High deposition rate high quality metal additive manufacture using wire + arc technology

Dr. Paul Colegrove

Professor Stewart Williams

Presentation Overview

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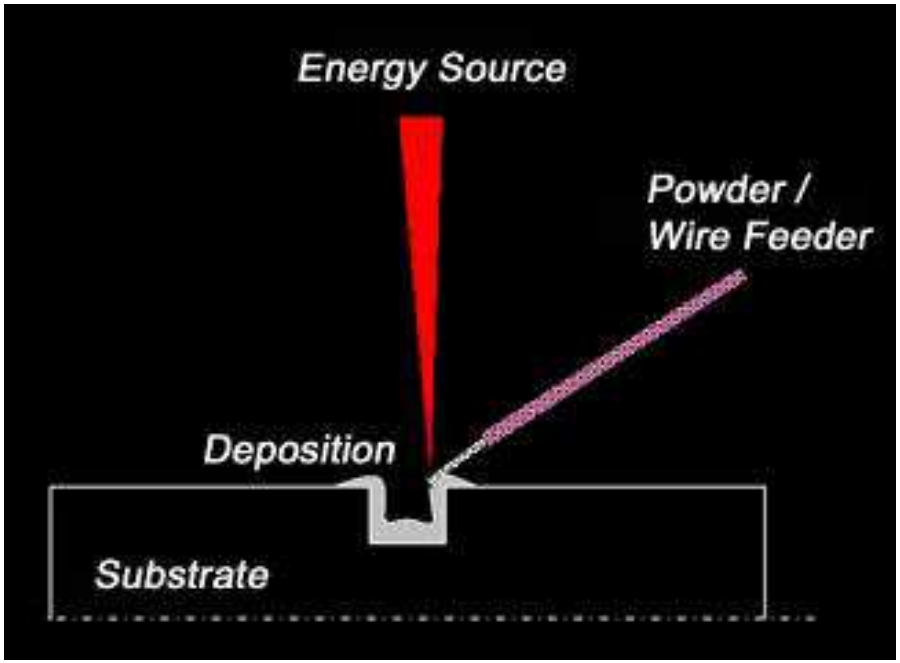
- **Wire + Arc Additive Manufacture (WAAM) basics and brief history**
- **WAAM process details**
    - **System configurations**
    - **Materials and process – control algorithms**
    - **Build features**
    - **Parts**
    - **Design studies**
    - **Mechanical properties**
- **Recent developments**
    - **Microstructure control**
        - Weld pool agitation
        - Thermal gradient manipulation
        - Rolling
    - **Process modelling**
    - **Very large part and integrated machining**
- **Future activities and developments**

What is a metal additive manufacture

Very Simply



And we have ours
Wire + Arc Additive Manufacture
WAAM

- **Also known as**
  - **Additive (Layer) Manufacture (A(L)M)**
  - **(Laser) Cladding**
  - **Buttering**
  - **Digital manufacture**
  - **Direct Light Fabrication**
  - **Direct Metal Casting (DMC)**
  - **Direct Metal (Laser) Deposition (DM(L)D)**
  - **Laser Direct Casting or Deposition**
  - **Laser casting**
  - **Laser clad casting**
  - **Laser consolidation**
  - **Laser cusing**
  - **Laser Engineered Net Shaping (LENS)**
  - **Lasform**
  - **Laser melting**
  - **(Metal) Rapid Prototyping**
  - **Net shape manufacture**
  - **Net shape engineering**
  - **Shaped deposition manufacturing**
  - **Shaped melting**
  - **Selective Laser Sintering (SLS)**
  - **Selective Laser Melting (SLM)**
  - **Shaped Metal Deposition (SMD)**
  - **Shape Melting Technology (SMT)**
  - **Shape welding**
  - **Solid freeform fabrication (SFF)**
  - **Weld build up**
  - **+ several more since I put this list together a couple of year ago**

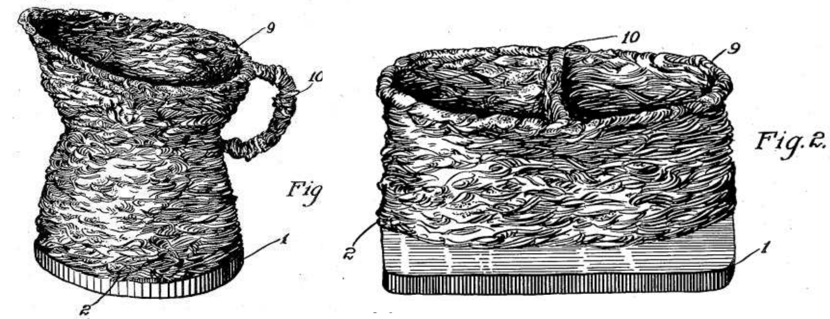
Metal Additive Manufacture - History

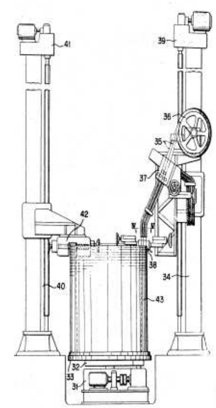
This has been around awhile!

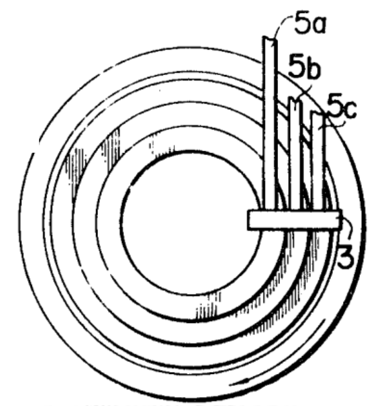
- 1926 Baker – patented “The use of an electric arc as a **heat source to generate 3D objects depositing molten metal in superimposed layers”**

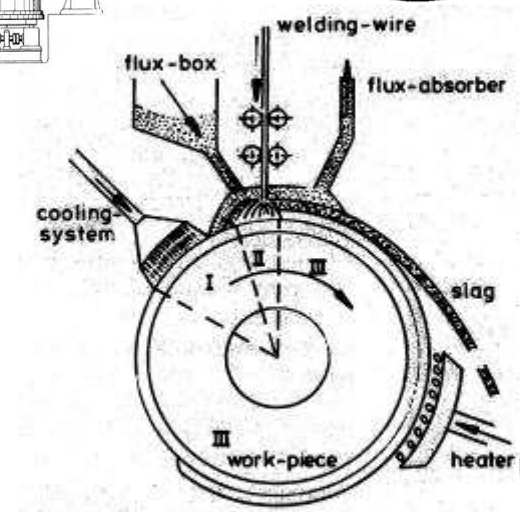
- 1971Ujiie (Mitsubishi) Pressure vessel fabrication using SAW, electroslag and TIG, also multiwire with **different wires to give functionally graded walls**

- 1983 Kussmaul used Shape Welding to manufacture high quality large nuclear structural steel (20MnMoNi5 5) parts – **deposition rate 80kg/hr – total weight 79 tonnes**









Metal Additive Layer Manufacture - History

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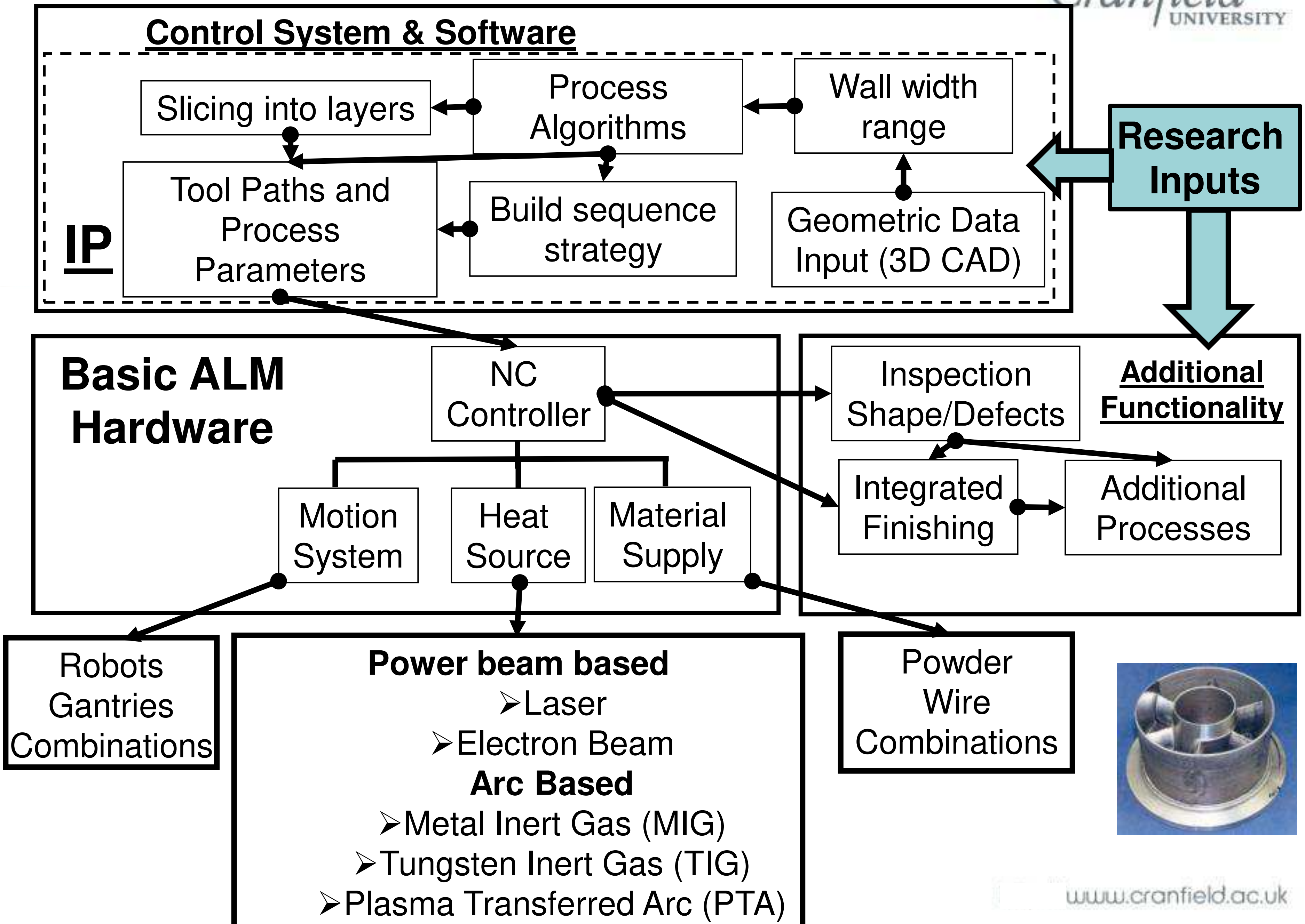
- 1993 Prinz and Weiss **patent combined weld material build up with CNC milling** – called Shape Deposition Manufacturing (SDM)
- 1994-99 Cranfield University develop Shaped Metal Deposition (SMD) for Rolls Royce for engine casings, various processes and materials were assessed

Basic Metal AM system



MAM – Process Options

Weld based Additive Layer Manufacturing - METALS

Powder based

Wire based

X Low deposition rates (0.1-0.2 kg/h)
X Low material efficiency (10-60%)
X Quality and flaw issues
X Very high part cost
✓High level of complexity

MAM – Process Options

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Weld based Additive Layer Manufacturing - METALS

Powder based

- X Low deposition rates (0.1-0.2 kg/h)
- X Low material efficiency (10-60%)
- X Quality and flaw issues
- X Very high part cost
- ✓High level of complexity

Wire based

- ✓High deposition rates (several kg/h)
- ✓High material efficiency (90%)
- ✓No defects
- ✓Low part cost
- x Medium to low level of complexity

__Primary Objective:__
Ti64 large scale structural components

WAAM Basic Process

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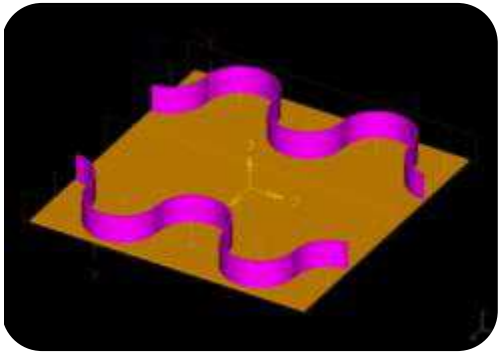
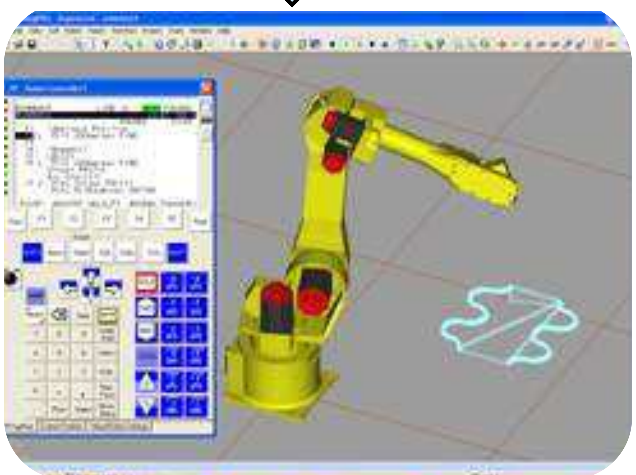


CAD STL



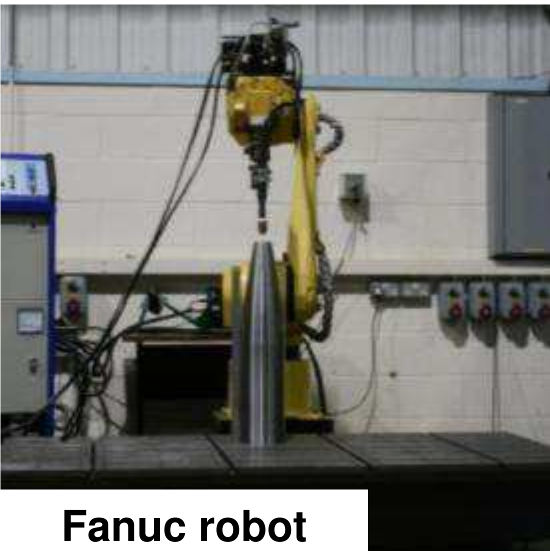
RUAMRob 2.0
Slicing and path generation
(within a couple of minutes)

WAAM Machine – Welding power source attached to Fanuc robot

WAAM workpiece

System development and integration

- Two robotic and on gantry based system built and developed
- Retrofit of WAAM process demonstrated by incorporation into Holroyd Edgetek 5-axis grinding system.



Fanuc robot

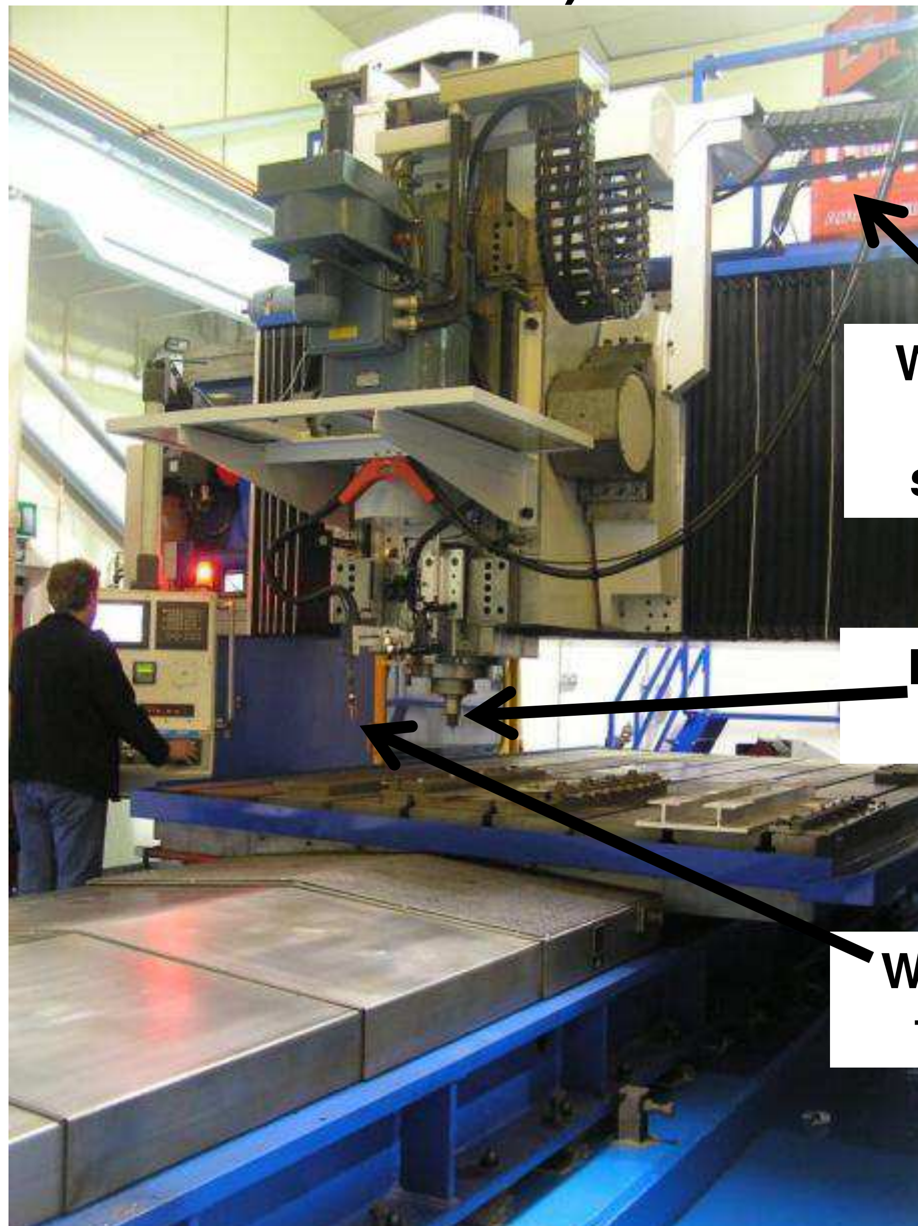
ABB-2 + 7th axis

5 Axis CNC Grinding system with WAAM

Open architecture systems

Installation of large scale ALM facility now complete – HiVE (old Airbus FSW machine)

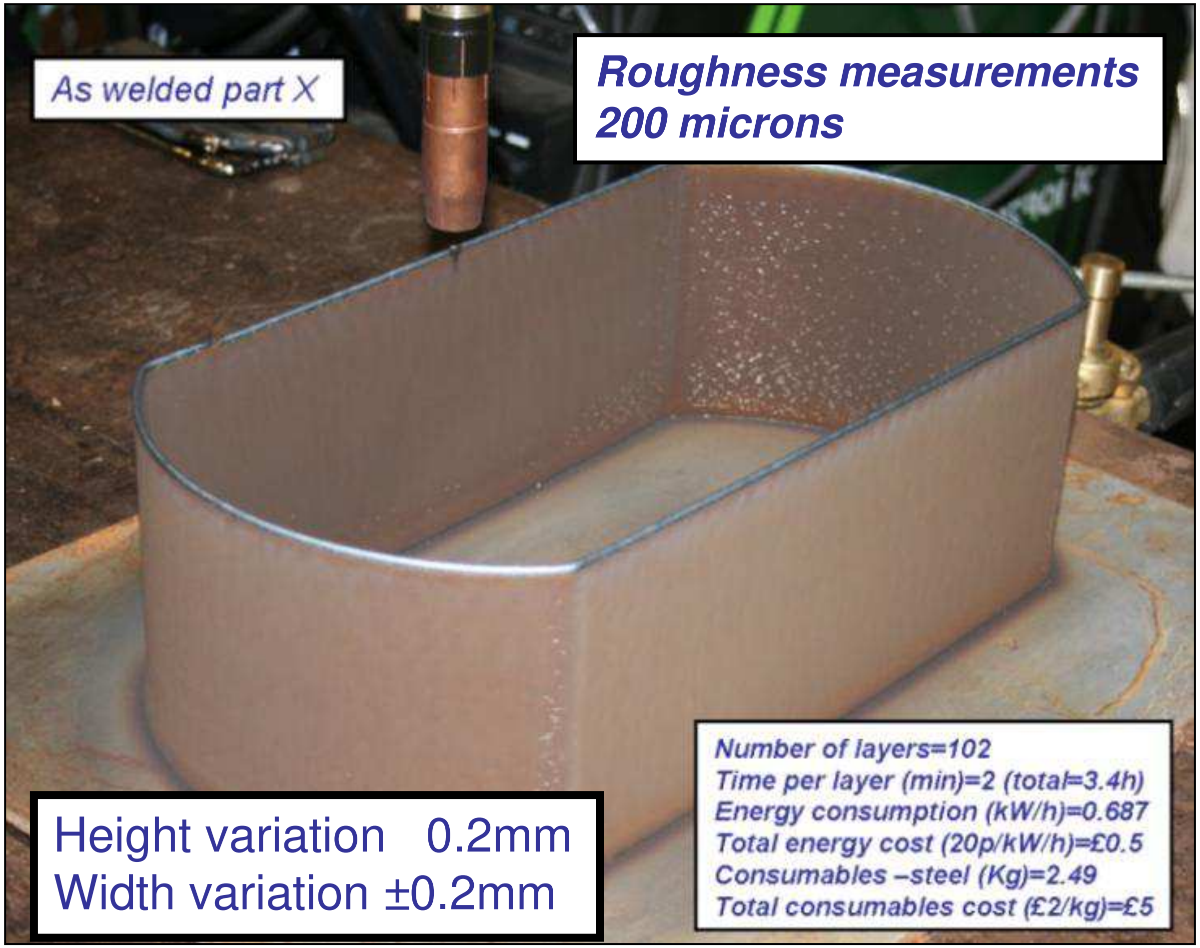
- HiVE Technology demonstrator system implemented for large scale WAAM incorporating milling, and rolling



WAAM Materials and Processes Investigated

- **Materials**
  - Mild steel
  - High strength steel
  - Stainless steel
  - Aluminium
  - Titanium (6/4)
  - Copper
- **Processes**
  - TIG (DC and pulsed) – high quality
  - High Frequency TIG (DC and pulsed) - high quality precision
  - Pulsed MIG – simple and cost effective
  - <u>Cold Metal Transfer (CMT) – low heat input, high process tolerance</u>
  - Tandem Pulsed MIG – high deposition rate
  - High power fibre laser – high quality
  - Plasma - high quality, wide deposition width

WAAM – 1st 2D Part – CMT – 2.9mm thick walls - mild steel



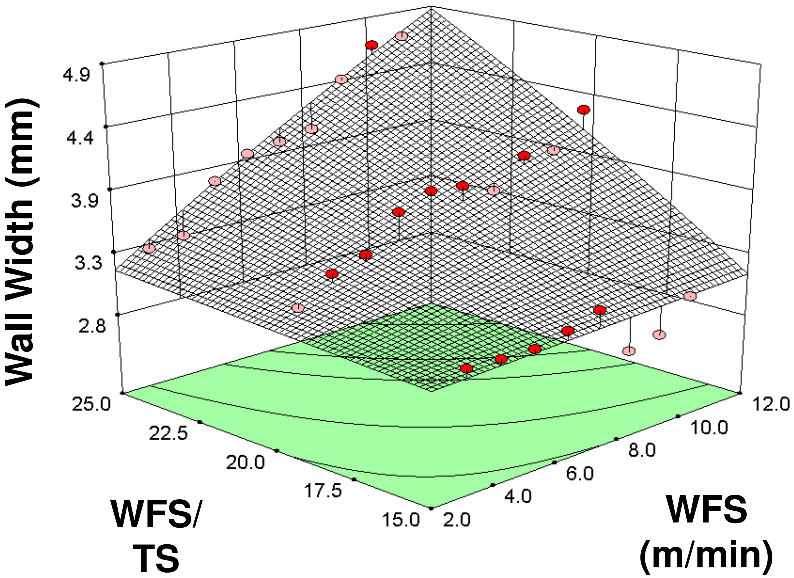
CMT Benefits

- ✓ Surface tension transfer
- ✓ Zero spatter
- ✓ Automatic arc control
- ✓ Lower heat input (30% less)

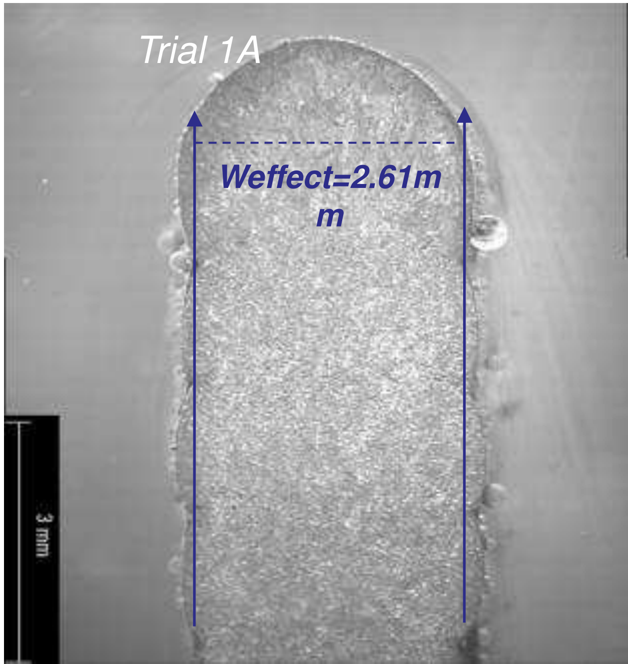
As deposited – time 3.4 hours

Empirical Process Control Algorithms

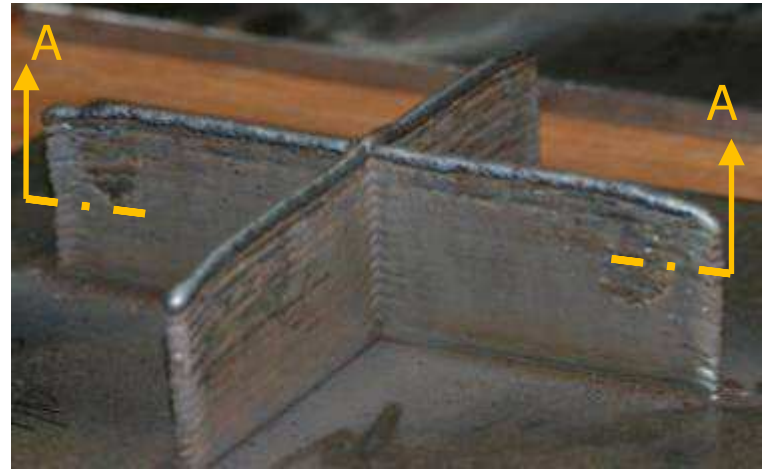
- Have been developed for
  - Steel – CMT and pulsed MIG
  - Titanium – CMT, plasma, pulsed TIG
  - Aluminium – CMT
- Relates process parameters to deposition geometry and other factors
- Includes layer number (no control system needed), deposition angle and effective wall width
- Will be a fundamental part of WAAM machine

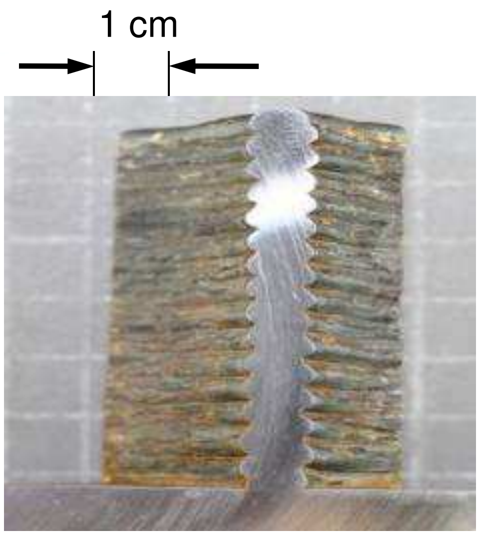


Effective wall width

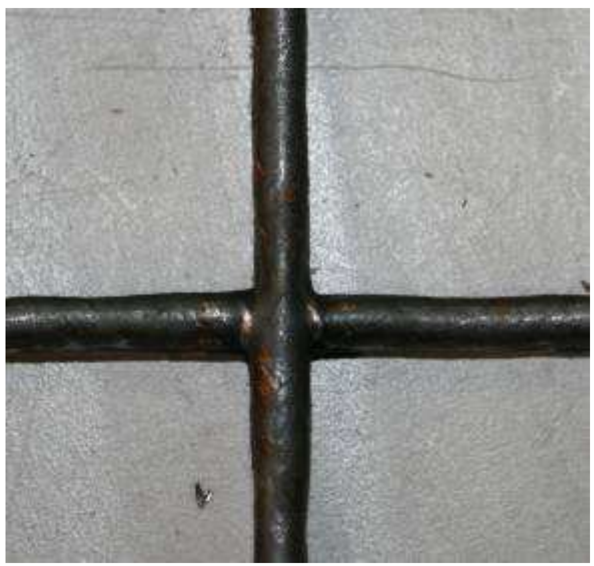


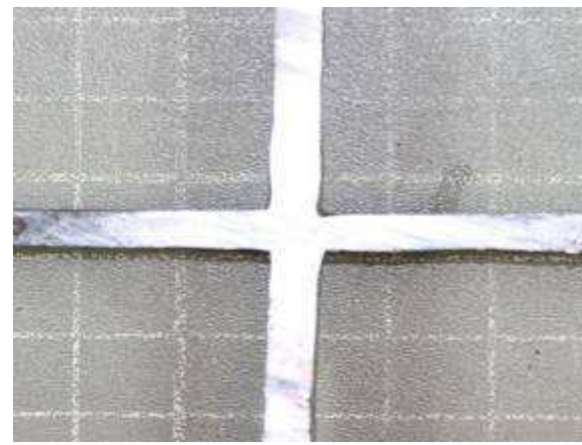
Design Features - Crossovers





45º section

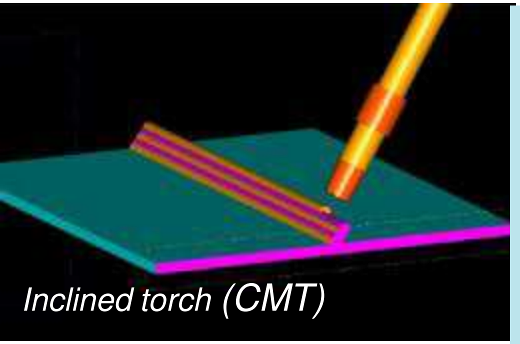


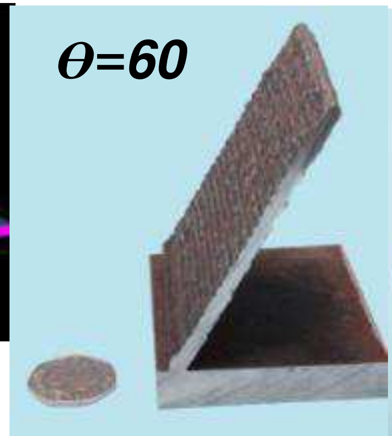


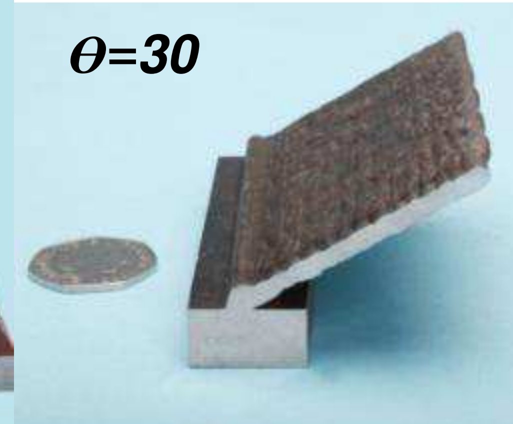
Section A-A

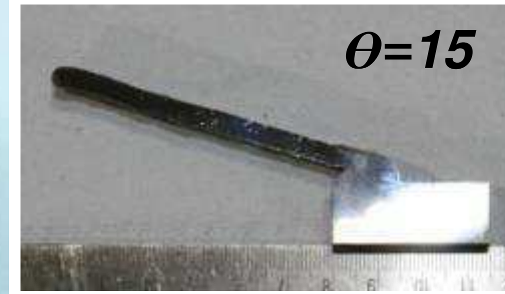
Design features– inclined and horizontal walls – enclosed section

Inclined









Horizontal

Enclosed section

Design features - quarter circle and round enclosure

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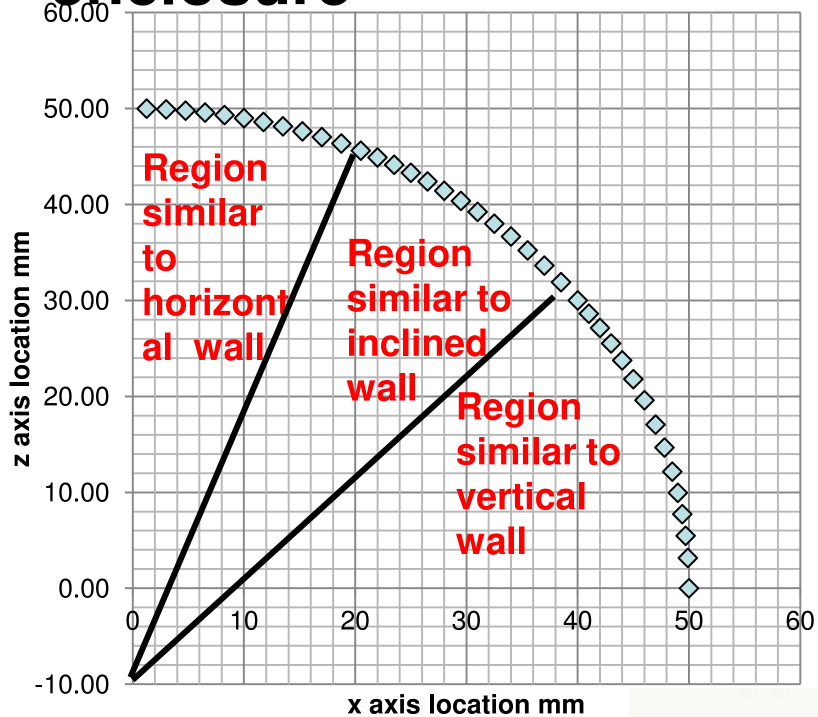

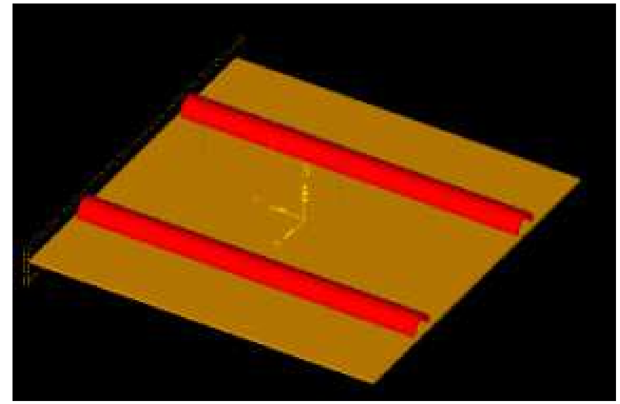

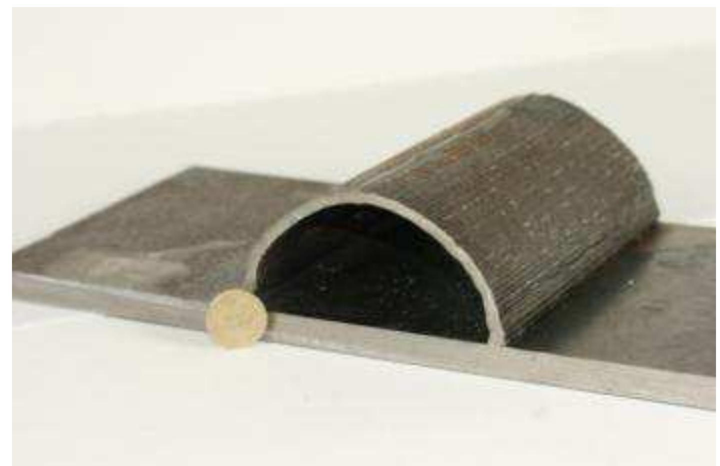

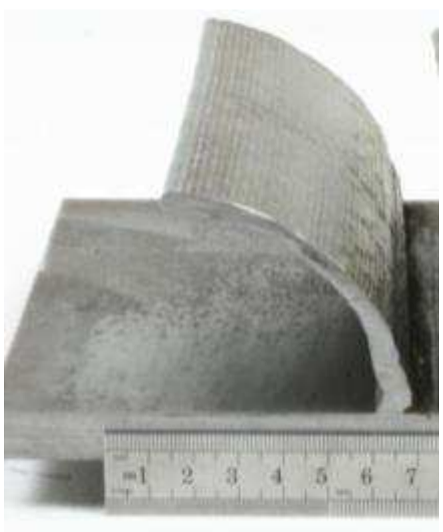

WAAM - Large parts - Intersecting Stiffened Panels

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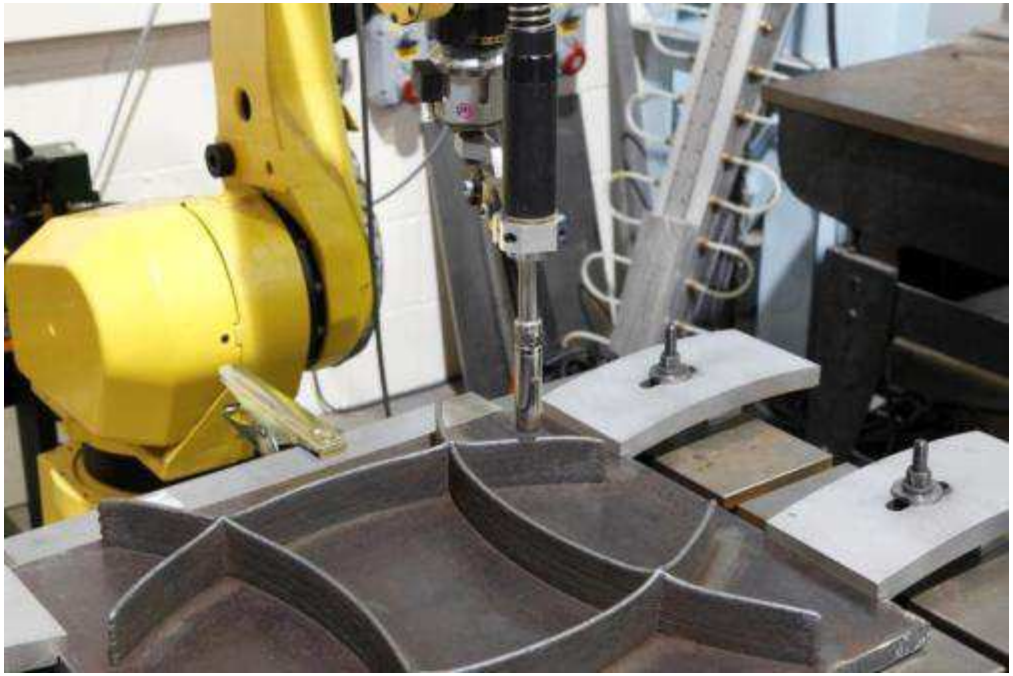
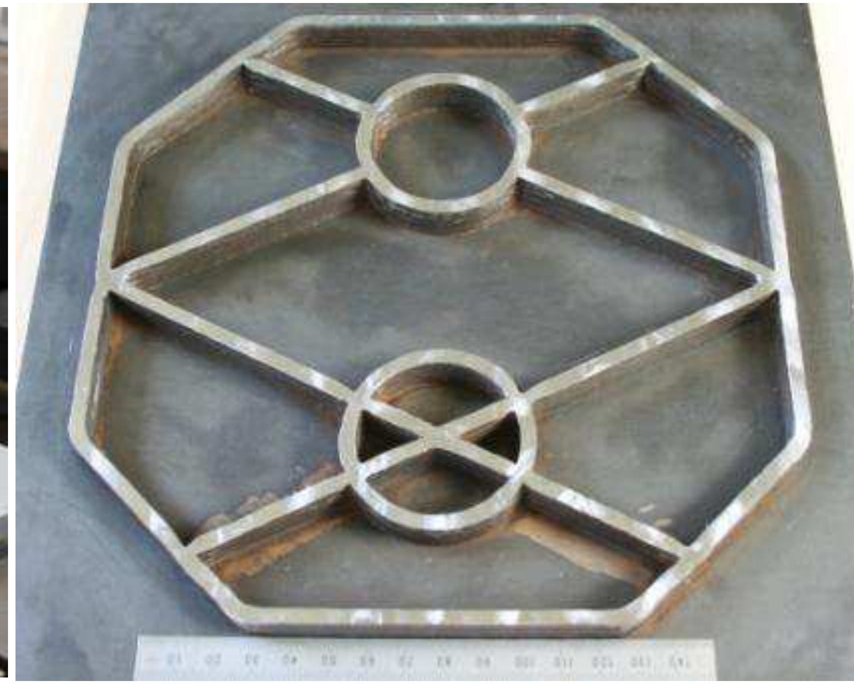
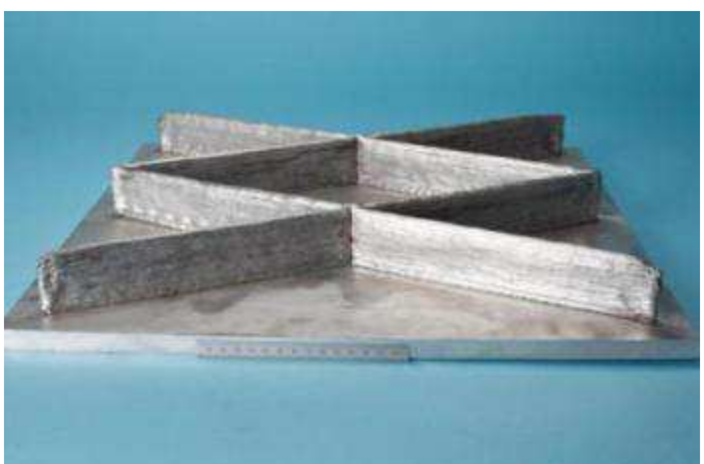
carbon steel (s355)





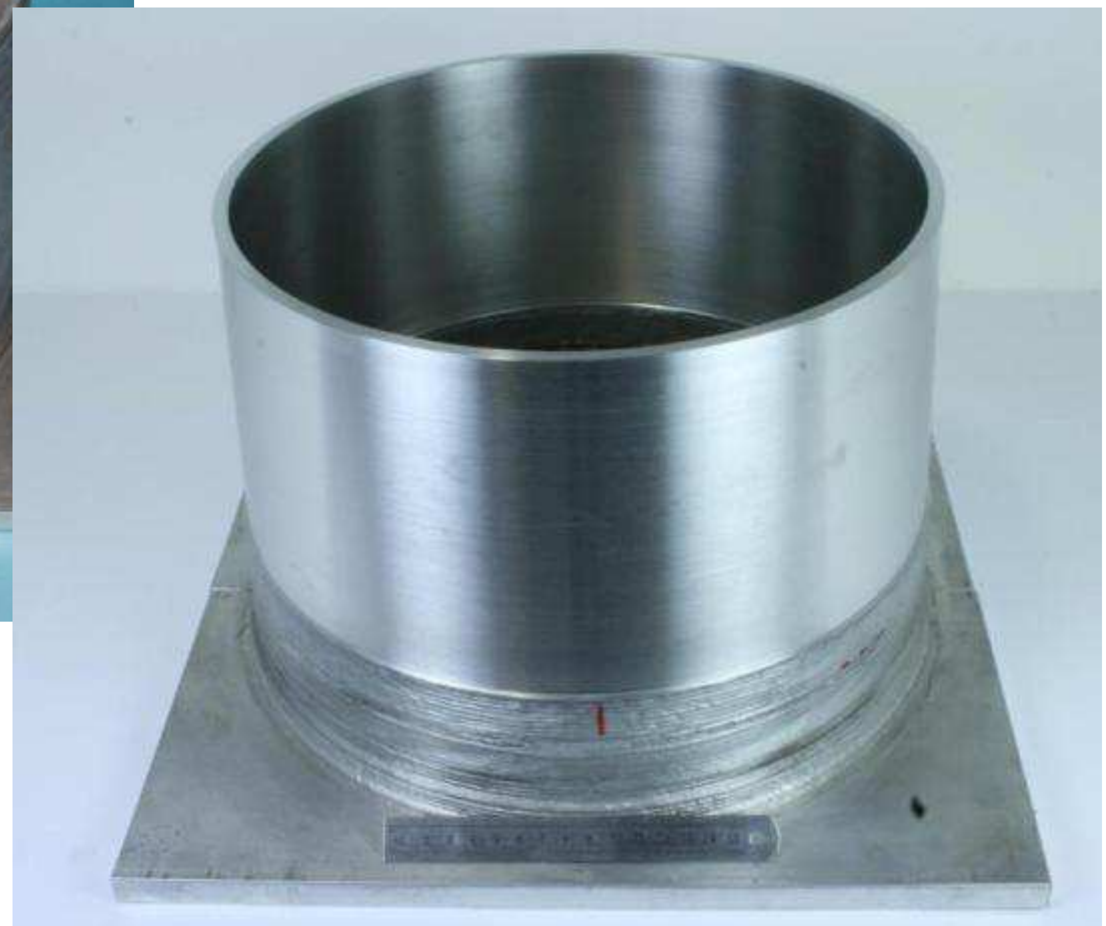


Aluminium

WAAM - Large parts Variable wall thickness cylinder – example satellite launch vehicle part

As deposited – 6 hours

After machining



WAAM - Large parts - Titanium test pieces

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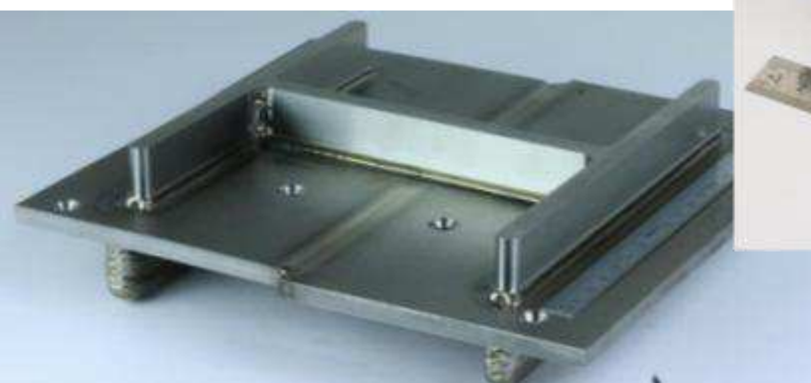
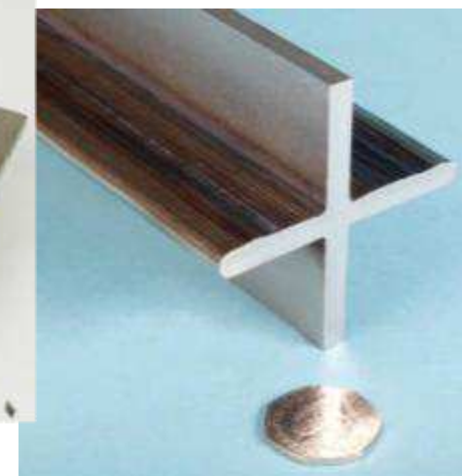
Ti walls 1000x200x4 mm^3 – mechanical test pieces – O_2 ~1500 ppm

Intersections including machining

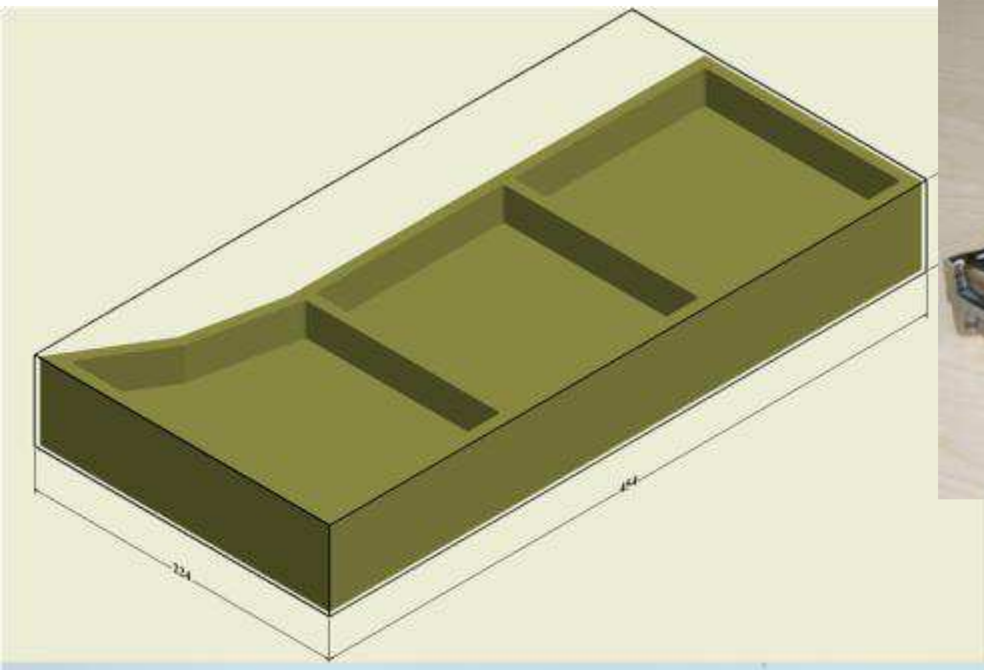


Thick wall crossover



Residual Stress Balanced Cruciform

Ti Stiffened panel



Deposition time ~ 1 hour

	Initial weight (kg)	Final weight (kg)	Buy to fly ratio
Machining	27.5	5.6	4.9
WAAM + Finishing	5 + 1.2 (wire) = 6.2	5.6	1.1

Ti 6Al 4V Mechanical properties summary

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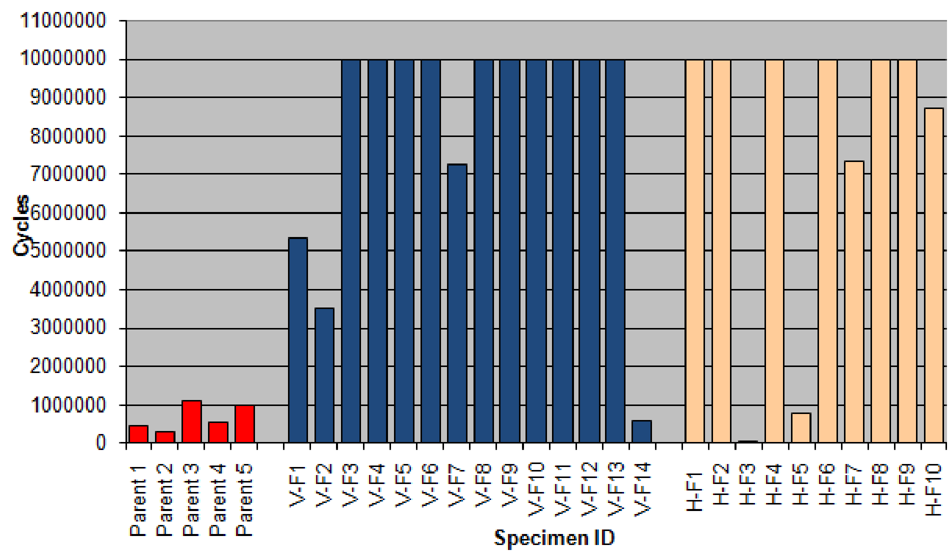
	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
Specification minima*	824	896	6.0
Wrought Ti64	950	1034	11.7
WAALM Vertical	805	918	14.1
WAALM Horizontal	865	965	8.2

*AMS 4985 Cast and HIP

	Kc (MPa.m$^{1/2}$)
Wrought Ti64**	75.0
WAAM Vertical	73.9
WAAM Horizontal	81.9

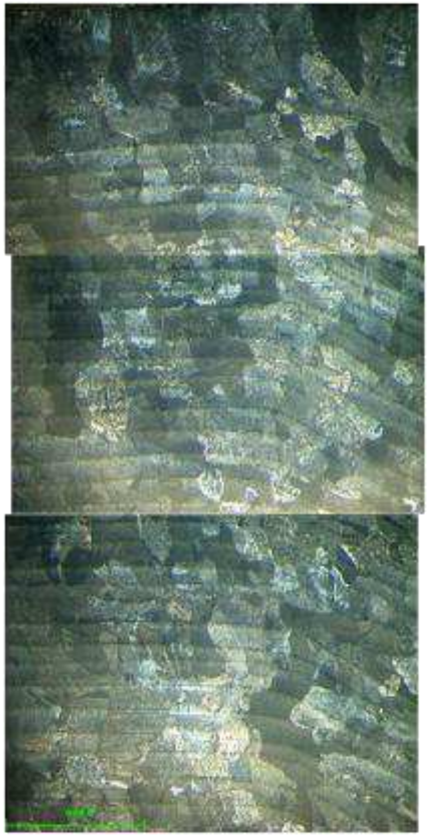
**Literature values

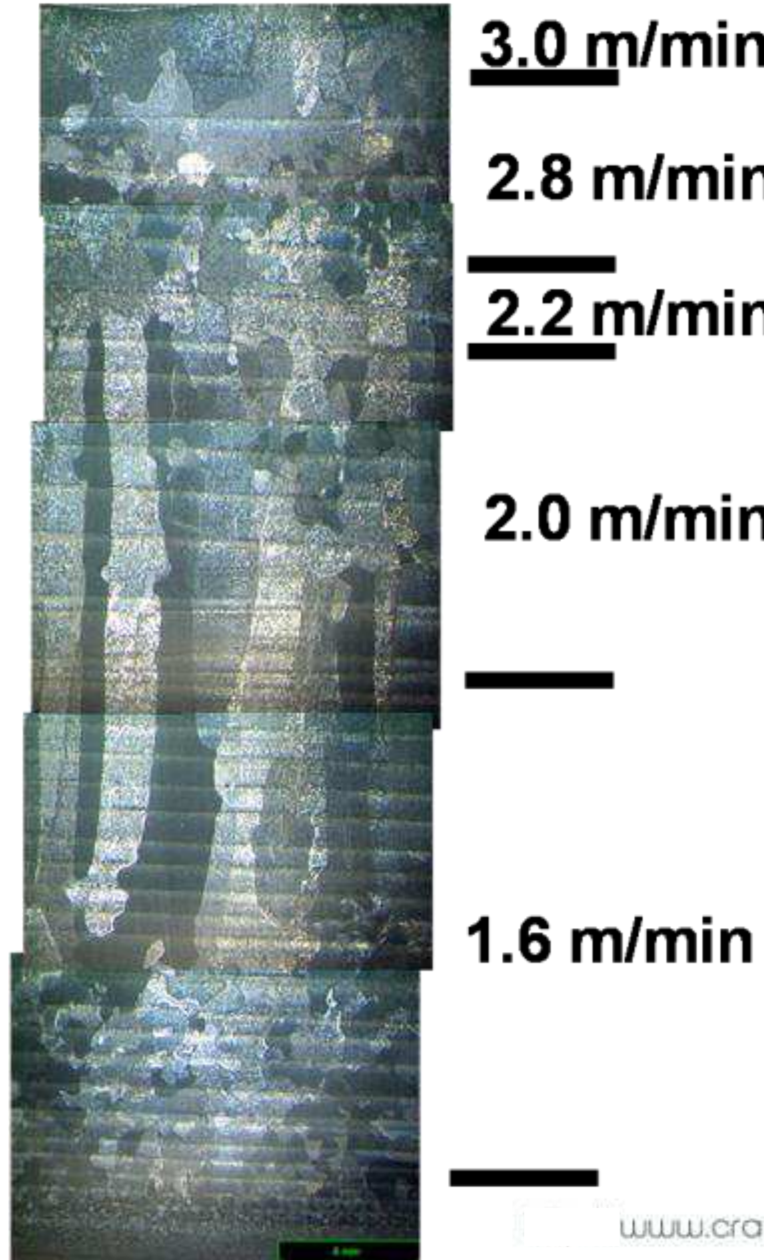


R-Ratio 0.1,
σ_{max}=600MPa,
Sinusoidal Waveform and 30Hz,

Grain refinement in Ti alloys (2) - Control of the cooling conditions

Full wall

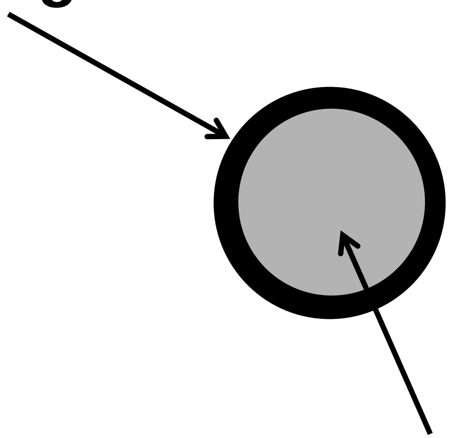




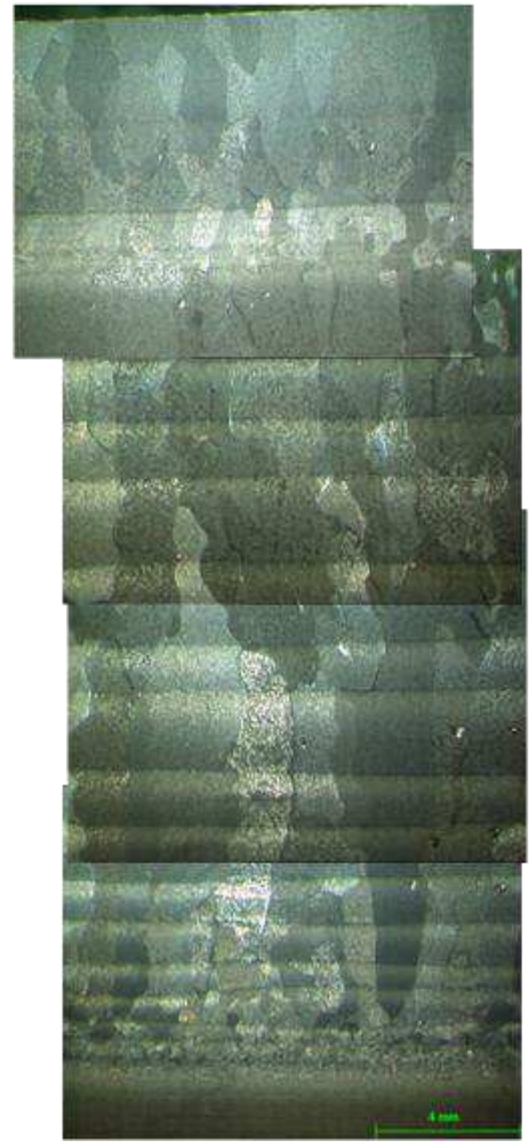
large columnar growth prior beta grains are blocked when wire feed speed is >2.0 m/min.
- Note in Arcam process this works by heating the weld pool from the bottom

Grain refinement in Ti alloys (3) - Use of grain refiner

Boron coating



Ti64 wire



Coated wire

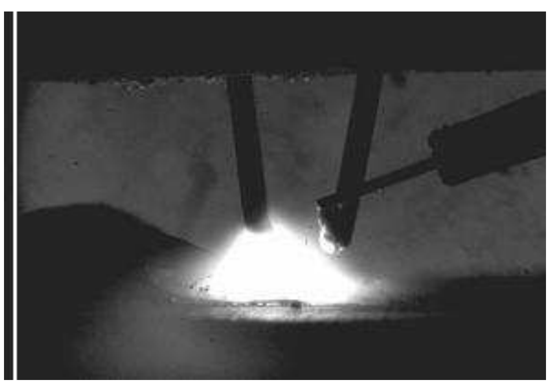
Normal wire

Future work will use xx for the coating for better adhesion and matching of mechanical properties

Methods of controlling deposition metal chemistry

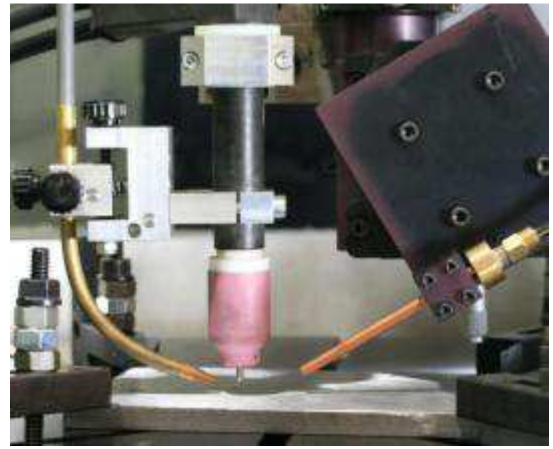
Multi wire approach

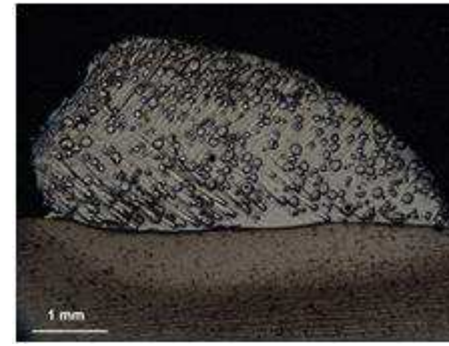
Aluminium hardness
1 wire Al6%Cu– 100HV
2 wire (Al4.5%Cu1.5%Mg) – 120HV

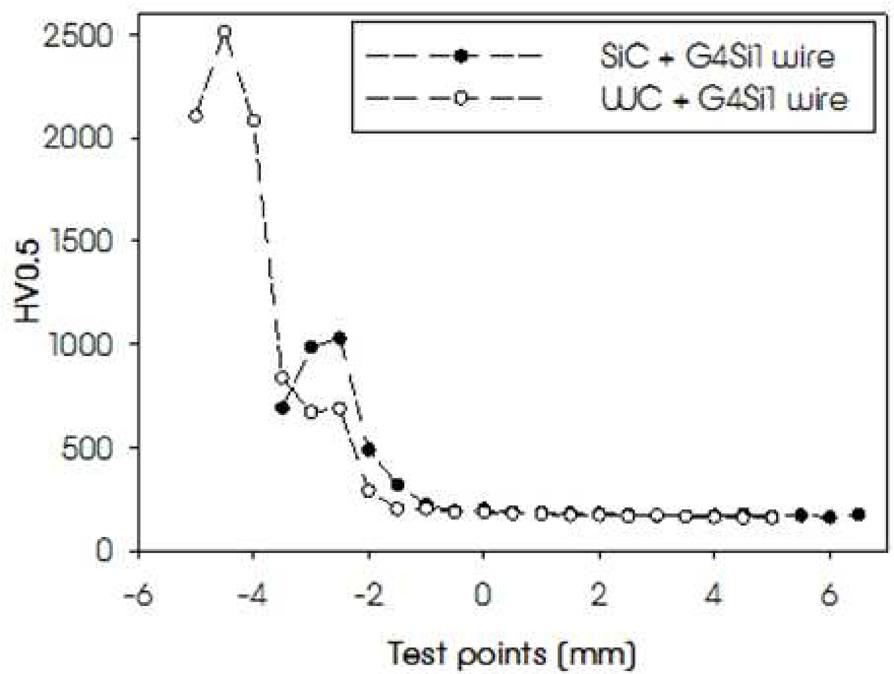


3 wire (Al8%Cu1.5%Mg – 140HV

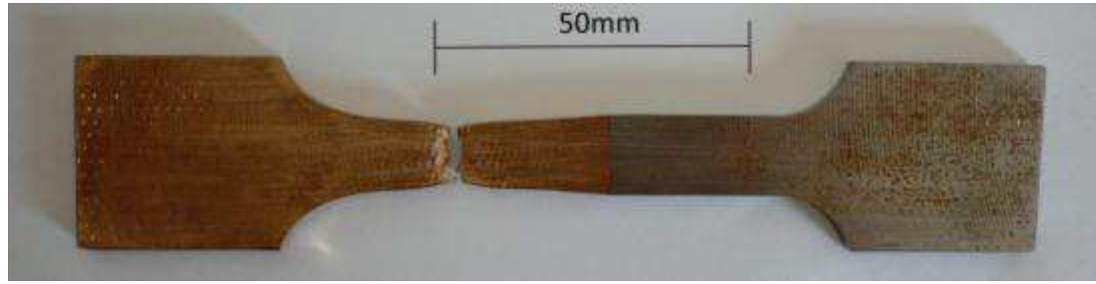
Wire + Powder



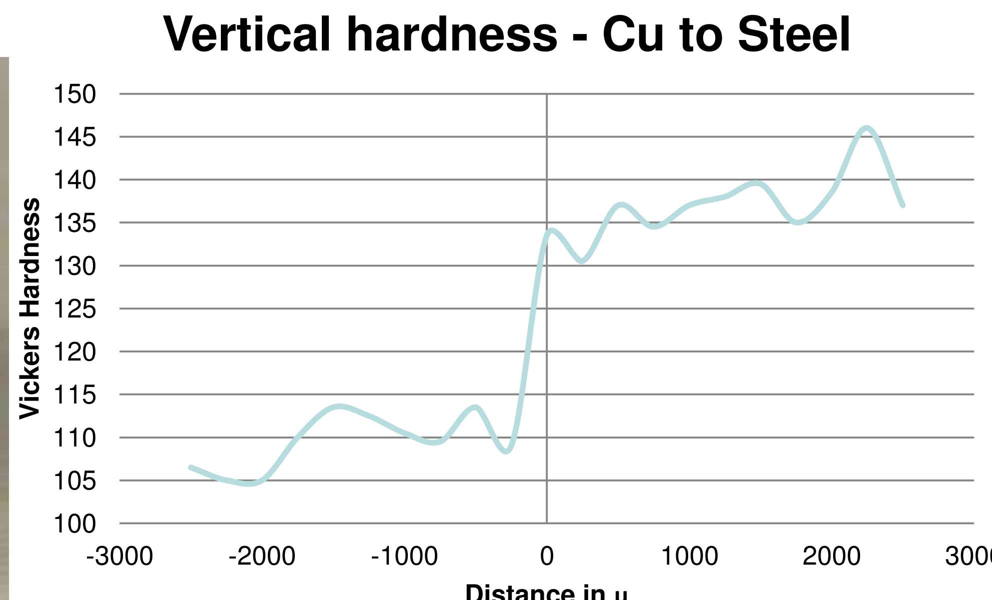




WAAM – Latest results – mixed material systems Steel/bronze (CuSi3%) parts



Yield 140 MPa, UTS 300 MPa, elongation 12%, failure in bronze



WAAM – control of microstructure– rolling* Video

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*Patent applied for

WAAM – latest results – rolling - effect on distortion and bead geometry

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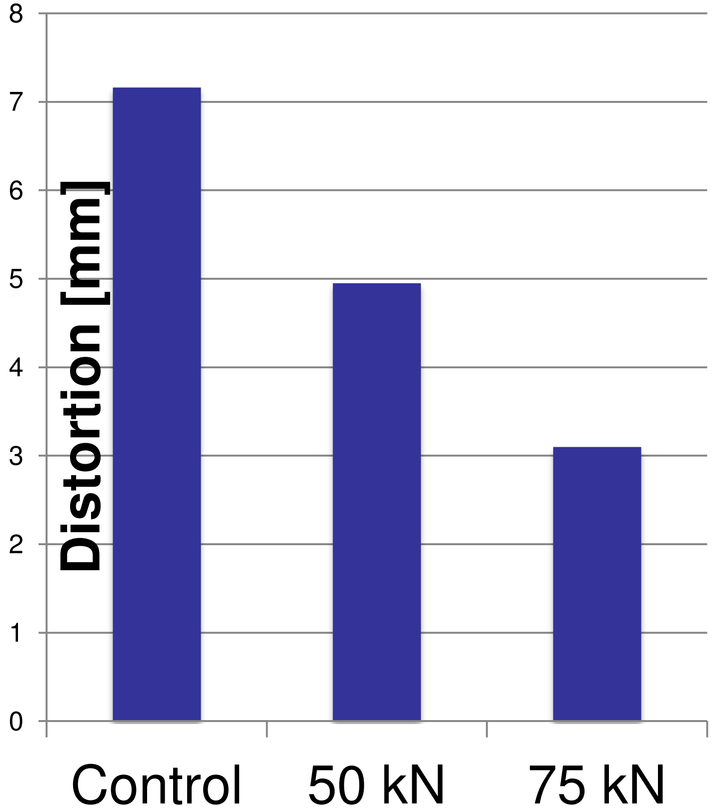

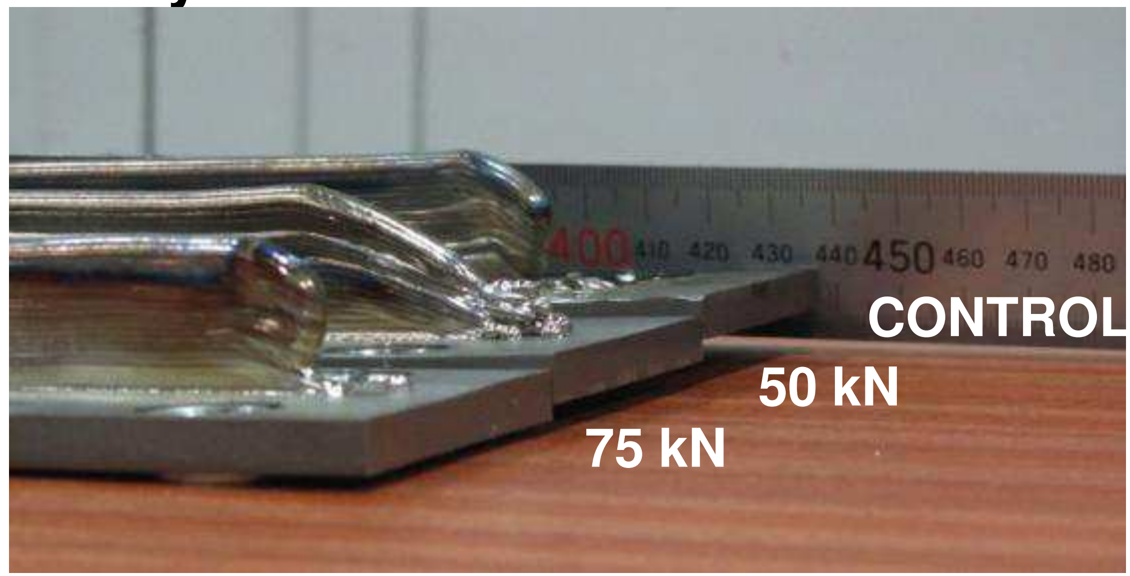

- Plates are 450 mm long

Effect on Geometry	Average L.H. [mm]	Std. Dev.	Average reduction after rolling [mm]
Control	1.13	0.19	-
50 kN	1.04	0.12	0.25
75 kN	0.93	0.09	0.37

Rolling improves process repeatability

WAALM – latest results – rolling - effect on microstructure

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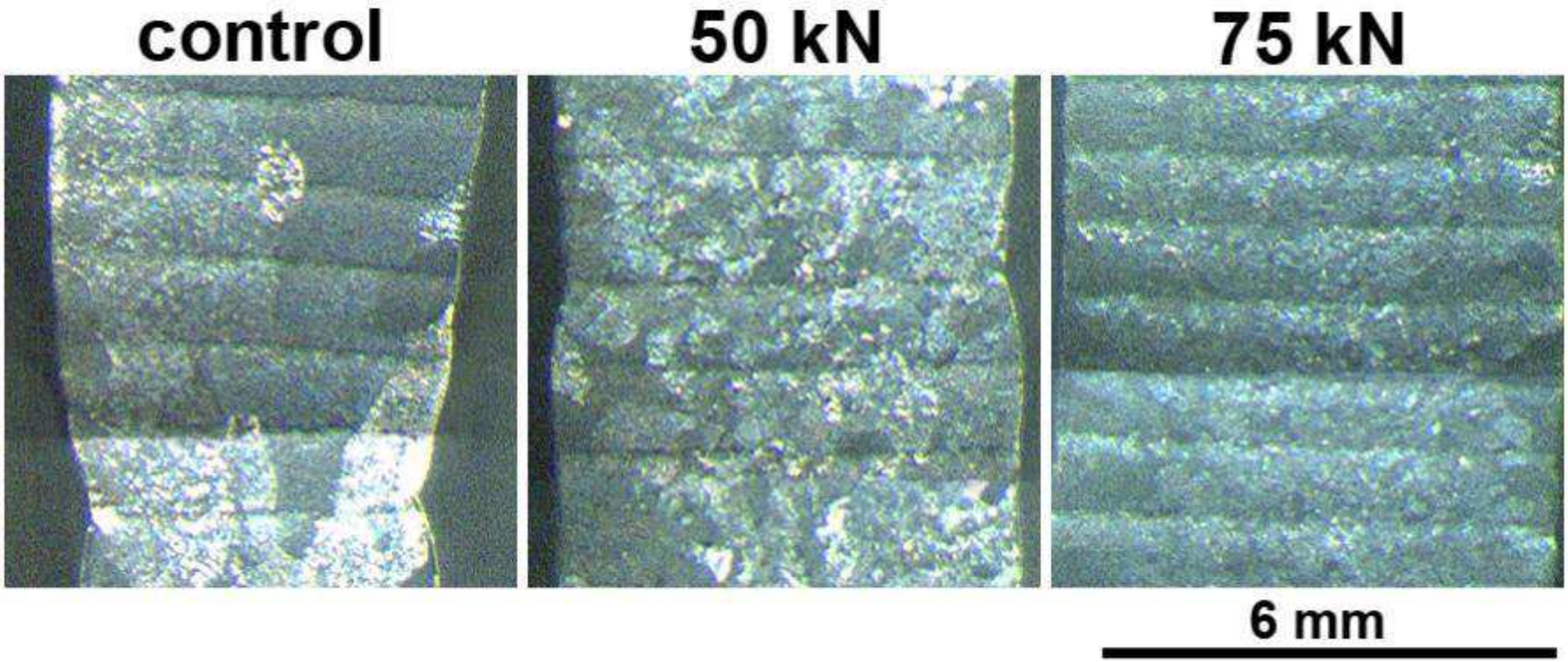

Rolling introduces **deformation**, **nucleation sites** and **stored energy** into the large beta grains, thus inducing **recrystallisation** when layers are reheated during the subsequent deposition

Reduction in grain size

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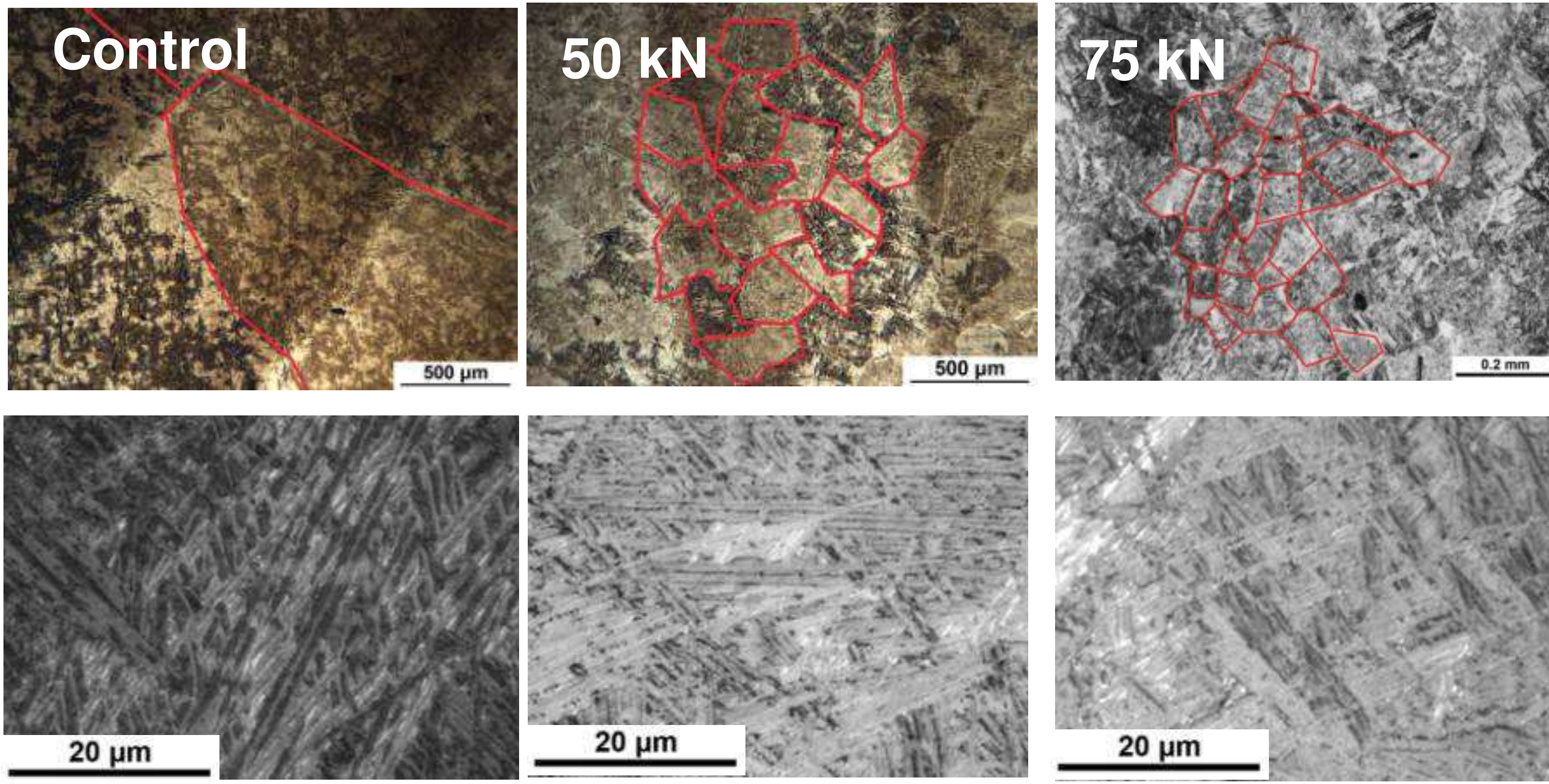

Grain size	Control	50 kn	75 kN
Primary grains	3 x 30 mm	124 µm	89 µm
Alpha laths length	21.1 µm	15.5 µm	7.7 µm
Alpha laths width	1.2 µm	1.0 µm	0.7 µm

Preliminary mechanical test data on rolled samples

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	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
Specification minima AMS 4985 Cast and HIP	824	896	6
Wrought Ti64	950	1034	11.7
WAAM Vertical	805	918	14
WAAM Horizontal	865	965	8
WAAM Rolled Horizontal (50 kN)	911	1006	11.5

Even more improvement likely for vertical direction

Grain size change tens of mm to ~ 130 μm

WAAM - Large parts – 4 x projectiles - Build sequence – high strength steel

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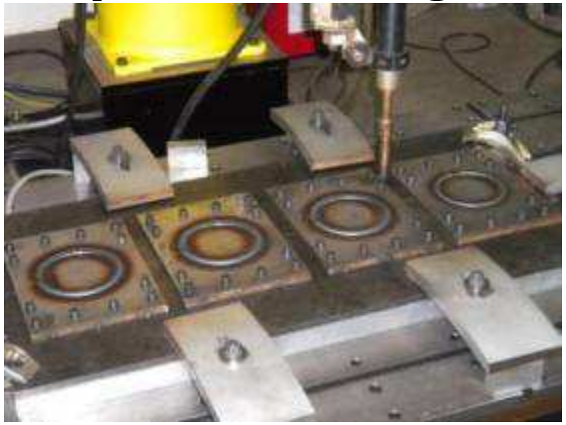

- Height 800 mm, diameter 160 mm, Wall Thickness 18 - 8 mm Mass 32 kg each
- Deposition method pulsed MIG - rate 4 kg/hr

WALM - Large parts – 4 x projectiles - profiles

Plain cylinder – 22mm wall thickness

Variable wall thickness ogive with overhang for threaded section

WAAM - Large parts – 4 x projectiles - After machining

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30-40% more weight efficient structure – only possible by ALM manufacture

WAAM – Large parts – thin walled structure

WAAM Process Modelling

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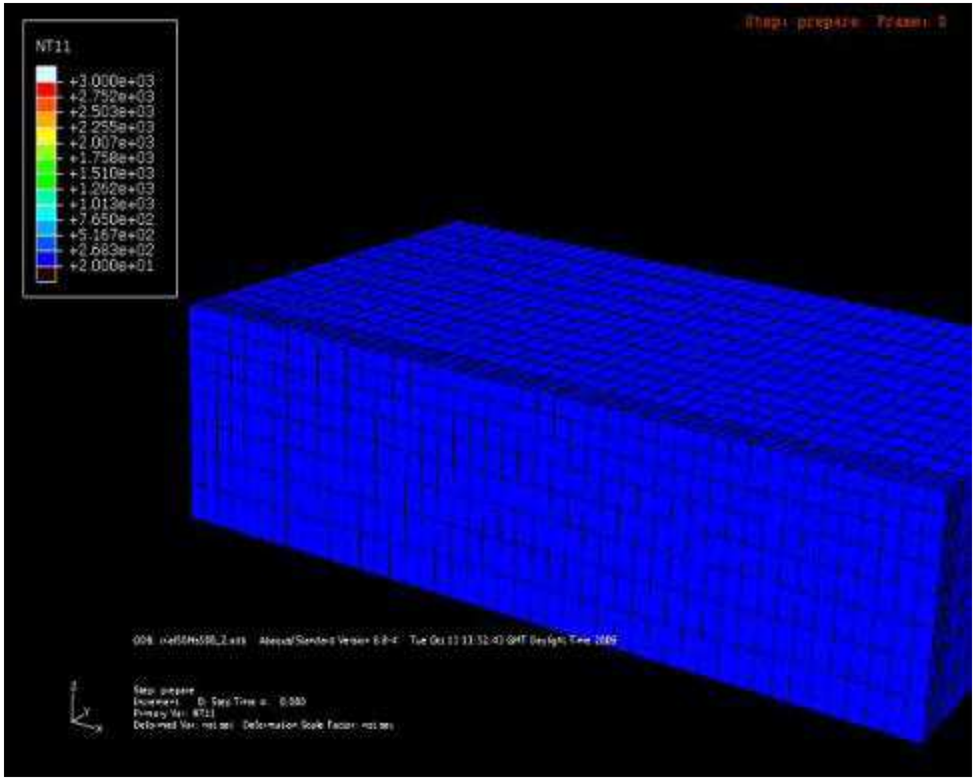
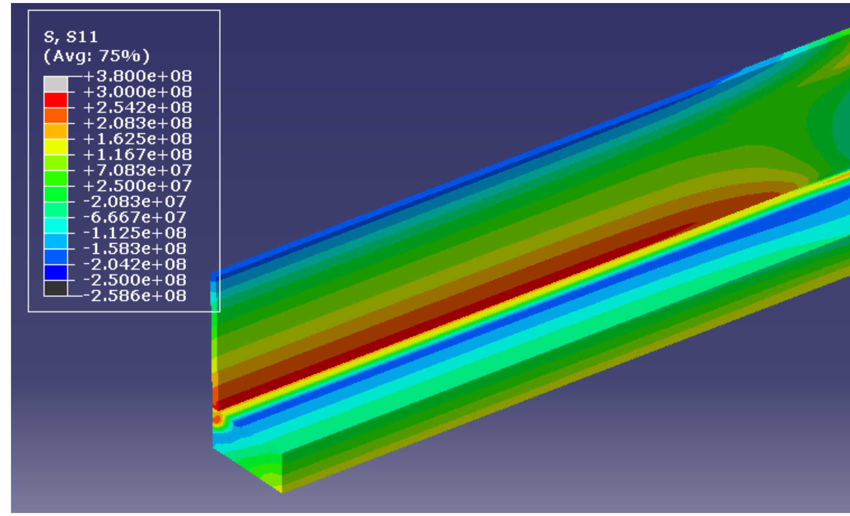
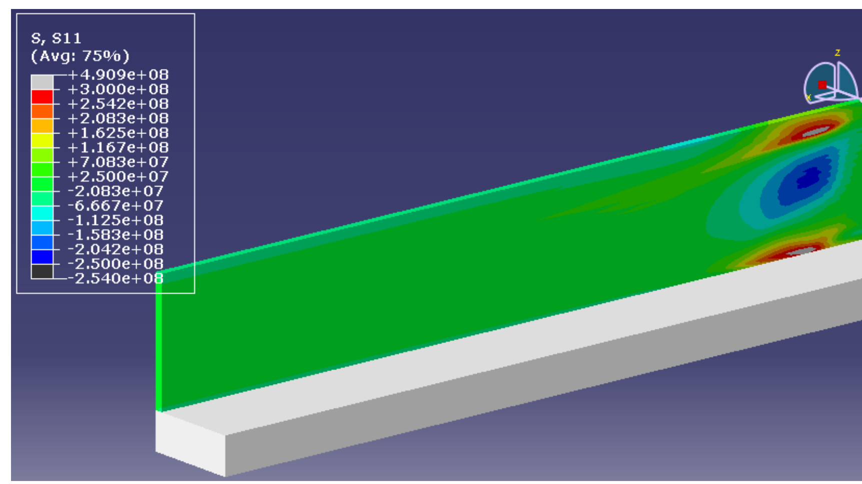


RS - 20 layers wall with base plate



RS - 20 layers wall without base plate



Thermal temperature and stress analysis

More process modelling and residual stress info here

Engineering approach for FE modelling of the WAAM process

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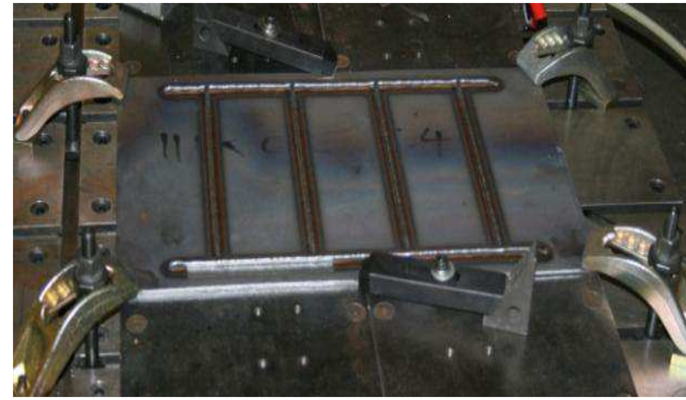
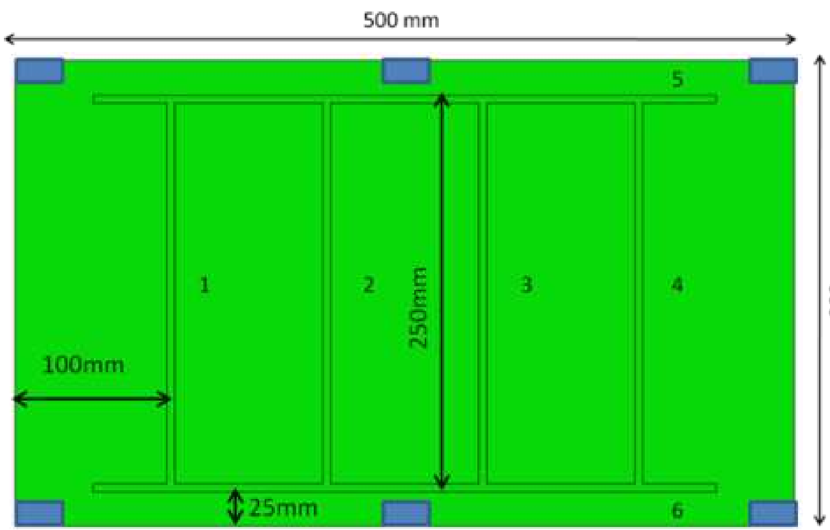
	Thermal analysis	Mech. analysis	Total time
Transient approach	51.5 hours	24 hours	75.5 hours
Engineering approach	10 minutes	32 minutes	42 minutes
Time saving	99.2%	97.8%	99.1%

Time comparison on the transient model and the engineering model. 4 layer 500 mm multi-layer wall structure.

Test case



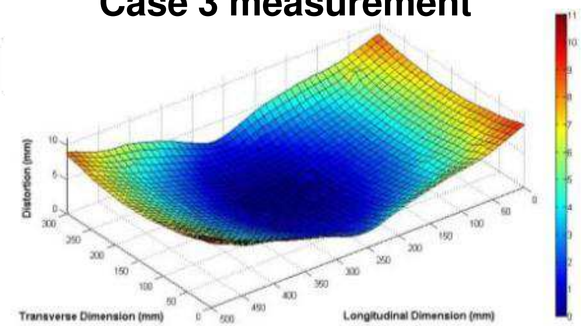


: clamps

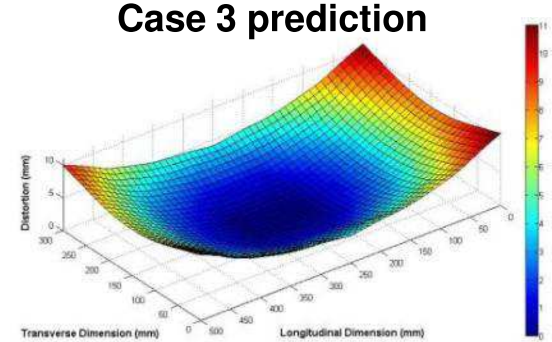
Name	Sequence
Case 1	1-2-3-4-5-6
Case 2	1-4-2-3-5-6
Case 3	2-3-1-4-5-6
Case 4	1-3-2-4-5-6
Case 5	2-3-5-6-1-4
Case 6	1-4-5-6-2-3
Case 7	5-6-1-2-3-4
Case 8	5-6-1-4-2-3
Case 9	5-6-1-3-2-4
Case 10	5-6-2-3-1-4

Distortion – Max case 3, Min case 8
Predicted and verified

Case 3 measurement



Case 3 prediction



Design Case study - generic

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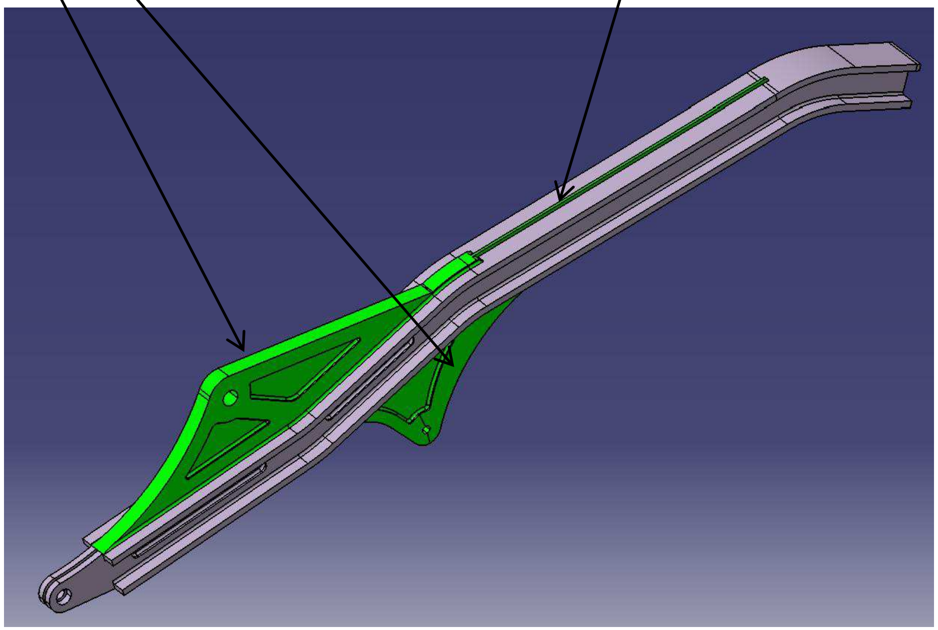
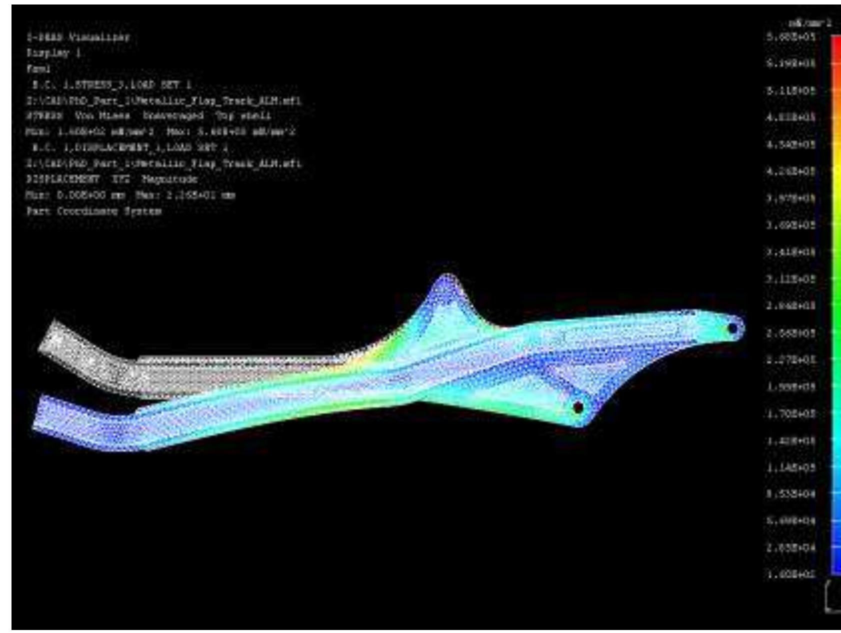
WAAM Features

WAAM Bead Stiffener



Hybrid Extrusion/ WAAM Part
Weight 13.2kg

Buy to fly ratio = 1.2 (from 6.3)
Weight Saving = 16%



Von Mises stresses
Reduced 25%

More design info here

Large scale WAAM – 1st part

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3m long aluminium stiffener, deposited and machined on the HiVE system

Future Developments - scientific and technical

- Guarantee of material properties, process control <u>and/or</u> on-line NDT
- Resolution of microstructural requirements for Ti64
- Production of net shape parts –
  - Integrated deposition and finishing
  - Other novel methods
- Control of residual stresses and distortion
- Production of fully automated large scale components – local shielding and automation solutions

Summary

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- Wire + arc (metal) additive manufacture has the potential to revolutionise fabrication methods for engineering components
- Applications vary from high end aerospace parts to general engineering.
- A wide a variety of system configurations can be implemented
    - Robots
    - Gantries
    - Integration to existing machine tools (e.g. milling machines)
- There is a major commercial opportunity for exploitation of the developments at Cranfield.
- For further information contact me on:

Email: p.colegrove@cranfield.ac.uk

Ph: +44 1234 754694

Improved fatigue performance

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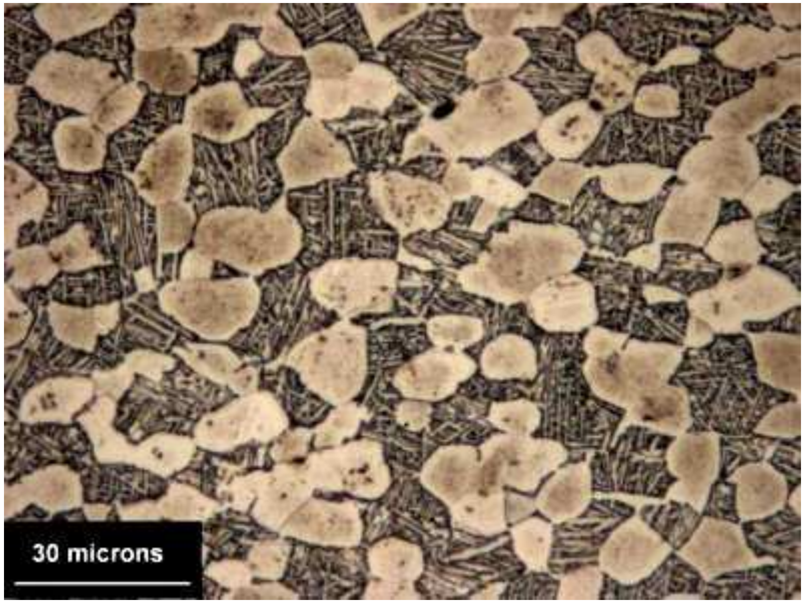
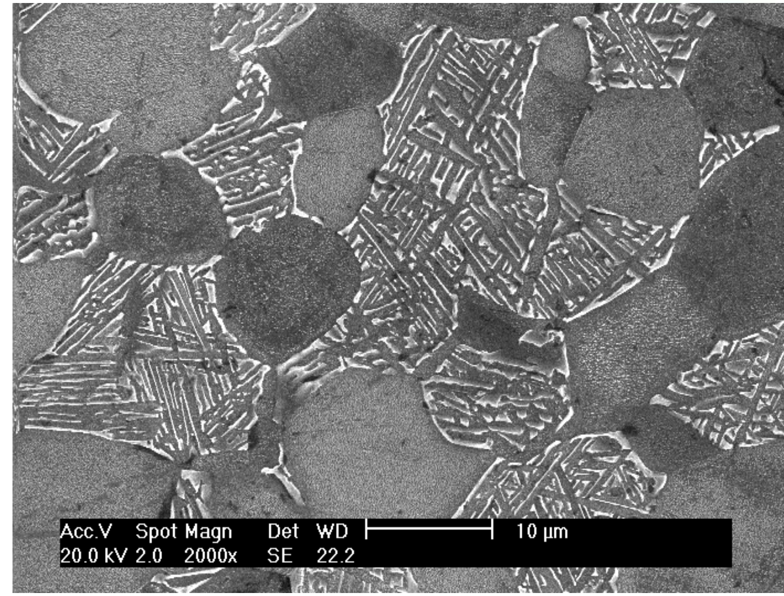
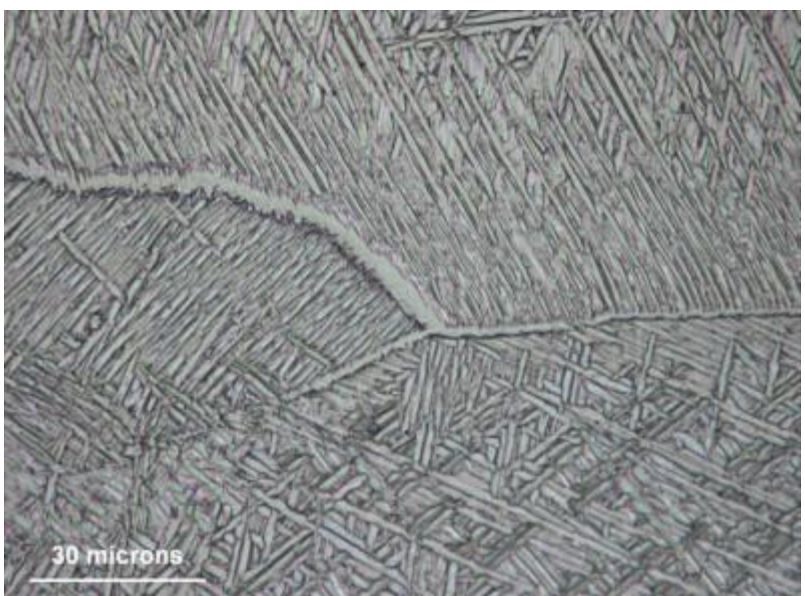
Wrought Ti64





heterogeneous bi-modal (duplex) microstructure

WAAM



- **Wrought material initiates at primary α particle or casting pores**
- **WAAM material does not initiate (in this test) or initiates at very isolated pores due to wire contamination**