Virtual Seminar Series – Tuesday 2, 9, 16 November

New Wire Additive Manufacturing (NEWAM) programme for next generation wire based additive manufacture

Presented by Prof. Stewart Williams
Director of the Welding Engineering and Laser Processing Centre
Cranfield University

Tuesday, November 9, 2021

New Wire Additive Manufacturing (NEWAM) programme for next generation wire based additive manufacture

- **Abstract**

An introduction to the NEWAM research programme, focused on the process, material and structural integrity of wire based directed energy deposition AM (w-DEDAM) processes. Four universities (Cranfield U., U. of Manchester, Strathclyde U., and Coventry U.) have joined forces to deliver an ambitious research programme over five years with EPSRC funding, and considerable industry support from AM equipment supply chain, service providers and end users.

- Why NEWAM? – current w-DEDAM processes have limitations, relatively low deposition rate, materials and alloys not designed for AM, no online monitoring system to guarantee the structural integrity of the built parts
- What does NEWAM propose? - using multiple energy sources to achieve independent control of deposited bead geometry (height and width) and thermal field or microstructure. This is targeting increasing the deposition rate, achieving net shape finish with precise control of microstructure and therefore properties. Synergistic design of processes and new materials and alloys for AM to achieve properties similar or better than the raw material. Physics based quality control using new in-process non-destructive testing techniques for quality control and in-process monitoring for quality assurance.
- How will NEWAM deliver? – through a fully integrated multi-disciplinary research programme delivered by four leading Universities. Process design, monitoring and modelling at Cranfield, material expertise and modelling at Manchester, material performance and behaviour at Coventry and in-process NDT at Strathclyde.

- **About the presenter, Prof. Stewart Williams, Cranfield University**

Prior to commencing at Cranfield University, Professor Williams was at BAE Systems Advanced Technology Centre for nearly 20 years. Here he managed a research group investigating mainly laser-based manufacturing processes for aerospace and defence applications. This included micro-machining, drilling of fine holes, surface treatments and welding. He was responsible for development of a laser-based wire marking method from which a company was set up to exploit the technology. He was also heavily involved in development and qualification of friction stir welding for Airbus.

At Cranfield University his main research activities are focused on additive manufacture and laser processing. Additive manufacture research is targeted at large scale engineering structures using the wire plus arc additive manufacture (WAAM) process. A multi project multi-client programme has been put in place, WAAMMat, aimed at maturing the technology so that it can be exploited by industry. The research is tackling problems such as automation, mechanical properties, residual stress and distortion control and how to build complex structures.

New Wire Additive Manufacturing

New Wire Additive Manufacture - NEWAM

Prenscia Workshop

Stewart Williams + NEWAM team

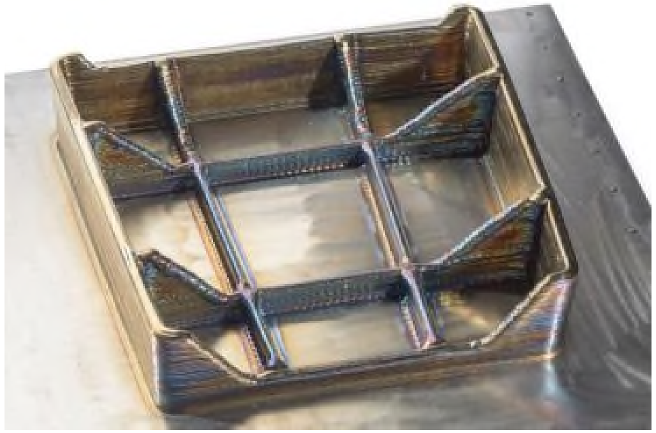
9th November 2021

Talk overview

- Current situation for wire base directed energy deposition additive manufacture (w-DEDAM)
- So, what's the problem?
- NEWAM
  - ❑Vision
  - ❑Team
  - ❑Challenges
  - ❑Projects
  - ❑Industry supporters
- Highlights to date

Wire based DEDAM - Business Drivers

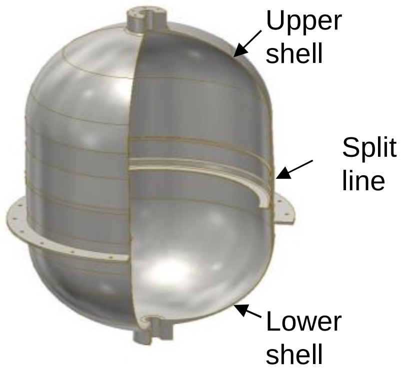
- Cost and material saving compared to current manufacturing methods
- Greatly reduced lead times
- Application of AM to large engineering structures
- Enabling new functionality in components

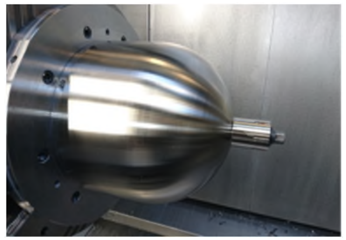


Titanium landing gear rib

Design option	Mass (kg)	BTF	Cost (£k)	Cost red.
Original machined	20	12	16.2	-
WAAM + machining	20	2.3	5	69%

Satellite propellant tank

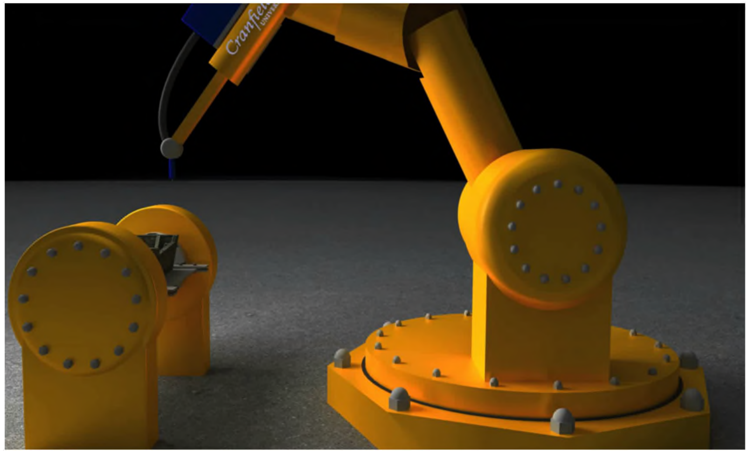




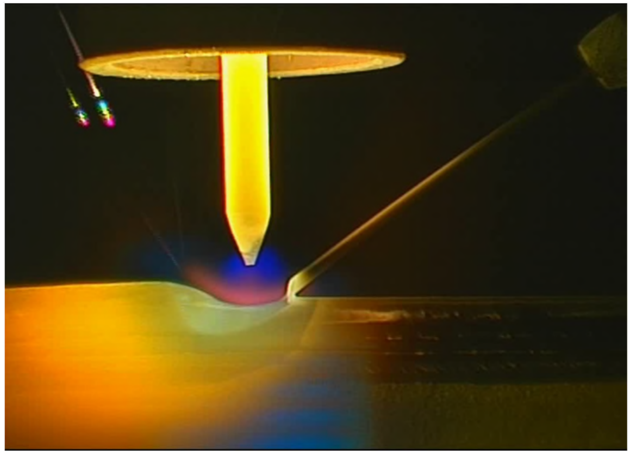
Business benefits

- Lead time reduced from years to weeks
- 50% cost compared manufacturing process
- Bespoke geometry for each mission

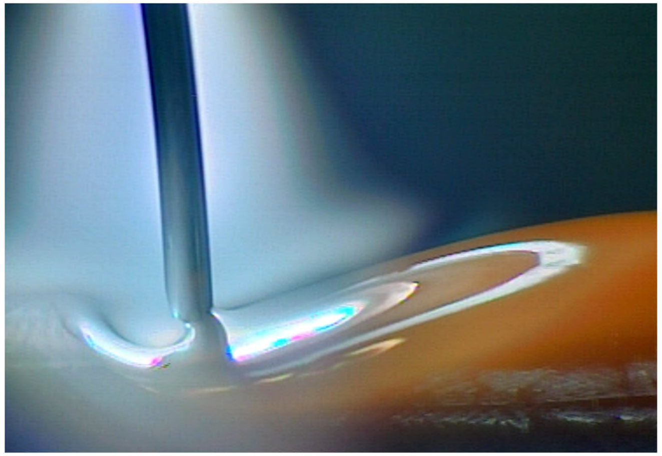
We have nice processes to put on the end of robots



Robotic deposition



TIG– large scale deposition of tungsten

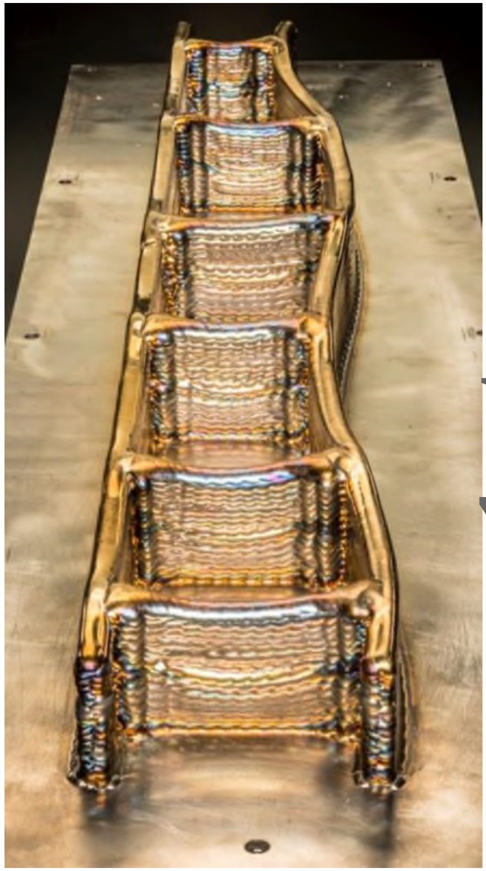


PTA – large scale deposition of titanium

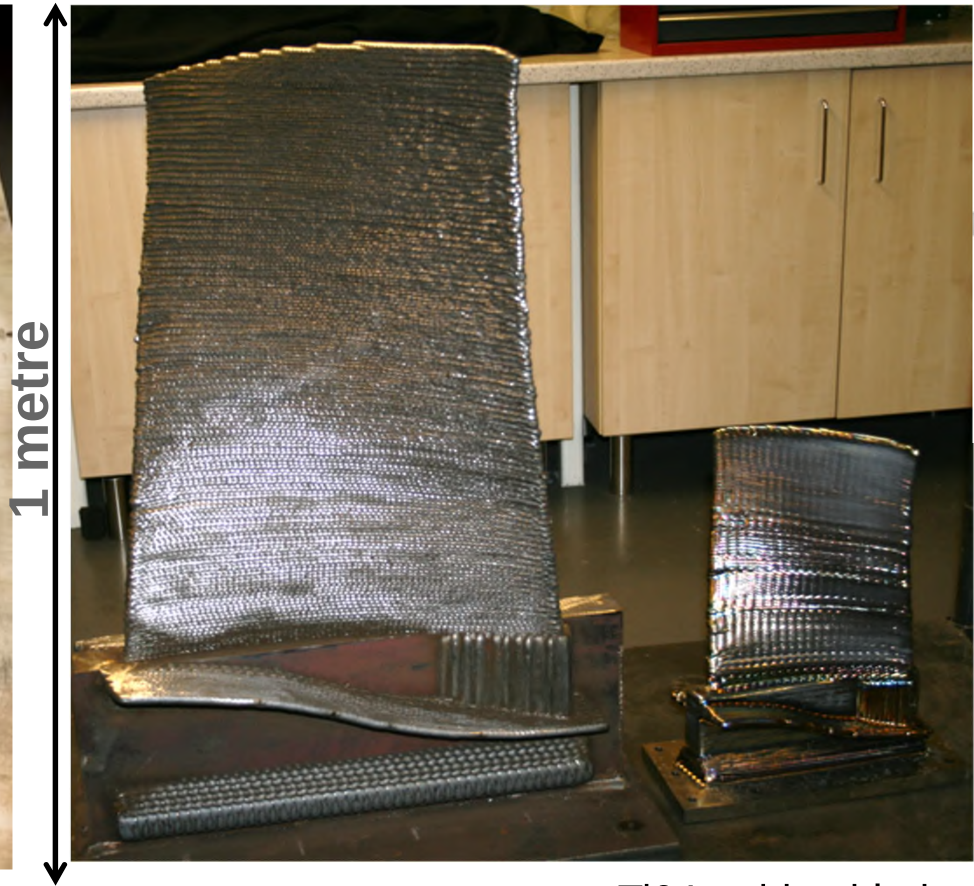
We can successfully deposit lots of materials with high quality

- **Titanium**
  - Commercially pure
  - Ti64
  - Ti64 + O_2 doping
  - Ti64 – Low O2
  - Ti5553
  - Timetal 407
- **Aluminium**
  - 2024
  - 2319
  - 4043
  - 5087
  - Safra 66
  - ZL205A
  - AlMgSc
  - AlLi
- **Refractory metals**
  - Tungsten
  - Molybdenum
  - Tantalum
- **Invar®**
- **Steels**
  - ER60
  - ER80
  - ER90
  - ER120
  - Maraging grade 250
  - Maraging grade 350
  - Stainless (15-5PH, 17-4 PH, 316L, 420, + others)
- **Inconel®**
  - 625
  - 718
- **Bronze**
- **Copper (high conductivity)**
- **Magnesium**

We can build high integrity complex parts



Ti64 spar



Steel turbine blade

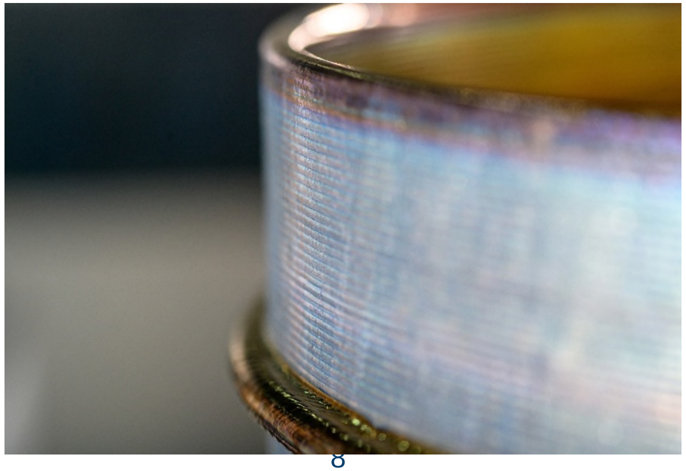
Ti64 turbine blade

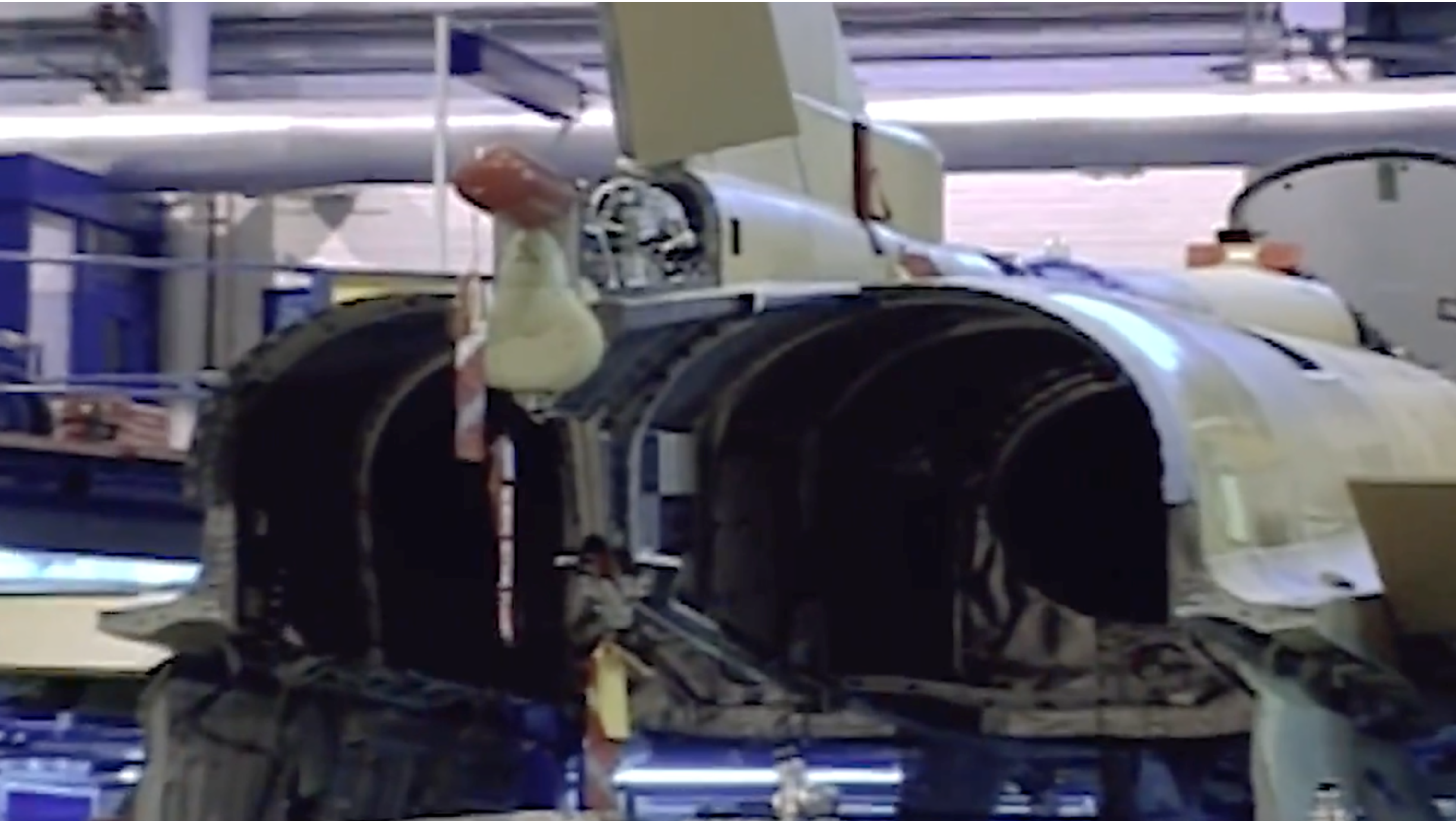
Ti64 landing gear rib

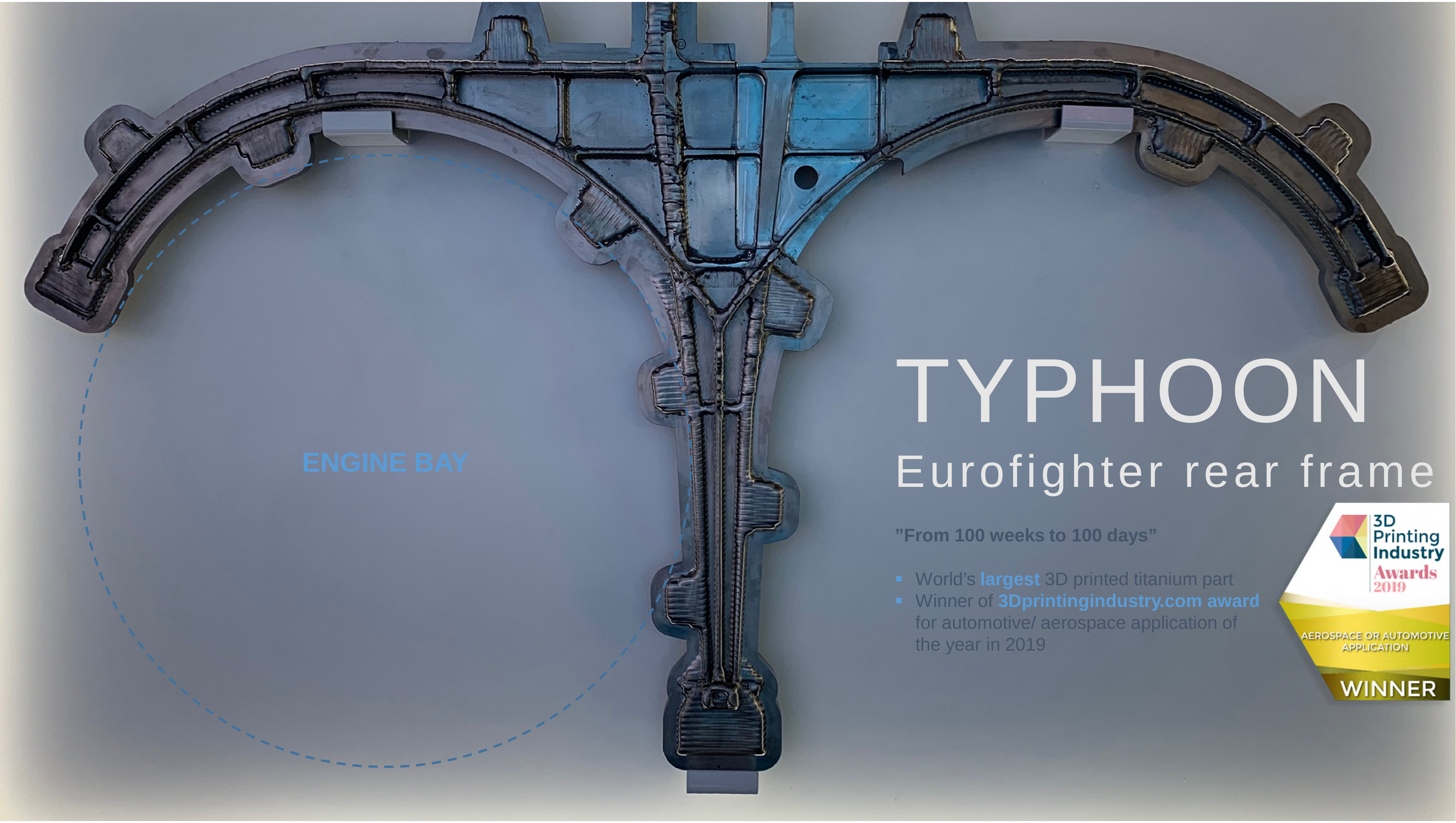

Half scale Ti64
blade
Worlds largest 3D metal printed part

Case studies - pressure tank for space missions

- Small batch
- Reduction in non-recurring costs (tooling and tooling iterations)
- Part consolidation
- Reduction in recurring costs
  - Machining
- 65% reduction in lead time
- 200 kg Ti64 saved – 40% cheaper







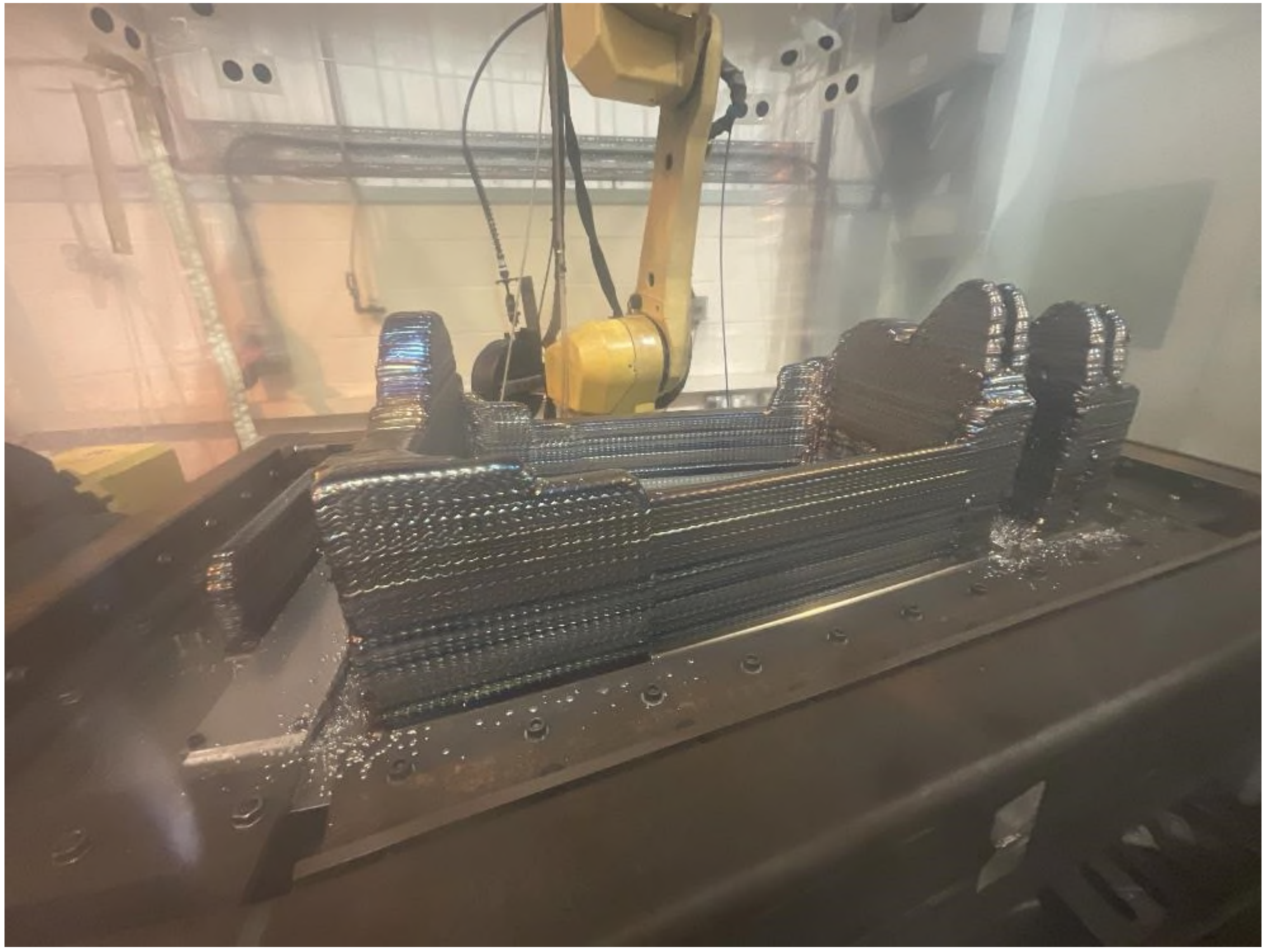
TYPHOON

Eurofighter rear frame

”From 100 weeks to 100 days”

- World’s **largest** 3D printed titanium part
- Winner of **3Dprintingindustry.com award** for automotive/ aerospace application of the year in 2019

Massive (180kg) titanium component



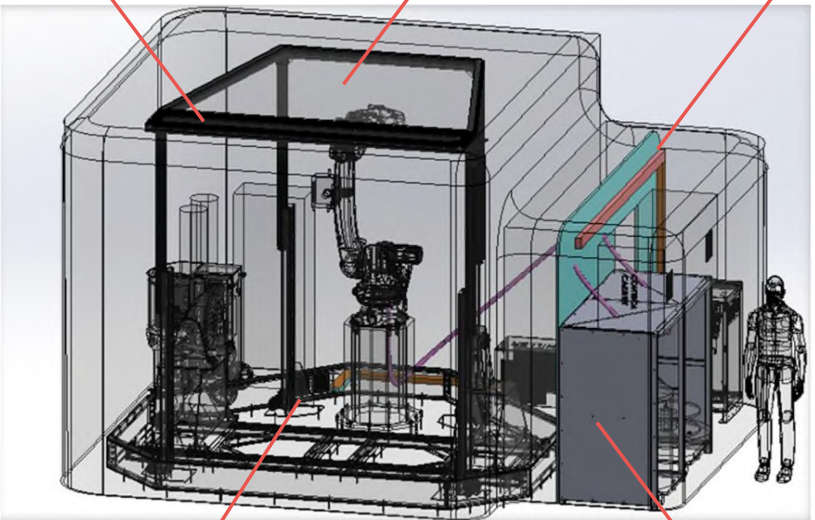
We have commercial fully integrated systems with sensors and software from e.g., WAAM3D

Fume management system™ (FMS™) with in-process filtration

Automatic gas purge and evacuation

All WAAM3D software and proprietary hardware (next slide)

Order now



Integrated safety systems

Bulk wire storage and handling

Standalone installation on shop-floor with full H&S compliant machine including fume treatment

So what is the problem??????

Requirements for metal AM industrial application

- **High quality**
  - Material properties as good as existing materials
  - Full structural integrity – zero defects
  - High quality feedstock
- **Production ready**
  - Simple easy to use fast path planning tools with in built process parameters
  - Fully automated process with in process monitoring and control
  - Mature intelligent turnkey systems capable of making large complex parts
- **Low cost`**
  - High build rates
  - Net shape finish – no finishing
  - In process NDT –guaranteed structural integrity
  - Improved matched materials

Focus for recent developments – WAAMMat and WAAM3D

Focus on future developments - NEWAM

W-DEDAM current issues

Current process based around commercial off the shelf equipment and materials

- **You get what you get**
  - Processes with either precise but slow and expensive deposition, or inexpensive at high build rate, but imprecise rough deposition
  - Properties are as they are, depending on precise process conditions build strategy and local thermal geometry, all using available (welding) materials
  - How do we cost effectively qualify components made by DED AM?

NEWAM - Research Vision for wire based AM

<u>Our vision</u> *is to transform wire based directed energy additive manufacture, by pioneering new high build-rate wire based processes with greater precision of shape and microstructure*

NEWAM Grand Challenges

- **New innovative** high build rate metal wire AM processes and systems for net shape deposition at low cost over large volumes with homogeneous microstructure and properties – **target 8kg/hr net shape for Ti**

- To build robust **physics-based process and materials' models** that give detailed process understanding, to enable more rapid process development and provide algorithms for **in-process microstructure control**

- Design of **new materials and alloys**, **tailored** to both existing and new deposition processes, giving performance **better than the equivalent wrought alloys currently used**

- To ensure guaranteed as-built structural integrity with process-independent **physics-based quality control and assurance** enabling low cost industrial qualification

NEWAM projects

Project 2- Material and process design

WP1 Material & process design
- Composition
- Thermal cycle
- In process deformation

Process tailored compositions
Mixed materials,

WP2 Effects of defects
- Lack of fusion, Pores, Cracks, Surface finish

WP3 Material Characterisation

Project 4 Q3 –quality control and assurance

WP1 Quality control
- Process monitoring - weld pool and/or metal transfer, topology and surface finish,
- Process Control - Layer height, thermal cycle

WP2 Quality Assurance
- On-line NDT,

WP3 In-process repair

Project 1 - New AM processes

WP 1 New processes - innovation and physics
- Process physics; Arc properties
- Material e interactions and transfer conditions

WP2 New processes
- Laser + wire - fine features
- Laser + arc + wire - high speed net shape
- Integrated high speed cooling
- On-line treatments

WP3 New wire configurations
- Shaped, coated, cored and multiple wire

Project 3 Process and material modelling

WP1 Physic based process models
- Fluid (melt) flow
- Thermo- mechanical

WP2 Material models
- Microstructure
- Properties

NEWAM project details

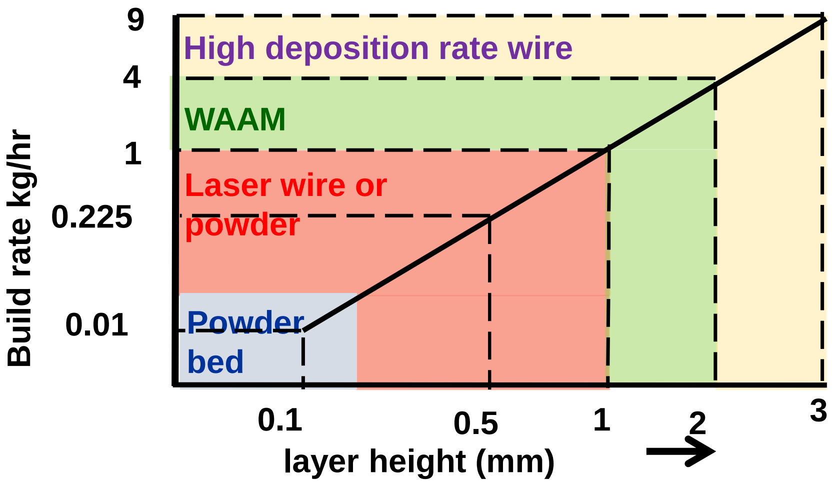
- Programme budget ~£7M + £3M industry support **<u>= £10M</u>**
- Programme duration 5 years
- Programme start date June 25th 2018
- Programme academic partners

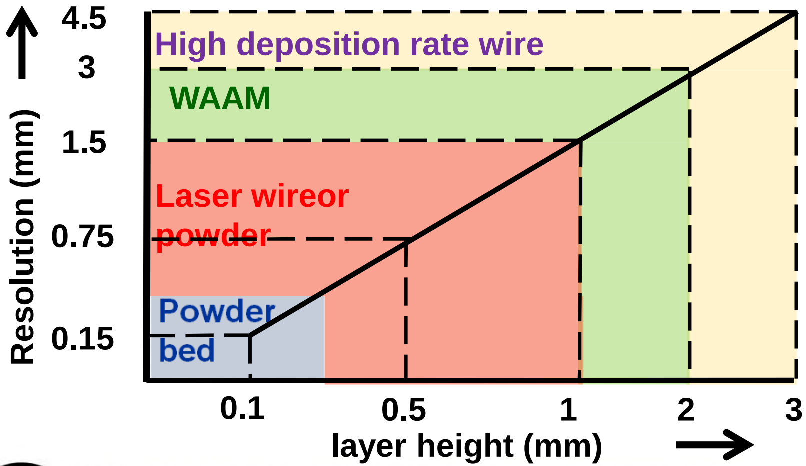
University	Lead Investigator	Programme role
Cranfield	Williams	Programme lead, process innovation and development, process modelling, sensors
Manchester	Prangnell	Materials expertise – characterisation, modelling and design
Strathclyde	Pierce	In process NDT
Coventry	Zhang	Effects of defects, structural integrity

NEWAM Industry partners

Partner Name	Role in project	Partner Name	Role in project
Lockheed Martin UK	End user	Kuka Systems	Robotic system supplier
BAES	End User	EWM	Power source supplier
Weir	End User	SPI	Laser supplier
Glenalmond	End user	Powerphotonic	Specialist optic supplier
TechnipFMc	End User	PWP	Specialist welding equipment supplier
Schlumberger	End User	Peak NDT	Specialist NDT equipment supplier
DSTL	End user	Perryman	Titanium wire supplier
AFRC	Research organisation	Wintwire	Specialist wire supplier
TWI	Research organisation	**Prenscia United Kingdom**	**Mechanical test service and performance software**
MTC	Research organisation		

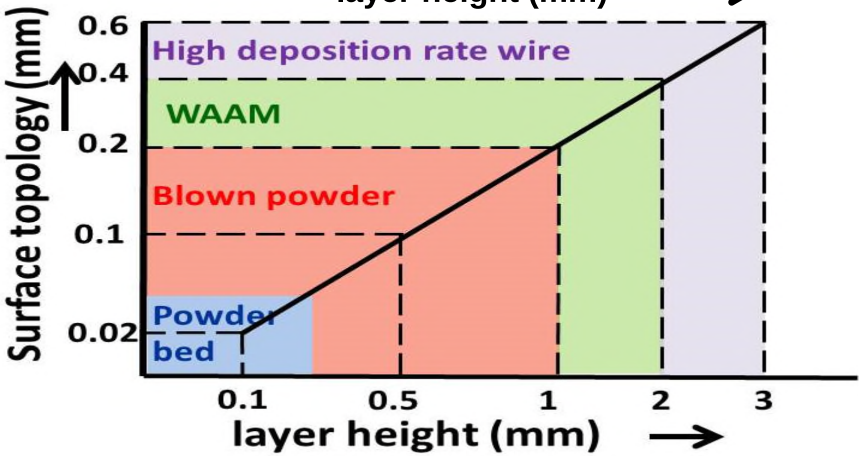
Challenge 1 - new processes - why





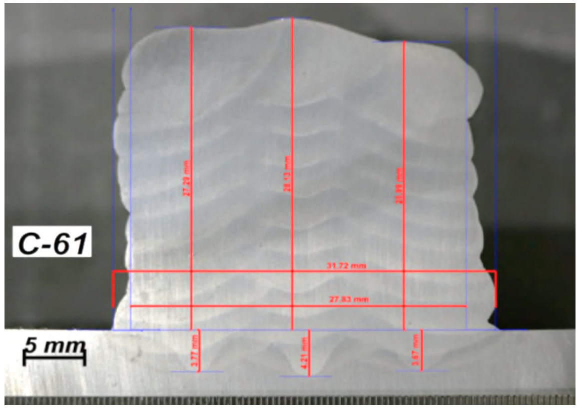
Resolution depends linearly on the layer height

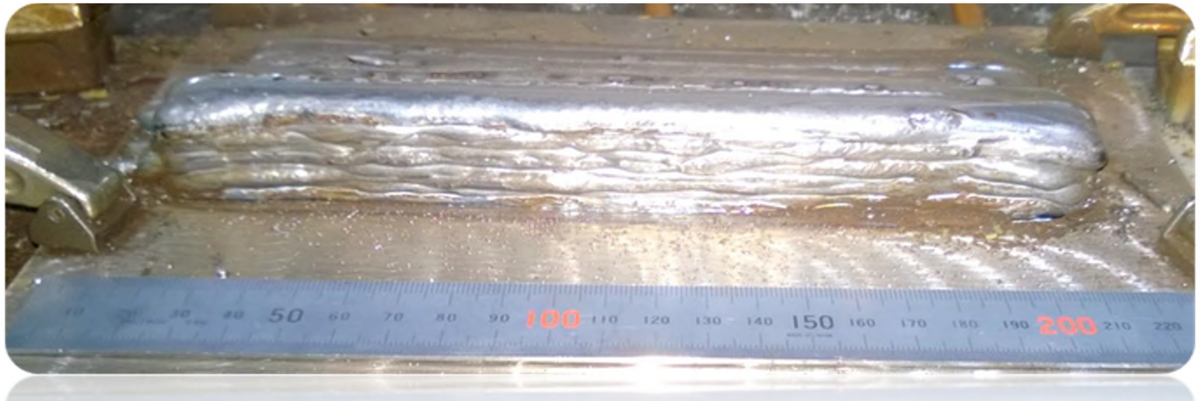
New processes are needed moving away from COTS systems with independent control of layer height and width, control of thermal conditions



Surface finish also depends linearly on the layer height

Grand challenge 1 – High Build Rate + Net Shape - complex process



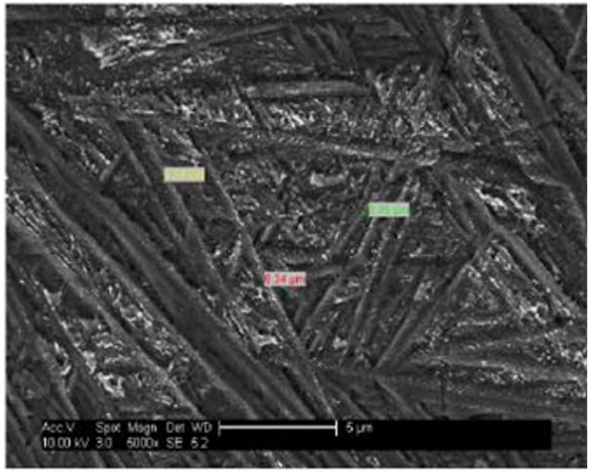


15 kg/ hour now achieved

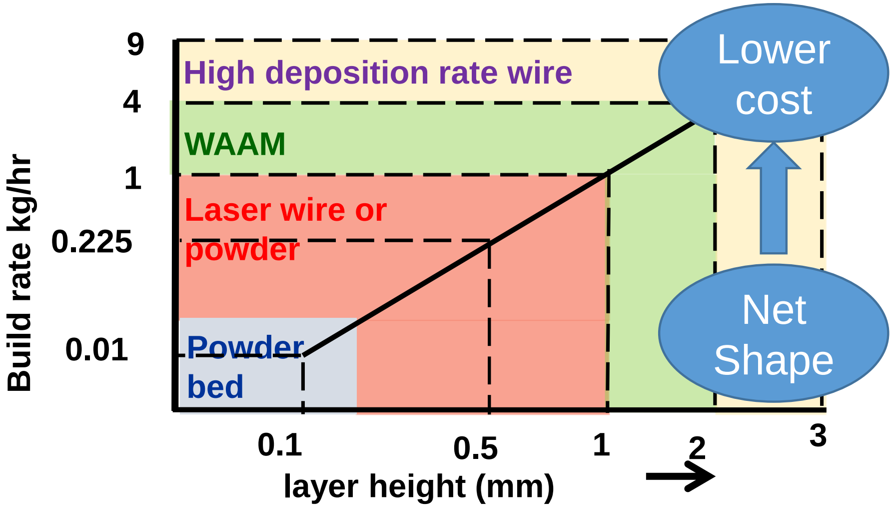
+

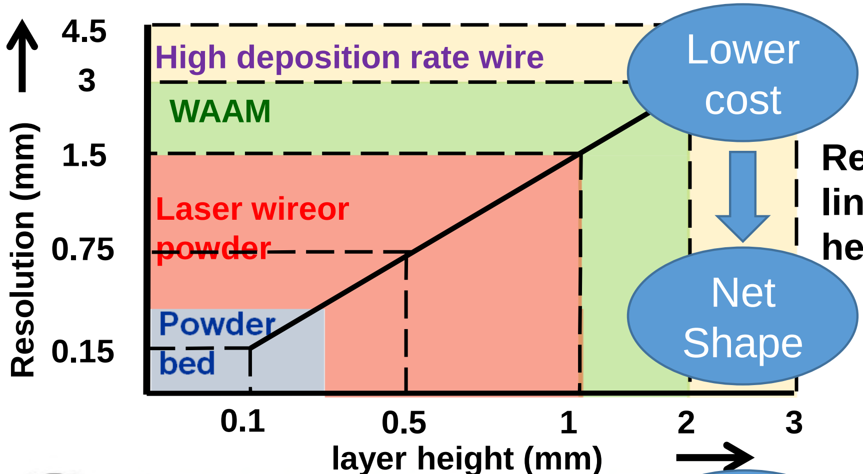
= 8kg/Ti64 netshape☺

+

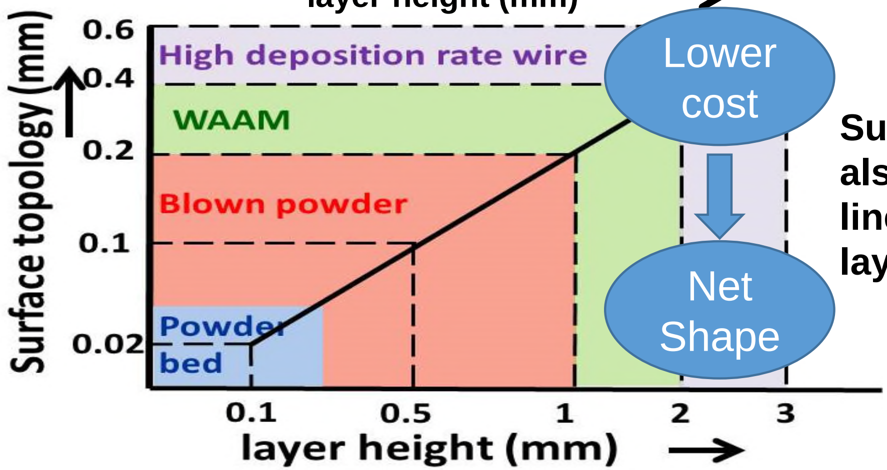


Basics of metal AM systems – What process or hardware should you use?





Resolution depends linearly on the layer height

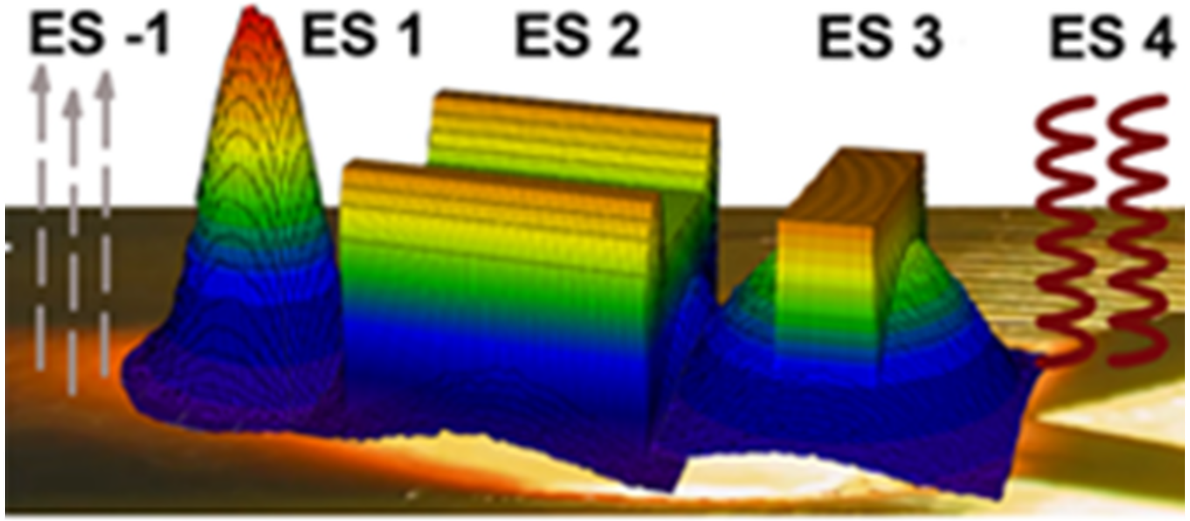


Surface finish also depends linearly on the layer height

How do we achieve this?

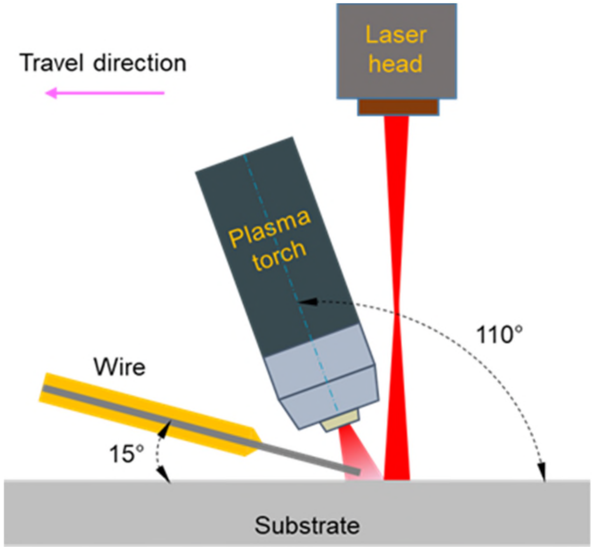
By getting **independent** control of the layer height and width

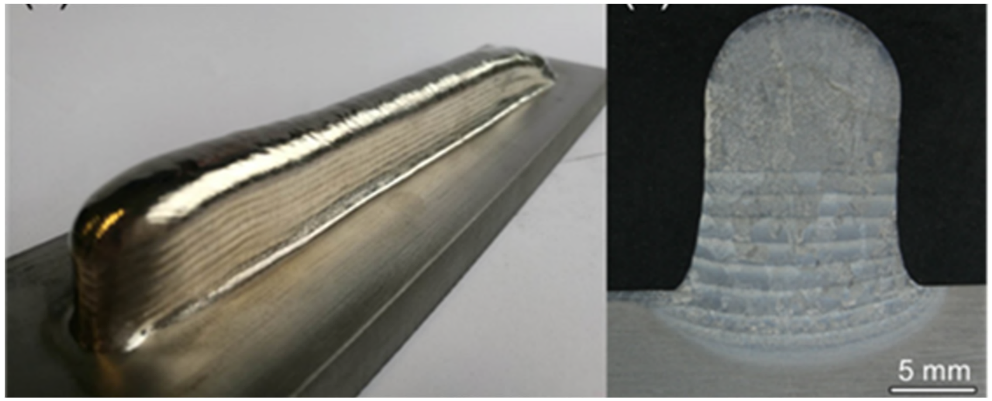
We are proposing a multi energy source (MES) approach



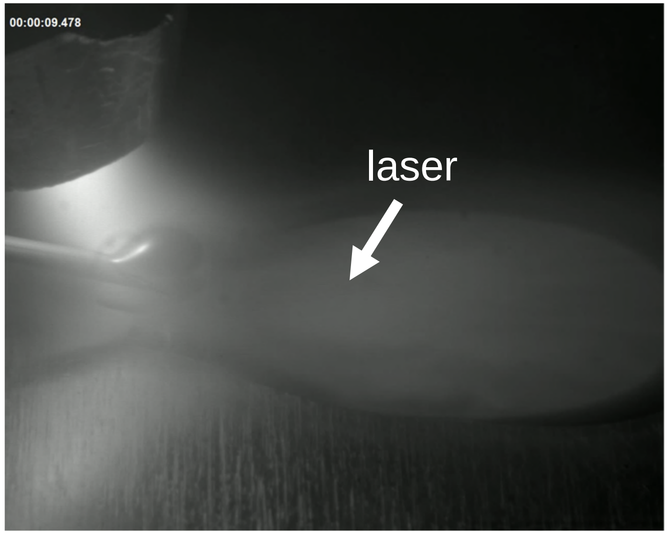
GB Patent number GB2569673

Simple MES - PTA + laser

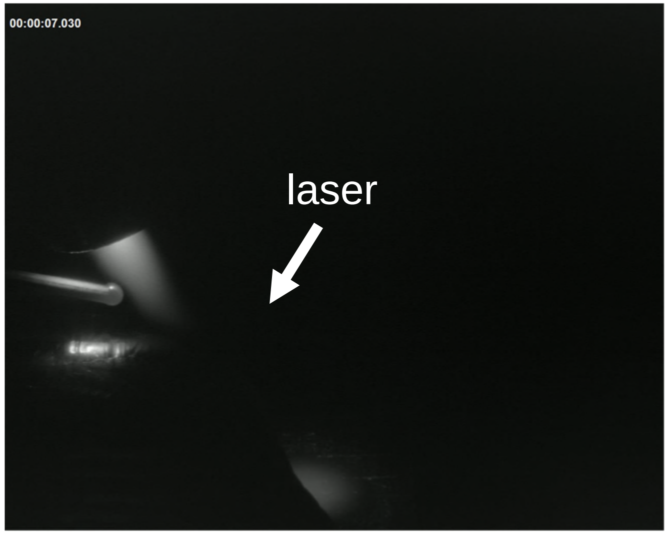




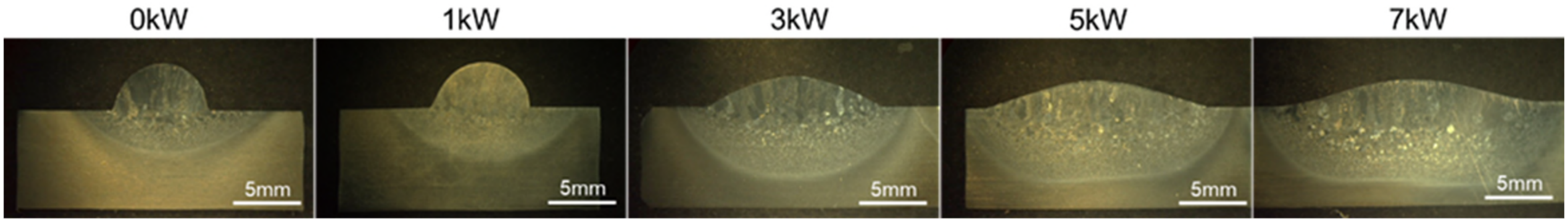
1st layer

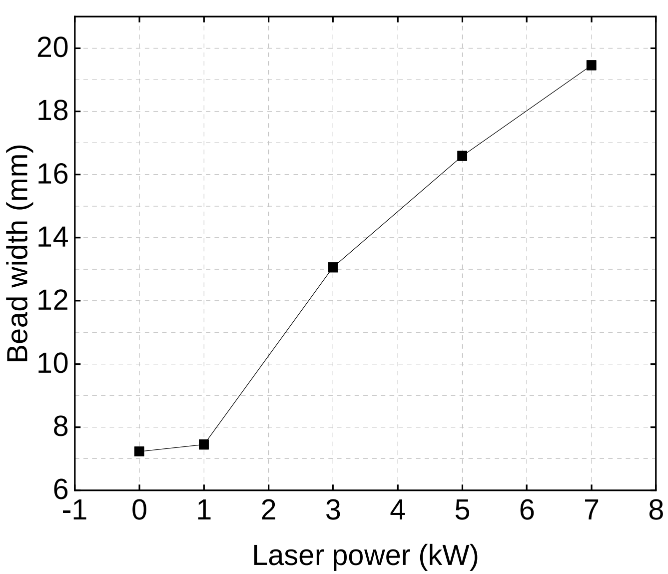


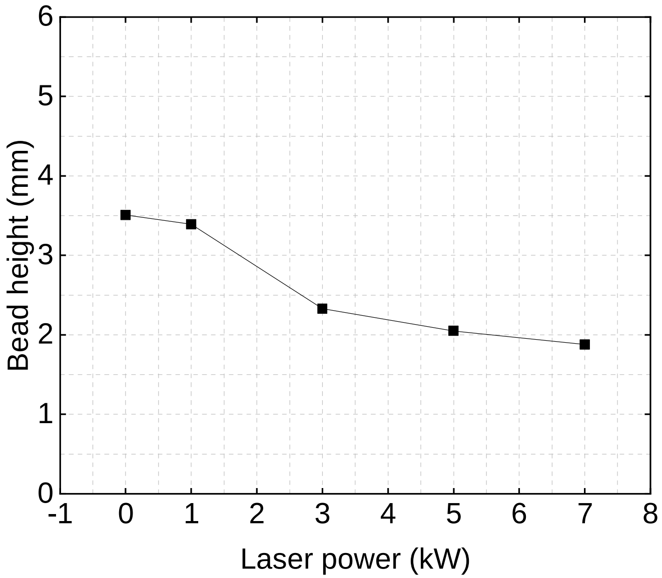
Subsequent layers



Effect of laser power on bead geometry

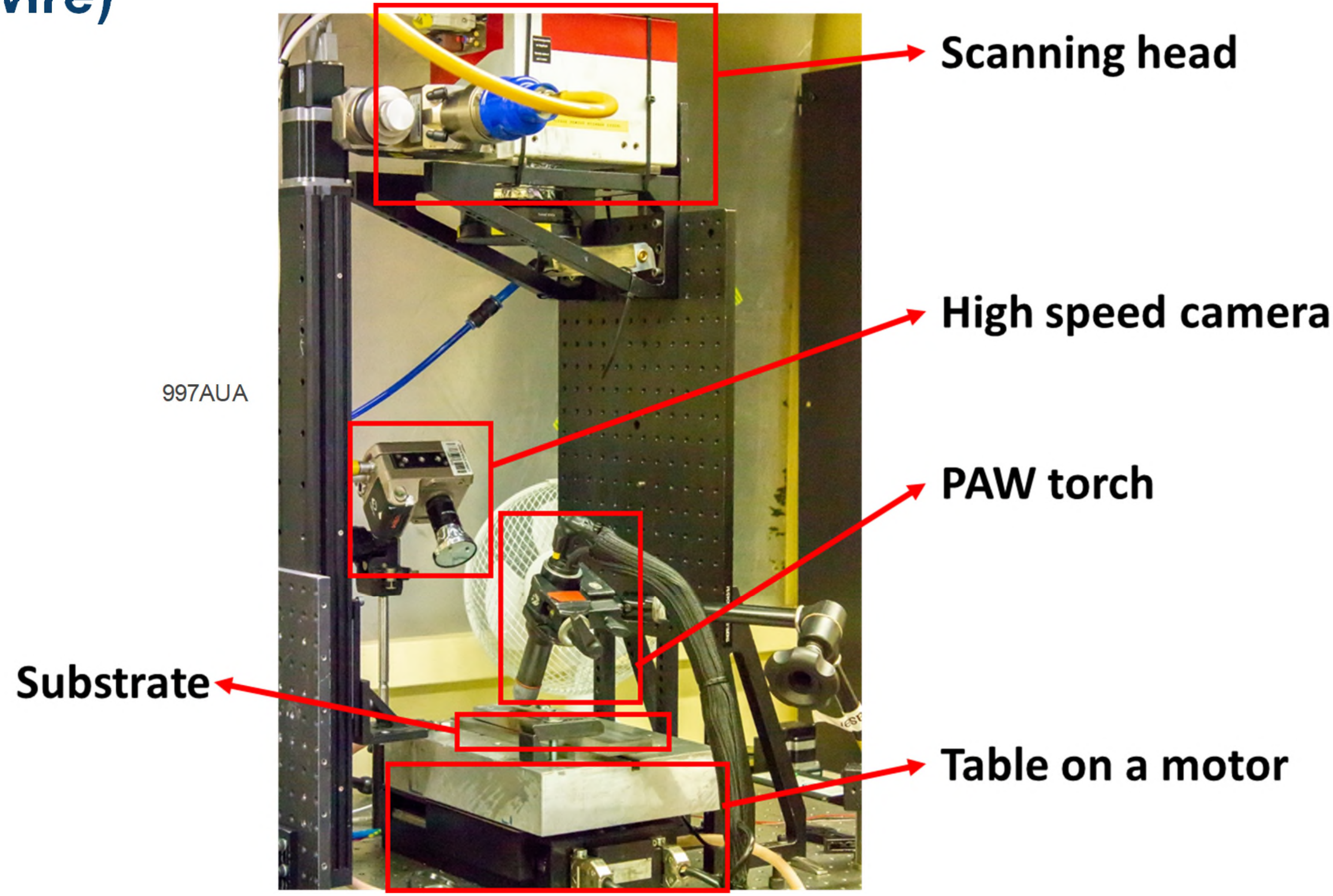




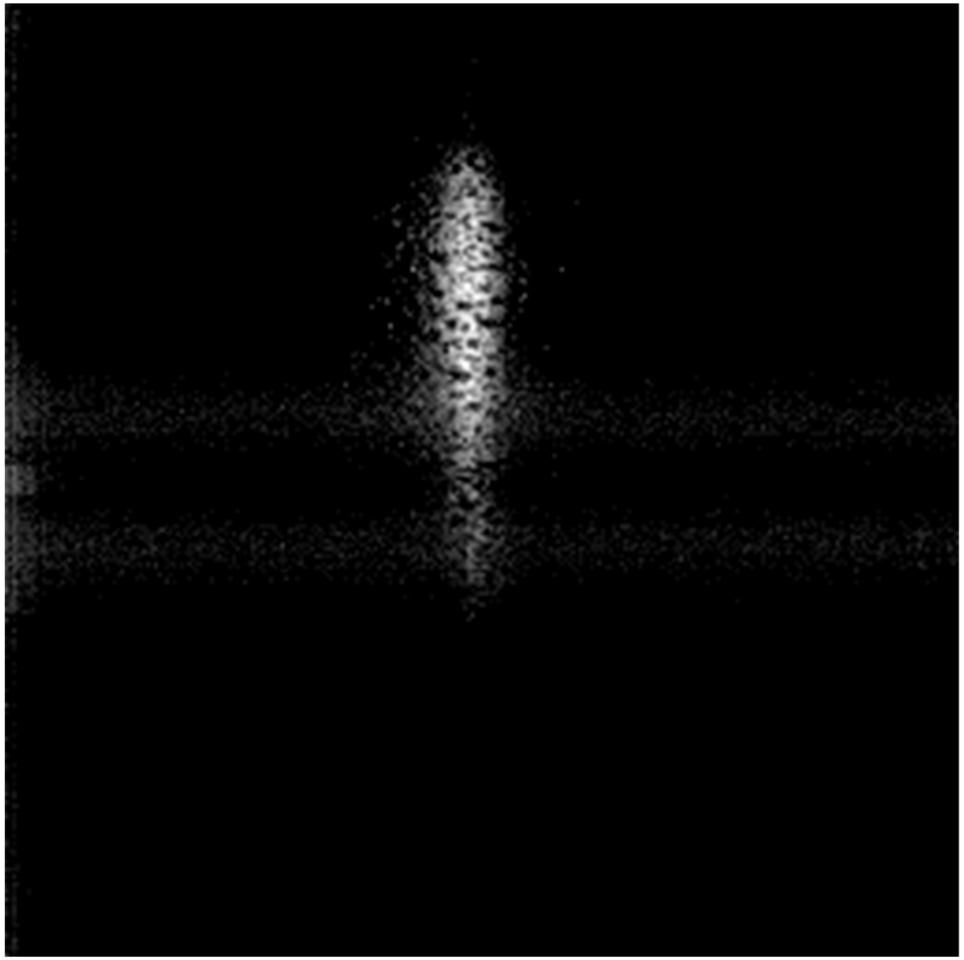


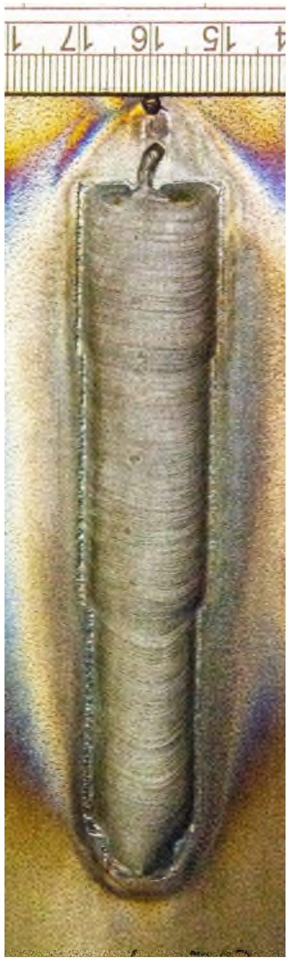
Multi-energy source (MES) concept (scanning laser – no wire)

997AUA



MES with scanning laser + wire - Dynamic width changing

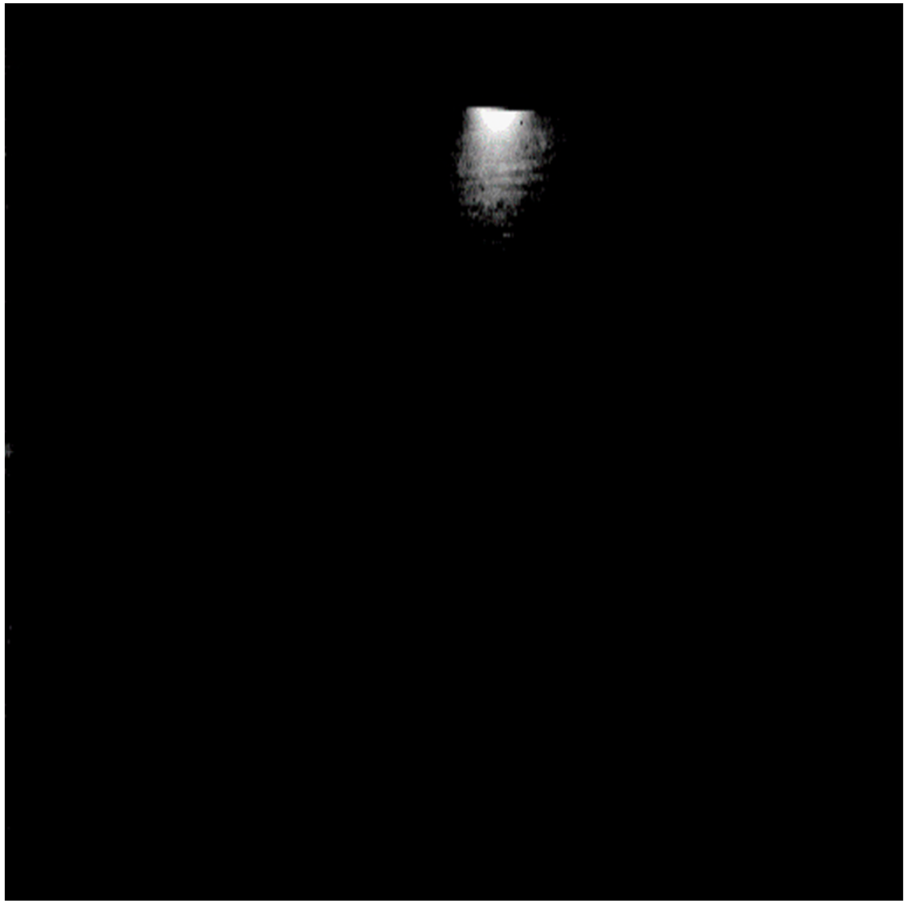




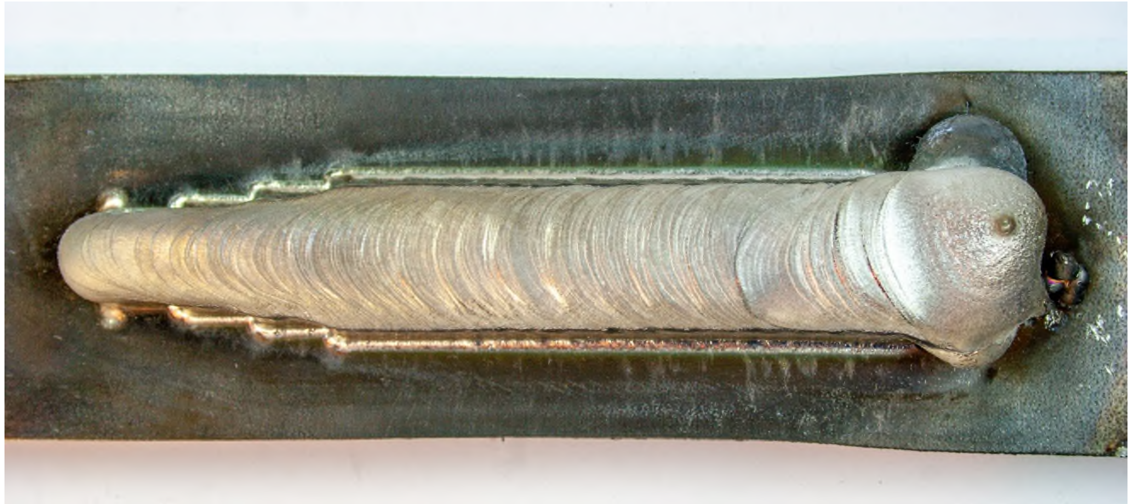
Multi-energy source (MES) (scanning laser) -wall building

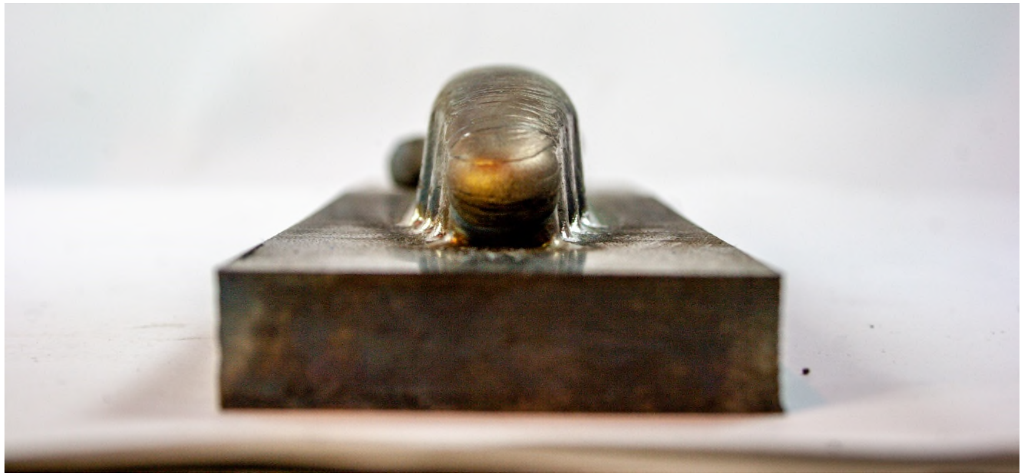
1st layer

Subsequent layers



MES wall – net shape

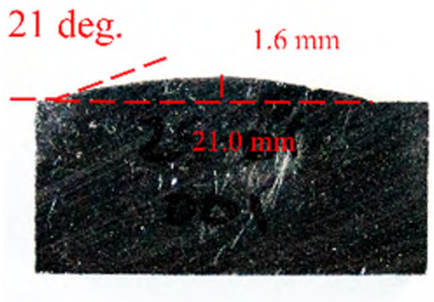




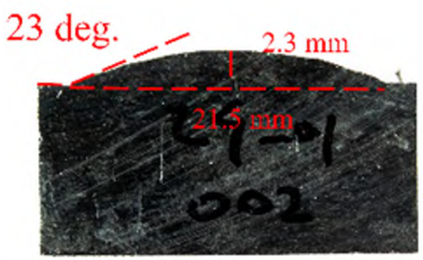
MES scanning – independent control of layer height and width

Constant layer width 21 mm – layer height 0.8 – 3.3 mm

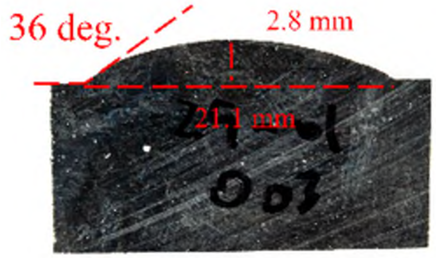
WFS=0.4 m/min



WFS=0.8m/min



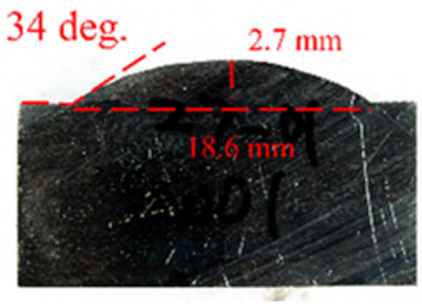
WFS=1.2m/min



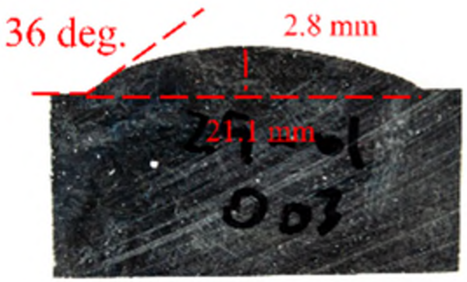
WFS=1.6m/min

WFS=2.0m/min

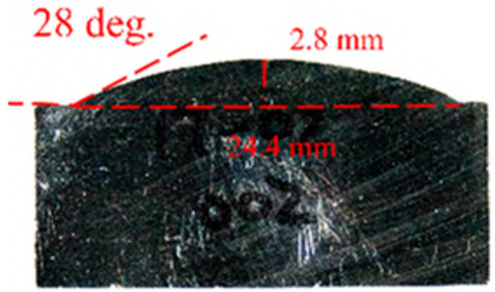
Constant layer height 2.8 mm – layer width 18.5 – 27.5 mm



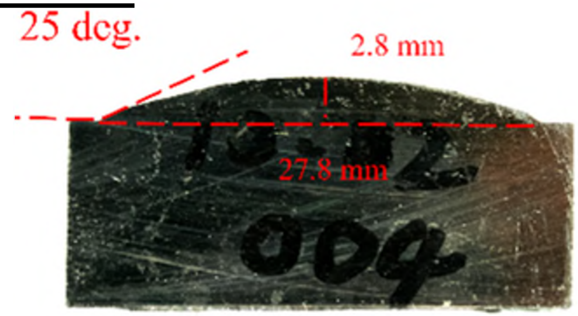
Scan width 16 mm



Scan width 23 mm

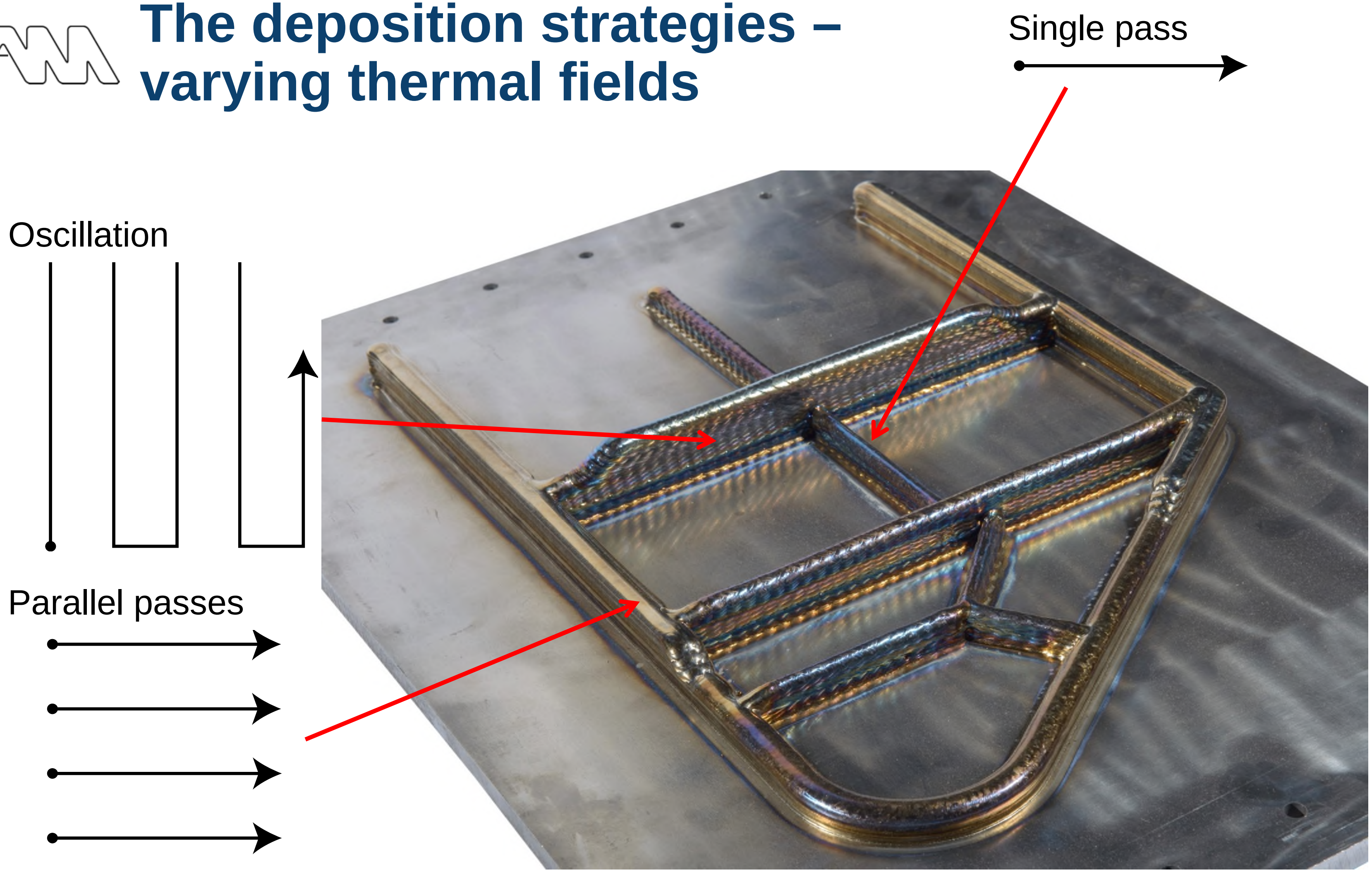


Scan width 23 mm



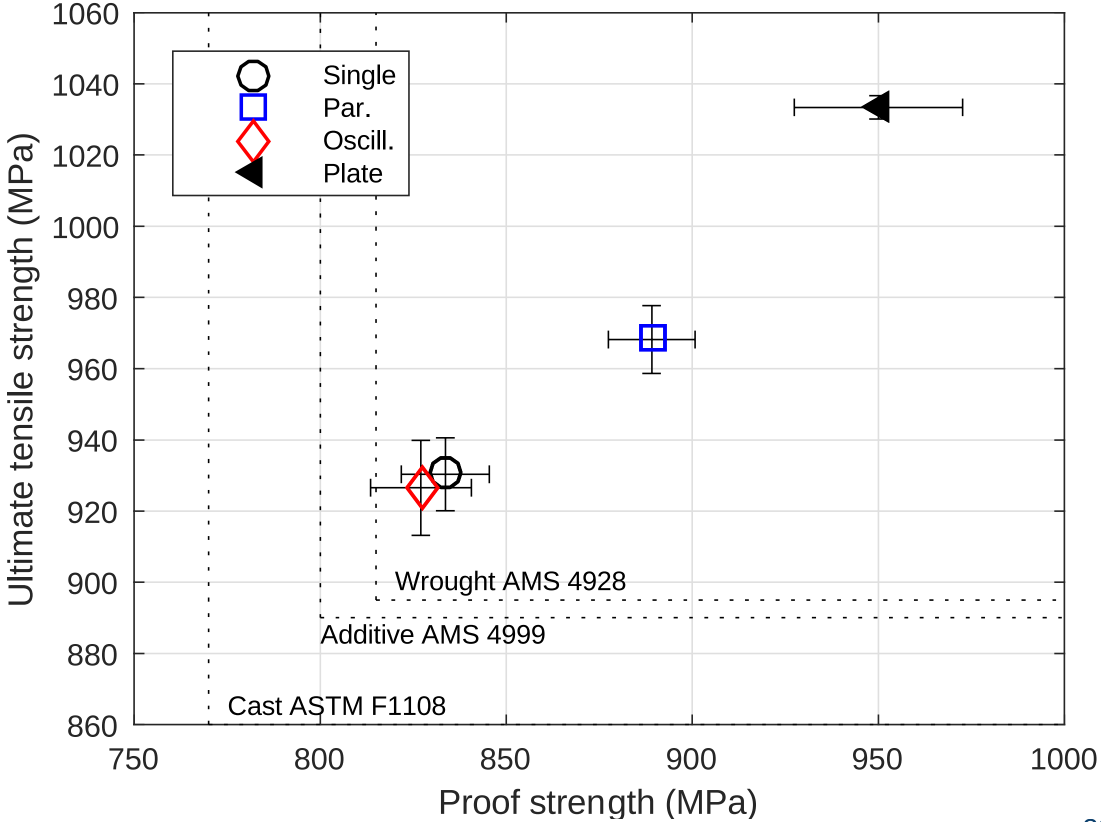
Scan width 26.5 mm

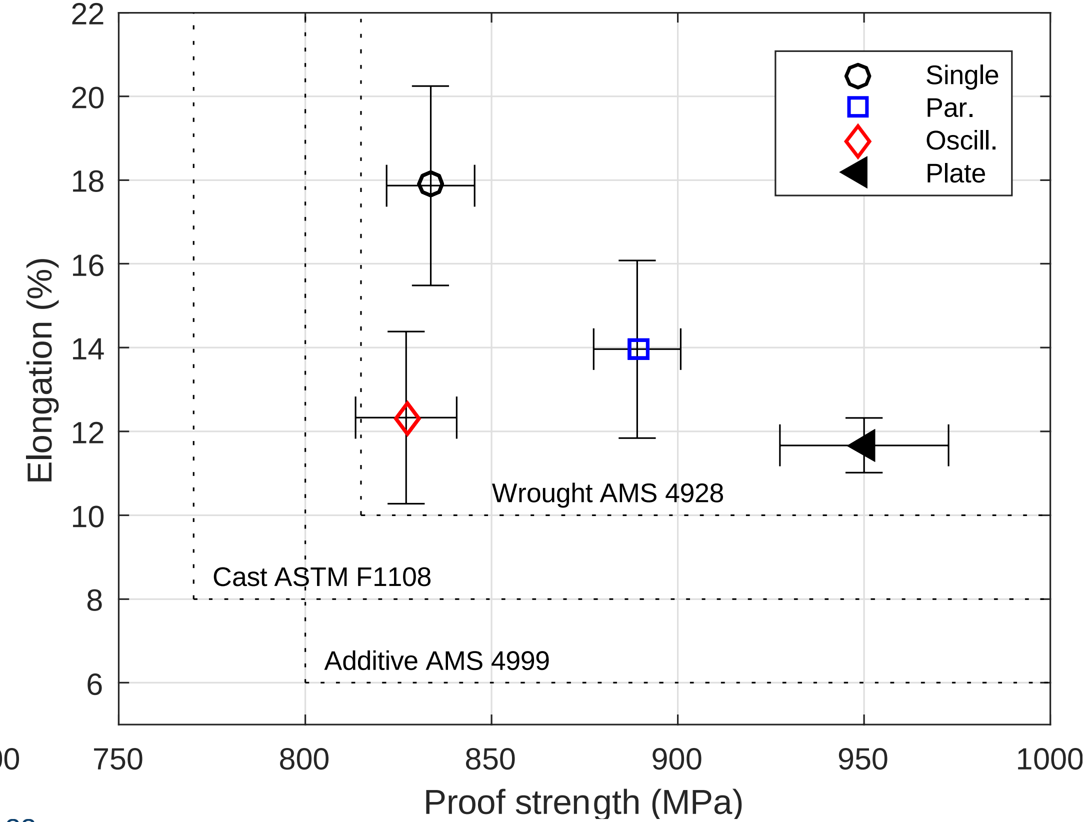
The deposition strategies – varying thermal fields



Ti64 // Static properties as deposited – leading to varying and isotropic mechanical properties which are a long way from wrought material

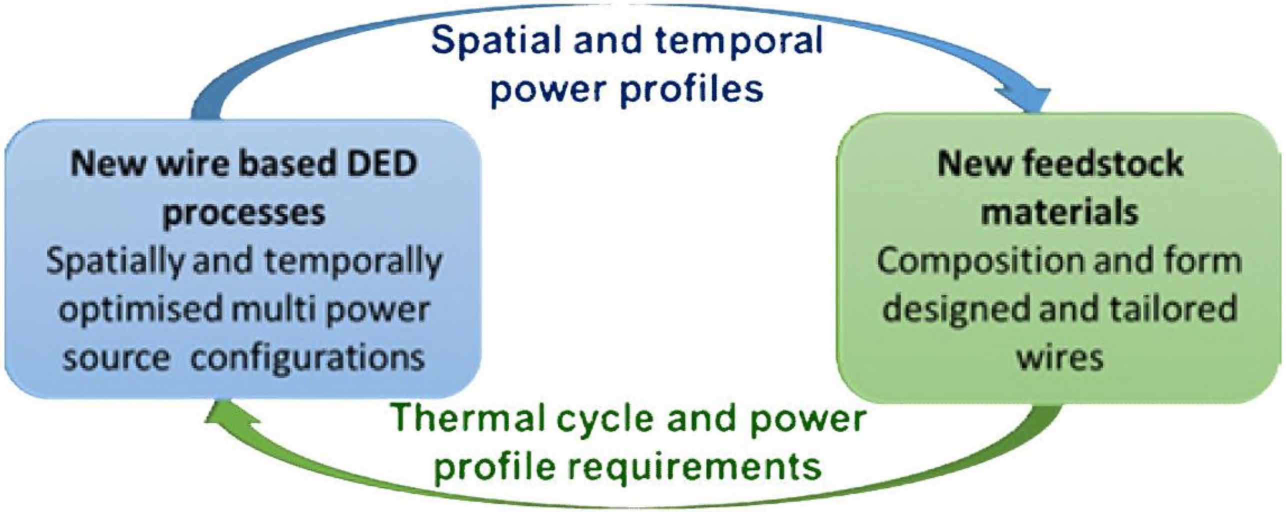
Average values



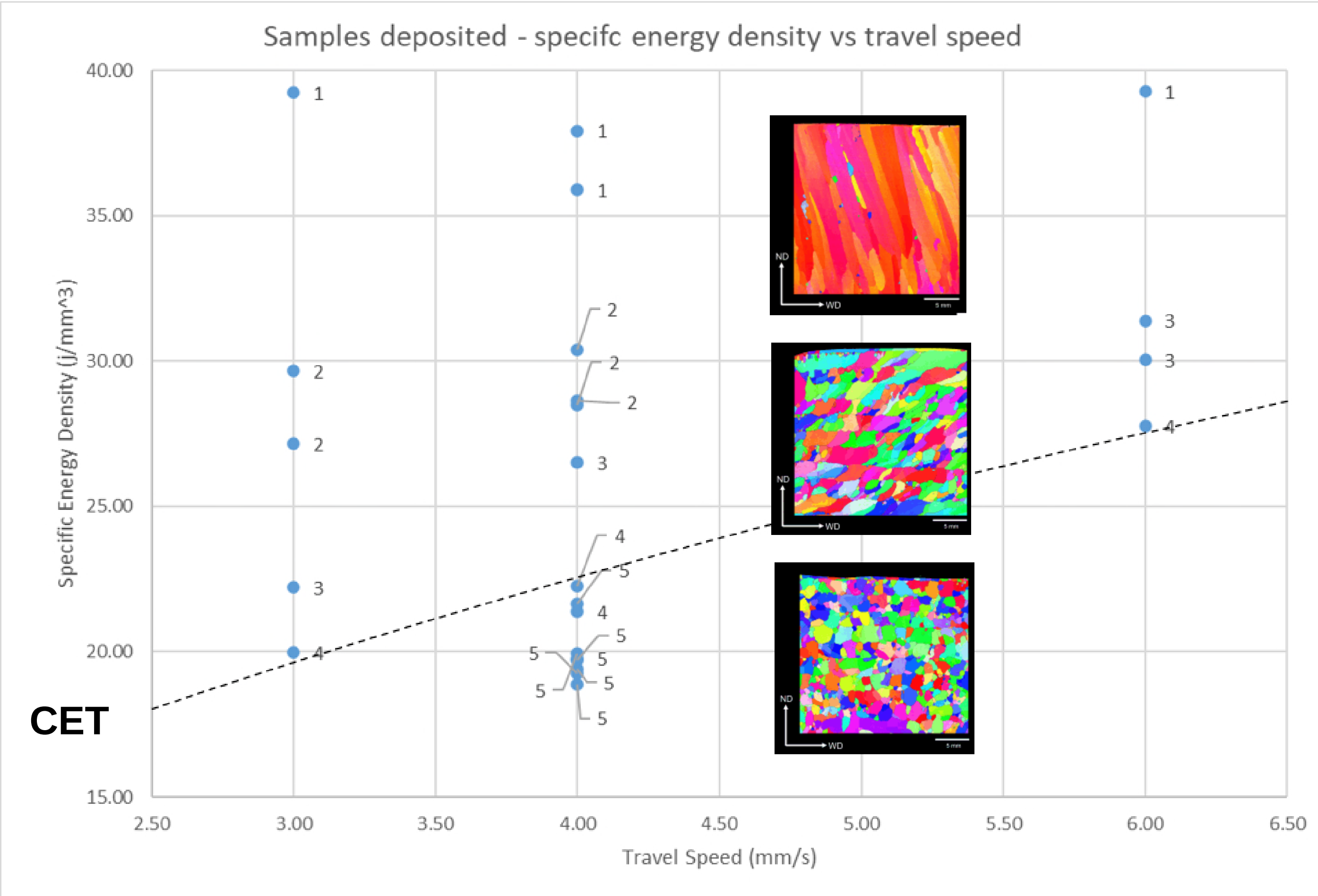


Grand Challenge 2 – process and material co-design

- Do not just use materials that are easily available☹
- Design material compositions matched to the process☺
- Design processes matched to the material requirements☺



Matching of processes to material – CET transition in TI64

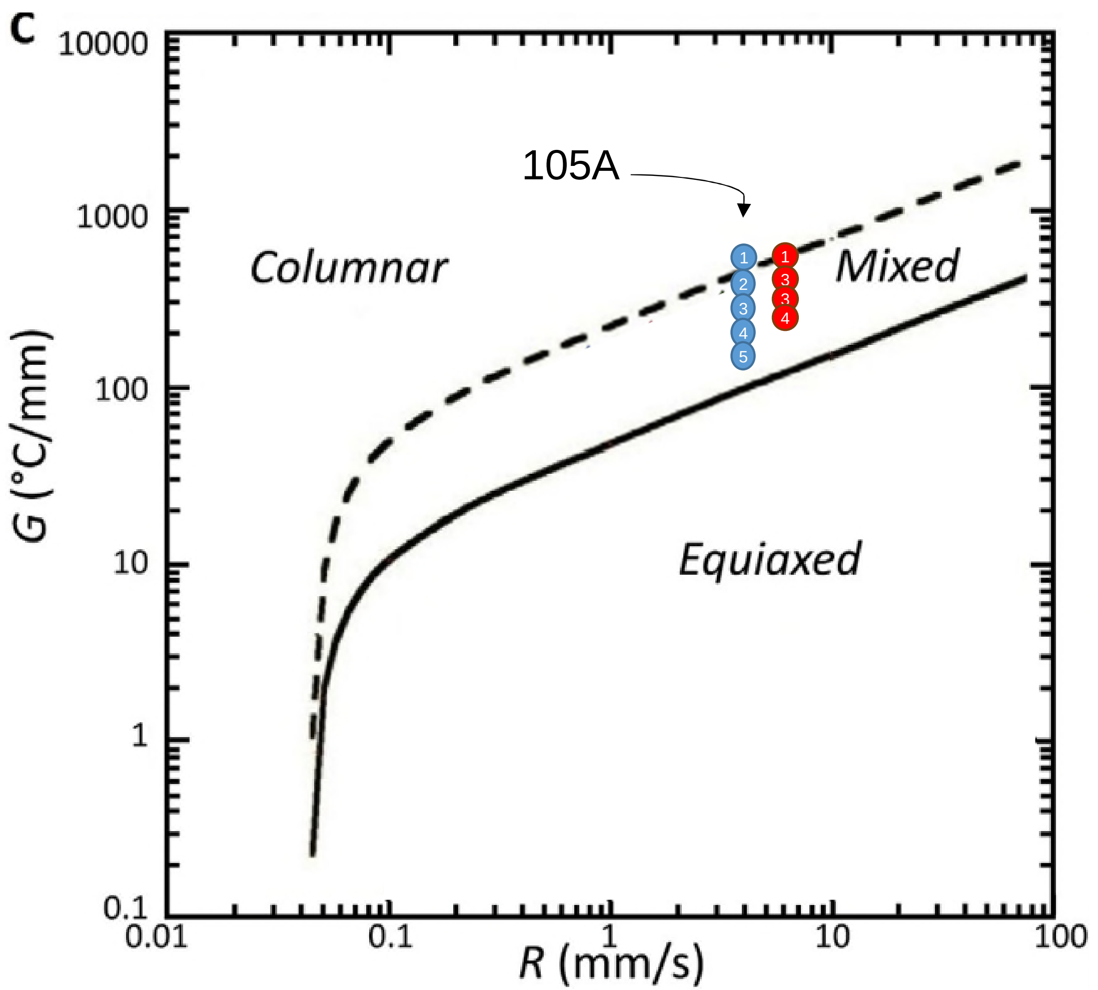


- 1 – Columnar
- 2 – Columnar dominant
- 3 – Mixed
- 4 – Equiaxed dominant
- 5 - Equiaxed

Thermal Gradient Approximation

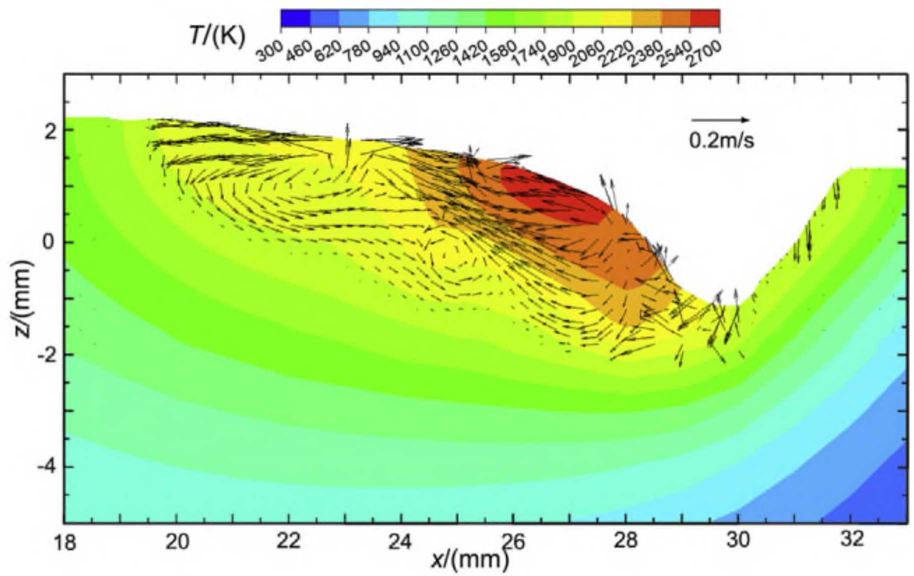
When increasing power from 105A to 160A, to maintain the SED we must increase the WFS. Thus WFS/TS ratio changes thus LH.

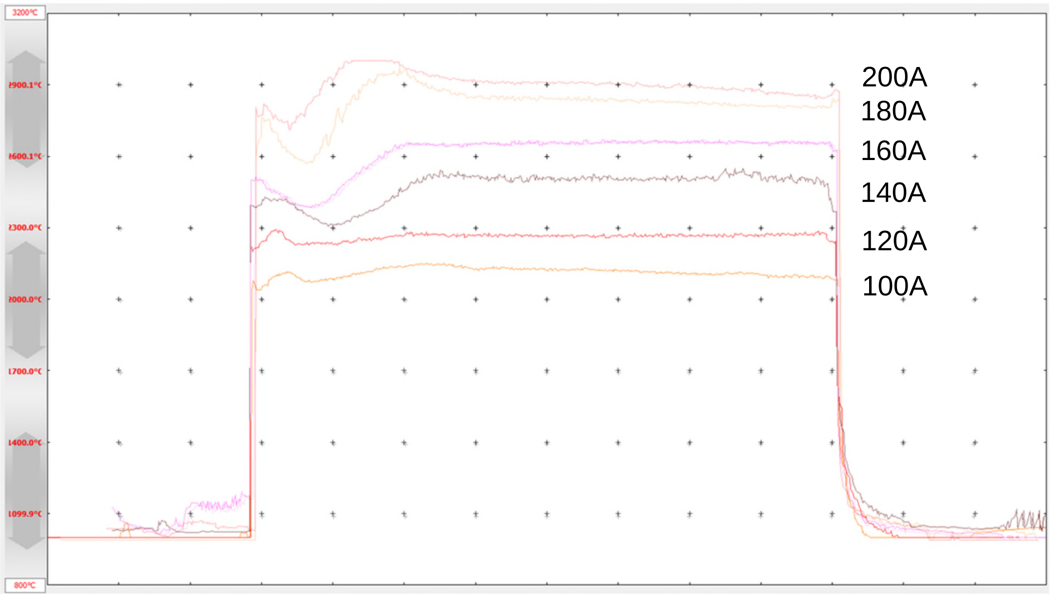
Current (A)	TS (mm/s)	WFS (mm/s)	WFS/TS	LH (mm)	SED (J/mm3)
105	4.00	26.7	6.67	**1.16**	37.93
160	4.00	46.00	11.50	**1.64**	37.83

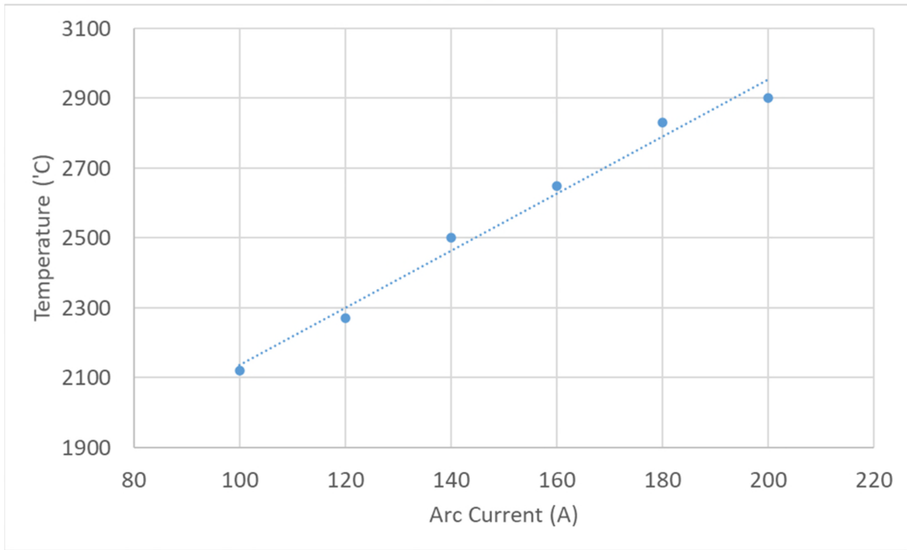


Thermal Gradient : Tmax

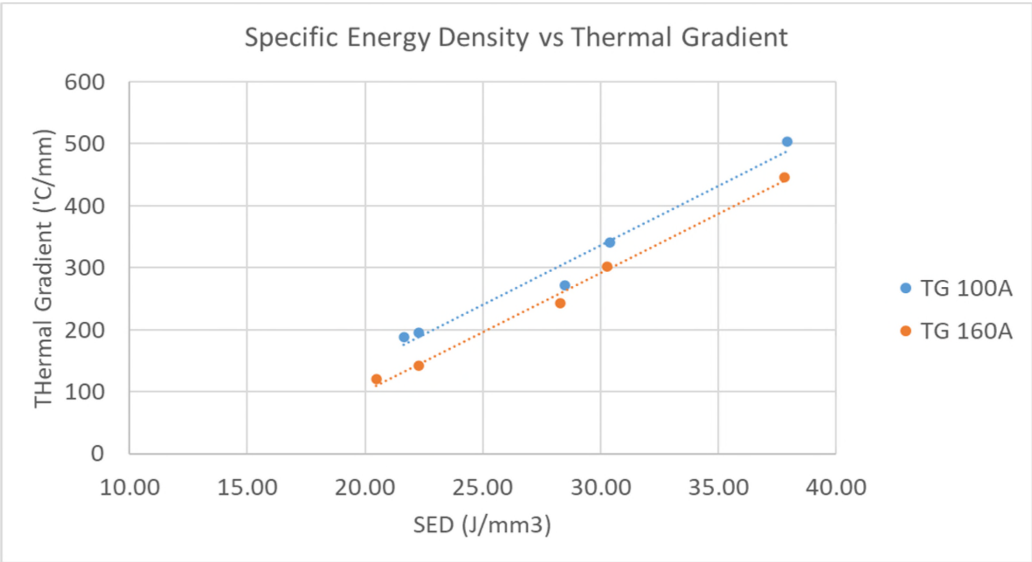
If we consider just increasing the arc current without feeding wire we see that the maximum melt pool temperature (just behind the arc) increases linearly – as expected.



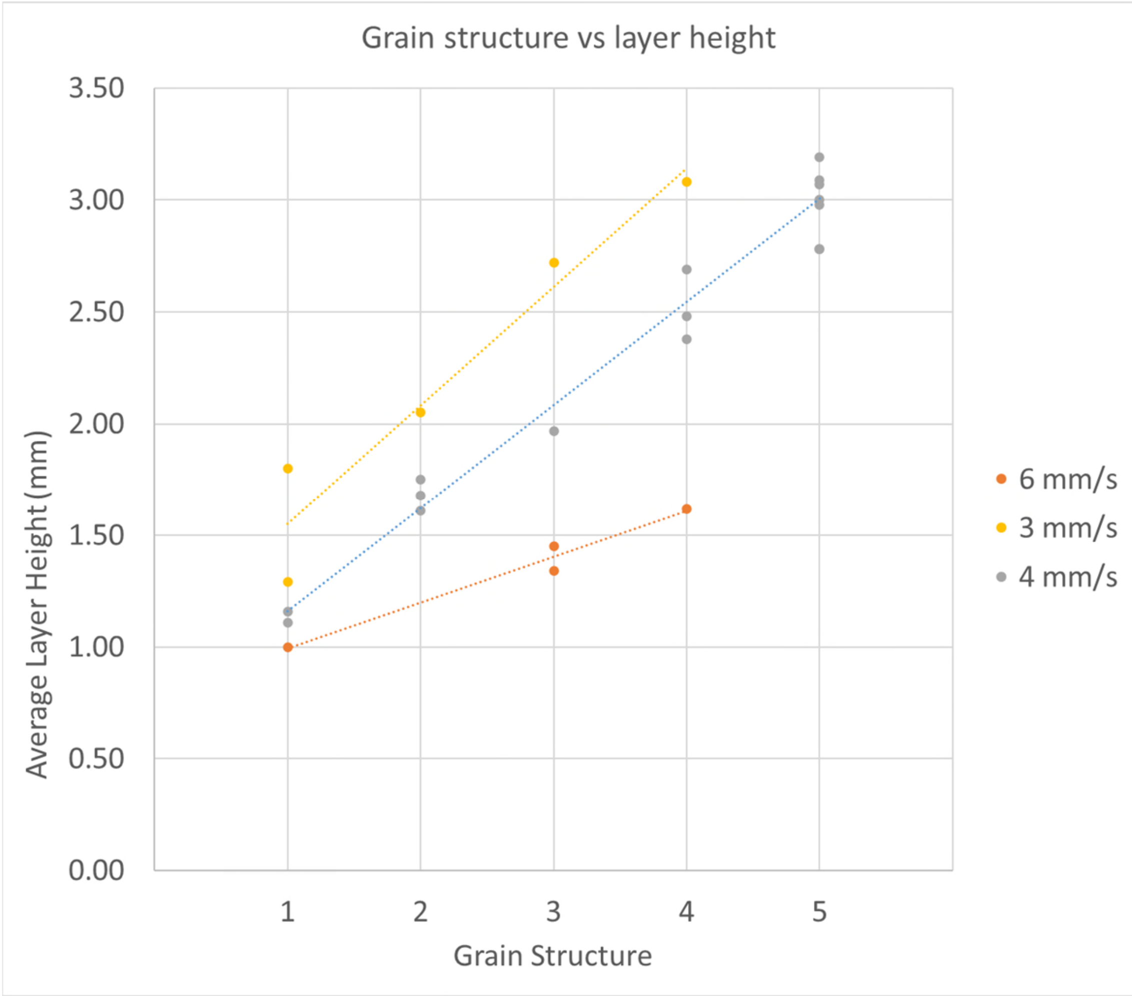




Summary

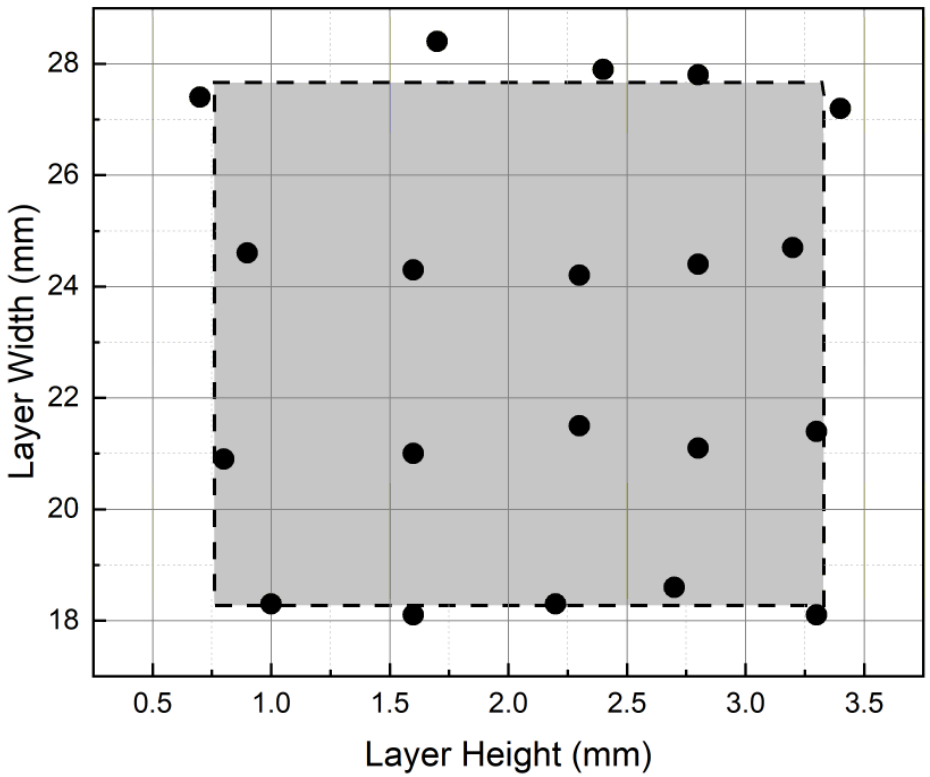


Specific Energy Density vs Thermal Gradient
THermal Gradient ('C/mm)
600
500
400
300
200
100
0
10.00
15.00
20.00
25.00
30.00
35.00
40.00
SED (J/mm3)
TG 100A
TG 160A



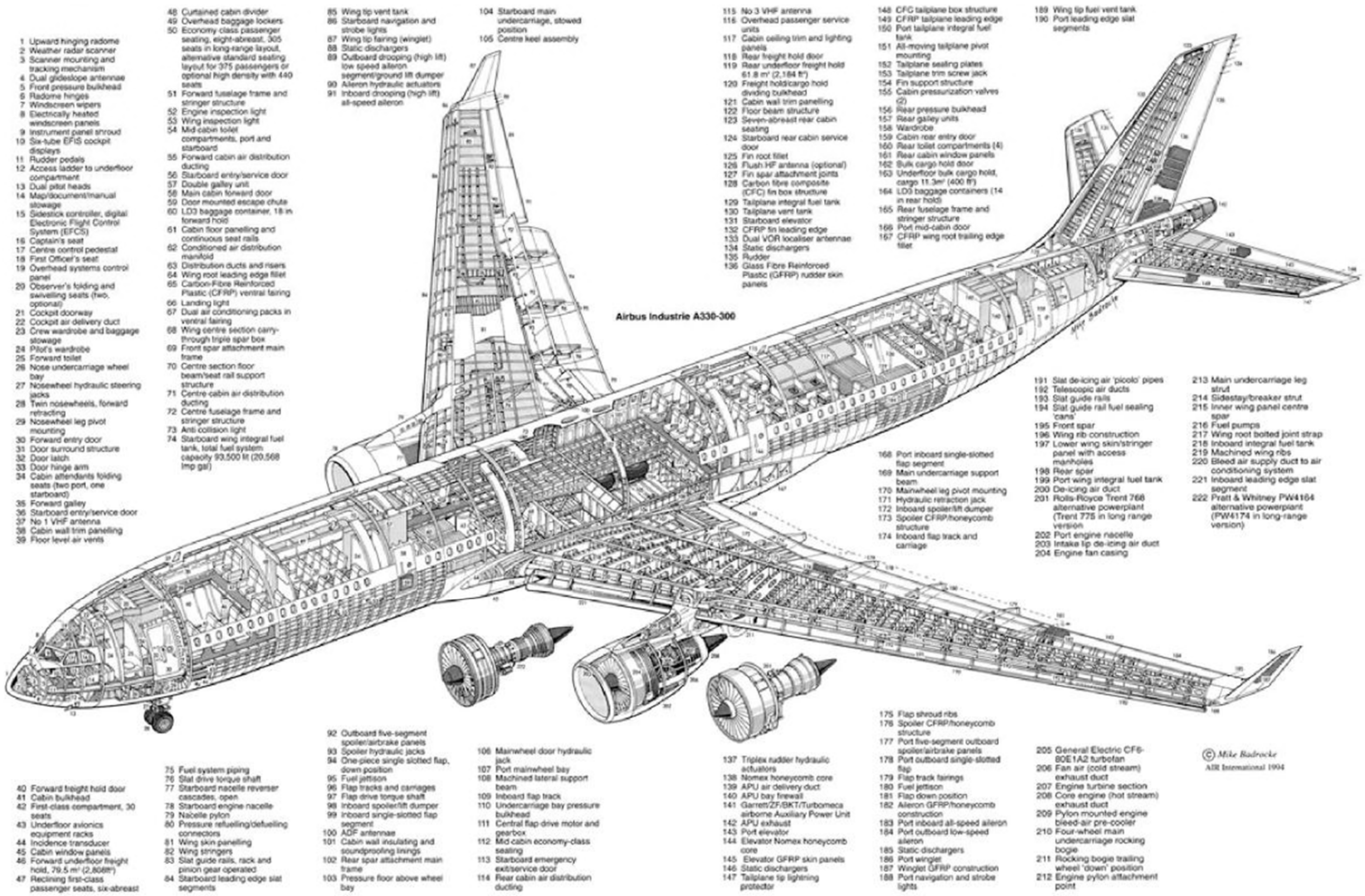
Grain structure vs layer height
Average Layer Height (mm)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
2
3
4
5
Grain Structure
6 mm/s
3 mm/s
4 mm/s

MES wall – Independent control of layer height and width



Any combination of layer width and height can be programmed in

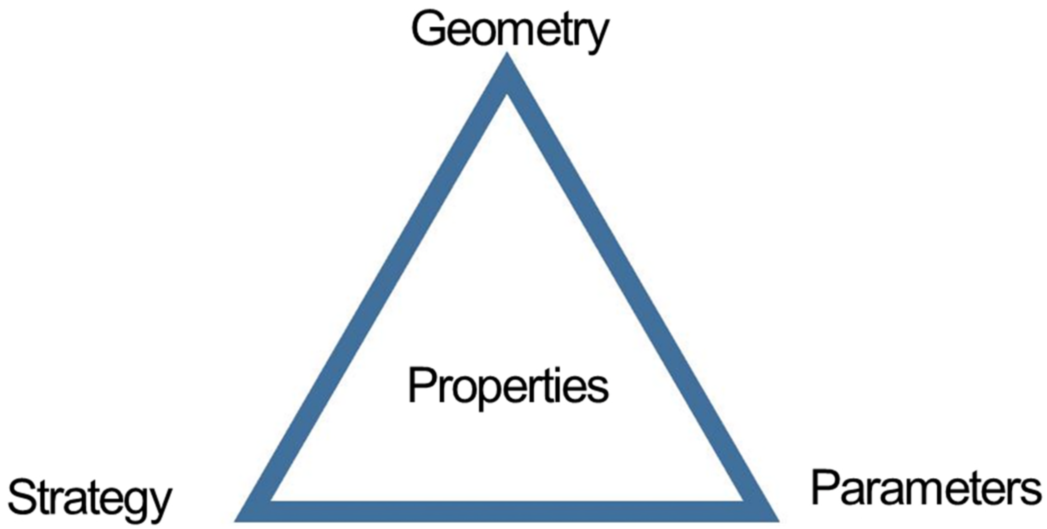
W-DEDAM part qualification – how?



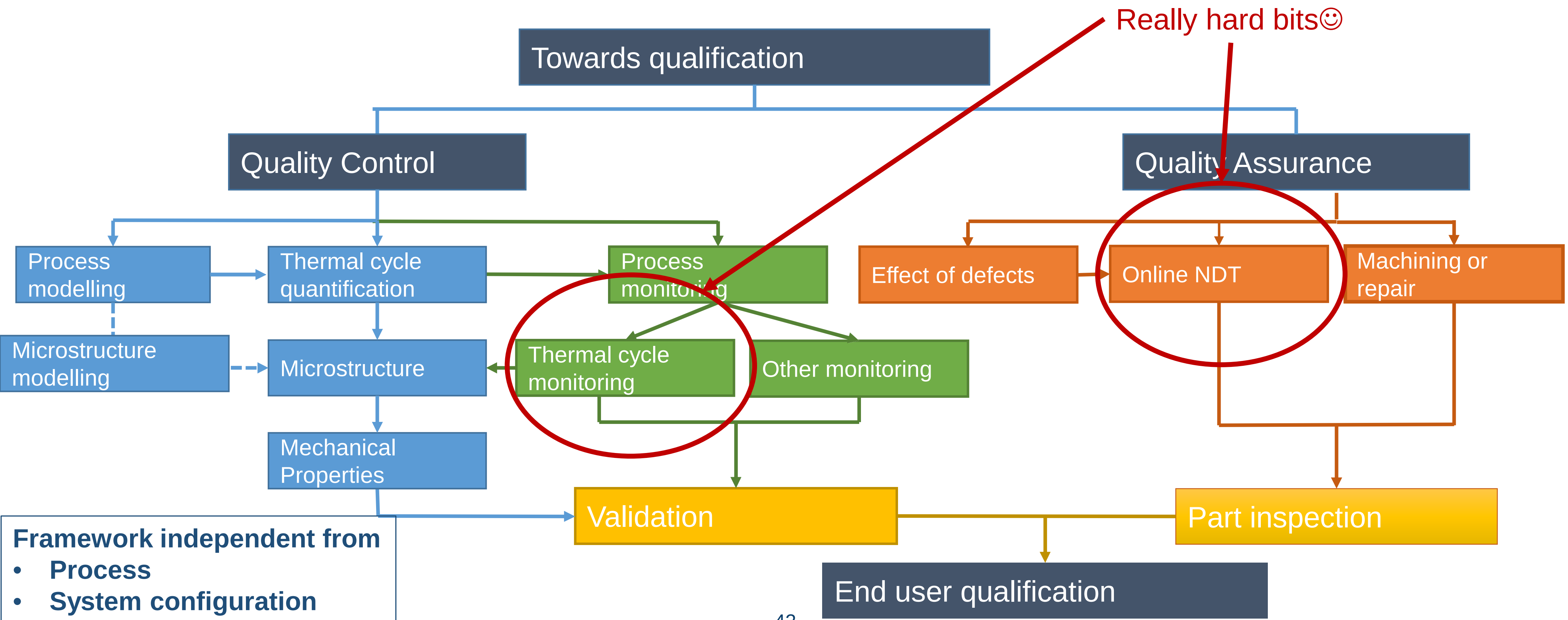
It's not about a one single part!!!

Qualification approaches

- Qualification based on:
  - ➢locked feedstock / parameters / part / machine - **insane cost**
  - ➢lowest properties - **insane mass penalty**
  - ➢safety factors e.g. casting factors - **recipe for disaster**
  - ➢physics - **insane difficulty** **NEWAM☺**



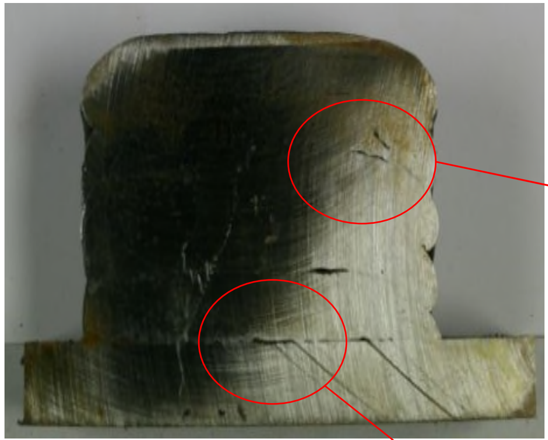
How do we fix it – Grand challenge 4 - Q3 project – Quality control and Quality assurance for Qualification

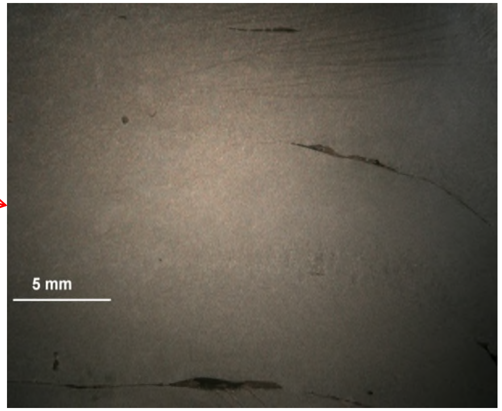


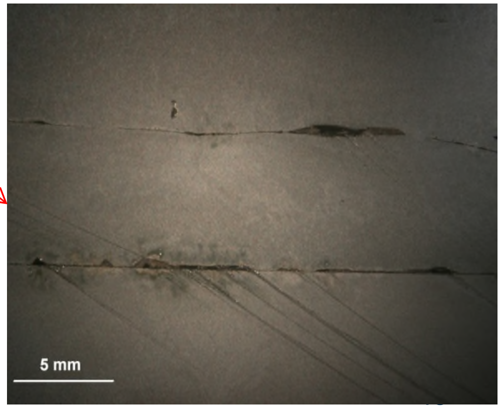
Framework independent from
- **Process**
- **System configuration**
- **Component**

Challenges: quality assurance

Effect of defects (HIPing is not an option)



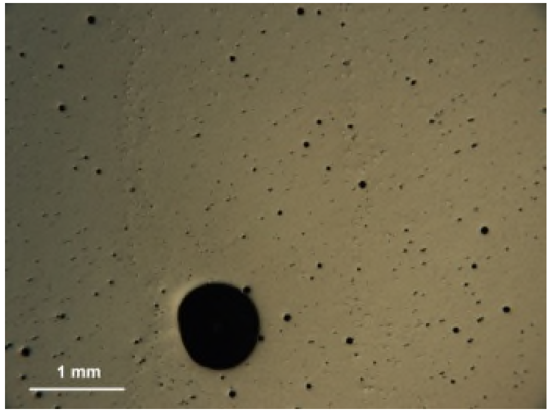




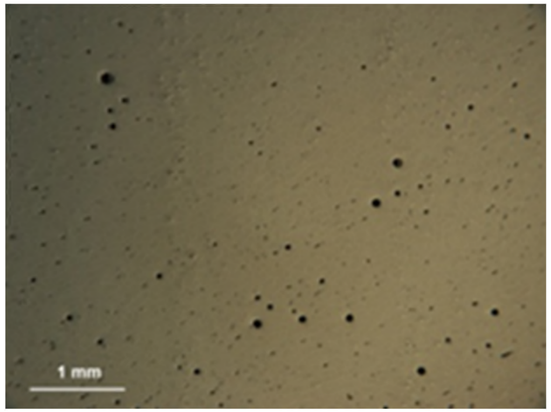
Lack of fusion

(aluminium!!)

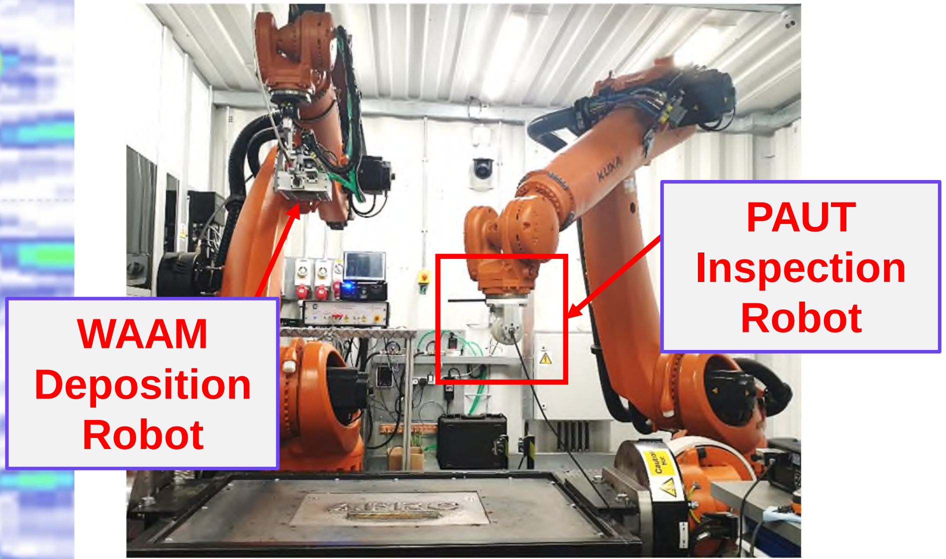
Macro porosity

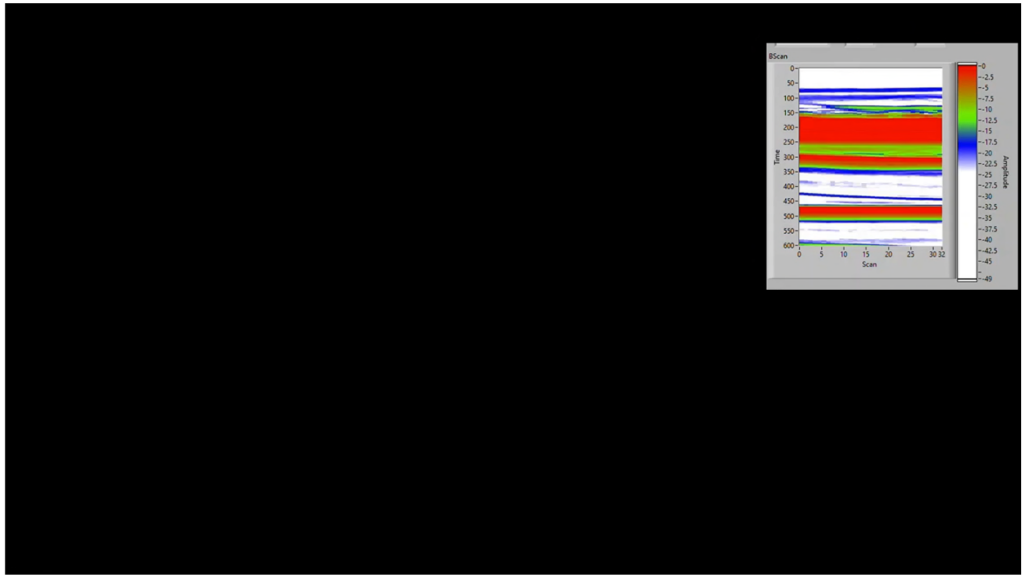


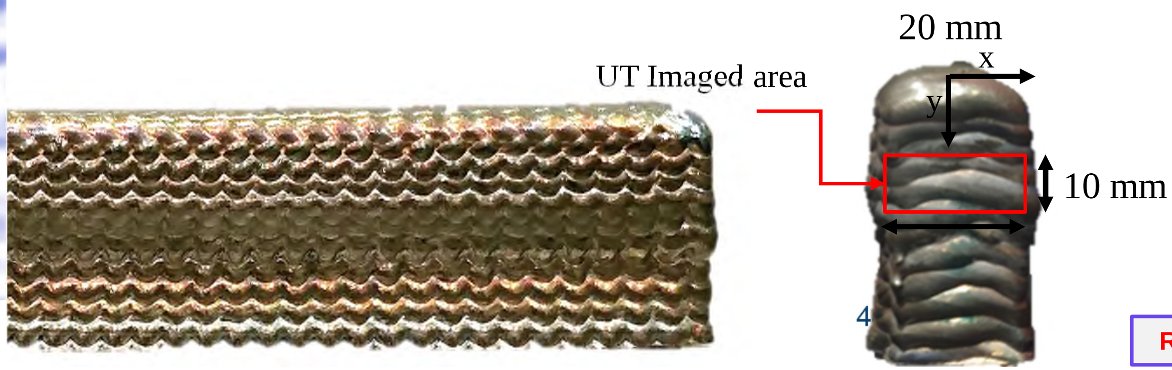
Micro porosity

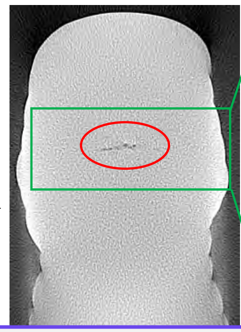


In-Process Dry-Coupled Phased Array Ultrasonic Testing of As-Deposited WAAM Components

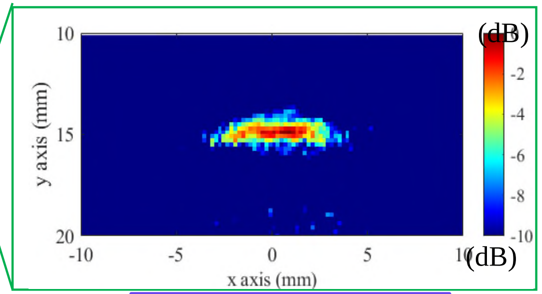








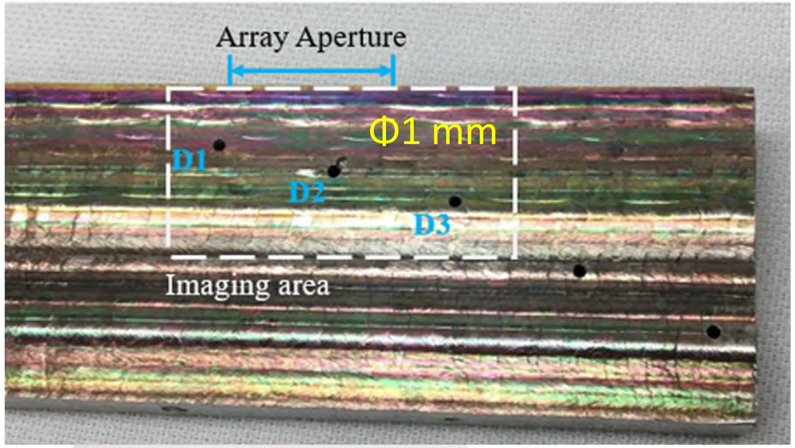
Reference XCT Image

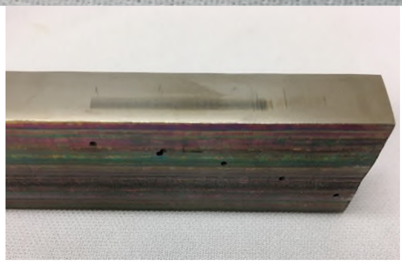


PAUT Imaging through as-built surface

Laser Induced Phased Arrays (LIPAs) for Inspection of WAAM

WAAM: Ti-6Al-4V

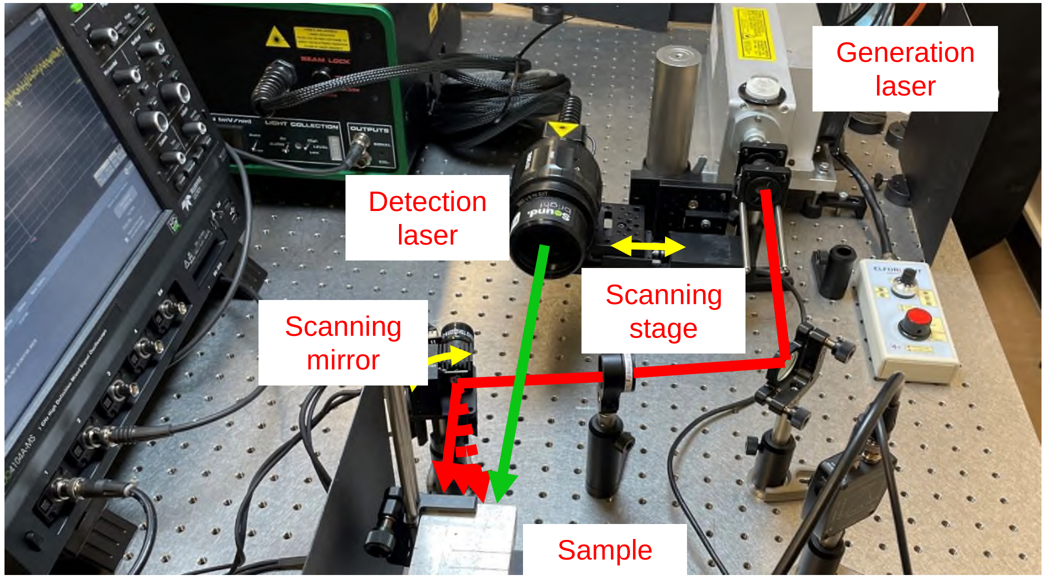


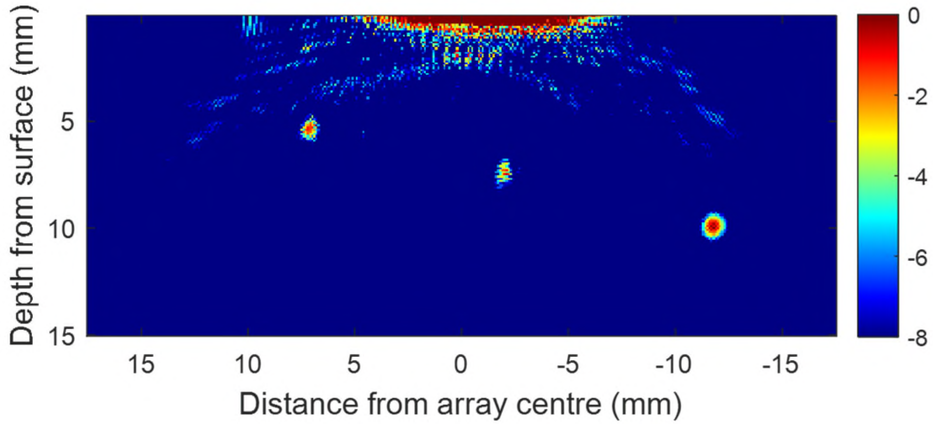


Longitudinal	D1	D2	D3
Measured size (mm)	0.83	0.75	1.1

Longitudinal wave, frequency = 6.3MHz

$\lambda_{ac} \sim 1$ mm





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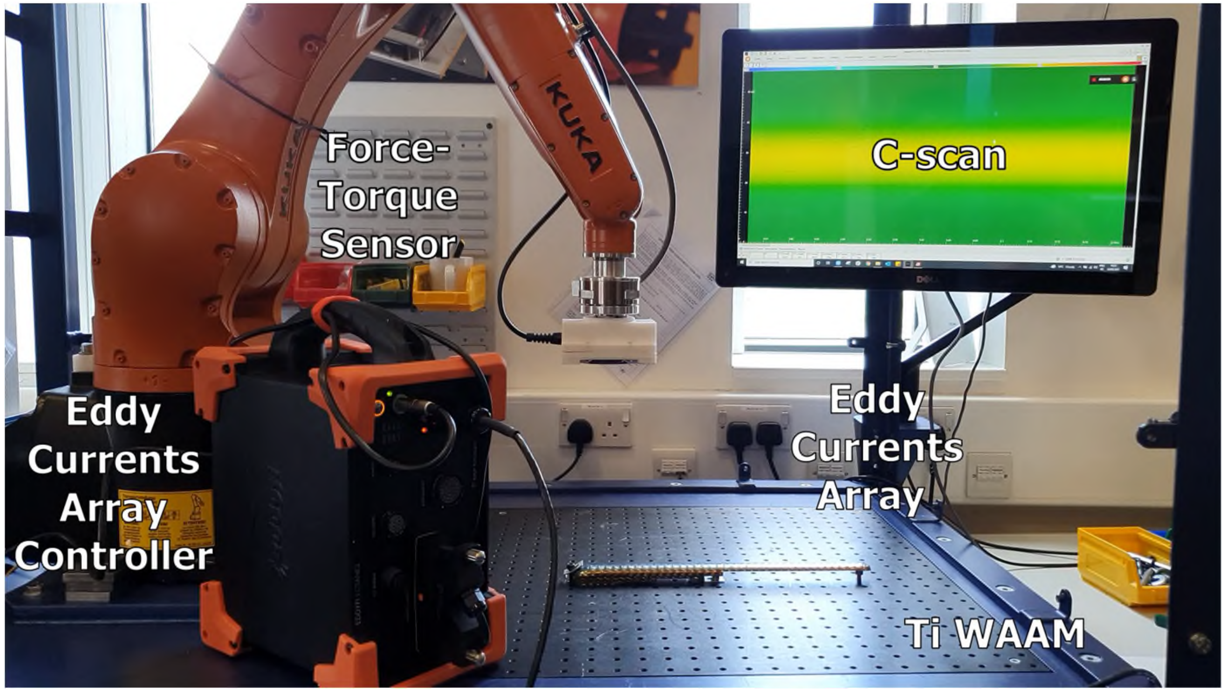
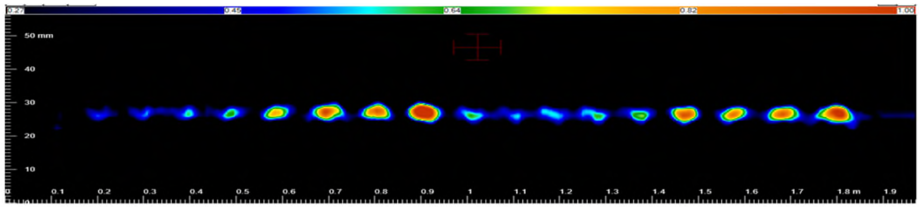
Robotically Deployed Eddy Current Inspection for In-Process Inspection of WAAM Components



EDM Notches (0.5 x 0.5 mm



Eddy Current C-Scan through as-built surface

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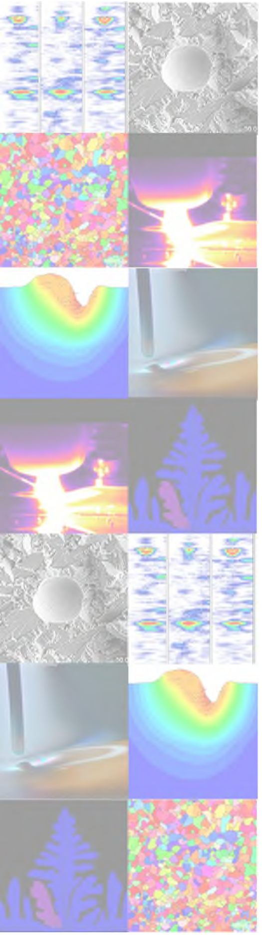
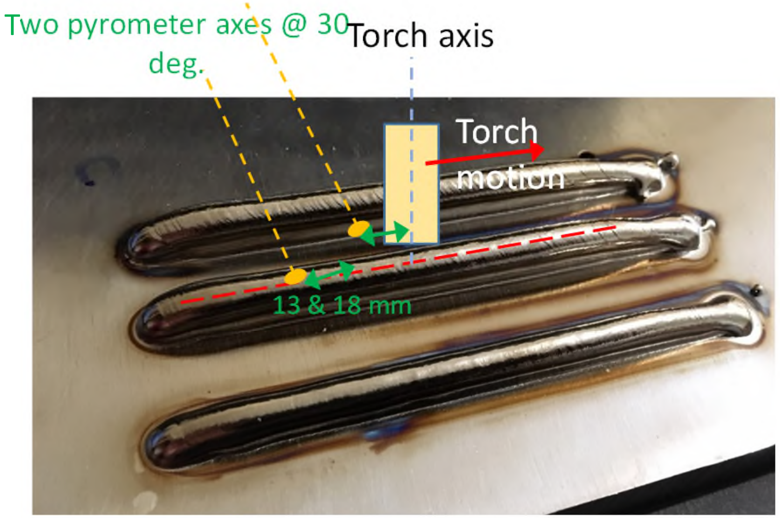
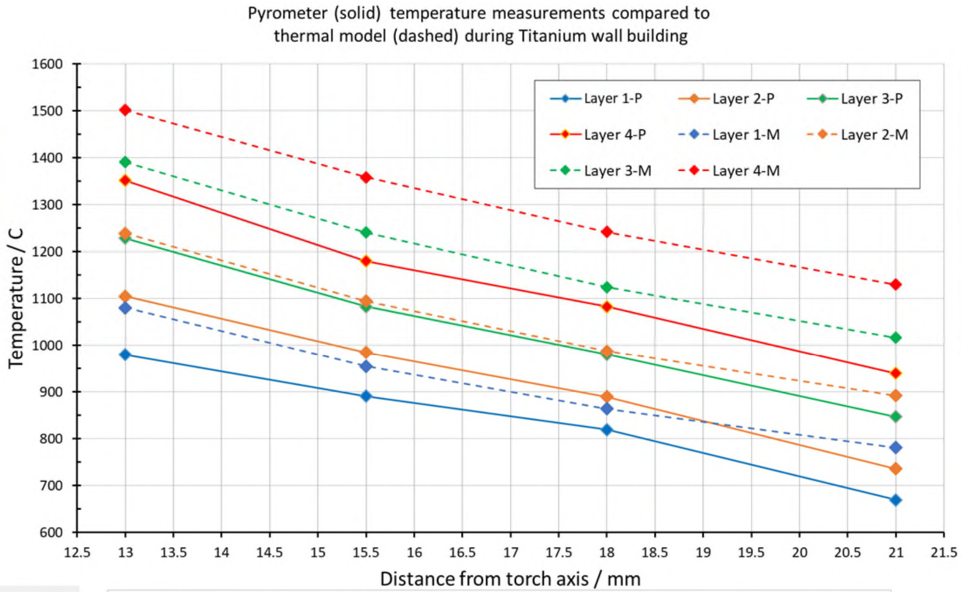
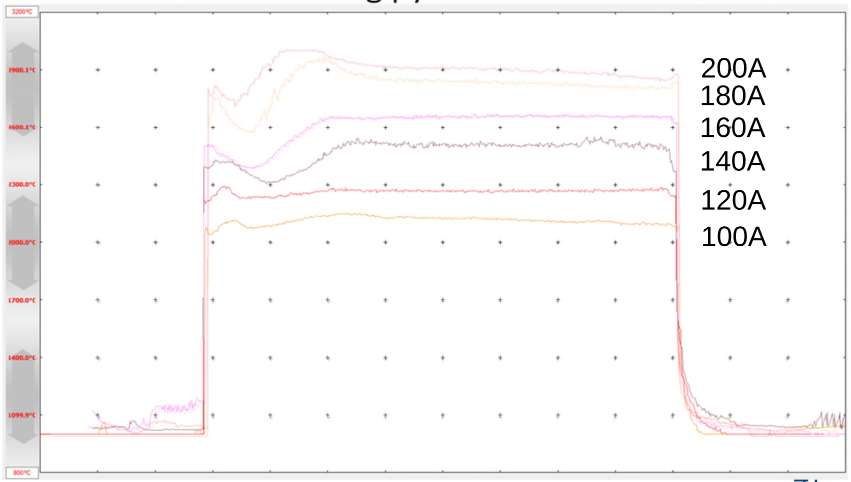
Quality control - Process monitoring – meltpool and temperature gradient measurement

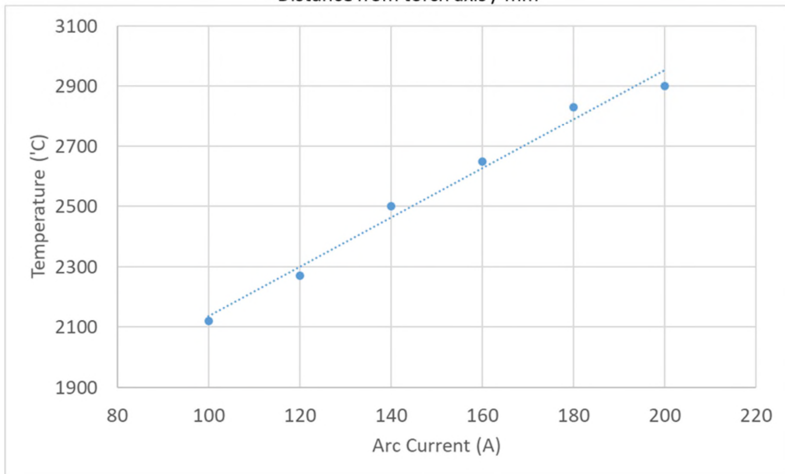




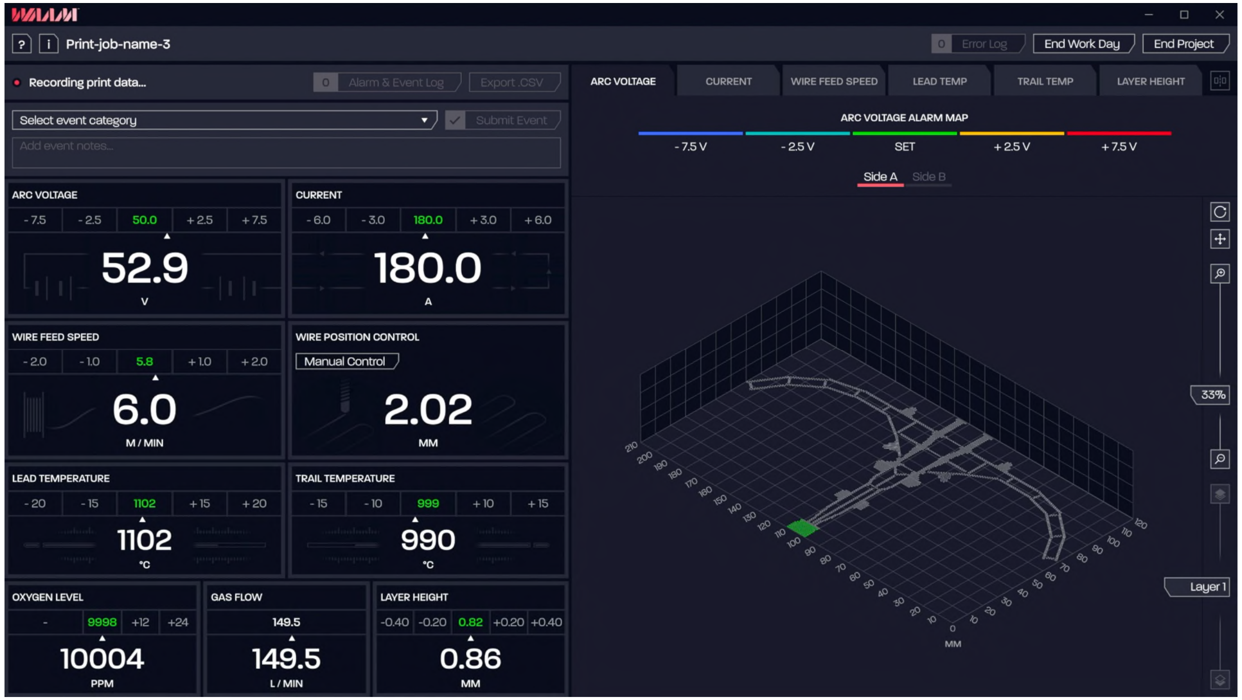
Titanium wall showing pyrometer orientations

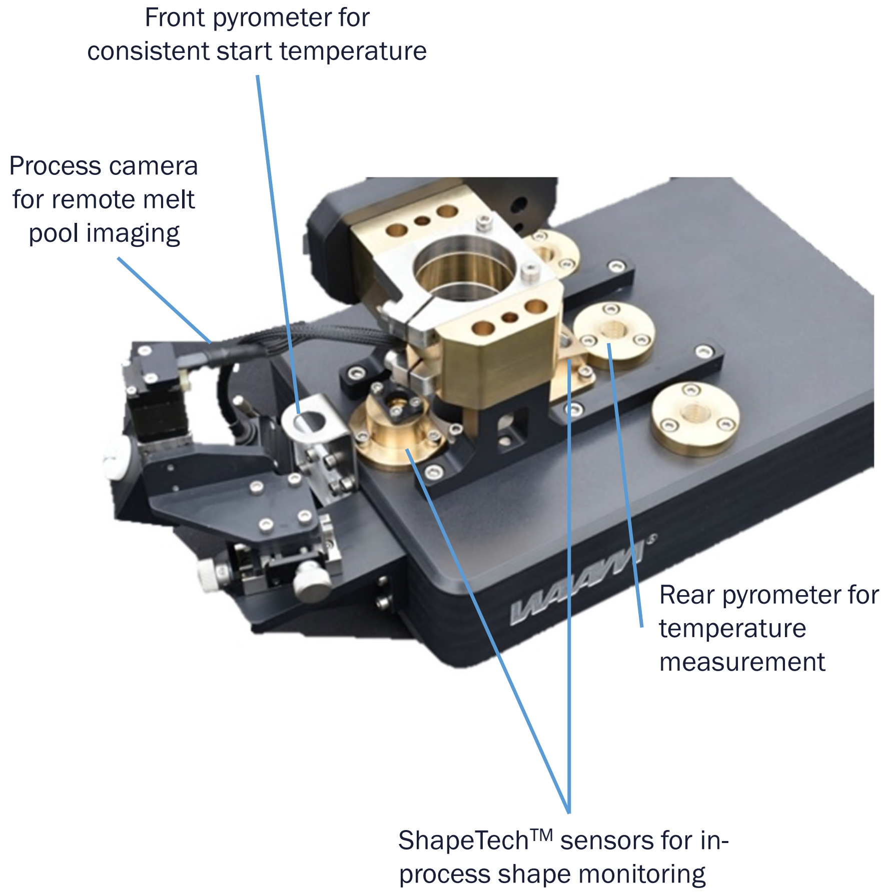






Commercial sensor system and software – WAAM3D





NEWAM project

- Designing next generation w-DEDAM processes with independent bead geometry and thermal conditions at high build rate and precision
- Matched designed processes and materials
- Physics based quality control and assurance for qualification – Q3

We are just half through - many exciting developments to come

More project information available at https://newam.uk/

Contact Stewart Williams – s.williams@cranfield,ac.uk

Virtual Seminar Series – Tuesday 2, 9, 16 November

New Wire Additive Manufacturing (NEWAM) programme for next generation wire based additive manufacture

Presented by Prof. Stewart Williams
Director of the Welding Engineering and Laser Processing Centre
Cranfield University

Tuesday, November 9, 2021