Growing through the challenges

NEW WIRE ADDITIVE MANUFACTURING

EP/R027218/1

Report

2020

CONTENTS

PROJECT OVERVIEW 2020

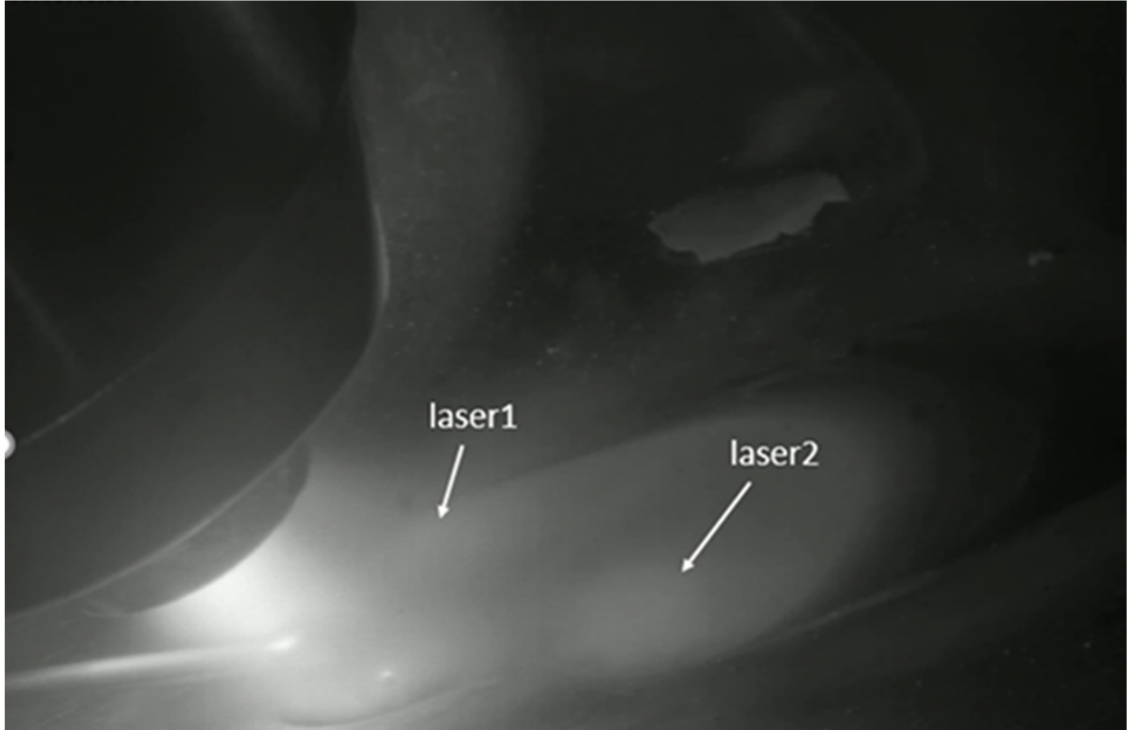
"Excellent progress is being made towards achieving this with all models developed and currently being validated."

Prof. Stewart Williams
NEWAM Principal Investigator and Professor of Welding Science and Engineering at Cranfield University

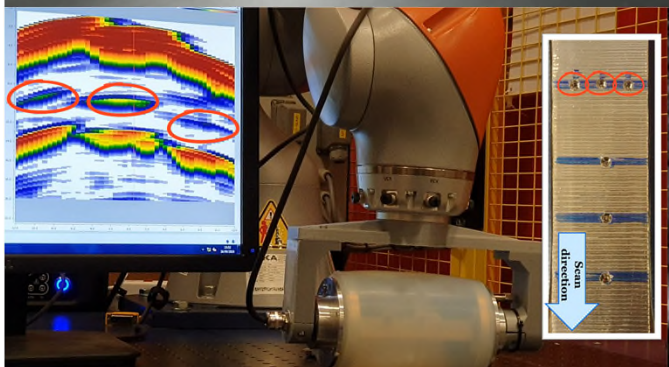
" This year has been very challenging year of course but, as expected, the whole NEWAM team has risen to these challenges with great strides forward being made towards our programme goals. Particular highlights for me include; validation of the multi-energy source concept, the first demonstration of robotic dry NDT for in-process inspection of AM components and real time shape measurement of deposited profiles.

Academically we have set the research team intermediate challenges to prove the much sought after concept of integrated materials and process modelling, combined with innovative process development to obtain full control of material microstructure in as-deposited materials. Excellent progress is being made towards achieving this with all models developed and currently being validated.

Perhaps the most satisfying aspect of NEWAM so far is that 4 research teams, based at 4 Universities, are now fully integrated and working in a highly collaborative way. This is leading to the whole being much greater than the sum of the parts. I believe this is major achievement which the whole team should be proud of."

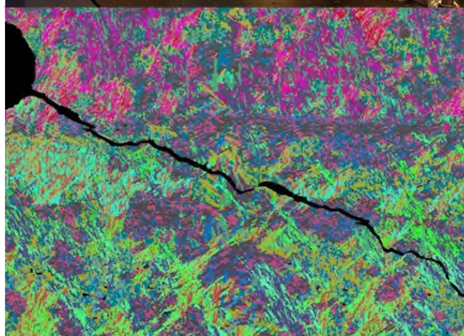


Multi-energy source (MES) with two stationary laser beams



Robotic NDT process inspection

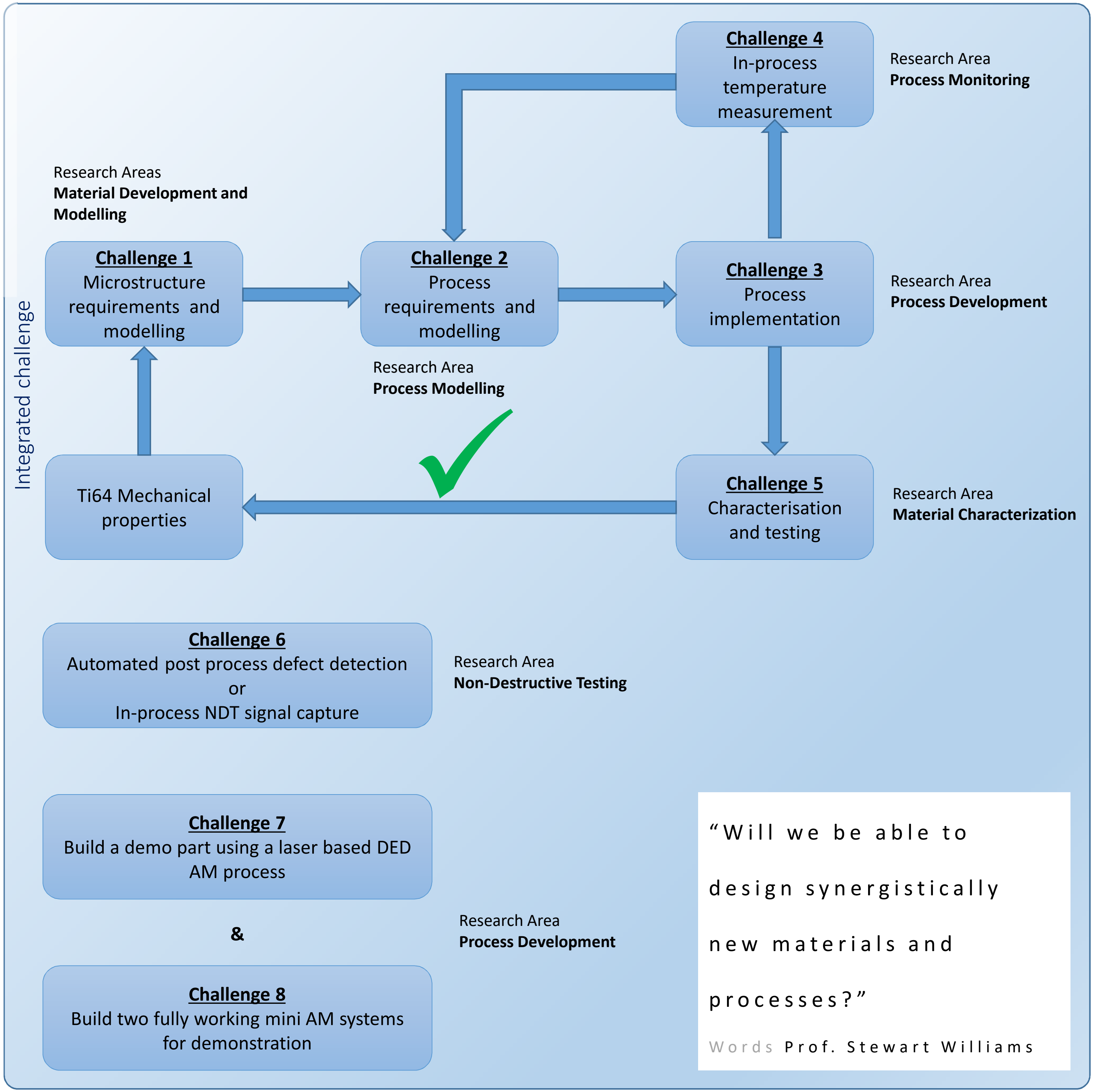
MES with oscillated laser beam



Fatigue crack growth analysis

Shape measurement of deposited profiles

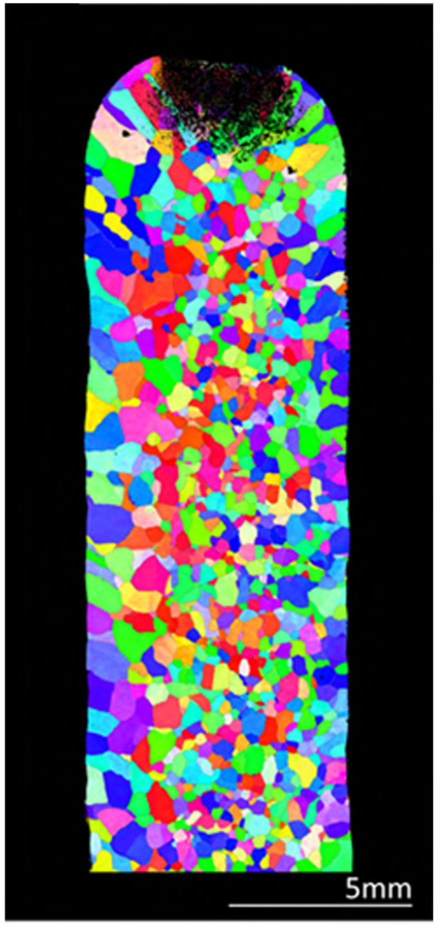
Our challenges for 2021



"Will we be able to design synergistically new materials and processes?"

Words **Prof. Stewart Williams**

Getting closer to our final goal



Smarter process better properties…
Extended process conditions and new way of melting feedstock to achieve equiaxed grains and isotropic properties

"New better process for high deposition net-shape and tailored properties…"

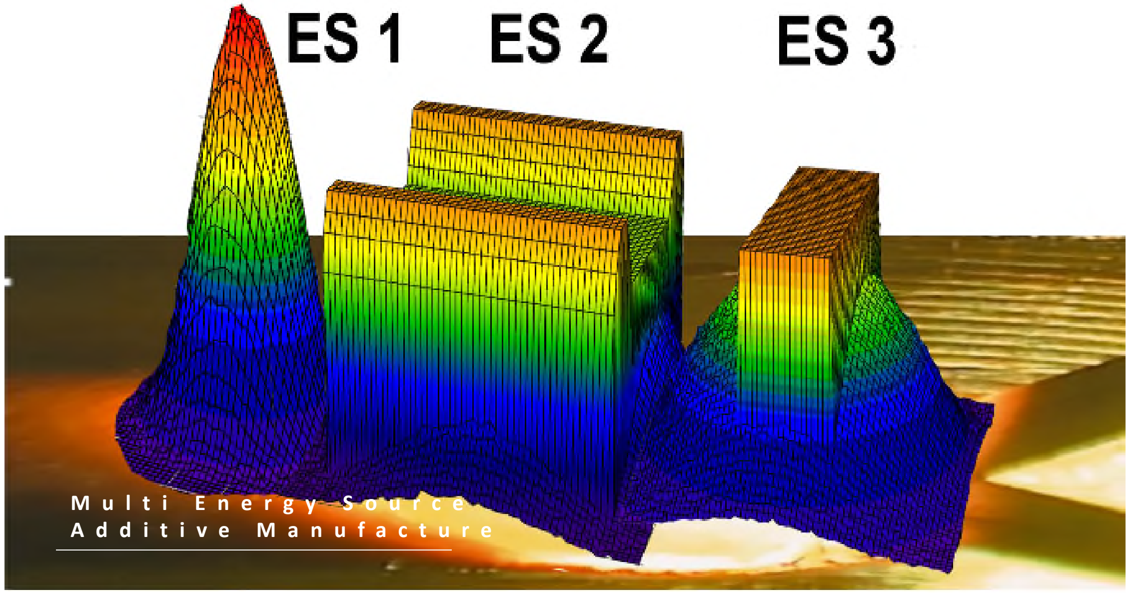
This research area acts as the engine room for all the development tasks in the NEWAM. Here we put together all innovations and validate them in semi-industrial conditions.

We aim to develop a new multi-energy source process using lasers and arc-based processes, for high fidelity high deposition rate wire-based additive manufacture. A new smart control of the energy distribution is the key to expand thermal conditions of the process to match the metallurgical requirements of the feedstock material, and hence enhancing mechanical properties of as built parts.

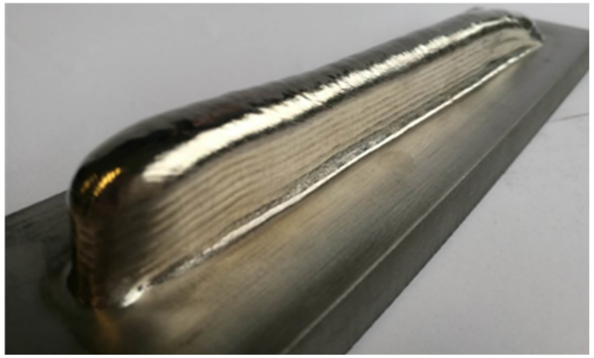
So far, the main hypothesis of the dynamic control of the energy distribution and the multi-energy deposition has been validated. We also understand how to tailor the process energy to the feedstock shape to maximise the utilization of energy and deposition rate.

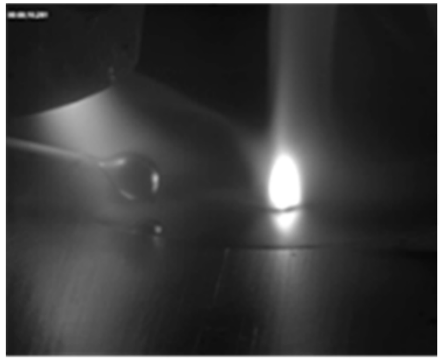
This process is going to revolutionise wire-based additive manufacture by providing net-shape parts at low cost and with tailored mechanical properties.

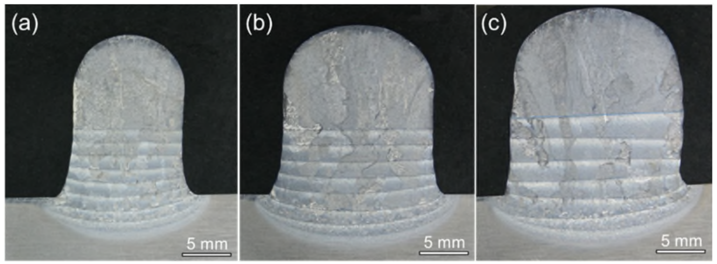
We are looking forward to prove it on real aerospace parts.

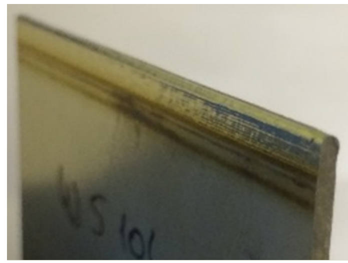


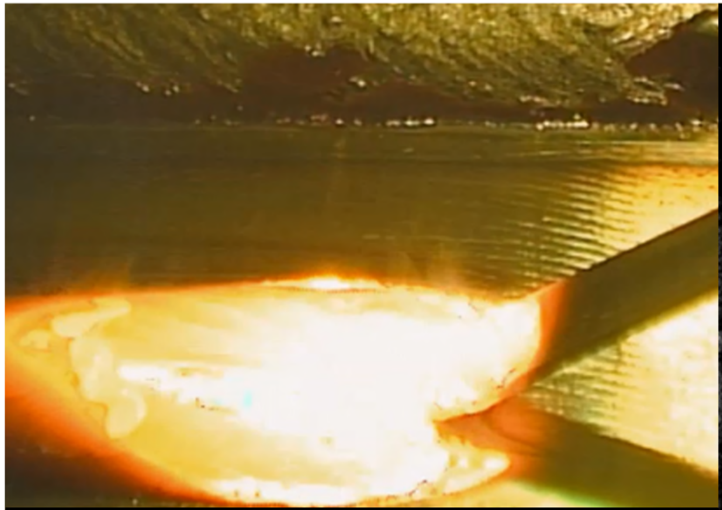
More than words…
Combination of the high resolution and precision of lasers with the efficiency of plasma arc into laser arc approach with a smart control of the energy distribution. High deposition rate with net shape and flexible control of printing resolution.

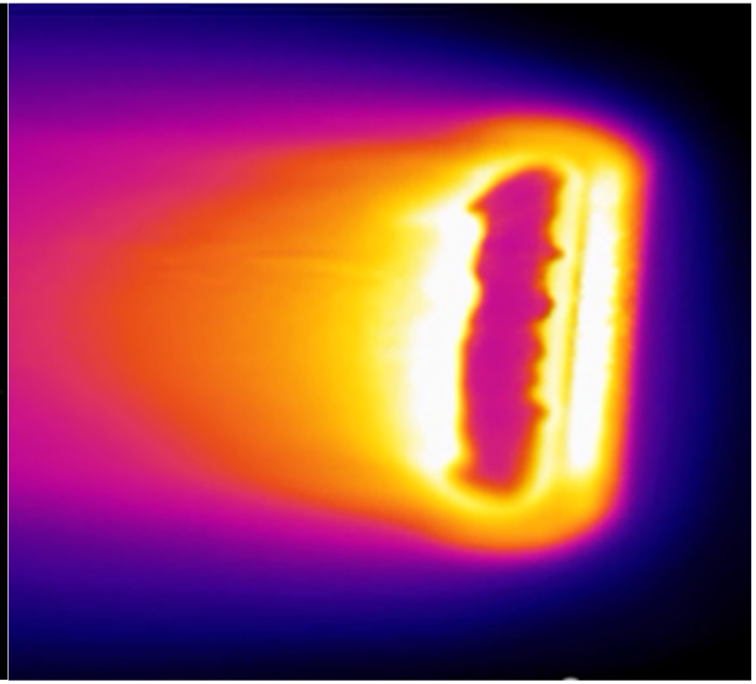












Shaped feedstock and tailored energy distribution key to high quality, efficiency and good control

Multi-energy source process development

A new hybrid process has been developed and its excellent versatility proven. We can achieve net-shape simple components (low surface waviness) at deposition rates of up to 4 kg/h in titanium. Good process tolerance to the wire positioning accuracy and independent control of deposition rate and thermal input makes it a perfect candidate for the next generation wire-based additive manufacture technology.

Tailored energy profile

Various beam shaping techniques have been modelled by the Process Modelling team and validated by the Process Development research area. This gives a high flexibility in controlling the heat source precisely, to deliver an accurate amount of energy just enough for melting of the feedstock, but without unnecessary re-melting and thermal damage to the underlaying layers. We can achieve the dynamic control of the processing conditions and hence control of the bead shape.

New feedstock wires

Different feedstock materials were tested, the shape of which was tailored for additive manufacture purpose, rather than for welding, unlike in the commonly used welding wires. By doing so we could improve melting efficiency and increase the deposition rate by a factor of two.

In process microstructure control

New feedstock wires and a smart control of melting characteristics enabled us to extend the process window to match the thermal requirements of α+β titanium alloys and achieve equiaxed grains with isotropic conditions. The basic concept has been tested the process robustness and tolerance are investigated.

Research Area Leader
Dr. Wojciech Suder

FIND OUT MORE
Visit https://newam.uk/research-areas/research-area-1

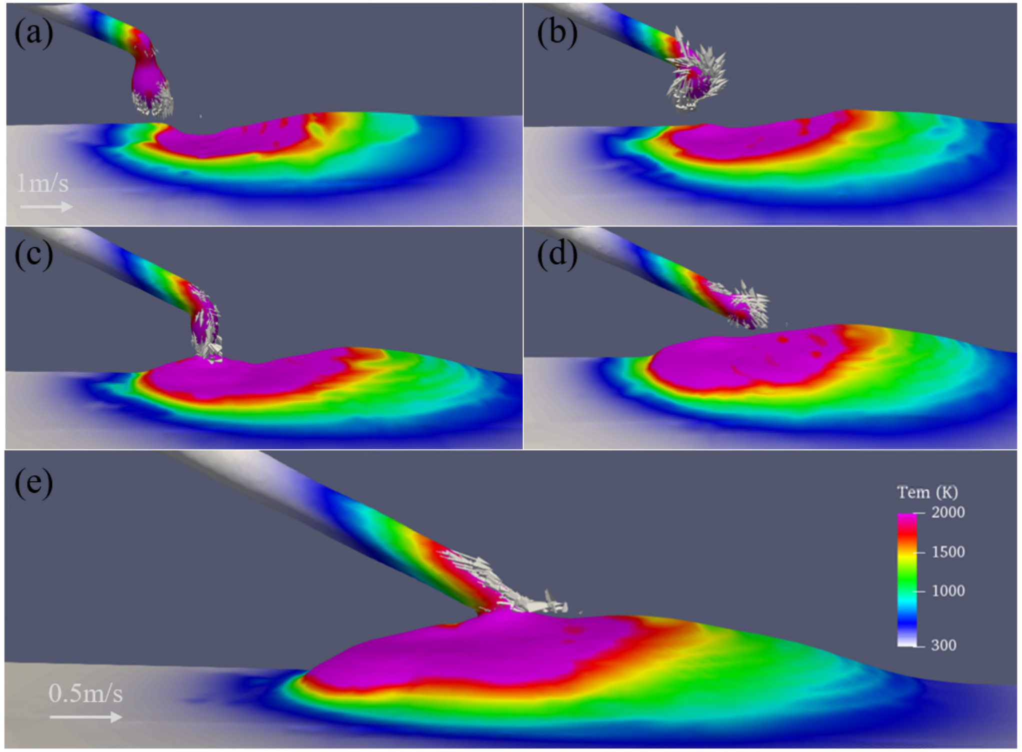


Figure 1: study of droplet transfer with different WFS: (a) 1 m/min; (b) 2 m/min; (c) 3 m/min; (d) 4 m/min; (5) 5 m/min.

CFD study of WAAM with wire meting and droplet transfer

A three-dimensional transient multiphase model has been developed to study the coupling behaviours of the heat transfer, wire feeding and melting, metal transfer, fluid flow and solidified deposition in the WPAAM process. The complex fluid flow behaviours and flow patterns in the melt pool considering the metal transfer effect as well as the surface tension, Marangoni shear stress, arc pressure and arc shear stress have been investigated. The effect of the metal transfer on the bead shape has been studied with this model and verified with experimental results. Figure 1 shows the melting and droplet transfer mode when different wire feed speed was used. When the WFS increased from 1m/min to 5 m/min, the transfer mode changed from droplet, to liquid bridge + droplet, to surface tension + solid. When the WFS is 5m/min, the wire is partially unmelt when it's fed into the melt pool, this introduce a cooling effect of the melt pool and narrows the bead geometry.

Study of thermal gradient and solidification rate with multi-layer model

In order to be able to predict the microstructure evolution, a multi-layer CFD model has been developed to provide detailed information of the thermal gradient and the solidification rate of the solidification front. Many different process conditions have been studied with variable travel speed, deposition rate, base temperature, and melt wire temperature. It has been found that increasing the base structure temperature can significantly reduce the thermal gradient, while increasing the travel speed can significantly increase the solidification rate, and both are better for obtaining equiaxed microstructure of the Ti64 alloy. This model will link to the material microstructure model and together the models will provide scientific understanding and guide to the process development. In the next step, this work will be extended to multiple heat source and the model will be validated with the experimental results.

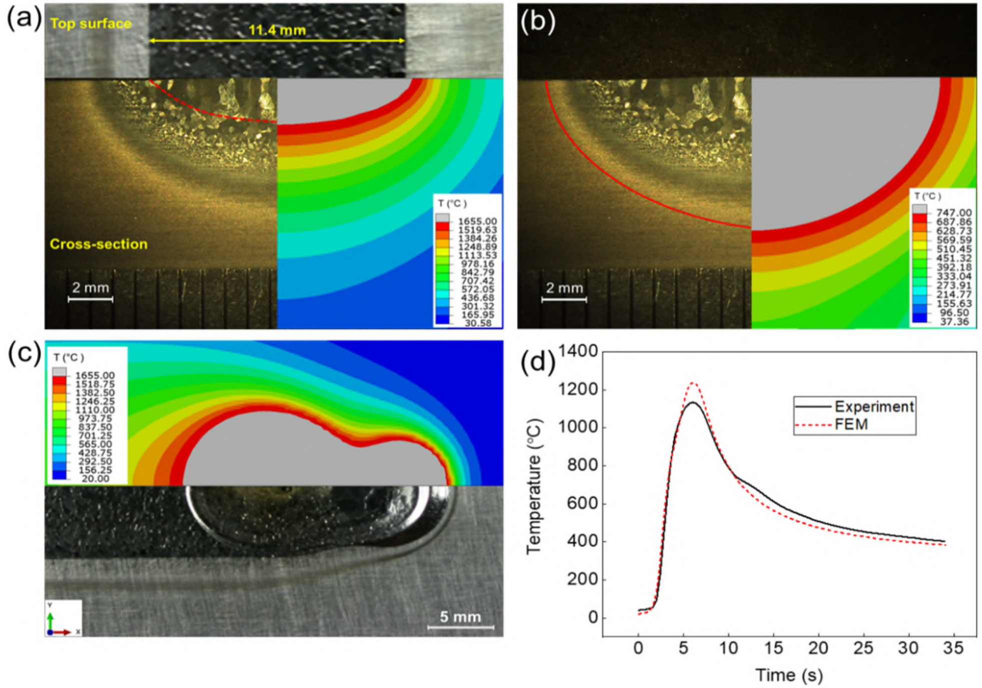


Figure 2: FE thermal model of laser + arc heat source

Research Area Leader
Dr. Jialuo Ding

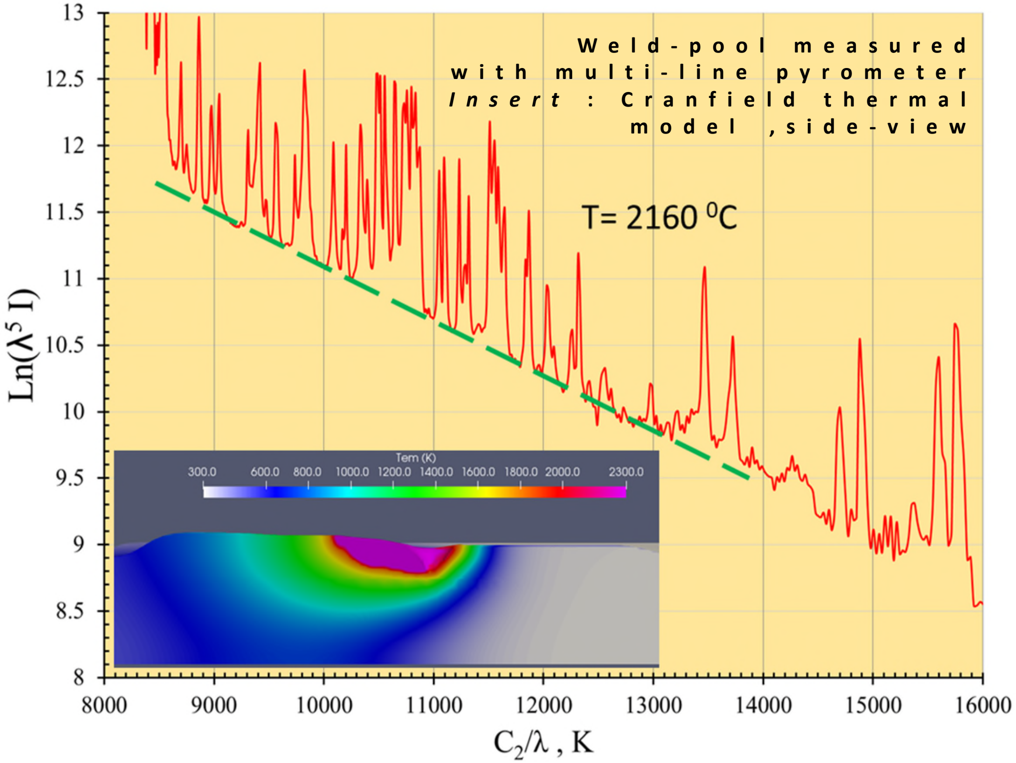
FIND OUT MORE
Visit https://newam.uk/research-areas/research-area-5

FE model of hybrid plasma arc- laser deposition process

A three-dimensional steady state finite element model has been built to study the effect of process parameters including laser power, travel speed, separation distance between two heat sources, and laser beam diameter on the thermal behaviour of Ti-6Al-4V in hybrid PTA-laser melting process. As shown in Figure 2, the model has been validated with experimental results and shows good match. This model can be used to predict the thermal behaviours of the hybrid process both effectively and efficiently. 2. The melt pool geometry responds more significantly to the total energy input compared to energy distribution. In particular, due to the increased energy input, the width and depth of the molten pool increase as the laser power increases and the travel speed decreases, and due to small changes in energy, the separation distance of the molten pool and the size of the laser beam are not sensitive to input. This model will be further developed to a process designer to be used for process parameter design.

Equivalent heat source model for scanning laser

An effective three-dimensional transient thermal model has been developed to study the thermal distribution of scanning lasers with different oscillation frequencies and paths. An adaptive convection boundary method has been developed, which can significantly reduce the number of model elements, thereby greatly reducing the calculation time. It has been found that for a constant oscillation width and sufficient laser power, when the oscillation frequency is higher than a few tens of Hz, the size of the molten pool becomes quasi-static along the advancing direction. An equivalent heat source with an energy distribution defined along the lateral direction can be used to achieve a molten pool size and thermal history similar to an oscillating heat source, which has been validated to experimental data. Since the steady-state thermal model can be used, the calculation speed can be greatly increased. This equivalent heat source model of the scanning laser will be integrated with the other heat source models to assist the multi-energy source design with fast thermal predictions.



TEMPERATURE – PYROMETRY

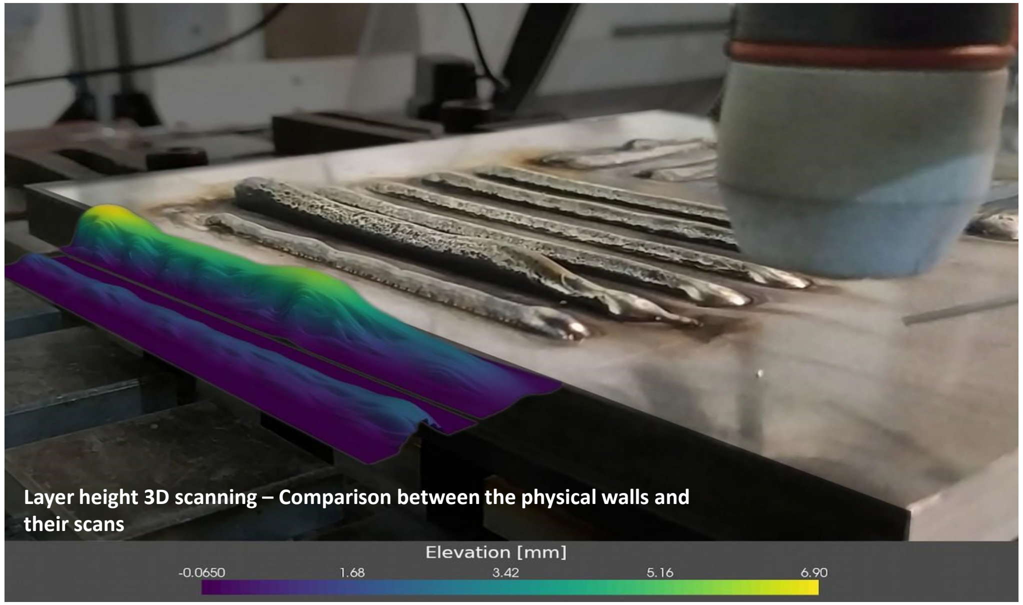
- Progress has been made in measuring the temperature gradient behind weld pool.
- Activity is now directed at measuring the thermal field of the weld pool to ensure equiaxed material properties during WAM deposition.
- Commercial pyrometers have, so far, been used to measure the weld pool at one location.
- Initial results compare well with thermal models.
- A `tunable` multi-line pyrometer has also been developed to measure weld pool temperatures.
- Key advantages of this technique are: immunity to plasma interference, independent of material emissivity data and process versatility.

TEMPERATURE – THERMAL CAMERAS

- Concept design work has started on using high resolution cameras to measure the 2D thermal field of the weld pool.
- These will have a filtered spectral response suppressing the plasma emission wavelengths.
- Camera optics to be investigated are endoscopes and conventional optics.

Research Area Leader
Prof. Ralph Tatam

FIND OUT MORE
Visit https://newam.uk/research-areas/research-area-7



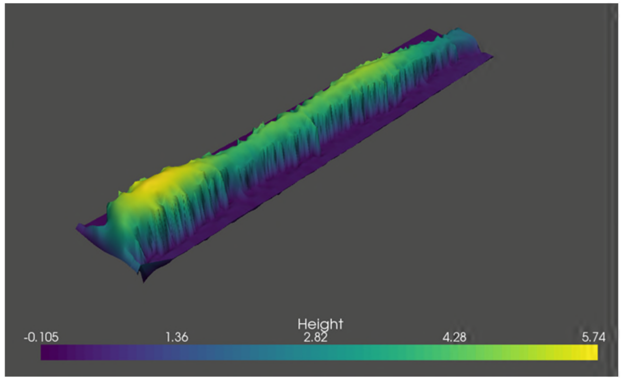
Layer height 3D scanning – Comparison between the physical walls and their scans

Layer height – 3D scanning

- Progress has been made in implementing a scanning system using Range Resolved Interferometry.
- Initially, the objective was to develop a static, layer height system.
- Due to the successful demonstration of a concept scanning system the development direction has changed.

For the scanning design, the remaining tasks are:

- Develop the embedded to software for driving the galvanometers.
- Develop the software for the acquisition of the 3D data.
- Design and develop a robust optical scan head for the layer height sensor.



Three dimensional surface extrapolated from the scanned point-cloud.

LASER ULTRASOUND

Laser ultrasound provides a truly remote and non-contact measurement capability. Traditional detection systems cannot operate effectively from the rough surfaces encountered in WAAM samples.

New rough surface interferometry provides the capability to operate from these real surfaces.

The instrument is fibre coupled to allow delivery in places of restricted access and allows stand-off distance of up to 500mm from the inspected component. Our aim is to use it as the detection system in 1D and 2D LIPAs (laser induced phased arrays), corresponding to 2D and 3D (volumetric) ultrasonic imaging on as-deposited samples.

FIND OUT MORE
Visit https://newam.uk/research-areas/research-area-6

HIGH TEMPERATURE ULTRASOUND PROBE

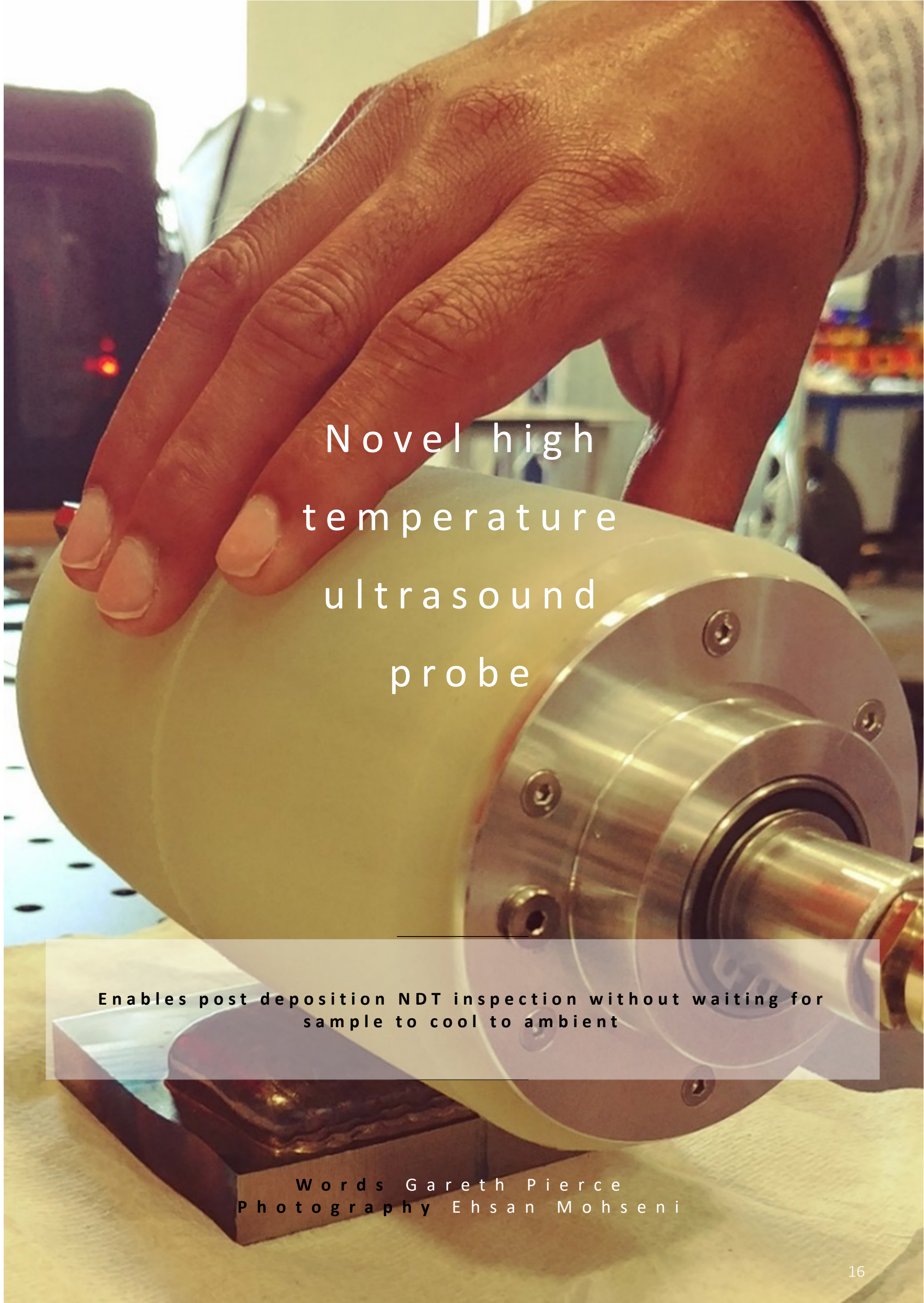
The novel high temperature ultrasonic phased array wheelprobe can operate on substrates up to 350 ^{o}C allowing for interpass inspection without having to wait for the sample to cool to ambient.

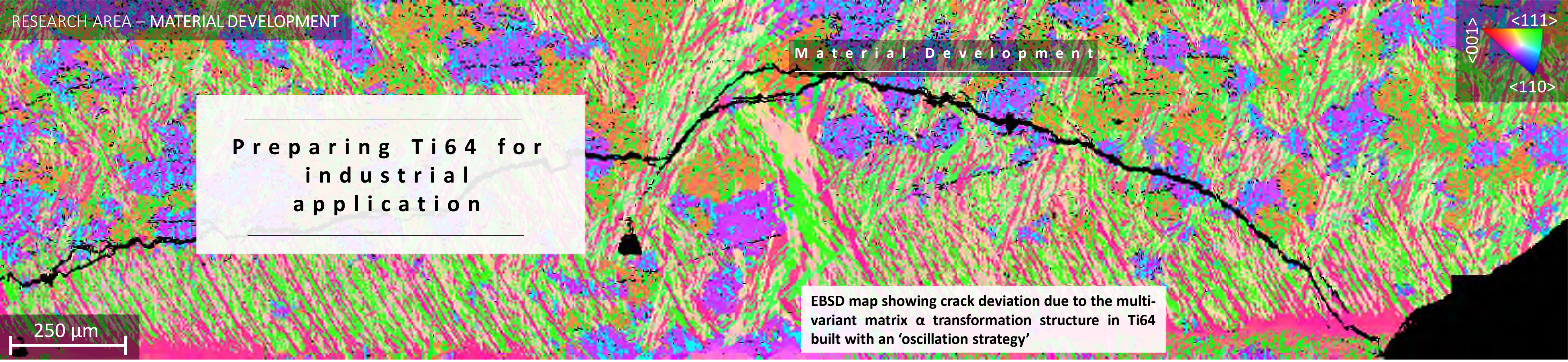
Using robotic delivery of the sensor ensures compatibility of the NDT process with the WAAM deposition process.

The conformable nature of the wheelprobe means the sensor is compatible with the rough and non planar surface finish of WAAM deposition.

New signal processing algorithms have been developed to compensate for the complex ultrasonic beam refraction encountered at interfaces in the ultrasound path.

Research Area Leader
Prof. Gareth Pierce





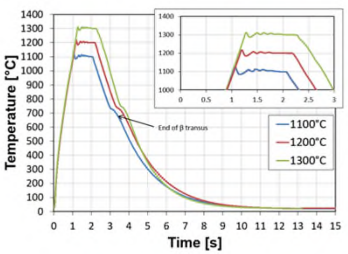
Preparing Ti64 for industrial application

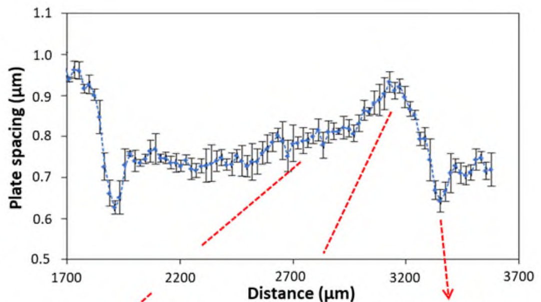
EBSD map showing crack deviation due to the multi-variant matrix α transformation structure in Ti64 built with an 'oscillation strategy'

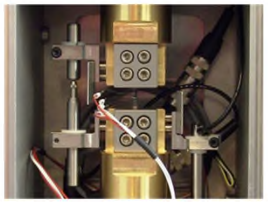
Aims

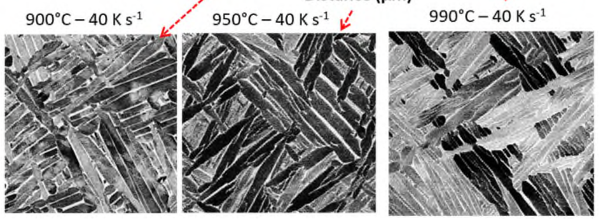
One of the aims of NEWAM is to increase confidence in using WAAM Ti64 components in the aerospace industry, by developing a deeper understanding of the microstructural factors that control their in-service behaviour and need to be optimized to ensure consistent, reproducible, performance. Aided by the mechanical testing studies performed at Coventry, this work is being extended to include a better understanding of the effect of the processing conditions on damage tolerance (e.g. fatigue crack growth) which is essential for aerospace applications.

Work at Manchester has focused on studying the relationships between the process conditions and microstructure development in WAAM builds, and in particular the micro-texture heterogeneity, which has been identified as being important in controlling fatigue crack propagation in WAAM deposits. A key aspect of this is understanding and predicting the transformation microstructure that develops from the primary β grain structure that forms on solidification and how this is affected by the multiple thermal cycles it experiences during deposition. We are also working towards obtaining more consistent transformation microstructure by predicting the microstructure formed as a function of the local conditions and developing post-build heat treatments.









Example of the coarsening of the α lamellar spacing measured across a typical added layer typically seen in an as-built WAAM component, caused by the steep thermal gradient below the heat source, replicated in an ETMT thermal simulator.

Modelling

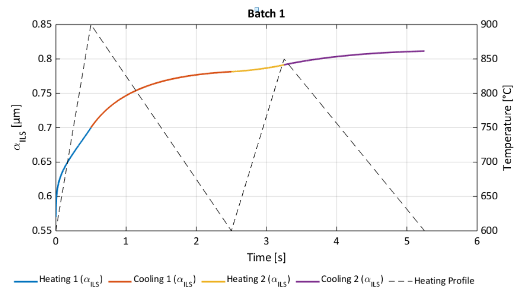
To date, a process model has been developed to predict the local α lath spacing after completion of a WAAM Ti64 part. To achieve this the thermal cycle was split into three regimes. A high temperature region above the β transus where β grain growth was modelled and the effect of cooling rate on the initial lamellar spacing was predicted. On subsequent thermal cycling below the β transus the behaviour of the transformation microstructure was split into two regimes; i) exposure to rapid high temperature rises within the β approach curve, where fast coarsening occurs assisted by partial dissolution of α, and ii) a lower temperature regime where longer-term thermal exposure can occur during building large parts.

When coupled to a process model, this approach is very useful for ensuring more consistent and uniform strength deposits, but it does not capture the complexity of the key features of interest, which are important in determining crack deflection, such as the width of the grain boundary α single variant colonies, the local texture, and scale of the multi-variant matrix colonies. Future work by the modelling team will therefore involve using more sophisticated phase field simulations to study further the β → α phase transformation response under WAAM conditions and subsequent coarsening during thermal cycling, which will then be coupled with crystal plasticity simulations using the DAMASK code modelling framework.

When starting with a refined β primary grain structure, we are also investigating the potential of using post build-heat treatments to produce WAAM parts with microstructures that fully replicate the β-annealed condition commonly used in commercial airframe applications for fatigue critical components.

"Ti64 is the workhorse titanium alloy for industry. Our research on maturation of WAAM Ti64 aims to increase understanding of the complex factors that control the microstructure-property relationships in components – to enable optimisation of performance and consistency."

Prof. Phil Prangnell
Research Area Leader



First stage process model output showing the predicted α lamellar response to two simplified linear heating and cooling cycles.

Refining the columnar β grain structure in WAAM Ti-64 using metallurgical additives

EBSD map showing the successful grain refinement due to TiN additions in top layers of an experimental build.

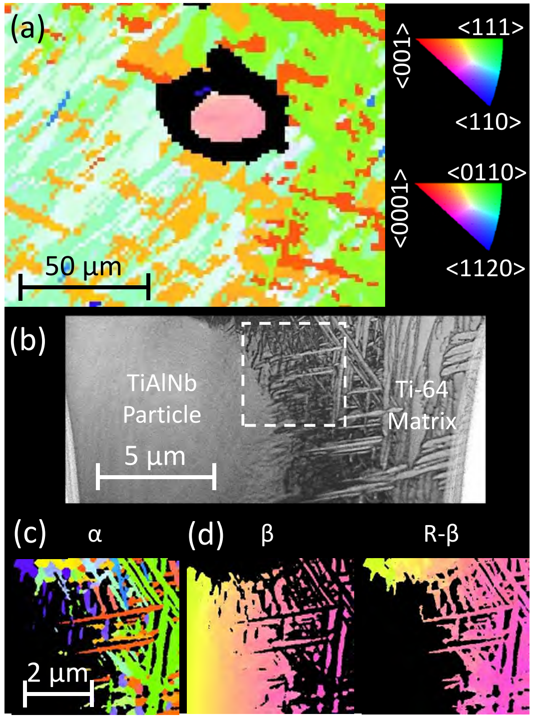
WAAM Ti-64 inoculation via TiN additions
Columnar β structure eliminated

Wire-Arc Additive Manufacturing (WAAM) of large near-net-shape titanium components has the potential to reduce costs in aerospace applications. However, with titanium alloys, such as Ti-6Al-4V, standard WAAM processing conditions result in solidification microstructures comprised of large cm-scale, <001> fibre textured, columnar beta grain, which are detrimental to mechanical performance. Within the WAAM project we are therefore investigating metallurgical additives that can reduce the size of the solidified β-grains, as well as refine their columnar morphology and randomise their texture. This includes the use of growth restriction additions and inoculants. Two types of inoculant are being investigated; i) phases that form stable compounds in liquid Ti, and ii) high melting point isomorphic Ti -alloy particles.

Successful refinement has been demonstrated with both approaches. Isomorphic additions have the advantage that they don't lead to brittle particles being dispersed in the material, but are more difficult to control as this technology is dependent on them surviving dissolution in the melt pool.

An example is included here of the high potential of cubic nitride phase inoculants, with both TiN and ZrN studied. To avoid the cost of manufacturing new wire experimental trials were performed using powder adhered to the surface of the deposited tracks. With TiN particle additions, the β grain size was successfully reduced and modified from columnar to equiaxed grains, with an average size of 300 μm, while ZrN powder was shown to be ineffective at the low addition levels of interest. Clusters of TiN particles were found to be responsible for nucleating multiple β Ti grains. By utilizing the Burgers orientation relationship, EBSD investigation showed that a Kurdjumov-Sachs orientation relationship could be demonstrated between the refined primary β grains and TiN particles.

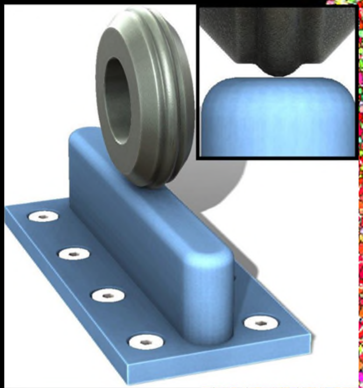
FIND OUT MORE
Visit https://newam.uk/research-areas/research-area-2

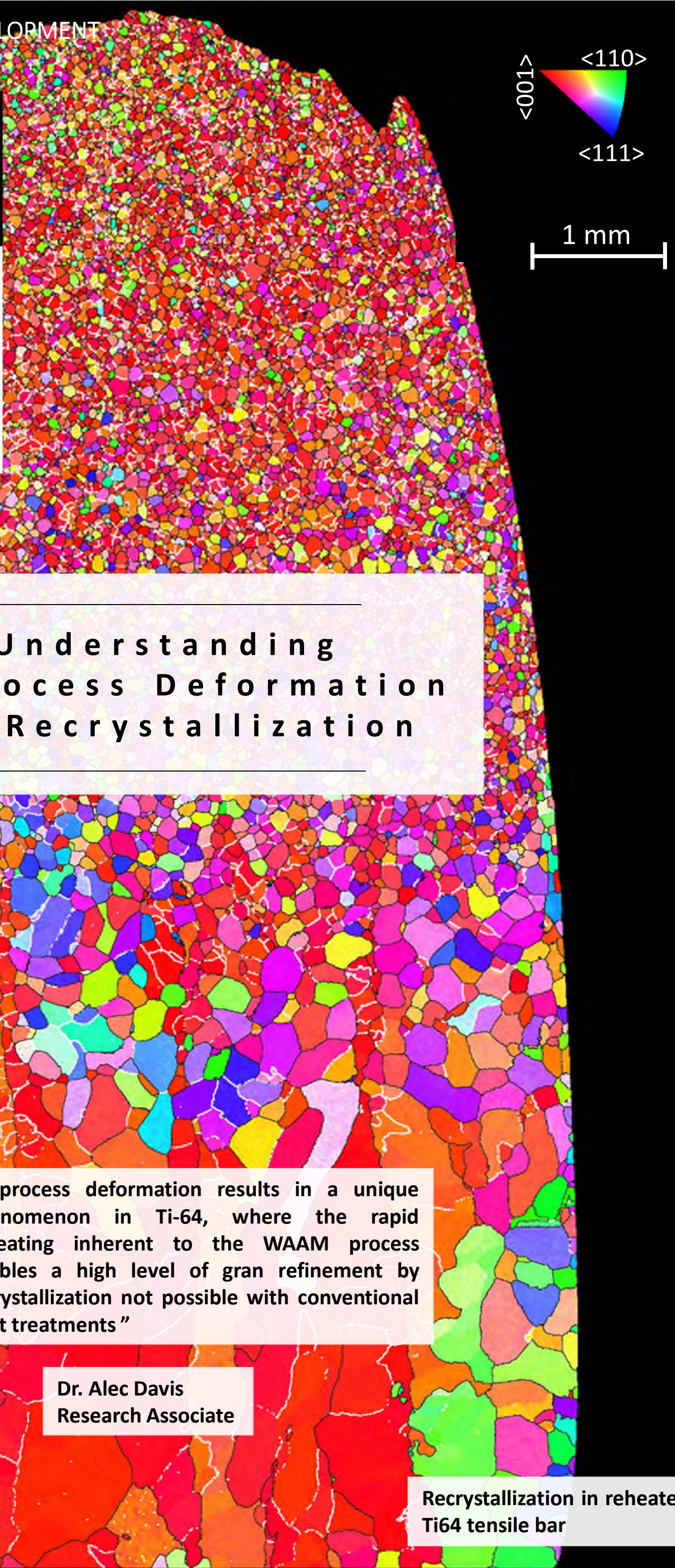


Isomorphic Inoculation of Ti-64
Non-Nucleation Mechanism Confirmed

The potential for using isomorphic inoculation (ISI) to grain refine titanium alloys in additive manufacturing was investigated by adding TiAlNb particles to Ti-64 during building test samples. Surviving particles were identified and their crystallographic relationship with the matrix studied by transmission Kikuchi diffraction (TKD). The particle and bulk matrix grain were shown to have the same crystallographic orientation, demonstrating that the ISI mechanism of solidification bypasses the nucleation step in favour of direct epitaxial growth.

(a) EBSD map showing a TiAlNb isomorphic particle and the surrounding α phase matrix. (b-d) High magnification TKD (TEM orientation map) investigation of the particle/matrix interface; (b) band contrast image across the interfacial region, (c) IPF ND orientation maps of the indexed α, and (d) a composite image showing coincidence between the directly indexed β, associated with the particle (left) and the reconstructed parent β orientation in the matrix (right).





Understanding In-Process Deformation for Recrystallization

"In-process deformation results in a unique phenomenon in Ti-64, where the rapid reheating inherent to the WAAM process enables a high level of gran refinement by recrystallization not possible with conventional heat treatments"

Dr. Alec Davis
Research Associate

Recrystallization in reheated Ti64 tensile bar

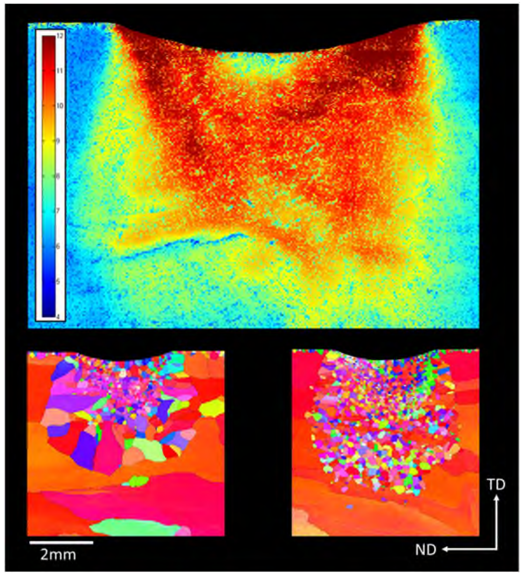
Material Development

It has been shown that the coarse columnar β grains in Ti-6Al-4V WAAM can be refined by the application of relatively low strain inter-pass deformation. In-situ experiments and simulation, has revealed that this probably occurs by a novel recrystallization mechanism unique to am that involves twinning during β regrowth on rapid heating through the α-β transus, which also reduces the texture strength.

Quantification of Strain Fields

Accurately measure strain with EBSD analysis

To understand the effectiveness of applying Inter-pass deformation to large parts, which necessitates the use of surface contoured rolling, or peening, an SEM-based strain mapping technique has been developed to quantify the depth of penetration and coverage of the plastic strain fields. This technique is based on calibration of the average point-to-point Local Average Misorientation (LAM) of α-phase lamellar variants in EBSD orientation data to the local plastic strain. When combined with the recrystallization and grain growth process maps it is then possible to predict the depth of recrystallization and grain size achievable.

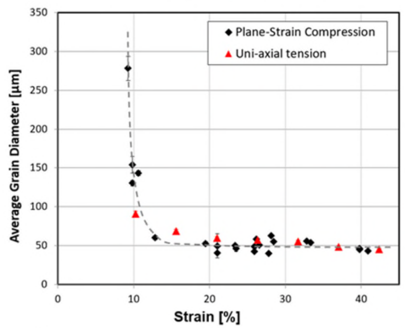


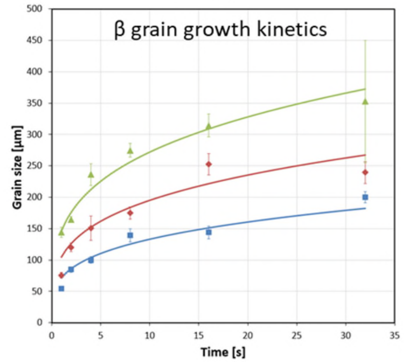
LAM strain map from a contoured surface roller (a) and levels of β recrystallization achieved for different rolling loads following a WAAM simulated heating cycle.

To develop a process map, and enable the texture contributions from different recrystallization mechanisms to be more unambiguously discriminated, samples were subjected to strain gradients using different deformation modes – uniaxial tensile deformation and plane-strain compression. At low strains the tensile-deformed samples (opposing page) produced the same unusual unique micro-texture seen previously in plane strain compression, despite the different deformation mode, but this disappeared at higher strains, providing more evidence in support of a new rapid heating β recrystallization mechanism.

Simulation of the deformation and modelling of the grain growth kinetics has shown that a consistent grain size can be achieved following the application of a readily achievable plastic strain greater than only ~ 15%, which has been attributed to the unusual α→β transformation related rapid heating recrystallization behaviour noted above. However, following recrystallization the grain size then increases significantly during thermal cycling above the β transus, indicating that the application of thermal control techniques would be beneficial in further reducing the final grain size achieved.

Recrystallized β grain size vs plastic strain





CIPHER: CALPHAD Integrated Phase-field Solver

CIPHER is a state-of-the-art computational tool developed to predict microstructure evolution in complex alloy systems.
Features include:

- Automatic parallel adaptive mesh refinement.
- Local truncation error estimates and adaptive time stepping.
- Designed for large number of phases (10-10000), with constant computational complexity.
- Efficient implementation with direct use of CALPHAD thermodynamic models for multi-component systems.
- Designed for MPI parallelization and scalability.

"Our work developing computational tools to predict microstructure evolution is a key step towards the digitization of wire-based AM technologies"

Dr. Pratheek Shanthraj, Research Area Leader

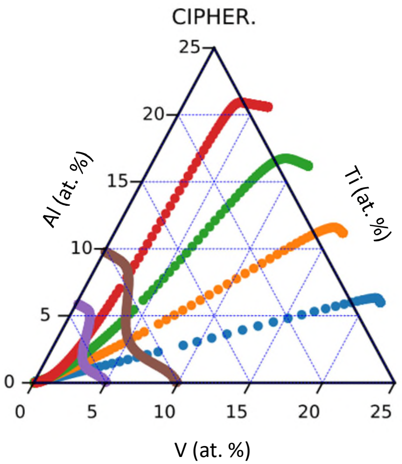
FIND OUT MORE
Visit https://newam.uk/research-areas/research-area-4

Multi-component diffusion

In titanium alloys, such as Ti-5Al-5V-5Mo-3Cr, the Wire-Arc Additive Manufacturing (WAAM) process can result in a significant amount of chemical heterogeneity in the from of segregation. Homogenization of these materials is often needed to improve mechanical properties.

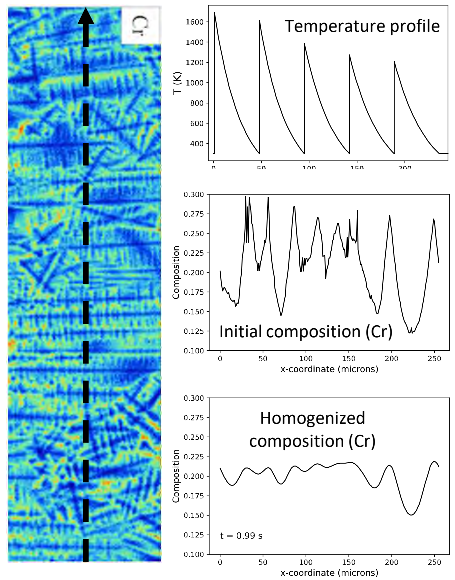
The complex multi-component diffusion pathways that result in homogenization is modelled in CIPHER through a CALPHAD-informed diffusion solver. The predicted diffusion profiles for a wide variety of ternary Ti-Al-V diffusion couples were shown to be in excellent agreement with experimental results.

This approach was used to predict the degree of homogenization during the in-situ heating occurring in a WAAM process, using measured composition distributions directly in a quinary Ti-Al-V-Mo-Cr diffusion simulation.



Predicted diffusion paths in the ternary Ti-Al-V system. The results match closely to data available from diffusion couple experiments.

In-situ homogenization

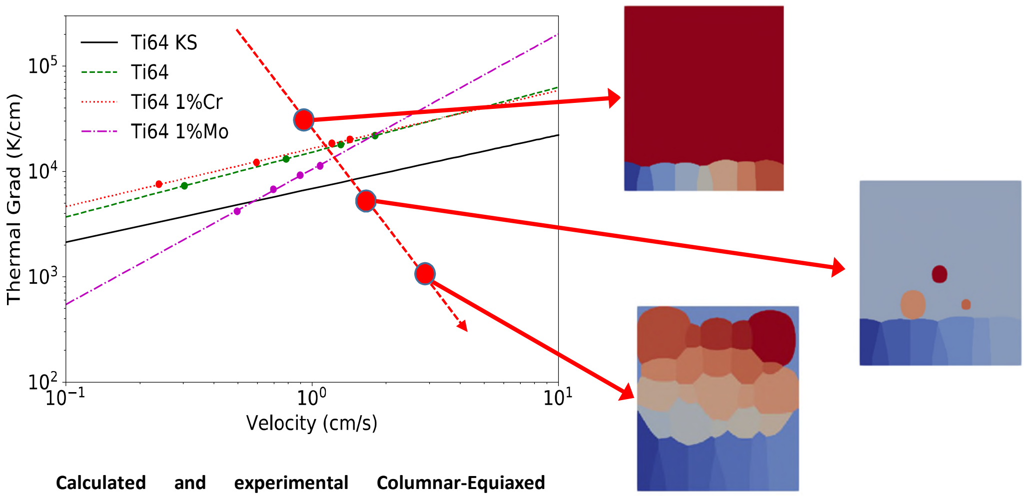


Distribution of Cr in a Ti-5553 sample measured by EPMA (left), and the homogenized composition profile obtained from a multi-component diffusion simulation (right).

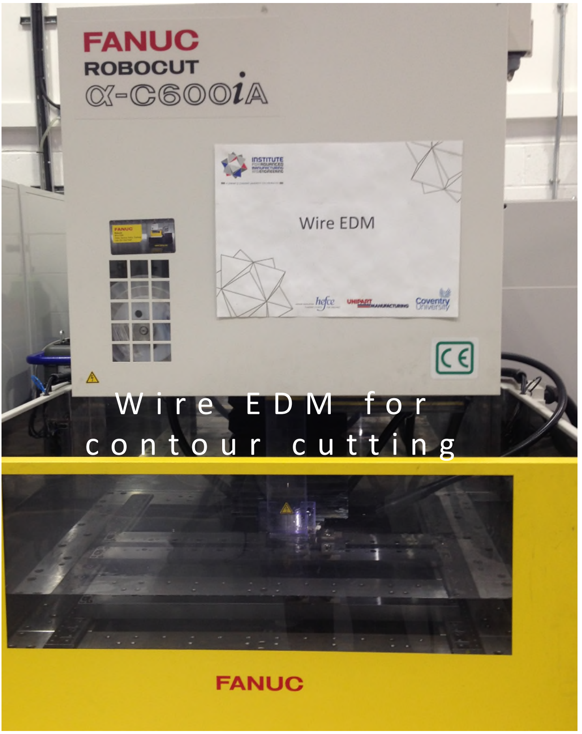
Columnar-Equiaxed Transition (CET)

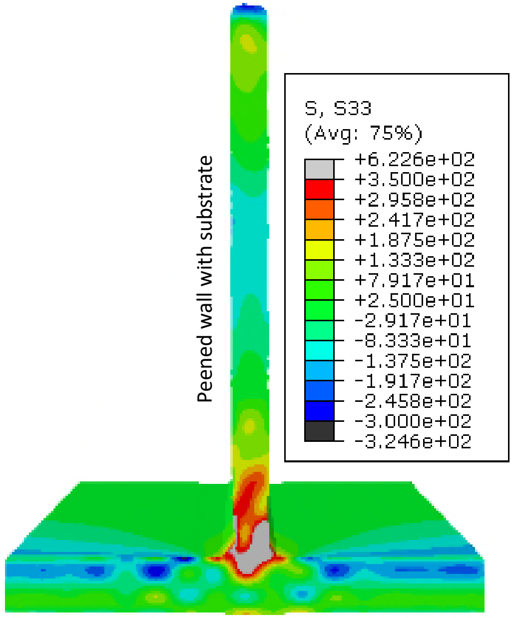
Wire-Arc Additive Manufacturing (WAAM) of titanium alloys, such as Ti-6Al-4V, result in coarse β-grain structures, which are detrimental to mechanical performance. Grain refinement can be achieved by promoting nucleation in the melt pool. During solidification, nucleation occurs when the solidification front velocity (v) is high enough, or thermal gradient (G) low enough, to create sufficient undercooling around potential nucleation sites. The limits where the G/v ratio is low enough are represented by a CET line, on a solidification diagram. CET lines are used to determine process parameters required to deliver equiaxed microstructures.

CET lines were determined virtually, through CALPHAD-informed phase-field simulations. The solidification conditions are controlled during the simulations through applied boundary conditions. The observed transition points from columnar to equiaxed microstructure over a wide range of simulations are used to determine the CET line.
The calculated CET line for Ti-6Al-4V has excellent agreement with experimental CET data. This technique we can screen candidate alloys.

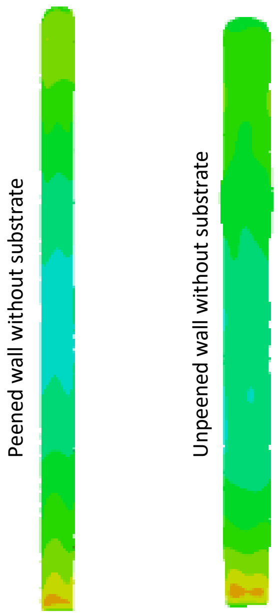


Calculated and experimental Columnar-Equiaxed Transition (CET) lines for Ti-6Al-4V showing the effect of alloy modification.



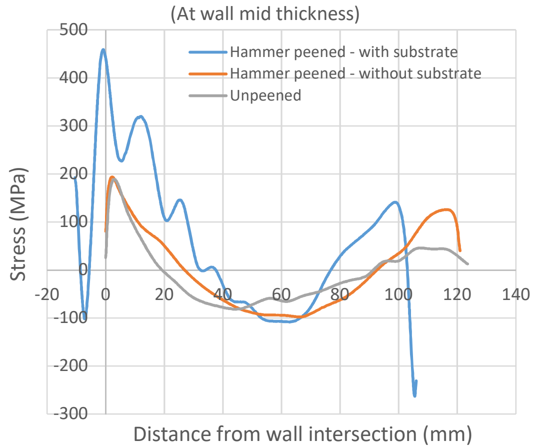


Contour maps of residual stresses (unit: MPa)



WALLS with HAMMER PEENING

Residual stresses in two single-bead walls with interlayer hammer peening, with & without substrate, were investigated with the contour method. The samples were cut with Fanuc wire electrical discharge machine (far left upper) and the cut surfaces were measured with Zeiss coordinate measuring machine (far left lower). The walls were about 7-8 mm thick. The wall with substrate had its top layer peened (left); the wall without substrate had top layer un-peened. Stresses in both walls are then compared with un-peened single bead wall (left lower, and also line plot below).

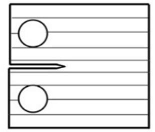


RESULTS OF WALLS MEASUREMENT

Without substrate, both peened and un-peened walls showed similar tensile and compressive stress along the wall height (above figure). Peened wall with substrate showed higher stresses (approaching 600 MPa) at the intersection as well as at wall top location (beyond -200 MPa), comparing to peened & un-peened walls after removing the substrate.

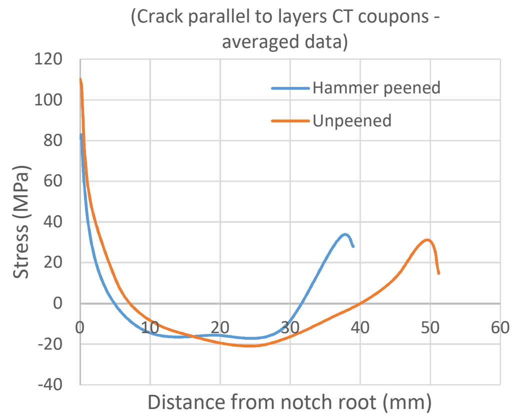
COMPACT TENSION TEST COUPONS

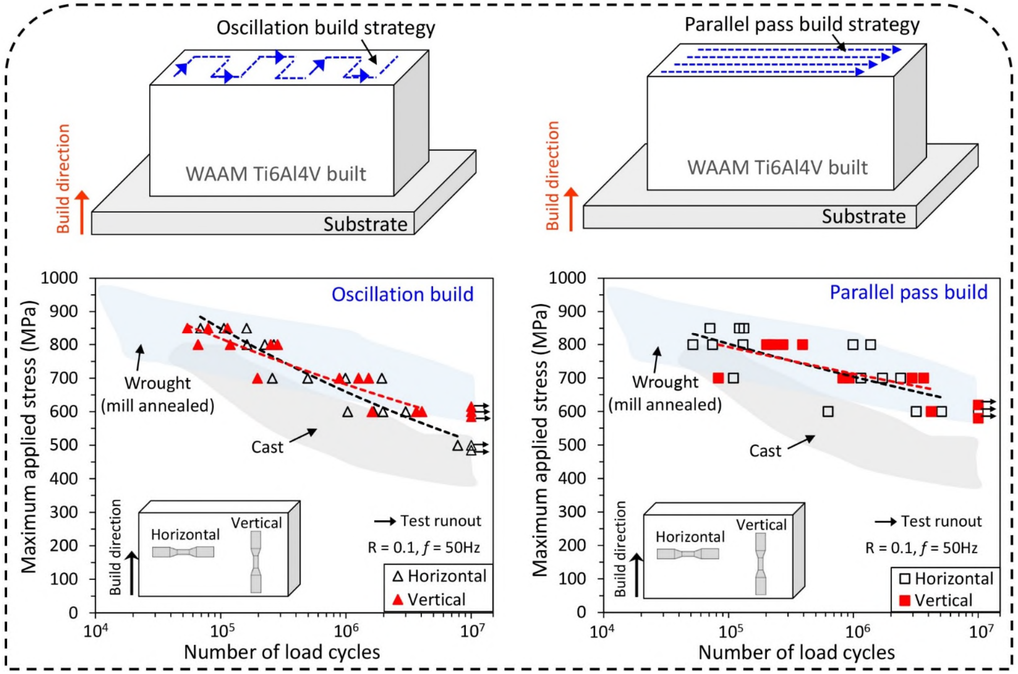
Residual stress in compact tension (CT) coupons extracted from interlayer peened wall was also studied. Two crack orientations were studied; crack parallel to additive build layers and crack across the layers. The result is then compared with CT coupons extracted from an un-peened wall. These samples were subsequently used for studying of fatigue crack growth behaviour and measurement of crack growth rate properties.



Crack parallel to layers

CT coupons extracted from both peened & un-peened walls had most of the process-induced residual stresses relieved after extracting them from the walls. Peak tensile stress is at the notch root and mild tensile stress at the far end. Coupons extracted from peened & un-peened walls show almost identical stress distribution along the length of the specimen. However a difference in the peak tensile stress of about 30% is seen at the notch root.





S-N data of WAAM Ti-6Al-4V built by oscillation and parallel pass build strategies, and comparison with conventional manufactured wrought (mill annealed) and cast materials

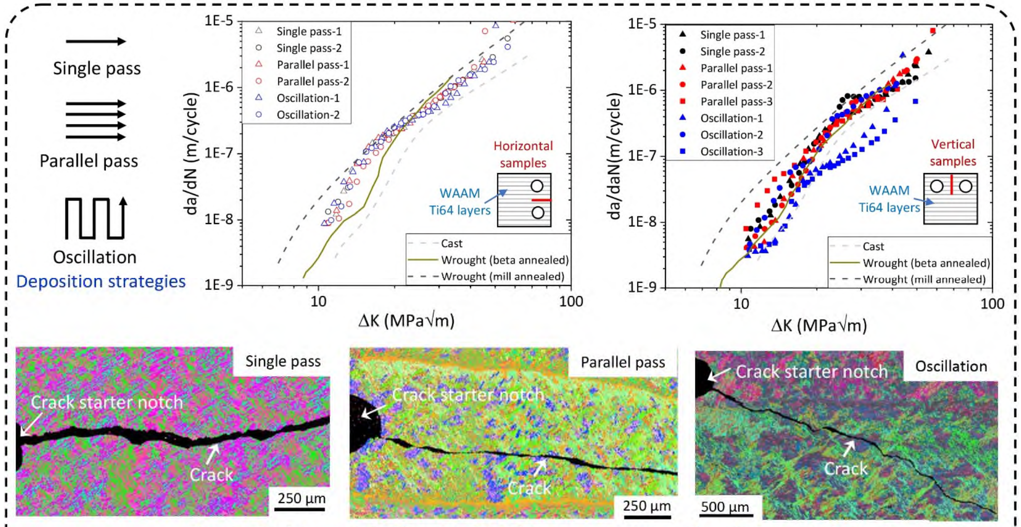
High cycle fatigue (HCF) performance of WAAM Ti-6Al-4V

WAAM Ti64 walls were deposited using a grade-5 Ti64 wire with a plasma arc as the energy source. Two build strategies were used, oscillation and parallel pass. During the parallel pass build, four single parallel layers were deposited consecutively in the same direction along the wall length with a 50% overlap between adjacent passes along the heat source travel direction. For the oscillation build, the plasma torch and the wire feeder have continuously oscillated across the wall thickness direction with about 50% overlap between the melt tracks.

Microstructure analysis has revealed that the primary β grain width in oscillation and parallel pass builds are 1.63 ± 0.58 and 0.37 ± 0.15 mm respectively. Measured average α lath width is 2.27 ± 0.12 and 0.93 ± 0.15 µm for oscillation and parallel pass builds respectively. High cycle fatigue (HCF) test results for both oscillation and parallel pass builds are presented above. Fatigue strength of the WAAM specimens was higher than the cast material and only marginally lower than the wrought mill annealed, except the oscillation build horizontal samples tested at 500 MPa. Of the two deposition strategies, parallel pass build shows marginally higher fatigue lives compared to oscillation build due to the presence of finer α laths compared to the oscillation build.

Sample orientation had little influence on the fatigue life. Only a mild anisotropic behaviour was found in the oscillation build at 10^7 cycles, where the vertical sample fatigue limit strength (600 MPa) was 12% higher than that of the horizontal samples (500 MPa). On the other hand, there is virtually no difference in the fatigue limit between the horizontal and vertical samples of the parallel pass build; hence the columnar primary β grains had little or no influence on high cycle fatigue performance.

Fracture surface analysis was carried out to identify the crack initiation locations. Majority of the samples had crack initiation from pores smaller than 100 µm in diameter. This resulted in large scatter in the fatigue data. Such small pores are inherent to the process, and the S-N data can be considered as the intrinsic material property. Unlike our previous work in 2019 annual report on larger than 100 µm pores by wire contamination, no correlation was found between the pore location/size and fatigue life.



Electron Back Scattered Diffraction (EBSD) images showing crack paths in vertical samples

Fatigue crack growth behaviour of WAAM Ti-6Al-4V built by single pass, parallel pass and oscillation build strategies

Fatigue crack growth (FCG) behaviour of WAAM Ti-6Al-4V

Testing materials were made using three different build strategies: i) single pass, ii) parallel pass with 4 parallel passes aligned with the wall length, and iii) oscillation build where plasma torch and the wire feeder have continuously oscillated across the wall thickness. The crack growth test samples are distinguished as either "horizontal" or "vertical", as defined in the above figure.

Fatigue crack growth rates of WAAM Ti64 are compared with conventionally built cast and wrought materials (mill annealed or β annealed). In the horizontal samples, all three build strategies showed similar crack growth rate. At ΔK below 12 $MPa.m^{1/2}$, crack growth rate was lower than wrought mill annealed that has recrystallized fine α microstructure, and higher than that of the cast or wrought β annealed material; both have coarse lamellar single α variant colony microstructures within a coarse β grain structure. The vertical samples showed considerable scatter. Both the single pass and parallel pass builds showed similar crack growth rate as the β annealed wrought, whereas the oscillation build showed marginally lower crack growth rate than the cast. Between the two sample orientations, the vertical samples (crack propagating along the primary β grains) showed marginally lower crack growth rates.

Influence of crack orientation on fatigue crack growth rate was more pronounced in the oscillation build vertical samples which also showed larger scatter, but more importantly, lower overall crack growth rates. The lower crack growth rates in oscillation vertical samples is mainly attributed to two factors: (1) oscillation build strategy produced coarser colony microstructure along the α_{GB} compared to single pass and parallel pass strategy as a result of a slower cooling rate and contributed to lower crack growth rate. (2) oscillation build vertical samples showed considerable crack path deviation (about 13°) which can be seen in the EBSD images above. The crack path deviation changed the mode-I loading to a mixed mode I and II, which reduced the mode I crack driving force thereby reducing the crack growth rate.

Research Area Leader
Prof. Xiang Zhang

FIND OUT MORE
Visit https://newam.uk/research-areas/research-area-3

49 PEOPLE

Different cultures

Different skills

Different ages

Different genders

Different …

Working in synergy every day

Our words…

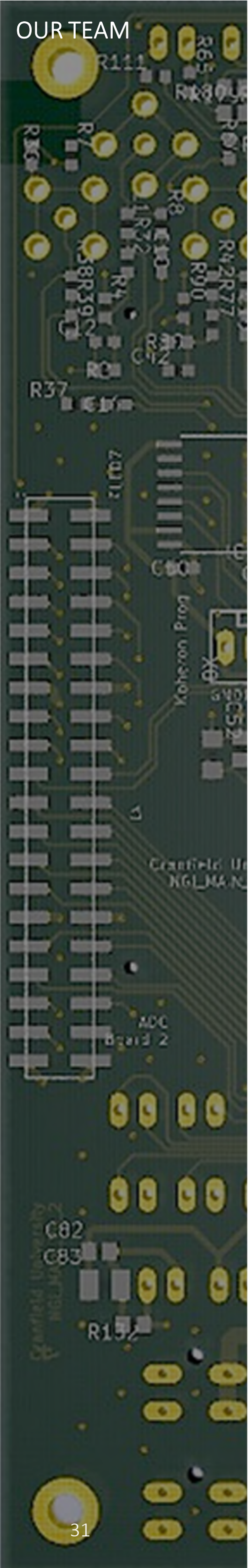
Mr. James Wainwright
PhD student, Cranfield University

"Working with the NEWAM team has been incredibly exciting, the combined knowledge of the members has allowed me to broaden my understanding of wire + arc additive manufacturing tenfold. The atmosphere that is generated when team members work together is particularly enjoyable, with individuals from many different backgrounds it provides a unique space to bounce ideas around and understand their implications from different viewpoints. With the current global situation, team working has become difficult, however, this is consistently improving with online meetings and activities. I believe the outputs of the NEWAM project will be of particular interest to the manufacturing industry and stand to make some substantial and fundamental changes. "

Prof. Xiang Zhang
Research Area Leader – Material Performance
Coventry University

"I really enjoy in working in the NEWAM team, particularly our cross-disciplinary approach to research, PI's excellent leadership, Project Manager's good organisation and coordination, senior academics world-class expertise, and our enthusiastic and hardworking doctoral and early career researchers.
The working atmosphere has been fantastic. It's worth mentioning the Team Building events every fortnight; these virtual meetings brought us closer in the current times, also provided good opportunities for our earlier career researchers to discuss their work in more details, with broader context and wider applications beyond the NEWAM project, which would have not been possible in formal meetings."

FIND OUT MORE
Visit https://newam.uk/team



“For me, the great advantage of being involved in the NEWAM program is to be able to learn from my colleagues who work in different research area than myself. This broadened my knowledge beyond my area of expertise. Working closely together also enables us to take advantage of each researcher skills and institution facility to deliver high-quality research work.”

Dr. Eloise Eimer – Research Fellow – Material Development.

“Even within my speciality of modelling, I have gained new insights into the CFD technique that I was hitherto unfamiliar with, through my cooperation with the process modelling team. Being part of a broader project also helps me to see the relevance of my research in a more holistic manner.”

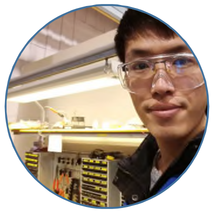
Dr. Rory Hulse. Research Associate - Materials modelling.

“The outputs of the project can significantly inspire the manufacturing industry.”

Mr. Guangyu Chen. PhD Student – Process Development and Modelling.

“It is a wonderful experience for me working in the NEWAM team with people from different universities and having different backgrounds. I have learned a lot about how to collaborate to tackle the challenges in order to deliver the same goal. We have had lots of team bonding activities in the last two years which takes our team spirit to a high level. “

Mr. Chong Wang. PhD student – Process Development.



“I think the NEWAM has a great team full of different people with different skills. I feel that there is a good environment and we can discuss our ideas freely. “

Dr. Goncalo Pardal. Senior Research Fellow – Process Development.

“I am grateful to have the chance to work with all the great minds that form the talented, hardworking, and cooperative team involved in the NEWAM. Therefore, it is inspiring, as a student, to have the chance to interact and learn from them while making my own contribution to the project.
I think that the main advantage/value of this project is on the team itself. Putting together valences of, not only, several areas of knowledge but also different cultures create a tremendously valuable networking resource.”

Mr. João Bento. PhD student – Process Development.

“I think there are mainly four positive aspects (in working in the NEWAM project): (a) Developing our own professional skills and also knowing and learning the whole related knowledge and skills in the development of the next-generation AM technique from other excellent team members; (b) Chances to meet more friends and potential cooperative partners; (c) Inspiring new projects or research issues; (d) Great project experience.”

Dr. Xin Chen. Research Fellow – Process modelling.

“This project has provided a platform to develop new research skills, knowledge and new research methodologies along with and insights into diverse research areas within the project. Working with both academic and industrial partners have strengthened the collaborations and enabled new collaborations. Using these collaborations, currently, I am in the final stages of submitting an exciting research proposal to EPSRC. In addition to the academic impact, this project has also helped to develop personnel effectiveness of the core individuals by learning strong research management and organisational skills.”

Dr. Abdul Khadar Syed. Assistant Professor – Material Performance.

“Working in the NEWAM project is a great experience. I have had the opportunity to collaborate with researchers who have come to the UK from around the world and have not only done great research but made friends that will last a lifetime.
Working during the pandemic has decreased the opportunities to meet and develop as a team. The consortium meetings were not only opportunities to share our research but to get to know each other and foster collaboration. Throughout the pandemic more team building and collaborative tools have been employed, Tea(M) meetings, a slack workspace etc. which help to continue the hard work done previously to make a good working atmosphere.”

Dr. Jacob Kennedy. Research Associate - Materials modelling.

Great team,

Great project,

Great success!

Our views about the future…

"The outputs of the project are not only potential but very much real. If the aim and objectives of the project can be achieved, it will significantly reduce the cost, lead time, material waste, and carbon emission compared to the traditional manufacturing methods, and revolutionise the manufacturing industry somewhat."

Mr. Chong Wang. PhD student – Process Development.

"The outputs will be extremely relevant to industry and in particular to large scale DED, if we can get our integrated vision we will be able not only to build net shaped parts at high deposition rates and we will also e able to predict and influence their microstructure and mechanical properties. We will also be able to guarantee due to in process inspection that the parts are free of defects and comply to the geometry. This will increase the productivity and reduce the post processing to obtain the final component, disrupting the traditional manufacturing techniques."

Dr. Goncalo Pardal. Senior Research Fellow – Process Development.

"The findings of the materials modelling team have the potential to be of benefit to industry. Our diffusion model may be able to help optimise heat treatments, which can be expensive. This model can estimate the time required to homogenise a component and so prevent an unnecessarily long heat treatment duration. Our modelling of nucleation can help to assess a candidate alloy's potential to produce an equiaxed microstructure, within the confines of the WAAM processing window. Such a microstructure is important, if WAAM is to be commercially viable."

Dr. Rory Hulse. Research Associate - Materials modelling.

"AM is currently a very highly active research area, both in the UK and globally. The multidisciplinary research project addresses the urgent need of developing new AM processes with large deposition rates without compromising material performance and cost compared to the current conventional manufacturing processes. The outcomes from this project will directly benefit the manufacturing industries by providing a new AM process with a unique ability to control process, microstructure and material properties to deliver user-specific materials or components. This will help the manufacturing industries to adopt and successfully implement "Smart Manufacturing (Industry 4.0)" and provide a greater socio-economical and societal impact."

Dr. Abdul Khadar Syed. Assistant Professor – Material Performance.

LOOKING FORWARD…

"I am very much looking forward to the exciting times ahead over the remainder of the programme. The research infrastructure and team are fully established, working effectively and collectively towards the original grand challenges we identified. The number and quality of research outputs is accelerating rapidly and I am anticipating some major breakthroughs in the next 12 months."

Words **Stewart Williams**

Contact: newam.prog@gmail.com

Acknowledgements

Abdul Khadar Syed
Alec Davis
Anne Fiorucci
Anthony Gachagan
Armando Caballero
Bilal Ahmed
Charles MacLeod
Chong Wang
Ed Pickering
Ehsan Mohseni
Eloise Eimer
Evangelos Rigas
Farhana Zakir
Gareth Pierce
Goncalo Pardal
Guangyu Chen
Jacob Kennedy
James Wainwright
Jialuo Ding
Jian Qin
Joao Bento
Joseph Robson
Katy Tant
Kevin Mullaney
Kuladeep Rajamudili
Michael Fitzpatrick
Momchil Vasilev
Muhammad Shamir
Nina Bihaei
Nina Sweeney
Phil Prangnell
Philippe Bridgeman
Pratheek Shanthraj
Ralph Tatam
Randika Vithanage
Rastislav Zimermann
Romali Biswal
Rongdong Qu
Rory Hulse
Sónia Meco
Stewart Williams
Teti Stratoudaki
Wojciech Suder
Xiang Zhang
Xin Chen
Yashar Javadi
Yipeng Wang
Yongle Sun
Zhen Qiu