered by a KUKA KR6 Agilus to the top as-built surface of a WAAM component containing far side (subsurface) EDM notches. All the notches, including the smallest one with dimensions of 0.5 X 0.5 mm located 2.5 mm beneath the surface, were successfully detected. The EC C-scan is not encoded as of yet however, it is planned as the next objective to be achieved in the project.

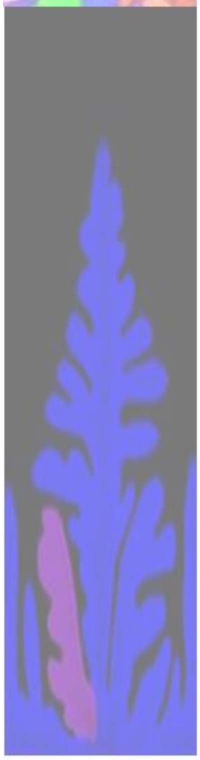


Strathclyde Team's robotic positioning and manipulation of the probe on the WAAM surface using the force-torque sensor feedback



- A controller was designed in the LabVIEW platform to update the robot's pose in real-time based on the feedback from the force-torque controller. The system allows to maintain a constant force between the NDT sensor (UT roller-probe / eddy current array) and the surface of the WAAM during the scan. Moreover, the controller enables the robot, and the sensor attached to it, to track and follow the WAAM surface contour during the scan allowing for a smooth scan of the WAAM while keeping the contact between the sensor and the surface intact. The package is already integrated within the RoboWAAM NDT system which will be demonstrated in the future issues.

Staffs & Students



New PhD student: Alireza M. Haghighi

- **Biography:** Alireza M. Haghighi is a PhD researcher at WELPC of Cranfield University. Alireza holds a BSc. degree of Mechanical Engineering-Heat & Fluids in Aug 2016. In Dec 2019 holds his MSc. degree of Applied Mechanics from Shahid Bahonar University of Kerman investigating on the effects of welding parameters, preheating and time interval on residual stress and distortion of joining ST52 T-shape stiffener ring in an AISI4130 thin-walled tubular shell. He has research background in fields of simulating and analyzing welding and additive manufacturing processes by means of numerical method and Image processing of porous materials. He has also industrial work experience with CNC wire cut machine at RADSANAT Co. at 2020-21. His hobbies are swimming and playing volleyball.
- **Project summary:** His research is focused on predicting the bead geometry of wire based direct energy deposition process by means of analytical and empirical methods and calculation of thermal mass of the process based on effective parameters such as tool path. Also, controlling the bead geometry according to the predicted thermal mass by means of adaptive parameters such as process parameters, deposition strategy and etc. and validating the results with numerical and experimental methods in order to modify and develop the bead deposition of wire based processes to a new level with less defects and higher precision and efficiency rate.

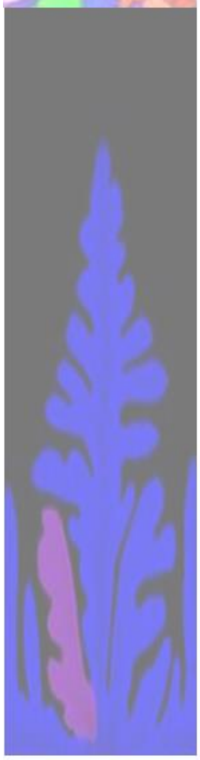
New PhD student: Farhana Zakir

- **Biography:** I started my PhD at Coventry University in September 2020. I completed my MSc in Advanced Materials from Cranfield University and bachelor's in Aerospace Engineering from Amrita University, India. My MSc thesis on hydrogen embrittlement in nickel fuelled my interest in mechanical performance of metals.
- **Project summary:** My research focus is on the fatigue and fracture behaviour of advanced titanium alloys fabricated by new wire additive manufacturing. Taking advantage of layer-wise deposition in the additive manufacturing process my project will focus on multi-material additive manufacturing of high strength titanium alloys. The joining of different metals can provide valuable insight for tailoring the performance of next-generation aero-engine products.

New PhD student: Jin Ye

- **Biography:** Jin Ye, one new PhD student joining the NEWAM team, comes from Guangdong Province, China. He completed his bachelor's degree in nuclear engineering at Grenoble INP, France in 2017 and one year later he handed in his master's degree thesis in ultrasonic non-destructive testing at University of Bristol. He was selected as the only intern in Bristol to Hitachi-GE Nuclear ltd, Japan, where he was working on stress evaluation in pipe cooling system in a power plant for two months. During his two-year professional stage as a research associate at a materials research centre in China, he had been involved in a few industry-related projects regarding residual stress characterisation and measurement in various fields including additive manufacturing. Since then, his research interest has moved to mechanical testing of additively manufactured samples for automobile and aerospace industries.
- **Project summary:** High strength aluminium alloys produced by the wire + arc additive manufacturing (WAAM) process will be the subject of his project. Current research has shown that AM processed aluminium alloys contain process-induced defects, e.g. gas porosity and lack of fusion defects, which can affect the mechanical properties especially under the fatigue load. For safety critical structural components, the influence of these defects on fatigue performance must be investigated before the applications. The main objectives are to investigate the defects in WAAM processed aluminium alloys, including the morphology, size and locations, to conduct experimental test under fatigue loads, to perform microstructure characterisation and residual stress analysis, and to conduct computer modelling of defect behaviour in order to understand the impact of these defects on fatigue strength of 3D printed aluminium alloys.

Staffs & Students



New PhD student: Panos Kamintzis

- **Biography:** I obtained my Masters of Engineering (MEng) in Electronics and Electrical Engineering from the University of Glasgow. I recently joined the Remote Ultrasonics Laser Lab. As a first-year PhD student in the FUSE CDT program, I could not be more excited for what lies ahead. I strongly believe that the work we are doing here in Glasgow will have a huge impact on the future of industrial ultrasonics as well as research. I am particularly interested in pursuing an engineering doctorate (EngD) in the sector of ultrasonic testing (NDT) or medical ultrasonics.
- **Project summary:** Panos is funded through the FUSE CDT, being sponsored by WAAM3D and the subject of his study is: "Automated Laser Ultrasonics for Metal 3D Printing Inspection". He is being supervised by Dr Stratoudaki and Dr MacLeod.

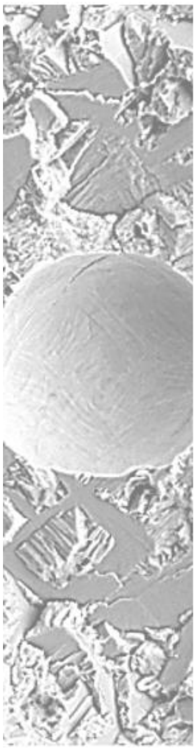
PhD graduation and new staff

Coventry University

Cranfield University

- Coventry Team's Shamir Muhammad, successfully defended his PhD thesis on 24/06/2021 with minor corrections. He started post-doctoral post with Cranfield University from April 2021.
- Cranfield Team are going to hire two new research fellows to work in the NEWAM project. The job advert has closed and the team have shortlisted the candidates to be interviewed. The team are glad that the research programme has attracted so many talented candidates from all around the world.

Conferences & Meetings



Strathclyde researchers' attendance of two conferences

The Cue will be presenting their WAAM-related research in the upcoming 48th Annual Review of Progress in Quantitative Nondestructive Evaluation which is organized by ASME and will be held virtually from July 28 to 30, 2021. The group has two submissions this year led by Ehsan Mohseni and Rastislav Zimermann. The titles for the two submissions are:

- A Bespoke Phased Array Inspection System Development Intended for Automated In-Process Inspection of Wire + Arc Additive Manufacturing (WAAM)
- Optimization of Virtual Source Aperture Imaging for Dry-Coupled Roller-Probe Inspection of As-Built WAAM Components

Abstracts accepted for:

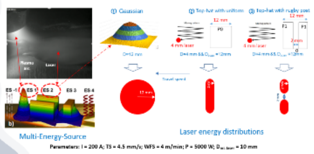
- "Adaptive Data Acquisition for Fast Ultrasonic Imaging Using Laser Induced Phased Arrays" Authors: P. Lukacs, G. Davis, T. Stratoudaki, S. Williams, C.N. MacLeod, A. Gachagan
- "Remote, Volumetric Ultrasonic Imaging of Defects Using Two-Dimensional Laser Induced Phased Arrays" Authors: P. Lukacs, G. Davis, T. Stratoudaki, Y. Javadi, S. G. Pierce, A. Gachagan .

I2MTC 2021 IEEE International Instrumentation and Measurement Technology Conference
To measure is to know
May 17-20, 2021 | Virtual Conference

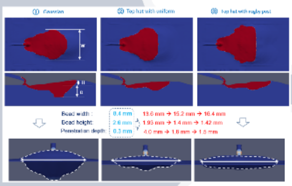
Presented: I2MTC, May 2021. Presentation of "Remote Ultrasonic Imaging of a Wire Arc Additive Manufactured Ti-6Al-4V Component using Laser Induced Phased Array" Authors: P. Lukacs, G. Davis, T. Stratoudaki, S. Williams, C.N. MacLeod, A. Gachagan

Invited presentation in Coupled 2021 conference: Numerical modelling of WAAM bead shape adjustment by adding a laser beam (Cranfield University)

X. Chen, C. Wang, J. Ding, S. Williams

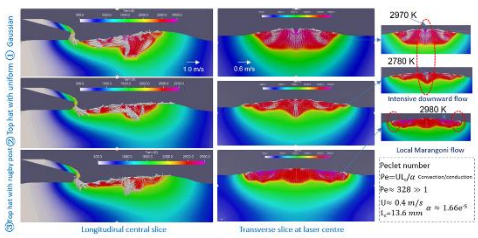


To control the melt pool size shape and melting feedstock independently during DED-AM, the multi-energy source is a good strategy. Recently, based on the NEWAM project, we realized the WAAM bead shape adjustment by adding a laser beam energy, including stationary laser and scanning laser. In this study, we want to better understand the underlying mechanism of bead shape adjustment with three different laser energy distributions by heat transfer and fluid flow modelling.



- The simulation results show that the width was significantly extended with laser energy compared to using single heat source (blue data). A wider and lower height bead shape can be obtained by adding a top hat with rugby-post laser energy, compared to the other two laser energy added. That bead shape is more likely to achieve near-net-shape deposition. Besides, a remelting in multilayer deposition would happen with a stationary Gaussian laser.

2021 COUPLED



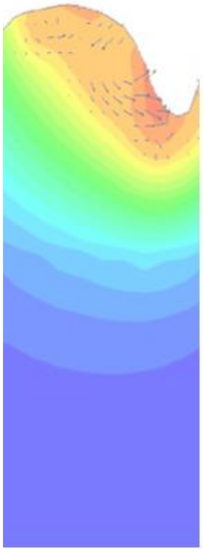
2021 COUPLED

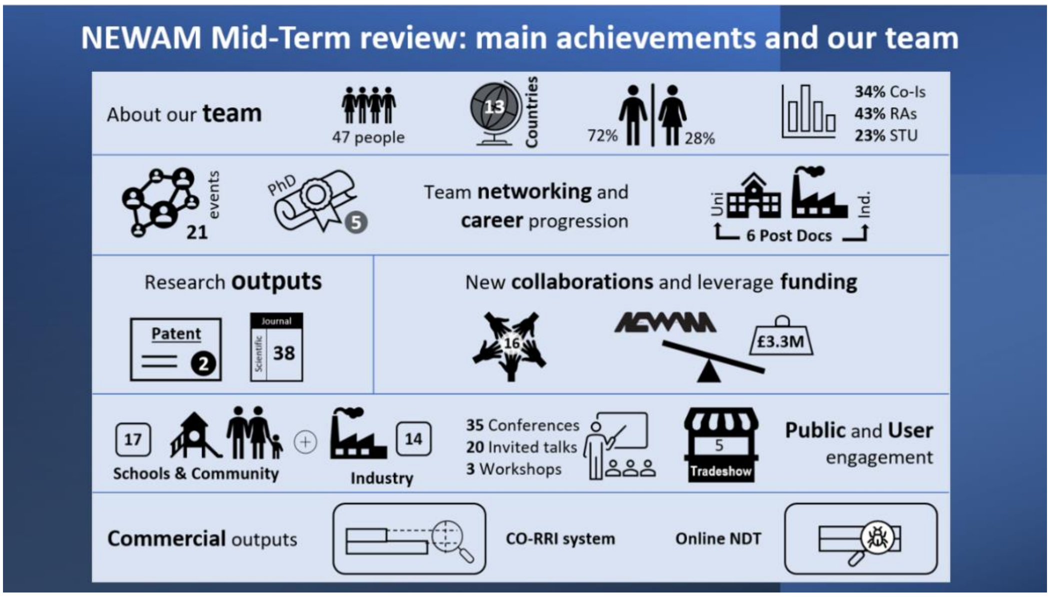
Invited presentation in Coupled 2021 conference

(Cranfield University)

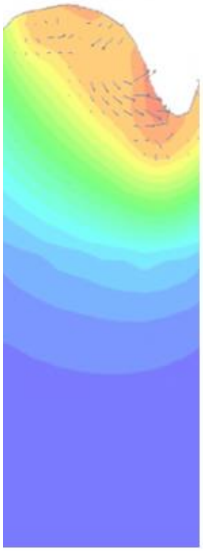
- The heat transfer and fluid flow simulations show that complex fluid flows occurred in the melt pool. The Peclet number is much larger than 1, inferring that the fluid flow dominates the heat transfer. The downward flow in the central melt pool at the laser input location increased the penetration depth. By adding a top hat with rugby-post laser energy, the local Marangoni flow increased the width and eased the central melt pool flow, which could play a key role in bead shape adjustment.

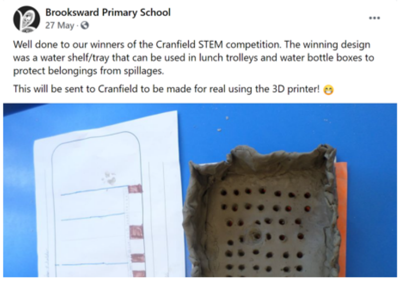
Collaboration & Impact





Outreach activity



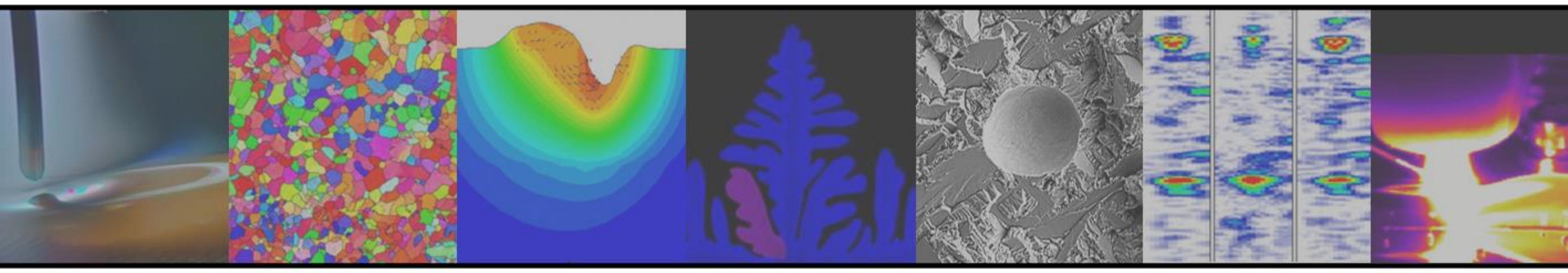


Outreach activity – Brooksward Primary School, Milton Keynes- Virtual event, May 2021

- On 25th and 27th May 2021, a team of Researchers and PhD students working on the NEWAM programme participated in the STEM week organised by Brooksward Primary School in Milton Keynes (4-11 year olds). Approximately 300 children took part of the event: on the first day, the pupils were shown the concept of Additive Manufacturing, how 3D printing worked and they also had a glimpse of the amazing work carried out in the Cranfield University laboratory. The children were then set with a challenge: design and build a model of something that would make the planet a better place (Foundation/Key Stage 1 pupils) and how to make the teachers' life better (Key Stage 2 pupils). On day two, each class presented their inventions to the NEWAM team, who voted for the best idea/concept. The winners will have their model 3D printed to display in their classroom. The children also had the opportunity to ask questions to the team about robots, science, apprenticeship, 3D printing and how much does an engineer get paid!

- **Feedback from Jen Swain, Head of School:** "Thanks again for organising this activity. It has really inspired a lot of them and some of the feedback I have had from teachers is that it engaged many of the children who aren't often that into designing and building and they have started to talk about other things they might want to design. The fact that all the children got to have a go and be involved was really great! Also, the children that were chosen to represent the year groups in many cases, were not the children that usually get chosen for things so it was great to see them get a confidence boost."

New Wire Additive Manufacturing



Further Reading

NEWAM website: https://newam.uk/
NEWAM LinkedIn: https://www.linkedin.com/in/newam-epsrc-programme-grant-6617091a9/
NEWAM ResearchGate: https://www.researchgate.net/project/New-Wire-Additive-Manufacturing-NEWAM

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