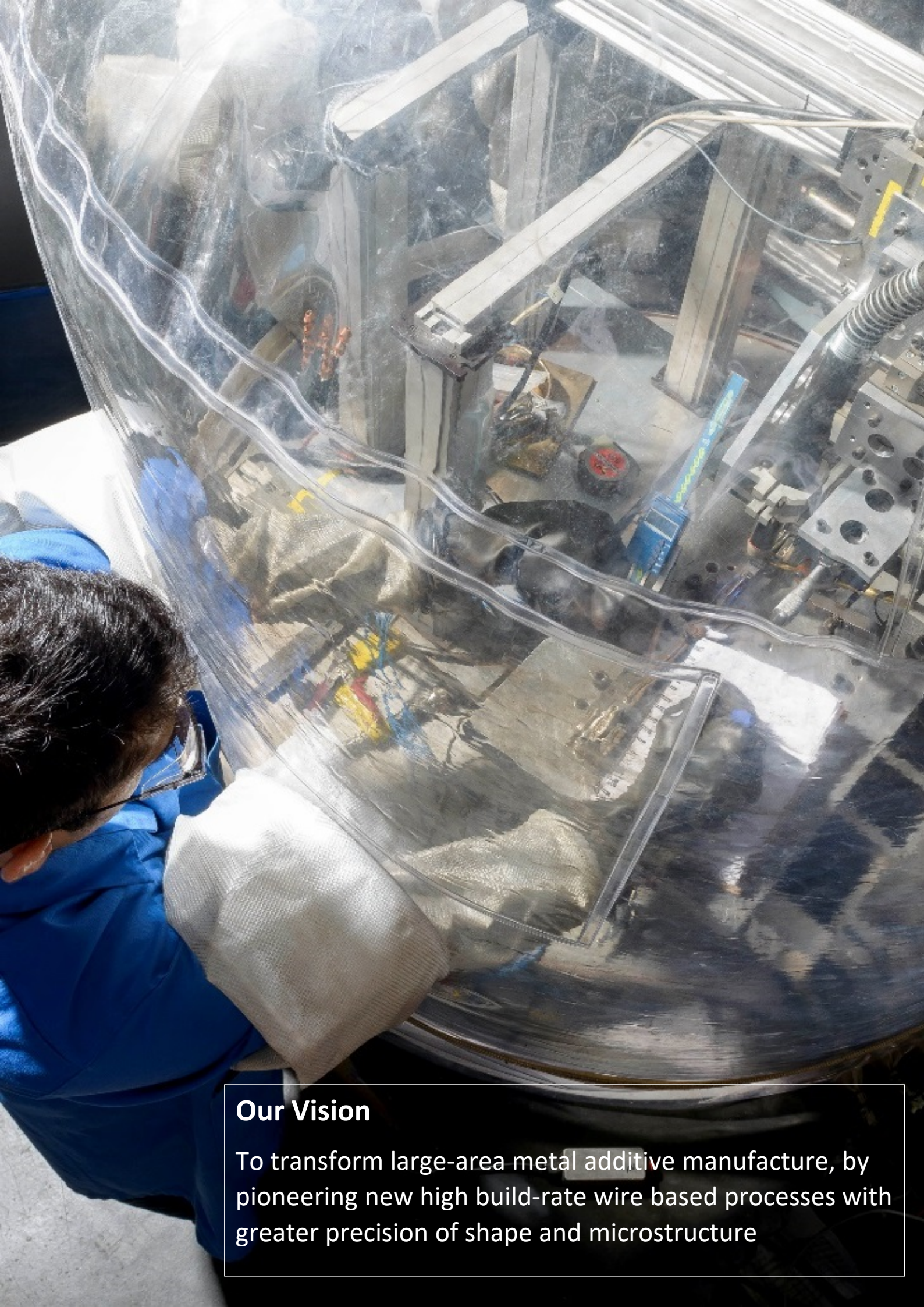**New Wire Additive Manufacturing**

Annual Report

2019

EPSRC reference: EP/R027218/1

Our Vision

To transform large-area metal additive manufacture, by pioneering new high build-rate wire based processes with greater precision of shape and microstructure

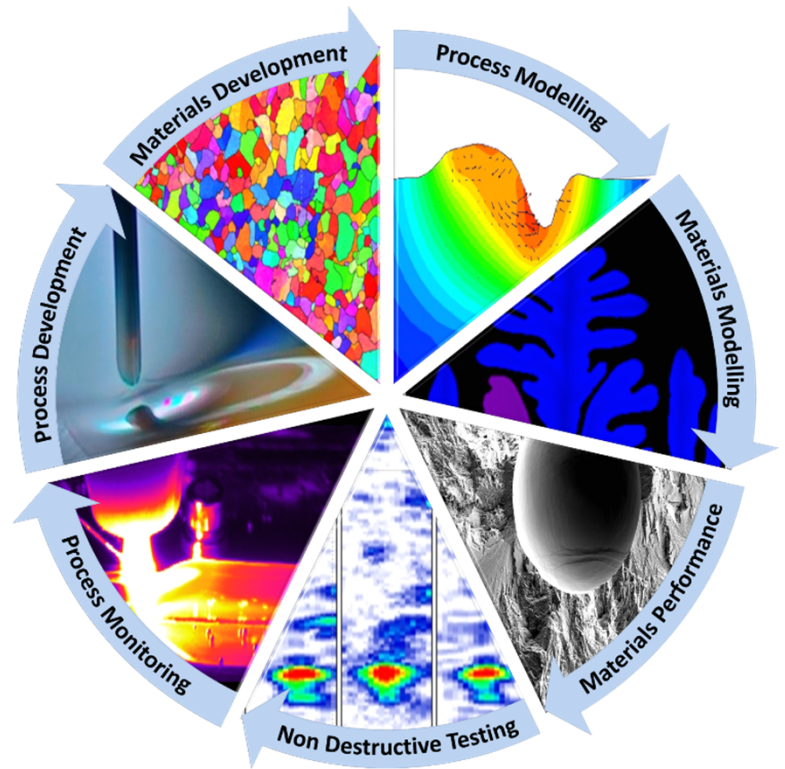# Contents

Research Programme

About NEWAM

Objectives

	• Design and development of new metal wire DED processes and systems capable of highly precise net shape deposition at build rates exceeding 8 kg/hr at relatively low cost over metre sized areas with homogeneous microstructure and high performance properties.
	• Design of new materials and alloys, tailored to the new and existing deposition processes, giving performance better than equivalent forged or wrought alloys currently used
	• To build robust physics-based process and materials' models that give detailed process understanding, enable more rapid process and material design and development and to provide algorithms for in-process microstructure control
	• To ensure guaranteed as-built structural integrity with process-independent physics-based quality control and assurance enabling low cost industrial qualification

Research areas covered in the research programme

Academic partners

Cranfield University

MANCHESTER 1824

University of Strathclyde

Coventry University

Focused on:

| Process development, modelling and process monitoring | Material development and modelling | Non-destructive testing | Material Performance |

Prof. Stewart Williams
Director of the NEWAM Research Programme

3D printing, or, Additive Manufacturing (AM), has rapidly come to prominence as a valid and convenient alternative to other production techniques, this is thanks to a growing body of evidence that its advantages in terms of lead-time reduction; design flexibility and capability and reduced manufacturing waste are not only potential, but very much real. Metal AM techniques can be categorised based upon the form of the material they use (powder or wire), the heat source (laser, electron beam, or electric arc), or the way the material is delivered (pre-placed bed, or direct feed). Each of the metal AM technologies, given its particular properties, is best suited for specific applications. For example, the selective laser-melting of a pre-placed powder bed yields precise, net-shape components that can be very complex in design. However, their size is limited, cost is high, and build rates are low. In contrast, the Directed Energy Deposition (DED) processes can build near-net-shape parts, at many kilograms per hour, and with potentially no limitation to a components' size. To date, most of the work in wire based DED has been carried out at Cranfield University, where a 6-m-long aluminium aero-structure was built in a few days. Research over the last 10 years has also proven the capability to make large titanium parts in a timely manner (weeks instead of months) and with much reduced cost (up to 70% cheaper than machining from solid), resulting in a tremendous industry pull.

However, manufacturing such components is extremely challenging. So far, it has been based on engineering principles. A great deal of empirical know-how is required for every new application, leading to long lead times and high cost for new applications and materials. These are ever-varying and numerous, in light of the heterogeneity of the end-users mix. Therefore, there is an urgent need to develop a science-based understanding of DED processing. This is key to exploit its full potential and enable the industrial pick-up its merits. Such potential could be increased by combining more than one process: E.g. an arc and a laser could be coupled into one symbiotic machine, generating a multiple energy source configuration.
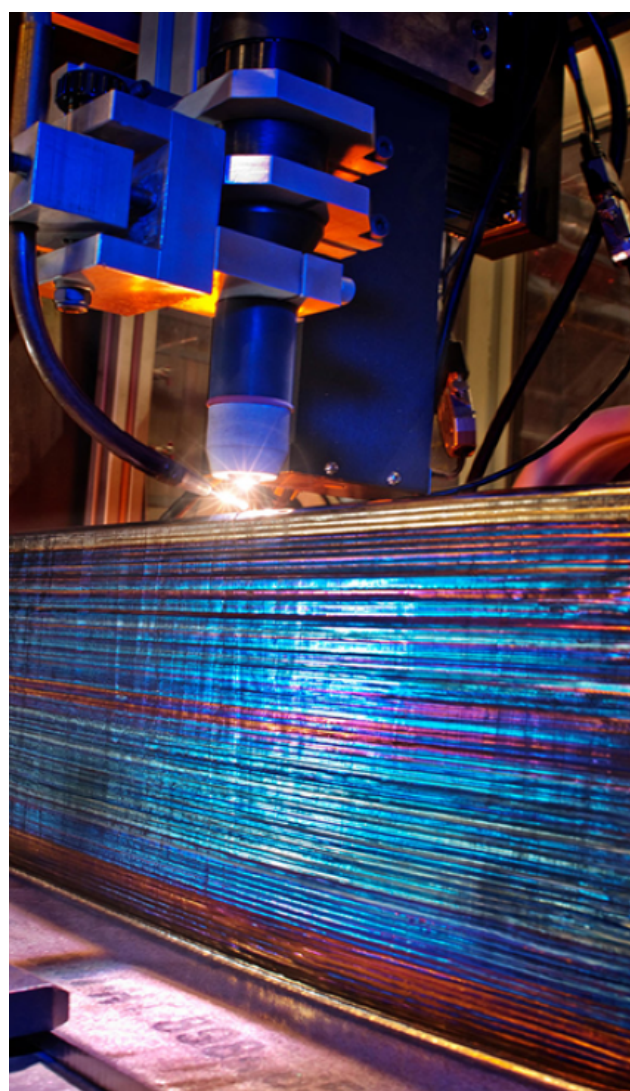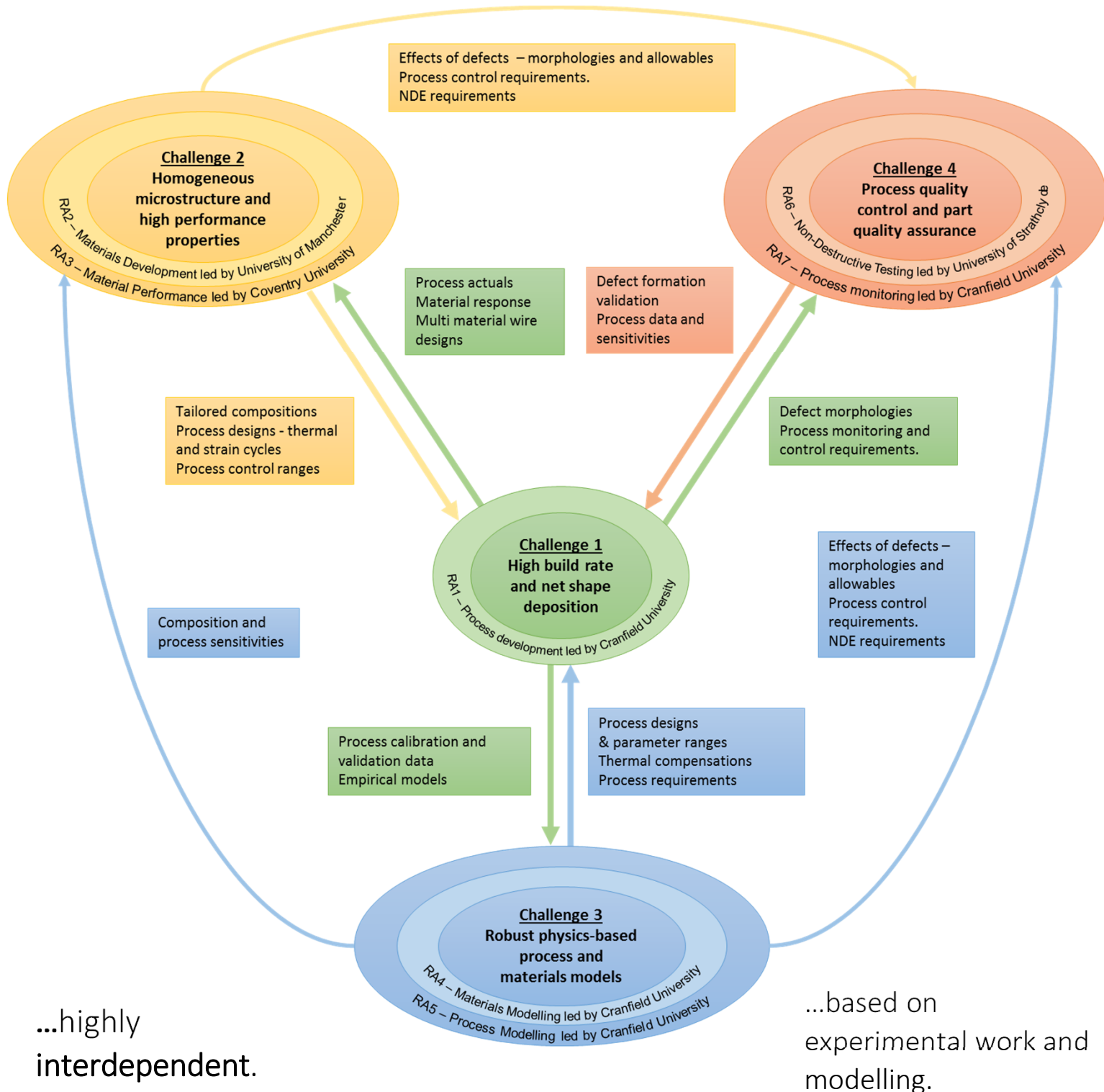

Figure 1. WAAM process with titanium wire.

About our research…

Effects of defects – morphologies and allowables
Process control requirements.
NDE requirements

Challenge 2
Homogeneous microstructure and high performance properties

RA2 – Materials Development led by University of Manchester
RA3 – Material Performance led by Coventry University

Challenge 4
Process quality control and part quality assurance

RA6 – Non-Destructive Testing led by University of Strathclyde
RA7 – Process monitoring led by Cranfield University

Process actuals
Material response
Multi material wire designs

Defect formation validation
Process data and sensitivities

Tailored compositions
Process designs - thermal and strain cycles
Process control ranges

Defect morphologies
Process monitoring and control requirements.

Challenge 1
High build rate and net shape deposition

RA1 – Process development led by Cranfield University

Composition and process sensitivities

Effects of defects – morphologies and allowables
Process control requirements.
NDE requirements

Process calibration and validation data
Empirical models

Process designs & parameter ranges
Thermal compensations
Process requirements

Challenge 3
Robust physics-based process and materials models

RA4 – Materials Modelling led by Cranfield University
RA5 – Process Modelling led by Cranfield University

…highly interdependent.

…based on experimental work and modelling.

…cover the main areas for process certification.

The research programme is organised into seven research areas (RAs) based on four research challenges:

Challenge 1: High build rate and net-shape deposition

New wire DED processes utilising the MES approach will be developed. Advanced physics experiments will be used to understand observed phenomena, support process modelling and ensure robust hardware solutions are achieved. This will be the core of the NEWAM programme and will be covered by the Process Development research area.

Research Area 1: Process Development

Challenge 2: Homogeneous microstructure and high performance properties

Focusing on alloy systems for high impact industrial applications new wire compositions will need to be developed to take advantage of the newly accessible thermal process regimes and the capability for property printing. The target will be generation of advanced microstructures that outperform those of wrought products and are customized for particular applications. Crucial data on formation of defects and their effect on mechanical performance will be determined by the Material Performance research area.

Research Area 2 and 3: Materials Development and Material Performance

Challenge 3: Build robust physics-based process and materials models

This will provide the key fundamental science and understanding focus for NEWAM, including developing the required advanced process and material modelling, needed for our knowledge-based approach. Physics based process models will be developed for process design and understanding. Thermal and fluid flow models will be implemented for bead shape prediction and control, automatic thermal compensation strategies and prediction of the formation of lack of fusion defects. Microstructure models will be developed for alloy systems of interest and these will be validated and used by the Process Development team to design bespoke materials and predict the process–property relationships necessary for advanced performance control and property printing. Acoustic wave prediction, based on microstructure, will be used to assist in the design of suitable transducers for the in-process Non-Destructive Evaluation (NDE).

Research Area 4 and 5: Materials Modelling and Process Modelling

Challenge 4: Process Quality Control and Part Quality Assurance to enable Qualification

In-process quality control and quality assurance is required for guaranteed mechanical properties and structural integrity in as-built components. Sophisticated process monitoring of the thermal profile and other crucial variables for quality control using thermal profiles as a proxy for microstructure and therefore mechanical properties. Algorithms derived by the Process Development and Material Modelling research areas will be used in an intelligent closed-loop process control system to guarantee mechanical properties throughout the whole of a component's structure. Quality assurance requires development of in-process NDE techniques suitable for DED AM, which will be used in-process to inspect every layer as it is built. A new hybrid NDE approach is required that has sufficient resolution without direct coupling and can be robotically deployed. The quantification of the effect of defects in material performance will be used to inform the requirements for this novel NDE system.

Research area 6 and 7: Non-Destructive Testing and Process Monitoring

Process Development

Research Area 1

Overview

This research area aims to develop new DED processes for high deposition rate, net shape wire additive manufacture. The main concept is based on independent control of the volume of deposited material and dimensions of deposited beads, which is achieved by dynamically varying the energy profile of the heat source through independent control of the energy density of different power sources. This allows to break natural aspect ratio of the liquid metal and build at higher rates whilst maintaining high accuracy. The main goal is to detach from standard processes established for welding and develop new processes optimised for additive manufacture, considering also the thermal requirements of advanced materials used in additive manufacture.
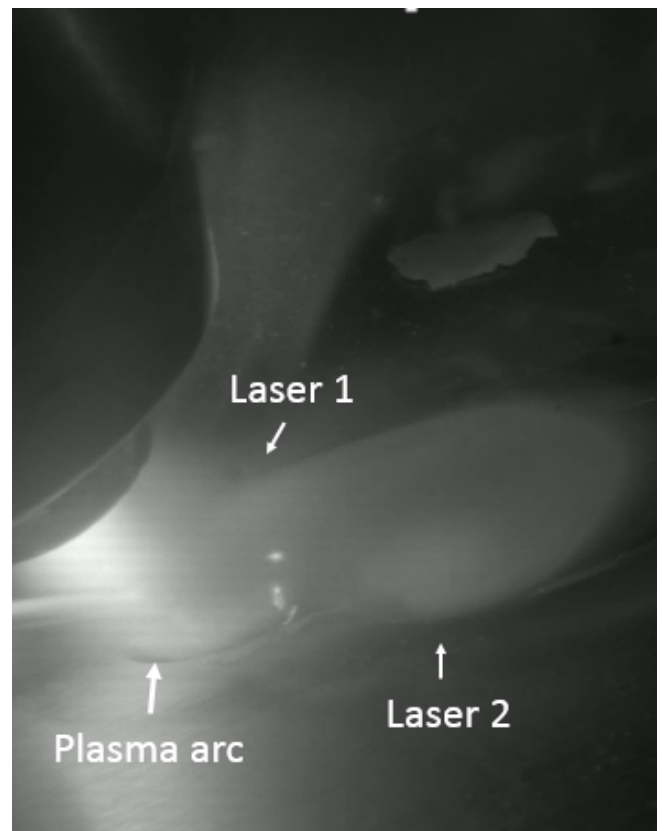
Figure 2. Multi-energy source deposition.

Novel wire melting

Study of the limits of wire melting using different processes and learning how the efficiency of the feed stock melting can be maximised. In standard processes with axisymmetric heat sources the melting of feedstock is limited by the ability to transfer sufficient amount of energy to the feedstock without generating excessive melt pool in the underlying material. Here we are working on optimisation of tailored energy profiles and matching shaped wires to enable high deposition rate with minimum energy and maximum control of bead shape.

Process measurements

Melting and formation of a weld bead is governed by the energy applied to the material, its distribution and the melt flow that it can induce. In this work the apparatus to measure the energy distribution and pressure induced by the arc is developed, which enables to verify the energy density delivered by arc based processes and understand how to tailor it to utilise the heat delivered to the melt pool more efficiently. By knowing the energy distribution and spot size over which the energy is applied to the material it is possible to better control the process and avoid unnecessary melt flow, which affects quality of deposited parts. In addition, understanding and controlling of the plasma pressure will lead to better design of plasma torch with lower likelihood of defects and improved deposition rate.
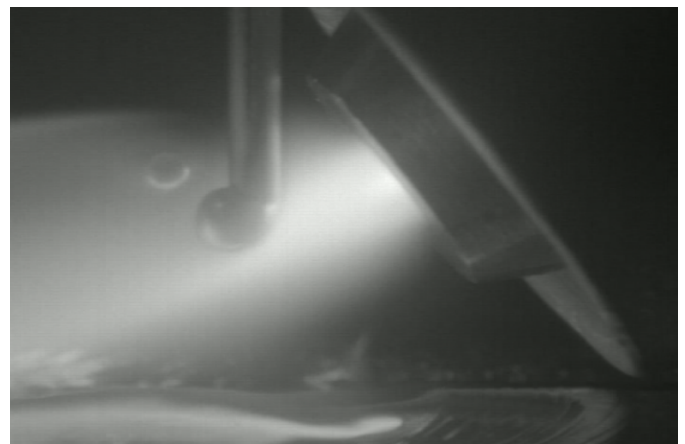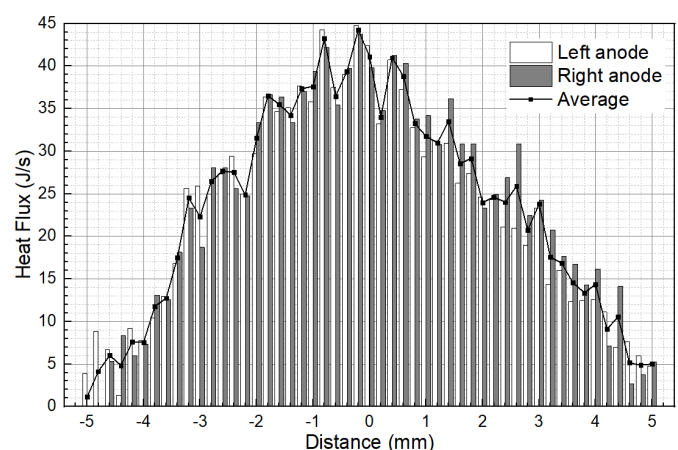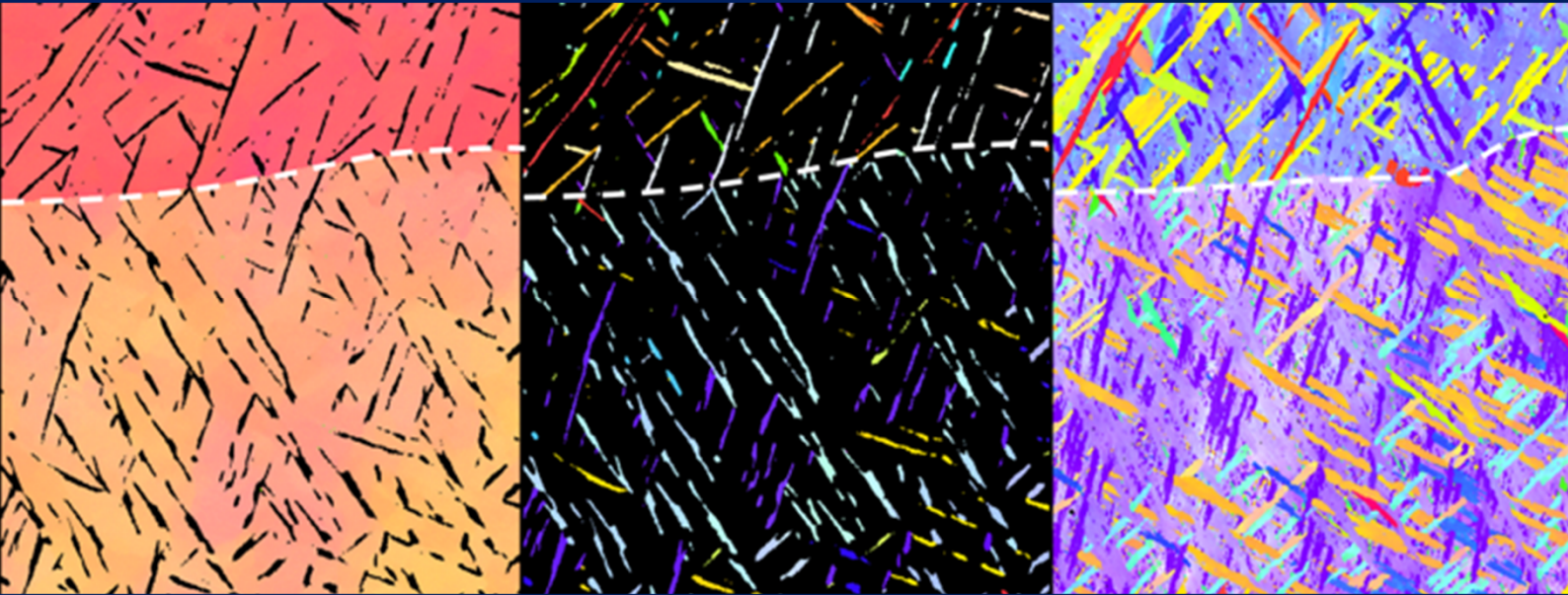

Figure 3. Pressure induced by arc plasma.

Figure 4. Energy distribution of an arc plasma.

8

# Material Development

Research Area 2

Overview

First-stage metallurgical investigations have been carried out, focusing on titanium, in order to better understand the limitations of applying WAAM to, alternative alloys, improve the consistency of mature alloys (Ti64), print novel material concepts, and guide the development of the process.

Four major areas have been the current focus of investigation: (i) Ti-64 microstructure quantification, to confidently understand WAAM deposition and microstructure development in Ti-64 so that with active thermal management 'constant' properties can be achieved and to develop a models to predict microstructure; (ii) Beta Ti-alloys, to extend the applicability of WAAM into high strength Ti alloys; (iii) Refine β grain structures with minimum metallurgical side effects by alloy and process modification, to refine the undesirable coarse columnar solidification structure found in WAAM of Ti to reduce the anisotropy and improve mechanical properties; and iv) Graded materials - Alloy-Alloy Composites (AAC) - to take full advantage of the nature of WAAM and build parts with tailored properties by using multiple alloys.

This work has taken advantage of novel techniques, such as in-situ heating of samples in the SEM, electron microprobe (EPMA) composition analysis and transmission Kikuchi diffraction (TKD) available at Manchester on material built by WAAM at Cranfield University. Substantial progress has been made on addressing the above topics utilising expertise from both universities to determine the best path forward in each area, combining metallurgical and process knowledge to optimize the results.

Ti64 Quantification

Research was carried out to more deeply understand the factors affecting the transformation microstructure formed in Ti-64 built during WAAM, and its heterogeneity, as a function of the cyclic-complex local thermal conditions, to prepare the process for industrial applications. Thermal simulations were performed to systematically explore the effect of key process variables and In-situ SEM experiments were performed in order to better understand the mechanisms involved, by directly observing the solid state phase transformations from alpha to beta and vise-versa, with EBSD maps performed through heating and cooling cycles to better determine the orientation relationships involved. The large packet alpha microstructure which can form in HAZ bands in reheated WAAM regions has been explained, for the first time, by remaining alpha laths which survive near the beta transus temperature that sympathetically bias the nucleation of laths with similar orientations during cooling. This understanding will be coupled with experimental work on longer-term effects, from extended build times, on different Ti-64 starting microstructures to provide data to validate models to predict the effect of WAAM cyclical heating on microstructure.
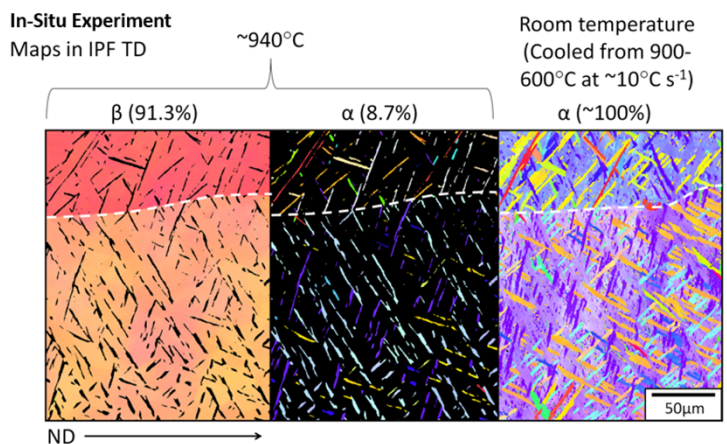

'Printing' graded materials

An advantage of WAAM is the ability to build property tailored parts out of multiple materials. Preliminary work has now been performed to assess the fundamental limitations of dilution and mixing with the current WAAM process, potential interface microstructure effects, and to evaluate the potential properties that could be obtained.

One such 'composite' material was built using alternating deposits of CP-Ti and Ti-64. This showed that excellent mixing occurs in the liquid phase. However, the currently high level of re-melting that takes place leads to dilution of the solute rich alloy and enrichment of the solute lean alloy, but each resulted with a consistent composition in the final material. As there is little time for solid state inter-diffusion relatively abrupt interfaces are formed. This leads to the potential to produce alloy-alloy composites with two phases of near-bimodal composition. Mechanical evaluation demonstrated that the tensile properties of this 'composite' material were determined by the weaker of the two phases, but there was potential for increasing crack path tortuosity in fracture toughness tests. Future work will explore the possibility of using dilution control and the micromechanical behaviour of differently graded interface structures between material combinations.
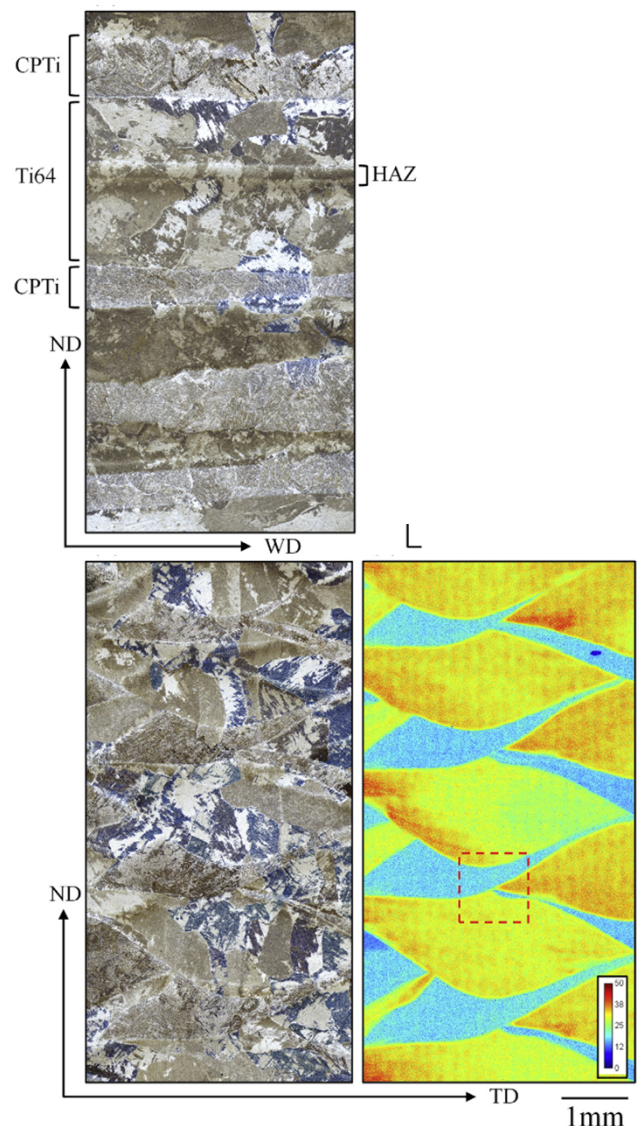
# Ti grain refinement by alloy and process modification

In common with other AM technologies, Ti alloys used in the WAAM process suffer from very coarse, textured, columnar β grain structures that develop during solidification of multiple melt racks. This can lead to excessive scatter and anisotropy in mechanical performance. Several approaches are being investigated to solve this problem including using alloy modification, process modification and inter-pass deformation techniques. Major progress has now been made in identifying the recrystallization mechanisms that lead to grain refinement with inter-pass deformation and developing process maps, showing that it is possible to obtain fine equiaxed grain structures with sufficient changes to the process parameters, and demonstrating the feasibility of alloy modification with inoculants and growth restriction additions. This latter more recent topic has used a simple first-stage approach to evaluate and down select potential inoculants such as TiN, added in the form of powders. This work will now be extend to identify solutions with the least damaging metallurgical side effects . An examples of the successes of these approaches are shown below where it is demonstrated that original cm scale β grain structure can be reduced to a size comparable to that in acceptable in wrought components.
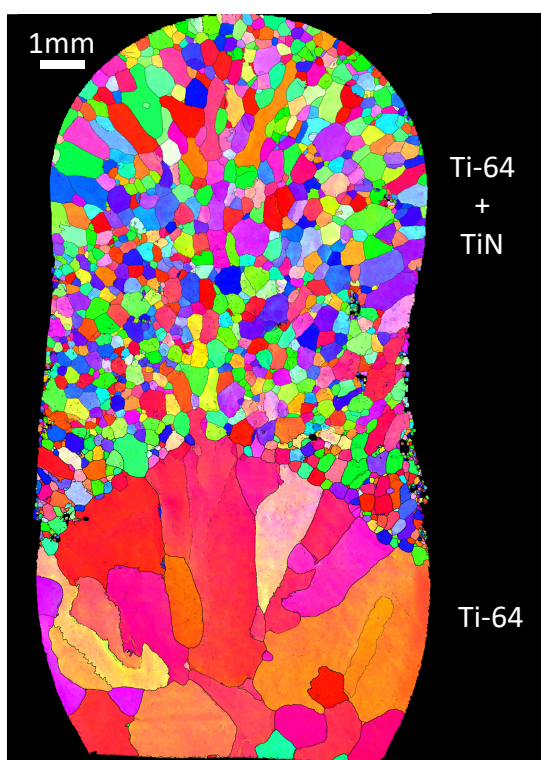
Applying WAAM to high strength beta Ti alloys

Metastable beta titanium alloys are of interest for high strength applications, such as landing gear. The metallurgical issues of printing one such typical alloy, Ti-5Al-5V-5Mo-3Cr is being investigated to expand the applicability of WAAM Ti builds to such applications. It has been determined that such materials undergo far more microsegregation during solidification than Ti64 and that reheating of previously deposited layers as the build progresses is of critical importance as it causes uncontrolled alpha precipitation. This has a profound impact on the as-built mechanical properties. In order to better understand this phenomena a semi-automatic thermocouple harpoon method was developed to repeatedly insert thermocouples into the melt pool during deposition and accurately capture the thermal history. Further work is ongoing to understand how to optimise the properties by process modification combined with the minimum amount of post-build heat treatment.
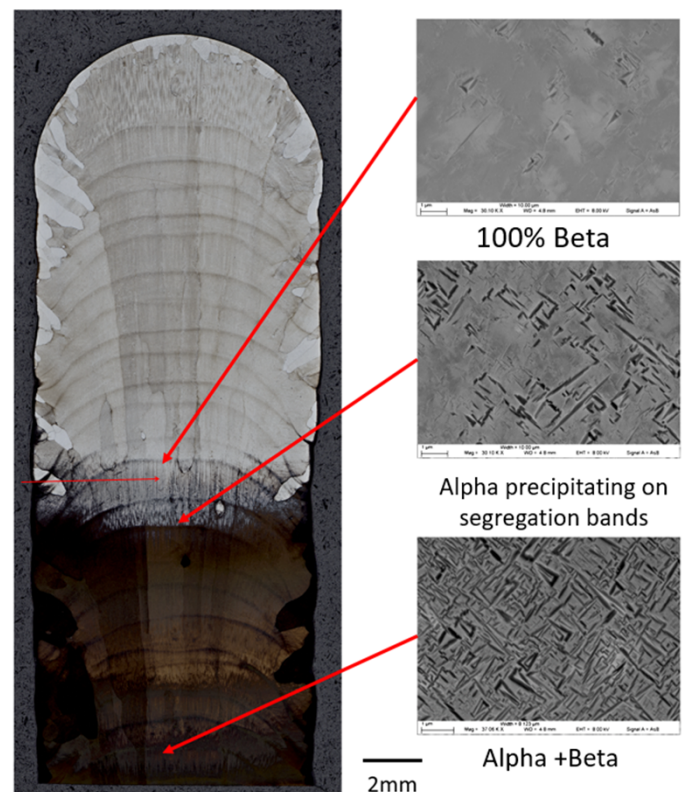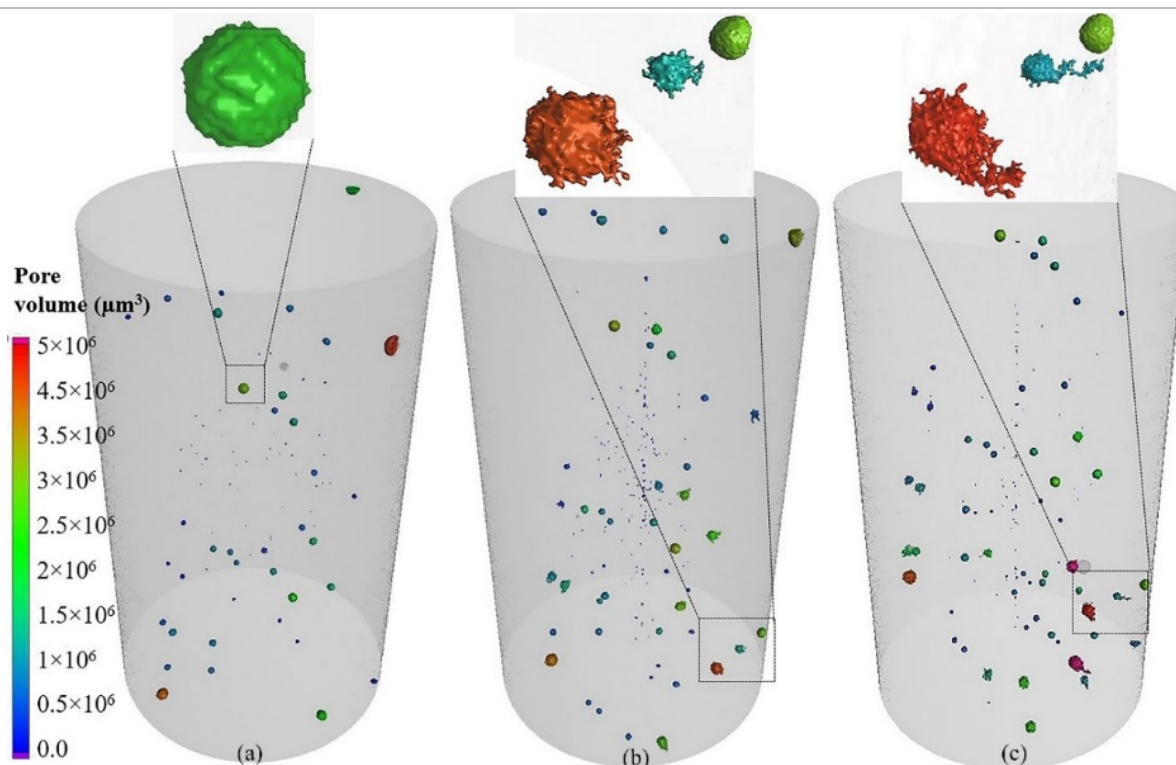
X-ray tomography images showing pore development under fatigue loads at 0, 25000, and 32000 load cycles, respectively.

Material Performance

Research Area 3

Overview

Titanium alloy Ti-6Al-4V has been investigated focusing on three research areas that are related to the durability and damage tolerance performance: (i) high cycle fatigue and effects of porosity defect and as built surface texture; (ii) residual stress distribution and magnitude in large WAAM builds and also in small test specimens extracted from large build for measurement of fatigue properties; (iii) fatigue crack growth rate and effects of process induced residual stress and heterogeneous microstructure. Main objectives are to find the influence of defects, surface texture, microstructure and residual stress on fatigue and fracture properties, to develop models and methods for assessment of defect tolerance and criticality under fatigue loads, and to deliver material fatigue and fracture properties for qualification requirement of wire additive manufactured titanium alloy used in safety critical structures. Research methods include computational modelling by fracture mechanics approach, experimental testing, and material characterisation at micro and meso scales using advanced imaging facilities, e.g. X-ray computed tomography during fatigue testing, fractography with scanning electron microscope, micro texture analysis via Electron Back Scattered Diffraction (EBSD). Residual stresses were evaluated by the contour method.

Two other types of defects in WAAM Ti-6Al-4V were also assessed in this work: the keyhole and lack of fusion (LoF) damage that may present in WAAM processed alloys, in collaboration with Cranfield University (sample building with deliberately created keyhole and LoF defects), Strathclyde University (ultrasound detection) and University of Manchester (X-ray tomography to give more detailed assessment of defect location and size).

High cycle fatigue strength and effect of porosity defects

Experiments were conducted under both static and cyclic loads. Defects were introduced intentionally by using contaminated wires at the specimen gauge section. Selected samples were also examined by periodical X-ray tomography at pre-defined fatigue loading intervals to monitor the development of porosity defects under fatigue loading (figure on the previous page). Relevance of this work to practical design is that AM feedstock may get contaminated that can cause gas pores of considerable size inside the material. Two key findings are described in the following.

First, porosity defects had little effect on the static strengths (yield and ultimate) even the pores were numerous and considerable size comparing to microstructure features (Figure 5a). In contrast, the ductility and fatigue strength were significantly reduced owing to the presence of defects (Figure 5b). Fatigue strength reduction showed good correlation with the reduction of ductility and also correlated to the pore size; critical pore diameter was found to be between 50-100 micrometers. This threshold pore size is related to the specific microstructure features and sizes of WAAM Ti-6Al-4V, i.e. changing AM processing may alter this threshold value of pore size.

Second, traditional S-N data cannot correlate the test results owing to different pore sizes and different applied stresses (Figure 5c). Using fracture mechanics and Murakami's equation for stress intensity factor arising from pores, good correlation has been achieved between the fatigue life and the stress intensity factor (Figure 5d). The El-Haddad method was used to establish the Kitagawa-Takahashi diagram for criticality analysis of porosity defects.

This work has resulted in three papers published in highly regarded journals [Biswal et al. 2018, 2019a, 2019b] and invited talks to international conferences in 2019 (TMS2019, ICAF2019) and a Workshop on "Fatigue of AM Metals".
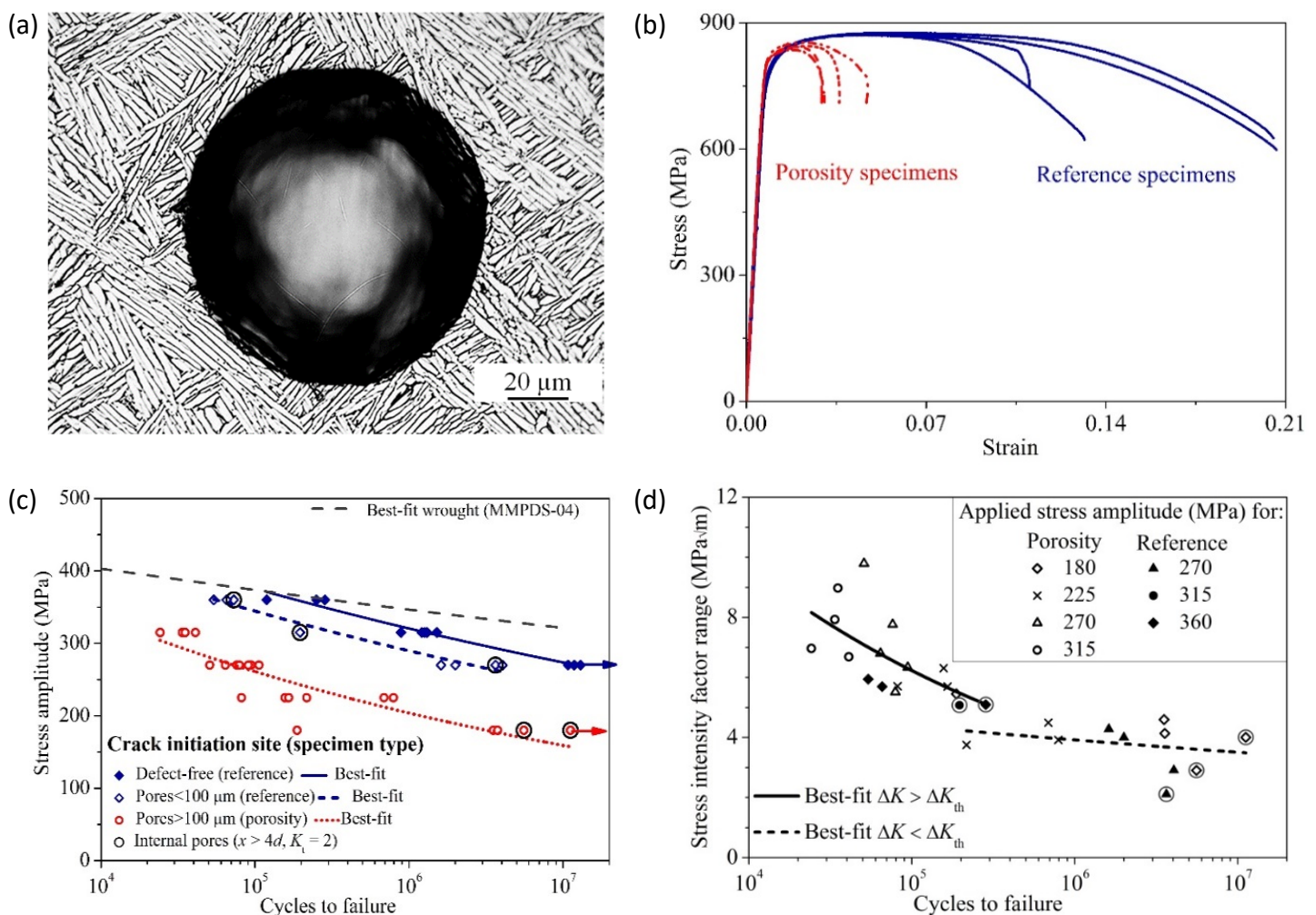

Figure 5. (a) a typical gas pore and comparison of its size with surrounding microstructure size, (b) Tensile test results under static load, (c) fatigue test results of reference and porosity specimens in S-N data format; trend curves suggesting a critical porosity size of ~100 micrometre, (d) fatigue test result in (c) is re-plotted against the stress intensity factor range, providing better correlation for fatigue life with both pore size and applied stress level.

Residual stress analysis

Residual stress analysis was performed for WAAM Ti-6Al-4V builds by the contour method. For this purpose, wall samples were built using three different build strategies, i.e. single bead, parallel pass, and oscillation build. The oscillation build walls were built on both sides of a base plate. Before undertaking the contour method, measurement walls were removed from the base plate. The maximum height and length of the walls was about 150 mm and 300 mm respectively. All three types of walls were cut at the mid length to measure the longitudinal stress component. Contour method results (Figure 6a) showed tensile stresses at the bottom and top of the walls, where compressive stresses were seen at the centre location. The parallel pass wall had the highest tensile stress approaching 280 MPa at the bottom of the wall, whereas tensile stresses were lowest for the case of oscillation build wall.

In addition to wall samples, residual stress was also evaluated in the compact tension (CT) coupons which were extracted from walls (mentioned above) bottom locations after performing contour cut of the walls. Two types of coupons were extracted: one for crack across the layers and other for crack parallel to layers. All CT coupons were extracted from centre of the wall. Contour results (Figure 6b) showed peak tensile stress at the notch root and low tensile stress at the opposite end, where compressive stress was present in the middle of the coupons. Crack parallel to layers coupons showed higher tensile stress at notch root than corresponding crack across the layers coupons. Peak tensile stress of about 150 MPa was seen in the single bead CT coupon with crack parallel to layers. Measured residual stresses agreed very well with finite element modelling of the sample extraction and retained residual stresses in the CT configuration.
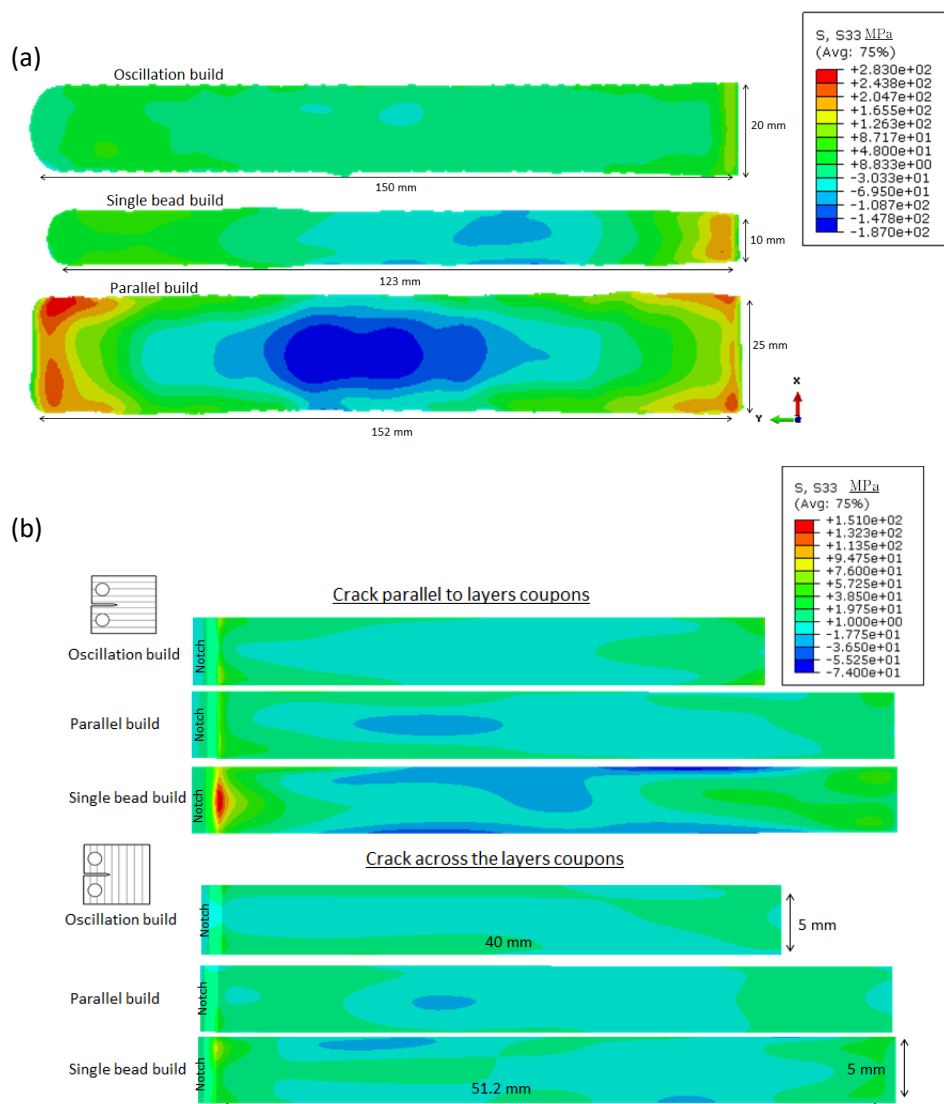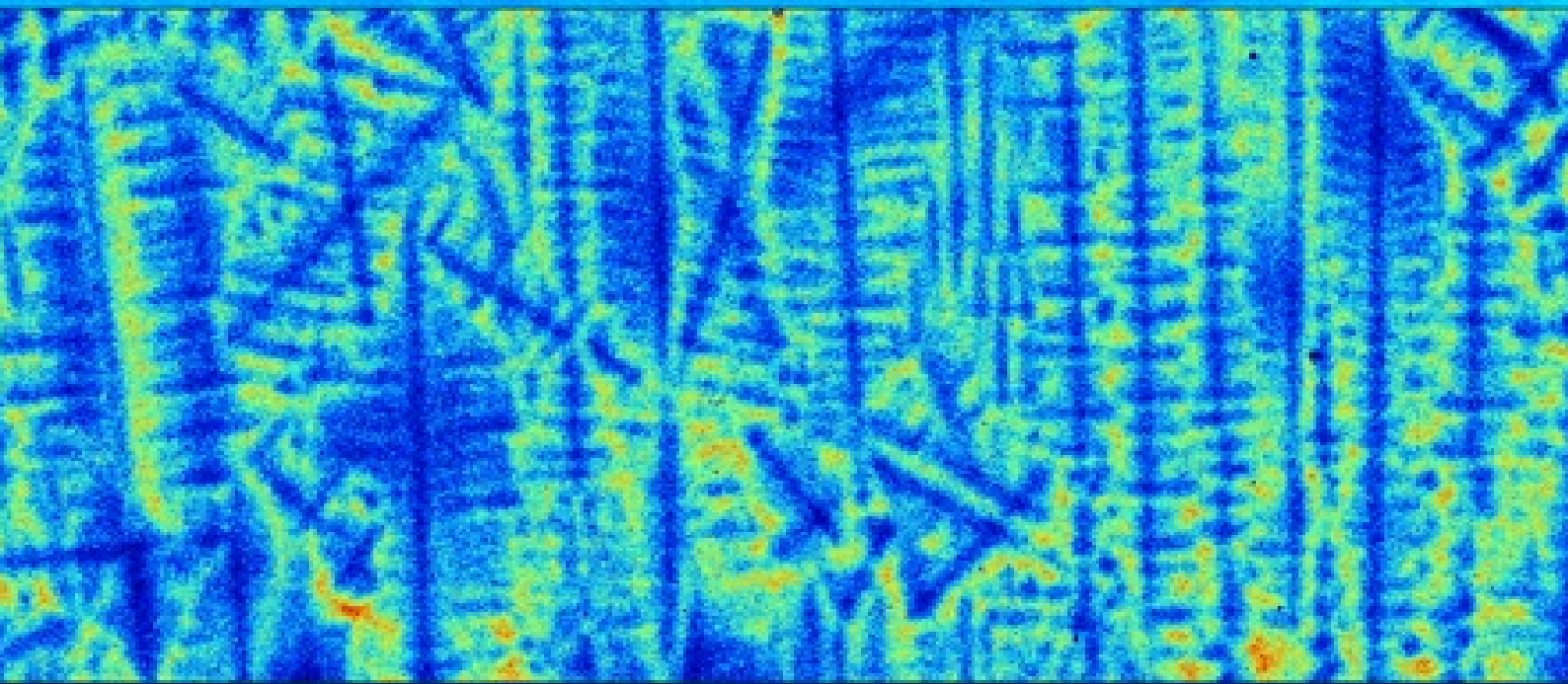
A few journal papers were published based on this work.

Figure 6. Residual stress profiles determined by the Contour method: (a) Wall samples by three build methods, (b) Compact Tension (CT) test coupons for fatigue crack growth rate measurement.

Material Modelling

Research Area 4

Overview

Mechanical performance of WAAM components is largely determined by their microstructure, which in turn is greatly influenced by solidification conditions and heat treatment. Experimentally probing the various parameters of solidification and heat treatment for different alloys is time consuming and expensive. The simulations developed within this research area will give an insights into grain growth, dendrite evolution and segregation and this will assist the Process Development team in optimising the processing parameters. With the CALPHAD (Calculation of Phase Diagram) integrated models, the behaviour of a variety of multicomponent systems can be replicated and this will help develop urgently needed WAAM specific alloys. The Material Modelling team will liaise with the Process Modelling team, giving them predictions of optimal thermal profiles. They in turn will calculate what processing parameters should be used to produce these profiles, and pass this data to the processing team.

The ability to predict elimination of microsegregation is particularly important in WAAM, because the repeated heat source passes may provide in-situ homogenisation. Predicting whether this has adequately homogenised the WAAM build, and what additional treatment may be required, is vital to creating a cost effective WAAM process that reduces any unnecessary post-WAAM heat treatments. A CALPAD based finite difference diffusion model was created for these homogenisation predictions.

A customised software package called CIPHER (CALPHAD Integrated PHase-field solvER) was used to simulate segregation during solidification. The work on this package is still ongoing with new features and are currently working on implementing a version that accepts temperature, varying with time.

Diffusion model for simulating homogenisation

Simulations of a heat treatments on Ti-5553, using the CALPHAD integrated finite difference model of a 2D dendritic structure were carried out. The dendrite cores were randomly placed in the 2D slice and the edges of each dendrite's domain was constructed using Voronoi tessellation. The starting compositions were estimated via a model based on Scheil segregation profiles, provided by the JmatPro software package, and an experimentally measured WAAM temperature profile. Ti-5553 was replicated by conducting a literature search to gather the necessary CALPHAD parameters. This model was used to predict that a time of 9 minutes was needed to eliminate microsegregation in a Ti5553 sample heat treated at 1273 K. Researchers at the University of Manchester carried out the heat treatment for the recommended time. Afterwards, optical microscopy analysis showed that the sample was homogenised.
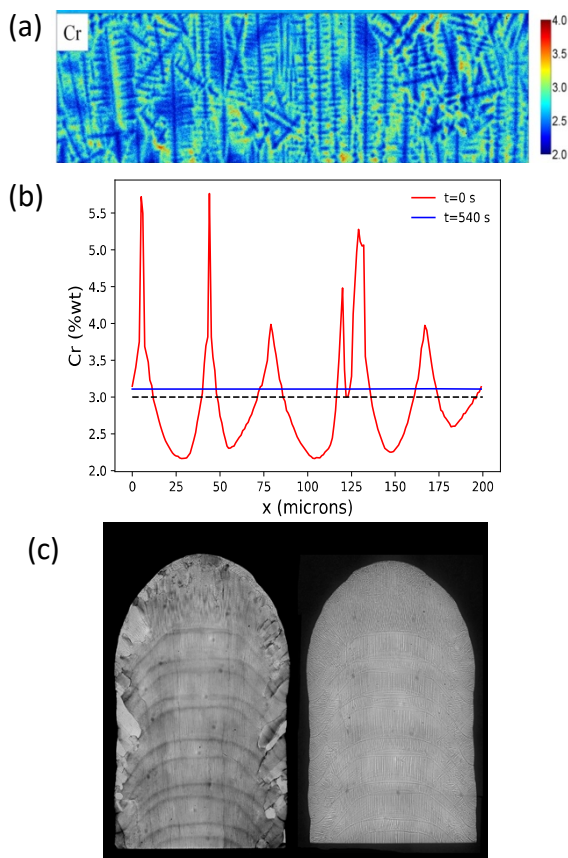
(a)

(b)

(c)

Figure 7. EPMA (a) analysis revealed microsegregation of Cr in a WAAM build. Our model (b) predicted that this microsegregation would be eliminated by a 540 second heat treatment at 1273 K. This was confirmed by the absence of banding in an optical microscope image of the post treated sample (c, right), compared with the same sample before the treatment (c, left).

Segregation model

The Scheil model is commonly used to predict microsegregation. However, the Scheil model cannot be used to predict segregation in systems with higher order than binary and predicts only in 1D. To compare the results of CIPHER to the Scheil model, a series of 1D solidification simulations were carried out with decreasing solidification front speeds (representing decreasing undercoolings). It was found that, as expected, lower front speeds led to profiles closer to that of Scheil, but there are increasing deviations from Scheil as the front velocity increases. This solidification speed effect is missing from Scheil models.

1D segregation profiles were also used to compare segregation effects for several Ti alloy systems: Mo-Ti, Cr-Ti, Ti-V. Mo-Ti and Cr-Ti showed significant segregation and Ti-V showed relatively little. These profiles can be used to create improved starting compositions for our microsegregation model, that relied on Scheil profiles. The focus of the work is now on the Cr-Ti-V system, which captures ternary effects that Scheil cannot replicate.
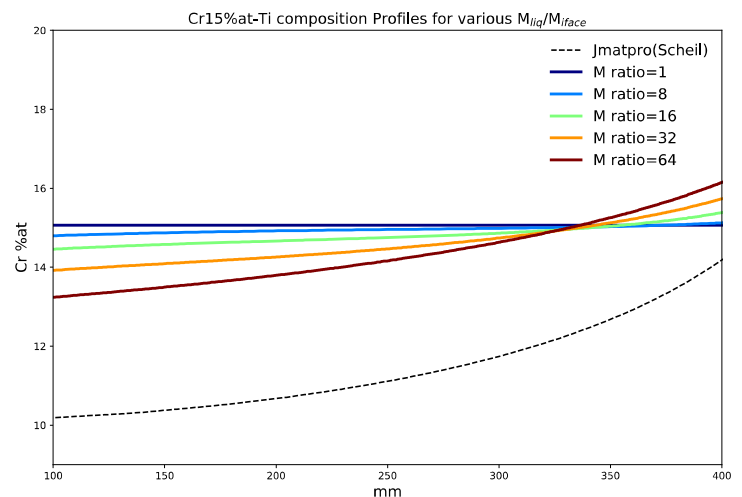
Figure 8. The 1D segregation profile for Cr-Ti from our model, where increasing M ratio represents decreasing solidification front speed. The Scheil prediction is provided for comparison.

Growth model

Phase field modelling in 2D and 3D was used to simulate growth from an irregular interface. This begins as a number of spherical caps in the base of the simulation domain. Then it was allowed to grow out to the point where the growth from the caps impinged on one another. The solidification front speed in a series of simulations was varied. It was found that, in agreement with solidification theory, at higher speeds a planar front resulted and when the front speed was reduced, a cellular front occurred. The segregation in the cellular front situation was analysed and it was found that it qualitatively agrees with the 1D segregation. The growth simulations this far, lay down the foundation for a more sophisticated solidification model, capable of achieving the aims of this research area.
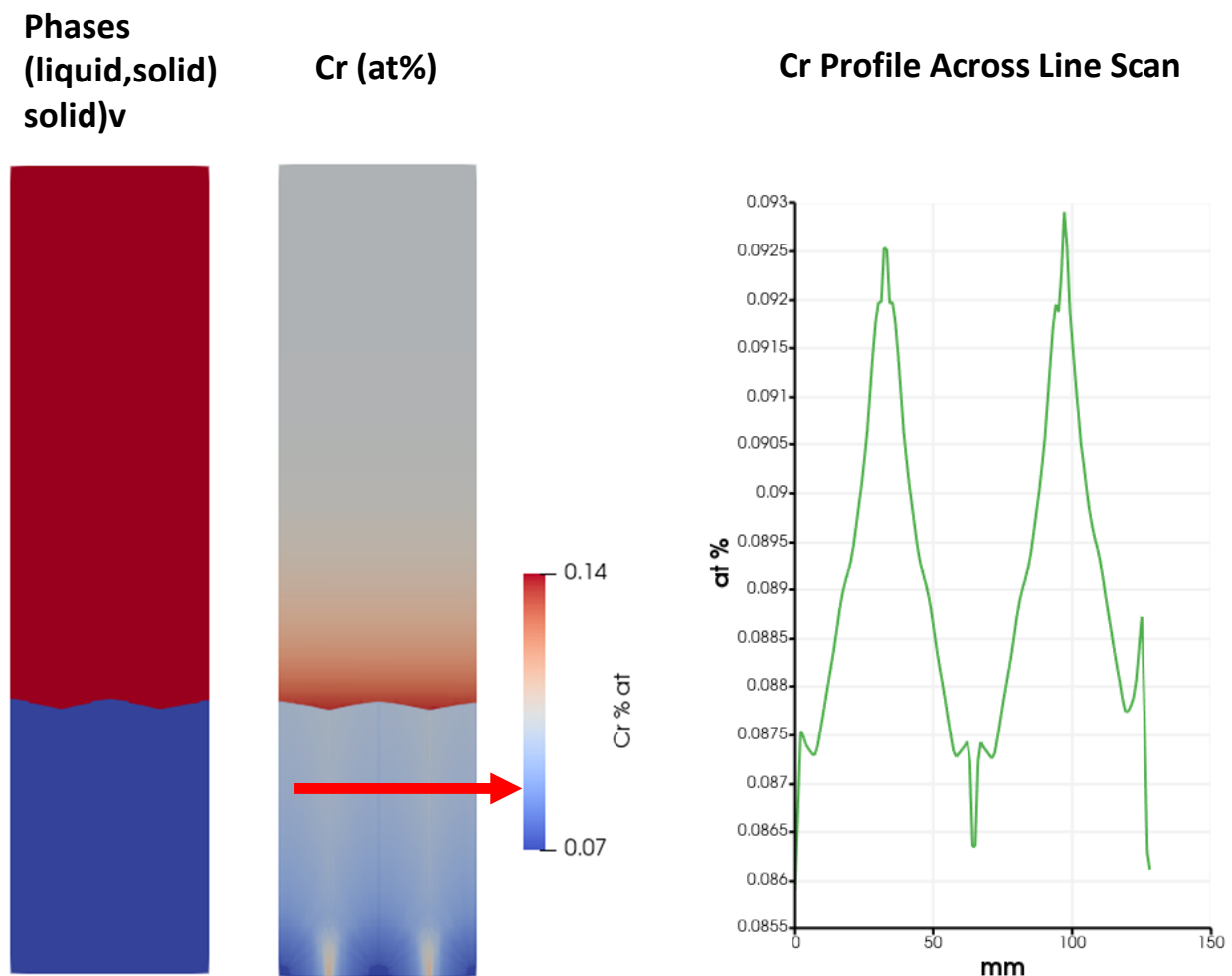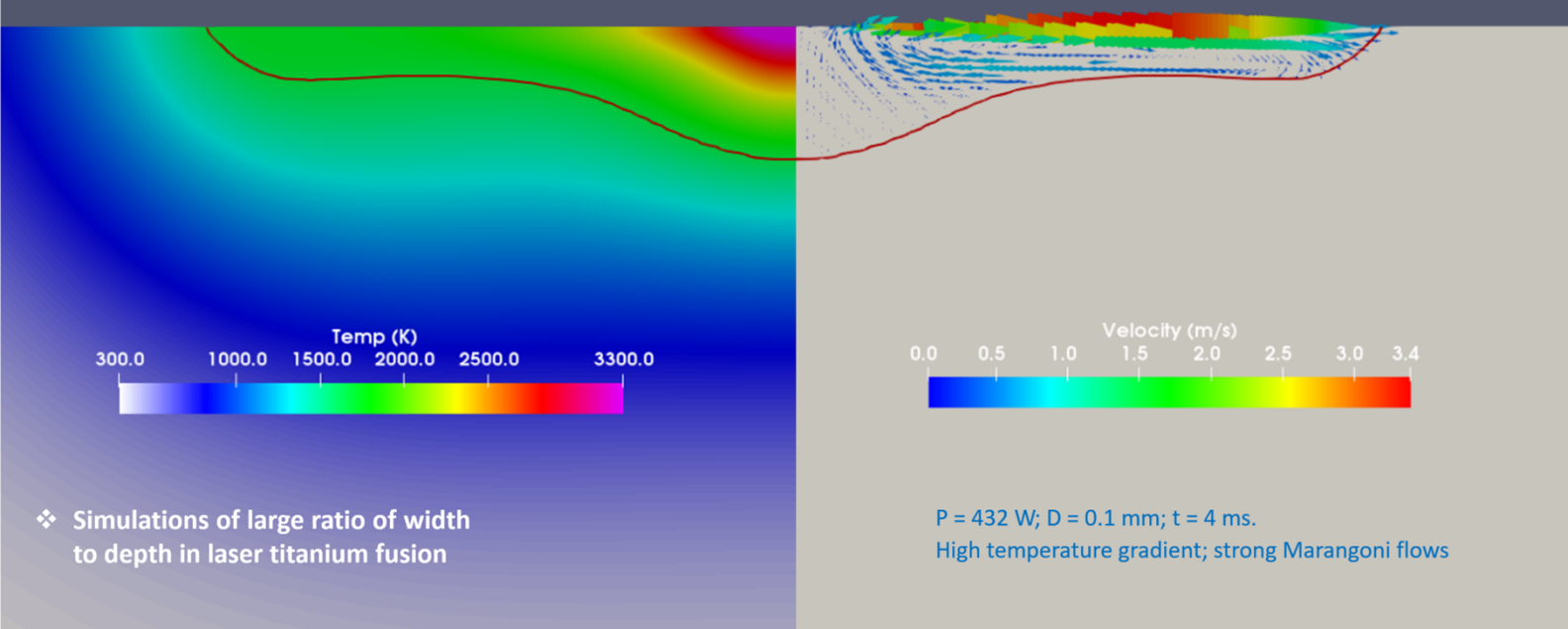

Figure 9. From left to right: Fro Cr-Ti, the liquid growing into the solid; a composition heat map that shows segregation across a cellular structure; a line scan profile showing qualities agreement with the Cr-Ti 1D prediction.

Temp (K)

300.0   1000.0 1500.0 2000.0 2500.0   3300.0

Velocity (m/s)

0.0   0.5   1.0   1.5   2.0   2.5   3.0   3.4

❖ Simulations of large ratio of width to depth in laser titanium fusion

P = 432 W; D = 0.1 mm; t = 4 ms.
High temperature gradient; strong Marangoni flows

Process Modelling

Research Area 5

Overview

The target of this research area is to assist the MES DED process development though the fundamental understanding with physical insights into process behaviour and accurate predictions of interactions between thermal fields, melt pool development and bead formation. A fluid flow model has been developed on the simulation of the coupled mass and thermal flow in the melt pool, and their effect on the material solidification and bead formation. The model has been validated on the plasma and wire AM process. Good agreements between the simulation and the experimental results have been achieved. This model will be extended for the multi-energy source with improved computational efficiency. Three FE models have been developed, which are on wire melting, hybrid laser and arc process, as well as scanning laser. The model on the wire melting has shown a melting efficiency of two times can be achieved by using a strip wire comparing to a round wire. Further development will focus on matching the laser beam profile to the wire shape to achieve the highest melting efficiency. Both transient and steady state FE models have been developed for predicting the thermal distribution of the hybrid laser and arc process. This model will be used for studying the thermal interactions of the different configurations of the arc and the lasers. A transient FE model has been developed for the scanning laser. Further work will be focus on the characterisation of the scanning laser and the development of an equivalent stead state heat source.

Mechanisms of large ratio of width to depth in laser titanium fusion with a small beam size

From previous experiments, the large ratio of width to depth physical phenomena were found in laser powder AM and laser metal fusion with a high power density and small beam size. However, the underlying mechanism remains unclear. In this work, a two-dimensional transient model was developed to investigate the physical process during laser titanium fusion with a power density of 5500 kW/cm^2 and a beam size of only 0.1 mm. The calculated cross sections are consistent with the experimental data at different interaction time parameters. Using this model, the mechanism of the melt pool formation can be explained. The figure on the previous page shows the distributions of temperature and velocity under an interaction time of 4 ms. When a high laser power density irradiates the surface of the substrate, the temperature at the centre point increases almost instantaneously to be around the boiling point of the metal (3375 K). Hence, a large temperature gradient occurs is present in the melt pool, causing a large Marangoni shear stress on the surface. The maximum speed of the transverse flow at the surface of the melt pool driven by the large Marangoni shear stress can reach up to 3.5 m/s in 4 ms. Thus, a large width is achieved with enough interaction time. The simulation results demonstrate that the large melt pool width obtained in the experiments is mainly caused by the enormous Marangoni flow generated by the large temperature gradient on the melt pool surface in the transverse direction.

Modelling of Wire-based plasma arc additive manufacturing

A comprehensive three-dimensional transient fluid flow model has been developed to simultaneously simulate the heat and metal transfer, fluid flow, metal solidification and deposition process. In this model, a novel surface heat source was developed. This heat source model is based on the experimental data and well considers the shading effect of the wire by using the Dirac-delta function and ray tracing method, as shown in figure 10. Most of the important factors including wire feeding, multiphase transformations, free surface tracing, fluid flows, and deposition, as well as the effects of the major forces such as surface tension, Marangoni shear stress, gravity, buoyancy, arc pressure, arc shear stress, and electromagnetic force are accurately considered in this model. The gas and liquid interface is tracked using the robust volume of fluid (VOF) method. The liquid and solid interface is tracked using the porosity enthalpy method. The surface forces such as surface tension, Marangoni shear stress, arc pressure and arc shear stress are incorporated using continuous surface stress (CSS) method. Additionally, the arc pressure used in the model comes from the experimental arc pressure measurements.
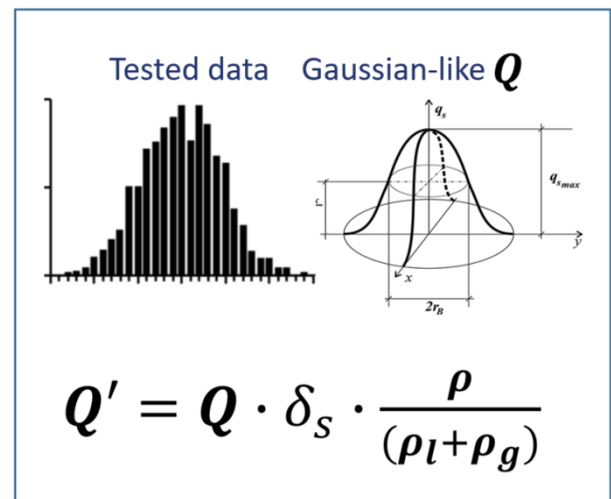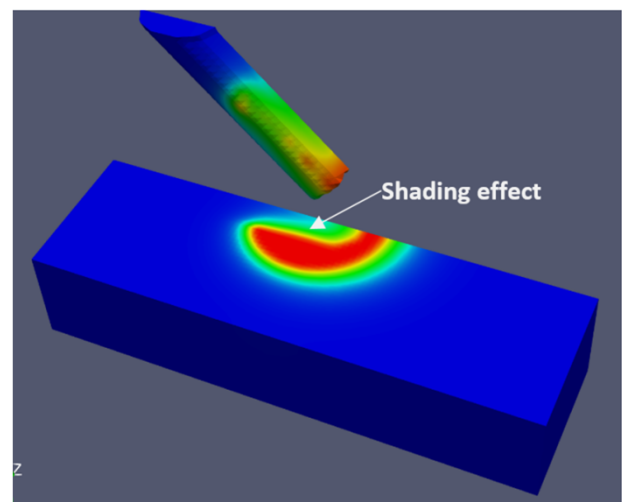

$$Q' = Q \cdot \delta_s \cdot \frac{\rho}{(\rho_l + \rho_g)}$$

Figure 10. Experiment-based Dirac Surface Heat Source.

Modelling of Wire-based plasma arc additive manufacturing (cont.)

Figure 11 shows a comparison of the deposition process between the experimental work and the modelling work. One can see that the model has accurately captured all the main interested stages of the process, such as the wire melting, droplet transfer, melt pool development and bead formation. This comprehensive model can be used as a good theoretical tool to deep studies on the physical process, defects formation and depression, and parameters optimisation methods for plasma arc wire-based AM. This model will be combined with the laser heat sources and help the understanding and explanation of the complicated physical interactions of the multi-energy heat sources in the NEWAM research programme. Computational efficient models will be developed in the next step for providing predictions of the thermal field and bead geometries which can be used for the development of the Research Area 1 (Process Development) and Research Area 2 (Material Development).
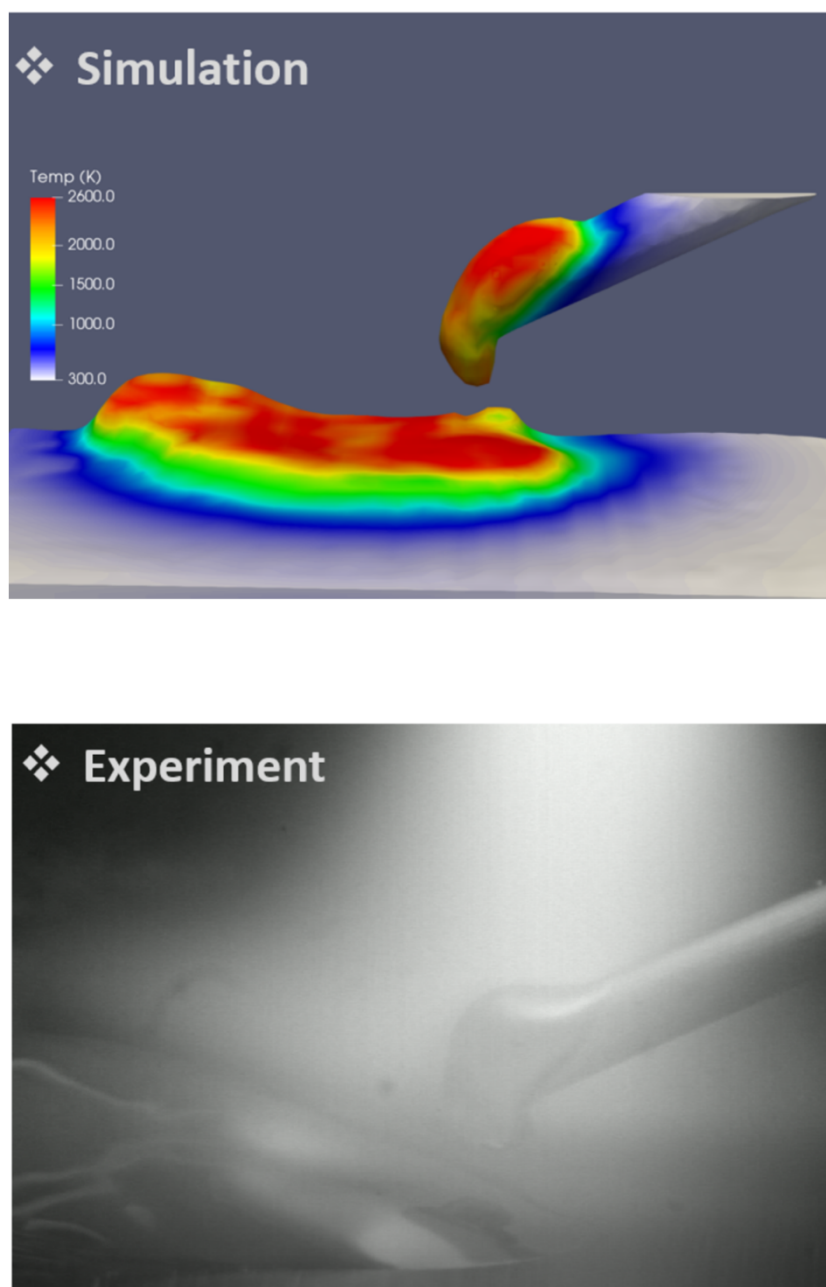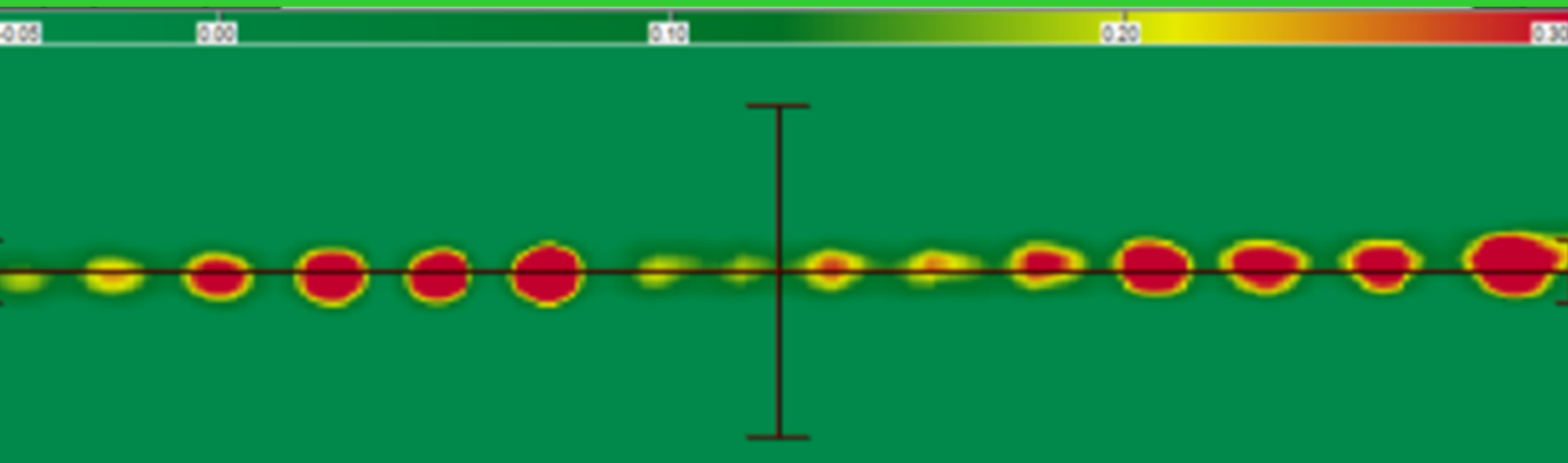

Figure 11. Simulation versus experiment.

Non-Destructive Testing

Research Area 6

Overview

In-process non-destructive testing (NDT) of WAAM components is an important part of the quality assurance of manufactured parts. Traditional NDT is deployed post manufacture often on finished or near finished parts. Deploying NDT earlier in the manufacturing process is advantageous as it allows for identifying problems earlier in the manufacturing process, potentially saving time and money. For metal additive manufacture (AM) an additional benefit of in-process inspection is that by finding defects during build, this opens a pathway for in-process corrective action to be performed (re-melting or machining and re-deposition).

Significant effort is required to move towards fully in-process identification of defects such as inclusions, porosity and lack of fusion.

The main challenges to address focus around:

• The transduction process (which process-compatible physical sensing technique is employed)

• The deployment process (how the measurement is deployed in-process)

• The data interpretation process (how data is interpreted and used to correct the process)

For the transduction process, attention has been focussed on the use of dry-coupled (no liquid coupling) contact ultrasonic inspection (mainly phased array approaches implemented as wheel probes). This has required the development of new process compatible materials to allow operation at elevated temperature (up to 350 ˚C), and to operate off non-planar surfaces.

As an alternative to ultrasonic inspection, eddy current testing has also been considered. In principle, this offers the possibility for non-contact inspection – although in practice many commercial eddy current systems employ a coil substrate and support structure which is in physical contact with the inspected surface (but not requiring couplant).

A third transduction option, that of fully non-contact, remote operation laser-ultrasound, is being considered. The team has existing expertise in advanced phased array implementation of laser-ultrasonics and preparations are in hand (a new £2.5M laboratory facility – Robotically Enabled Sensing will be available in late 2020) to support this activity.

For deployment, sophisticated robotic deployment has been employed thus ensuring compatibility with the WAAM manufacturing process. The team has deployed measurements through conventionally programmed industrial robots, novel RSI (Remote Sensor Interface) programmed robots, and new full force-feedback collaborative robots.

For data interpretation, the use of calibration artefacts is important to understand the system response to known defects before attempting to assess the condition of real process driven defects. A systematic approach to manufacturing such known defects has been developed and calibration samples with side drilled holes (SDH) and flat-bottom holes (FBH) have been produced.

Ultrasonic Wheel Probe Inspection

Contact (or immersion) ultrasonic testing (UT) is known for its high-performance bulk inspections of many diverse materials. The method benefits from new advances in phased-array technology, allowing for electronic steering and focusing of the beam at different spots in a sample under test. There is an increasing trend of research devoted to imaging using ultrasonic arrays, which brings about even more possibilities with Phased Array Ultrasonic Testing (PAUT). However, the complexity of the as-built WAAM surface renders the deployment of conventional off-the-shelf phased array probes and their stand-off wedges nearly impossible, since these are designed to match flat or surfaces with specific curvature.

Therefore, a new concept for a dry-coupled high-temperature (< 350 ˚C) compliant wheel probe comprised of a tire made from a high-temperature resistant silicon rubber, a linear ultrasonic array enclosed within the wheel and a solid or liquid fill material has been researched and developed. The wheel was designed according to the results obtained from a series of numerical simulations and experimental tests for sound propagation and heat transfer within different constituent media. The wheel probe assembly has been rigorously tested to push the limits of its endurance and detectability. For instance, Figure 12 shows the

capability of the wheel probe in detection of subsurface flat bottom holes of 2 mm in diameter in a titanium WAAM sample.
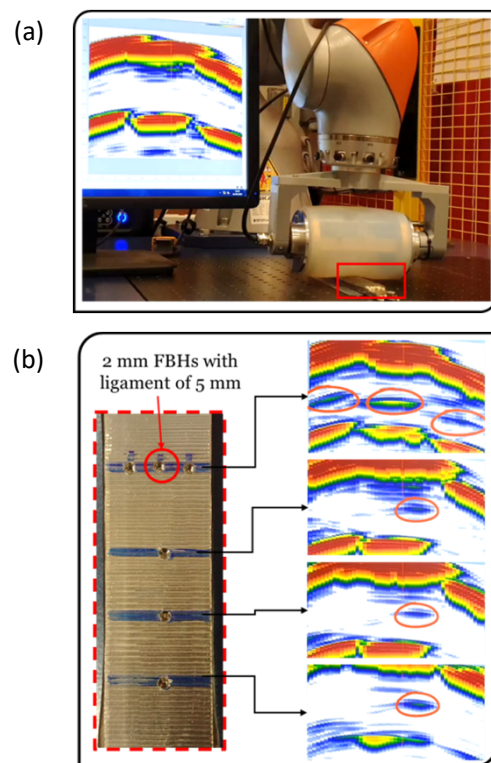

Figure 12: (a) The assembly of the ultrasonic wheel probe mounted on an LBR robot and scanning a WAAM component while contact pressure is maintained constant, and (b) Flat bottom holes drilled in the underside of a WAAM sample and B-scan images showing their scan results when the wheel probe is scanned from the top curved surface of the WAAM sample.

Ultrasonic imaging through non-planar interfaces

New imaging algorithms, based on the Adaptive Total Focusing Method (A-TFM), are being developed to inspect the WAAM component through the curved and irregular surface, and form fully focused images as shown in Figure 13. Such algorithms will be able to update the profile of the surface, based on the ultrasound reflections, and regenerate the Total Focusing Method (TFM) image accordingly, as the scan progresses.
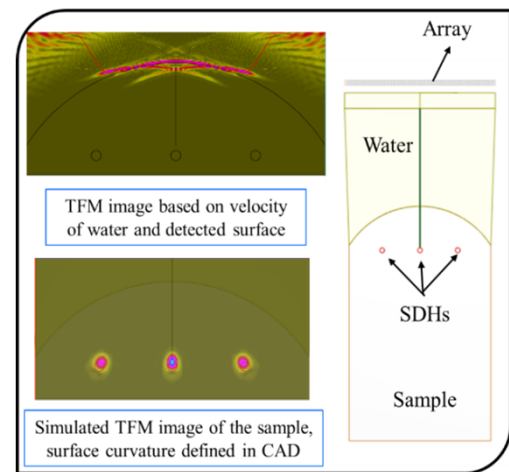

TFM image based on velocity of water and detected surface

Simulated TFM image of the sample, surface curvature defined in CAD

Figure 13: Total focusing method (TFM) image formed for the section of the mock WAAM showing a strong indication for the side drilled hole.

Eddy Current Inspection

To investigate the response of Eddy Current testing in WAAM samples, a sensitivity block was prepared. A titanium straight wall sample deposited using the WAAM technology at Cranfield University was cut and machined to build the sensitivity block. Electrical discharge machining (EDM) was utilized to fabricate fine notches on the bottom surface of the machined block with smallest of them having only 0.5 mm in length and width. The depth of these notches and their distance from the top surface of the WAAM wall were planned in a manner that fall at the limits of eddy current penetration depth at the selected frequency. A customized eddy current array was employed on the top surface of the wall to inspect the far side EDM notches which are shown in figure 14.

The eddy current results, as demonstrated in the following image, suggest that even the smallest defect of 0.5 mm by 0.5 mm located at the depth of 1.6 mm under the surface could be successfully detected using the array. The spacing between the transmitter and receiver coils in the array, the operating frequency of the array, size of the coils and the transmission topology are the parameters that require optimization to obtain satisfactory results. Furthermore, further design for the array is required to make it operational at high temperatures of up to 200 ˚C. Further research would be required to integrate the Eddy current head and its controller together with a robotic arm equipped with force/torque sensors, so (a) the robot will be able to keep the sensor on the surface of the WAAM component during the inspection and follow the complexities of the surface while maintaining a constant force, and (b) the inspection results can be associated with the position of the robot to enable pinpointing of the defect location.
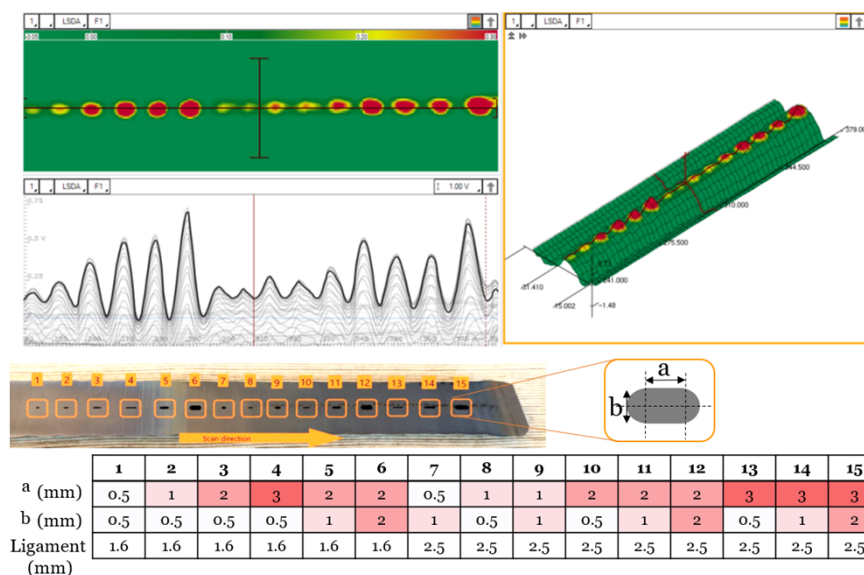

Figure 14. Dimensions of the electrical discharge machined notches fabricated on the bottom of the titanium WAM components and the eddy current inspection results when the array is scanned from the top as-built surface of the sample.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
a (mm)	0.5	1	2	3	2	2	0.5	1	1	2	2	2	3	3	3
b (mm)	0.5	0.5	0.5	0.5	1	2	1	0.5	1	0.5	1	2	0.5	1	2
Ligament (mm)	1.6	1.6	1.6	1.6	1.6	1.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5

Artificial defects in WAAM samples

To investigate the ultrasonic response to defects of known size and position, a series of samples were manufactured with intentionally embedded tungsten inclusions (balls and rods). Tungsten-carbide balls (ø1-3 mm) were intentionally embedded inside the WAAM sample after the 4th, 8th, 12th and 18th layers (Figure 15a). The tungsten balls served as ultrasonic reflectors, simulating WAAM defects, in the PAUT inspection system. A 5 MHz transducer (64-element array) was used to inspect the WAAM sample from the top surface which was machined. The majority of the reflectors were detected successfully using PAUT and TFM (Figure 15b). This proved that the tungsten carbide balls were successfully embedded during the WAAM process and also that these are good ultrasonic reflectors. Owing to a lack of standards and codes for the ultrasonic inspection of WAAM samples (A. Lopez, R. Bacelar, et al., 2018), a calibration method and step-by-step inspection strategy were introduced and then used to estimate the size and shape of an unknown Lack of Fusion (LoF) indications. This was then validated by destructive testing, showing a good correlation with the phased array results. This work was a collaboration between Strathclyde and Cranfield universities and published in Additive Manufacturing journal (Javadi et al., Additive Manufacturing 29, 2019).
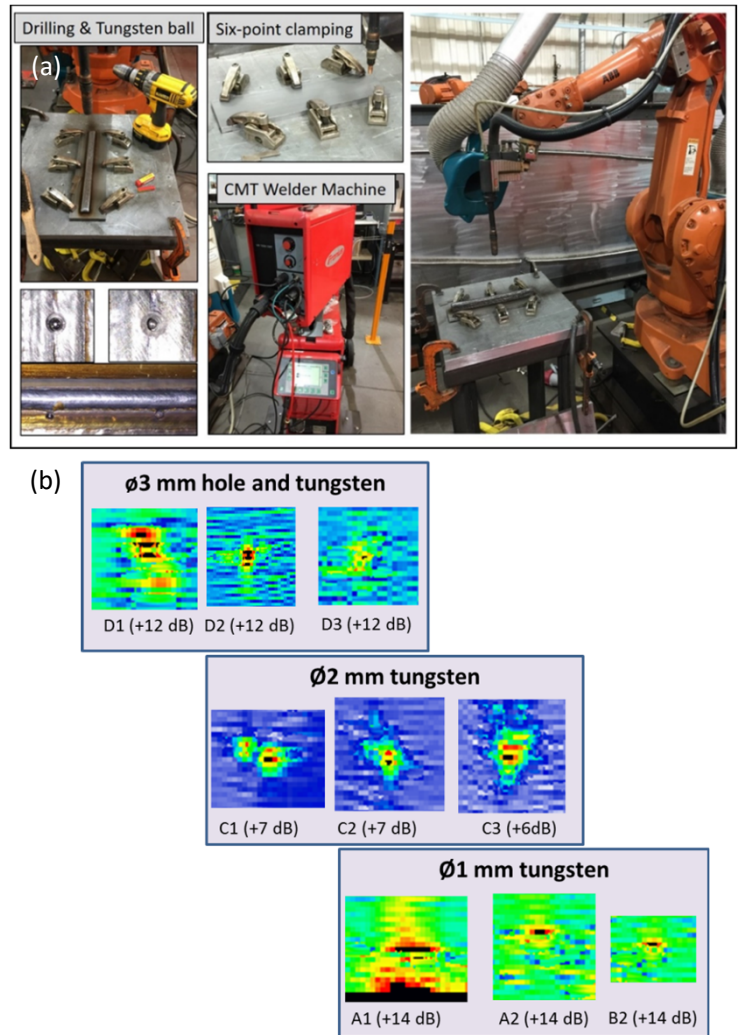

Figure 15. (a) Procedure established for manufacture of artificial defects in WAAM samples, and (b) measured ultrasonic response to the artificial defects [Javadi et al., Additive Manufacturing 29, 2019].

Summary

The team have investigated dry-coupled contact based ultrasonics and eddy current approaches for the fundamental measurements process. Novel wheel probes have been developed which can operate at temperatures up to 350°C and can image and inspect as-built WAAM samples. Deployment of the probes has been undertaken using a fully robotised solution with force control such that irregular and changing surfaces can be accommodated for inspection. Employing sophisticated imaging algorithms such as TFM allows for correction of imaging focal laws to accommodate curved and irregular interfaces.

Eddy current inspection has been shown to image and inspect titanium WAAM samples. This is a proof of transduction principle at present and does not have the same level of deployment integration demonstrated for the ultrasonic approach.

Calibration samples with artificial defects including flat bottomed holes, side drilled holes and tungsten inclusions have been manufactured so that defect response indications from real defects can be compared to a reference signature to assist in correct flaw sizing from indications.
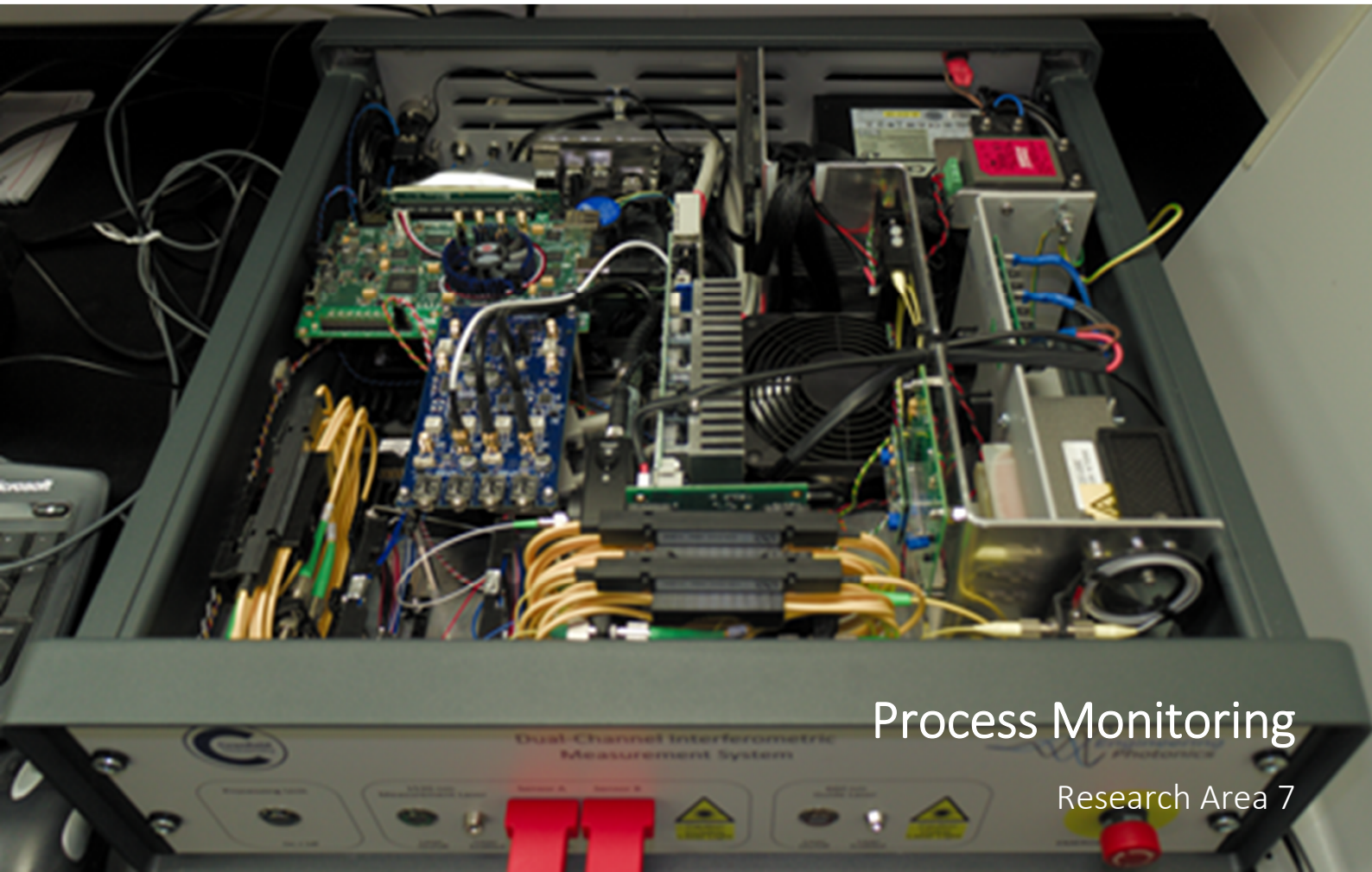
Process Monitoring

Research Area 7

Overview

This research area has two main goals: (i) to investigate the use of pyrometers to monitor the material temperature during the wire additive manufacture deposition and (ii) layer height measurement using coherent range resolved interferometry (CORRI). When producing a part, the main geometrical parameters to control are the effective wall width and the layer height. Utilising in-process layer height measurements a closed loop can be formed in order to control the build parameters and subsequently the finished part. For these measurements, an 8-channel Coherent Range Resolved Interferometry (CORRI) system is proposed being developed. Each sensor will measure in real time the distance of the wall currently being built from the sensor and calculate the height of the deposited layer.

Figure 16. New development of the CORRI system.

In-process pyrometry thermal profile measurement system

The instrument which was evaluated was a two colour pyrometer (Metis M322), supplied by Sensotherm. This pyrometer option is supplied with a 2.5 m fibre optic cable with an optical head and can be operated in either single-channel mode (1 colour) or 2- channel mode (2 colour). The spectral ranges of the two colours are: channel 1, 1.65 - 1.8 µm and channel 2, 1.45 -1.65 µm. The temperature range of this pyrometer is 400-1600°C with a measurement uncertainty of specified as 0.3%. In single channel mode, it measures infrared radiation from objects in one spectral range. In 2-color mode, it measures in two separate spectral ranges simultaneously and determines the temperature from the ratio of the two radiation intensities.

The pyrometer head was mounted behind the plasma torch at a distance of 110 mm from the top of the weld wall. The measurement spot was 2 mm diameter and located 18 mm from the centre of the torch axis. The geometrical configuration used to mount the Sensotherm pyrometer is shown in Figure 17. The measurement spot location was adjusted so that it always tracked along the top of the weld centre-line during deposition.

The temperatures recorded during the first WAAM layer are shown in Figure 18.

Six more WAAM layers were then deposited with the temperatures recorded as each layer progressed. Figure 19 shows the maximum temperature attained during the seventh layer. The pyrometer has also recorded the beta-phase transition of Ti64 as it cools down after welding.

The difference in temperature observed between the two-channel measurement and the single channel measurements is due to a scaling error. The two channel measurement is more representative of the actual temperature of the wall surface.

The preliminary work undertaken with the Metis 322 2-colour pyrometer has shown that it is an accurate instrument for measuring process temperatures during a Ti64 WAAM deposition process.

Further work should be undertaken to assess the impact on measurement repeatability of variations in oxygen levels from 20-1000 ppm and different weld geometries.
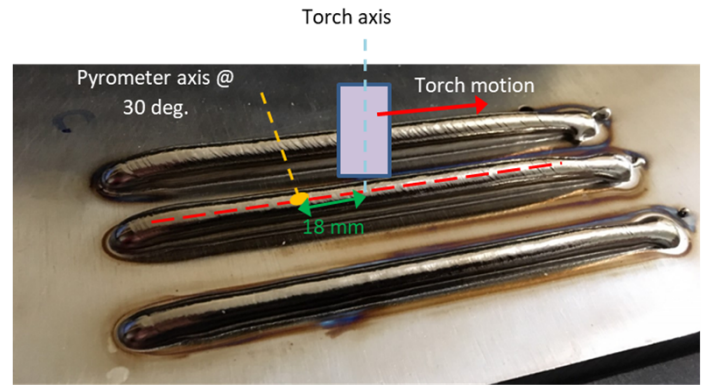

Figure 17. Titanium wall showing pyrometer orientation during wall deposition.
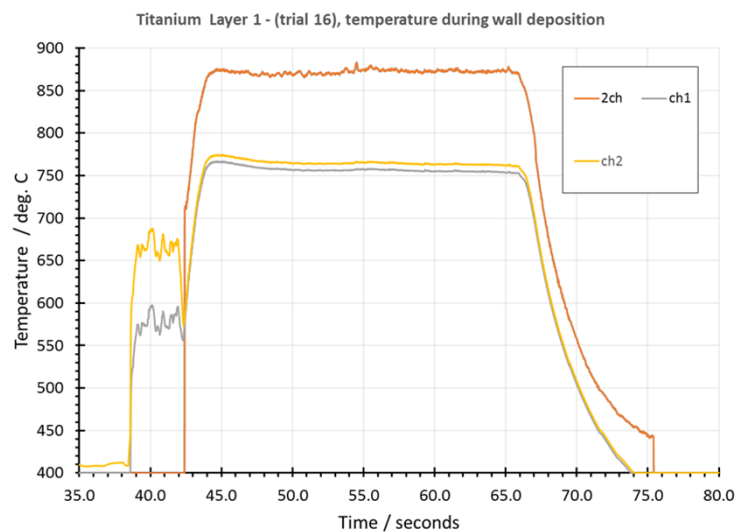

Figure 18. The measured temperatures recorded during the deposition of the first Ti64 layer. The channel 1 (ch1), channel 2 (ch2) and two channel (2ch) temperatures are shown, together with the time period over which the plasma torch was active.
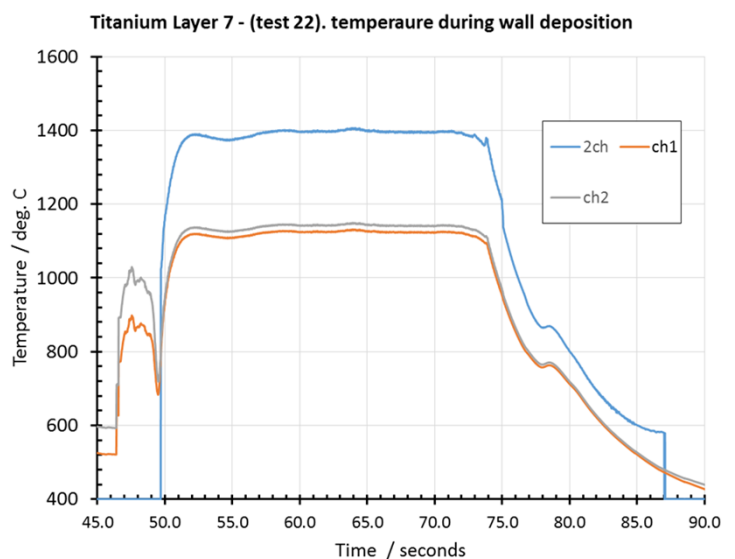

Figure 19. The measured temperatures recorded during the deposition of the seventh Ti64 layer. The channel 1 (ch1), channel 2 (ch2) and two channel (2ch) increased temperatures are shown, together with the appearance of the beta transition temperatures after 78 seconds.

CORRI system development

The layer height measurement system is composed of 3 main components: the fibre optics, the data capture electronics and the embedded processing unit. This system is based on an earlier development system with two processing channels. As shown on Figure 20, that system is overly complex and it cannot be easily converted to handle up to 8-channels. Instead, a simplified version was designed.

To minimise the complexity of the overall system the individual components were integrated. The result can be seen in Figure 21. This is typically a quarter of the size of the system shown in Figure 20.

For the 8-channel layer height measurement system the following components were redesigned. The first was the embedded processing unit which is comprised of a custom printed circuit board (PCB) that acts as a main board and hosts a Field Programmable Gate Array (FPGA). This FPGA device is responsible for generating the appropriate signals to drive the electronics, as well as to process the acquired signals and calculate the distance of the wall from the sensor and thus determine the layer height.

Along with the processing unit, a custom photodetector board was designed and manufactured. This board is responsible for the conversion of the back-reflected light from the wall into an analogue voltage. This analogue signal is then digitised by the on-board Analogue-to-Digital converter chip. The digitised signal is passed to the FPGA for processing and extracting the distance information.

One of the main components of the system is the laser diode. For the operation of the laser two controllers are required. These are for regulating the temperature and the electrical current of supplied to the diode. On the earlier prototype these controllers were integrated to the vertical PCB mounted at the centre of the system.

For the new system the size of the controller was decreased by a factor of 4. Additionally, the controller is now incorporated into the diode mount further reducing the size and improving the thermal design.

Another component that has to be redesigned is the fibre optic setup, so it can handle up to 8 sensing channels. Furthermore, the arrangement of the sensors has to be reviewed as the position of the sensors can affect the accuracy of the measurement.

Finally, apart from the hardware components, there was an effort to improve and optimise the speed of the signal processing yielding real-time layer height measurements. This required implementing the algorithms in a lower-level programming language taking advantage of the latest features found in current generation CPUs.

A measurement system for detecting the layer height during welding has been designed. During the design phase, various components were evaluated, redesigned, and tested.

Further work should will be undertaken to finalise the design and test the instrument. This will involve assembling the components to form the final unit. When this is done, the system will be tested and later incorporated into the WAAM system.
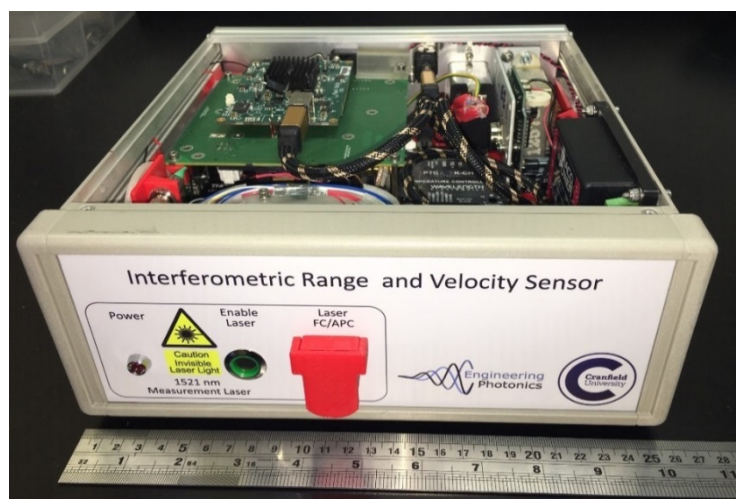

Figure 20. First prototype system.

Figure 21. New development system.

Our team

Collaborative

Diverse

Knowledgeable

Professional

Motivated

Fun

Our team
Working together

We believe the success of the research programme relies on the motivation and engagement of the team. That is why we value good working atmosphere. Team building events are organized throughout the year to encourage the team to form new and strengthen existent bonds. The events are aligned with the consortium meetings where all team is gathered to learn the progress of the full programme. The team has the opportunity to discuss the technical content of the projects in a more friendly and relaxed environment. A good collaboration between the academic partners lead to more high quality collaborative projects.

Team bonding activities

Collaborative outreach activities
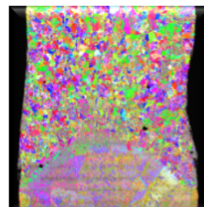
Collaborative projects

Academic partners

NEWAM will build on and exploit the UK's substantial lead in wire-based DED technology.

2019

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