Recent developments in fusion processing of aluminium alloys

Professor Stewart Williams

Director Welding Engineering and Laser Processing Centre

Presentation overview

- Weld metal engineering for 2024 alloy
  - Requirement for crack free welding
  - Microstructural modelling of optimal compositions
  - Production of crack free welds in 2024 alloy
- Joining of aluminium to steel – seam welding
- Additive manufacture of aluminium materials
  - What is additive manufacture
  - Additive manufacture of aluminium
  - Latest developments in additive manufacture

Aluminium armour: new materials?

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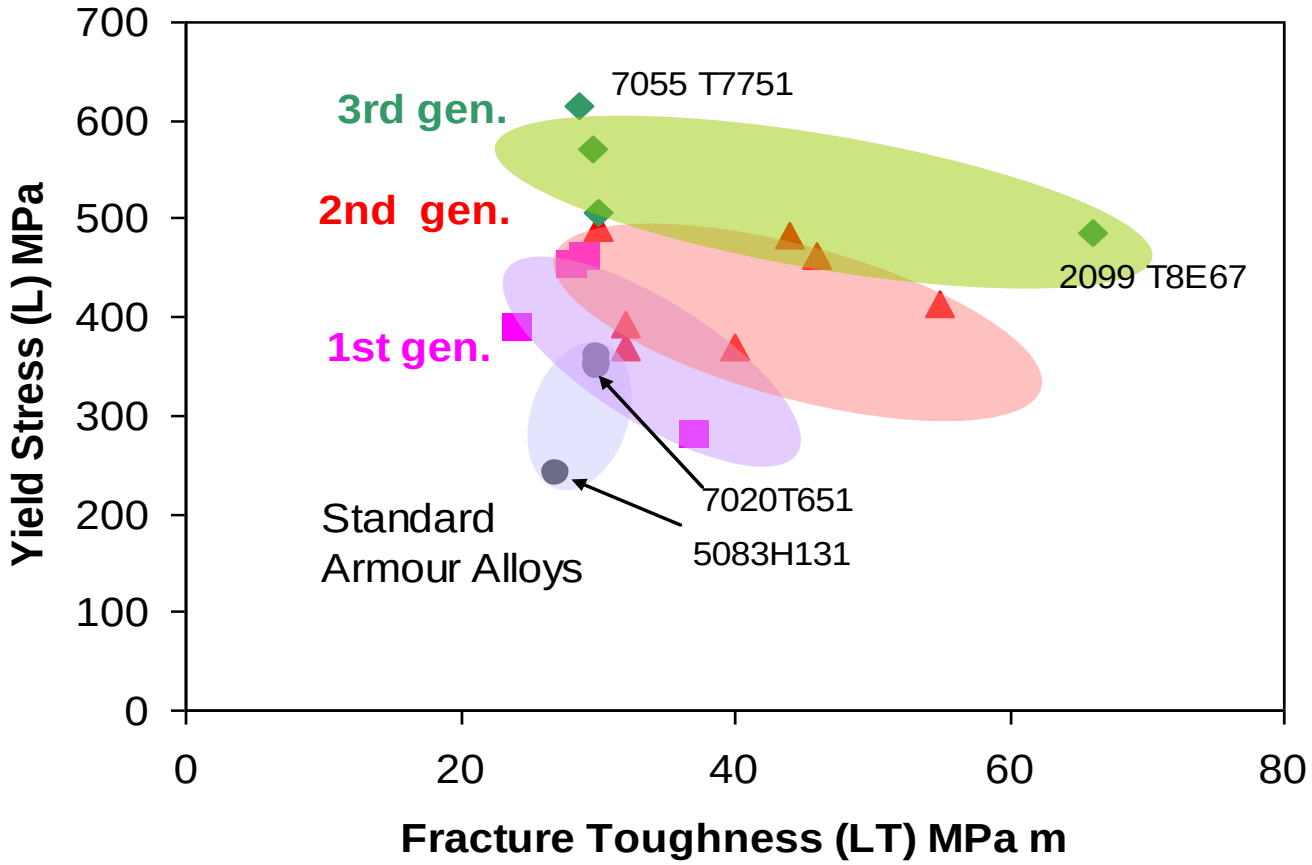
- New state of the art Al- alloys have substantially higher static properties than standard armour alloys (30 - 150% greater)

- Compositions and tempers designed to combat stress corrosion



Ballistic testing – FFV and Frag summary.

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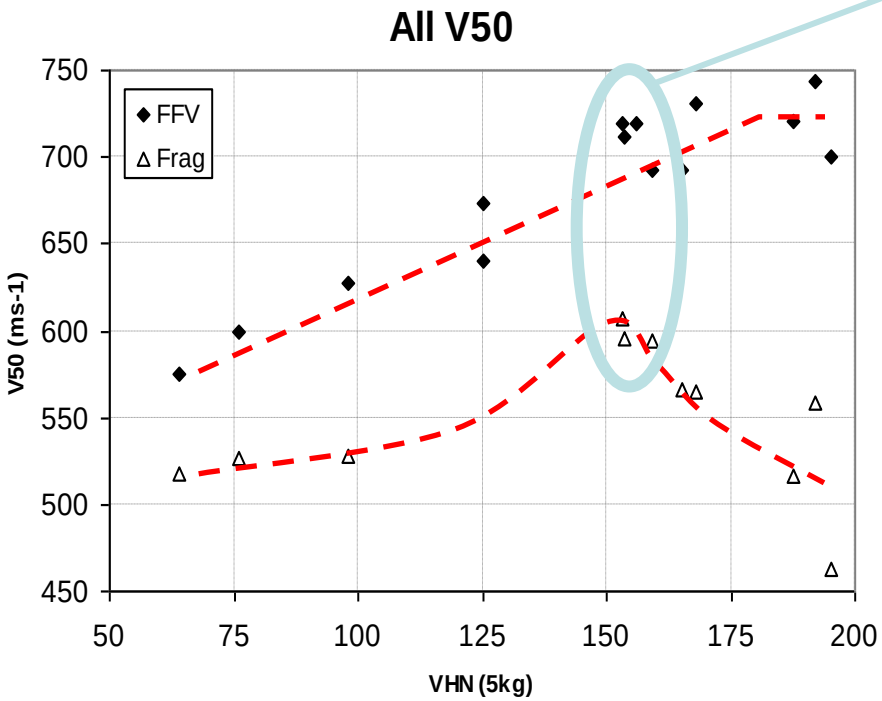

Compromise position for optimum FRAG performance

7010-W51

7010-T7+

7010-HAZ200

7017-T6

2024-T351

2124-T851

2624 –T851

No stress corrosion cracking!

FFV round – Bullet..

Frag. - 20mm diameter steel plug.

But it needs to be fusion weldable

Problems in fusion welding 2024

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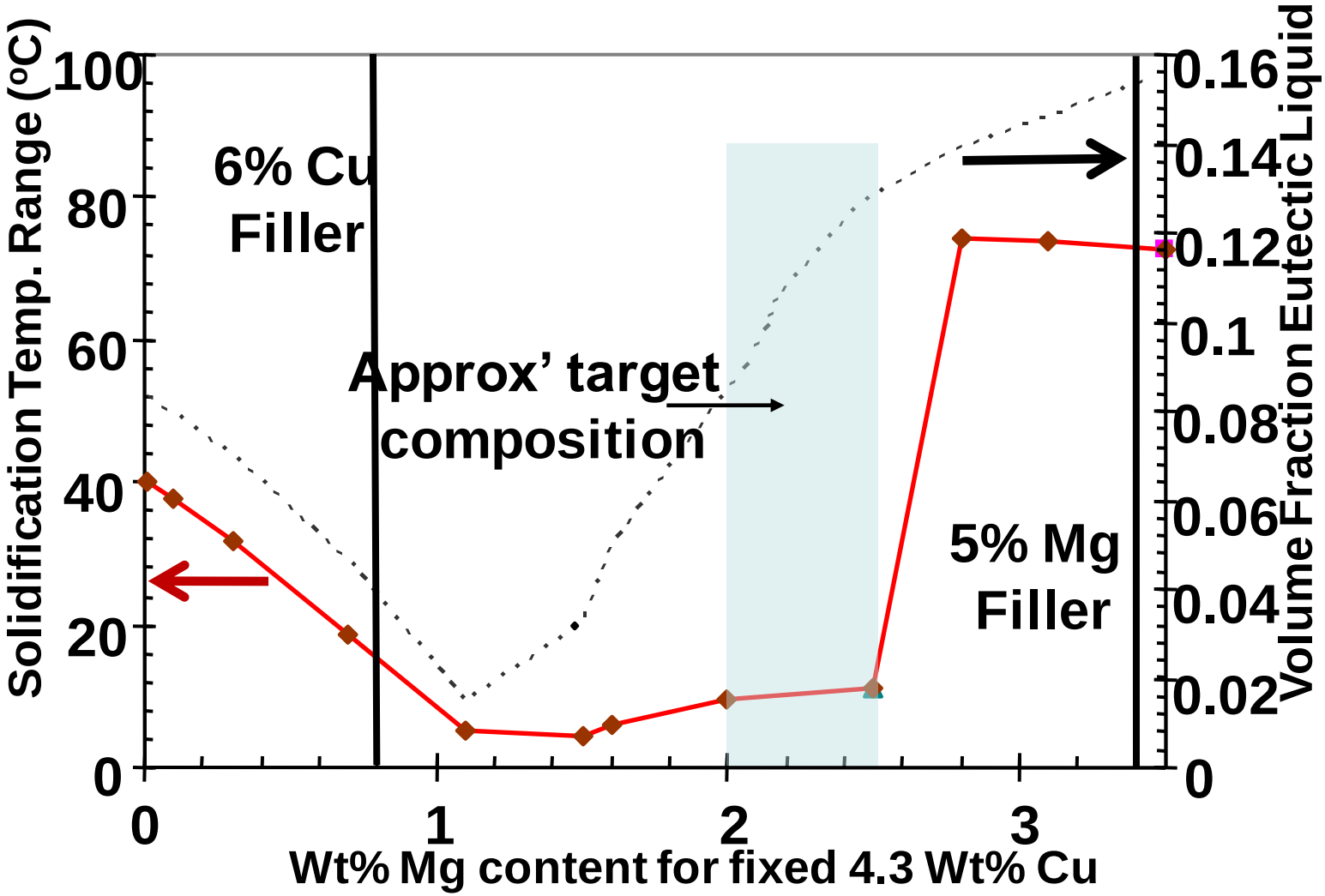
- **2024 is highly crack sensitive and is considered unweldable**
- **Filler wire issues**
  - **Available filler wires typically binary – base materials are ternary**
  - **No commercial aluminium filler wires have been developed and marketed since 1960's**
  - **Only filler for 2XXX series is binary 2319 (6%Cu) originally developed for binary 2219 (6%Cu) base material.**
  - **Cost of development is prohibitive and one off prototype filler wires have variable quality**
  - **Elemental recipe is highly subjective**
  - **A large range of fillers must be developed for the range of alloys**

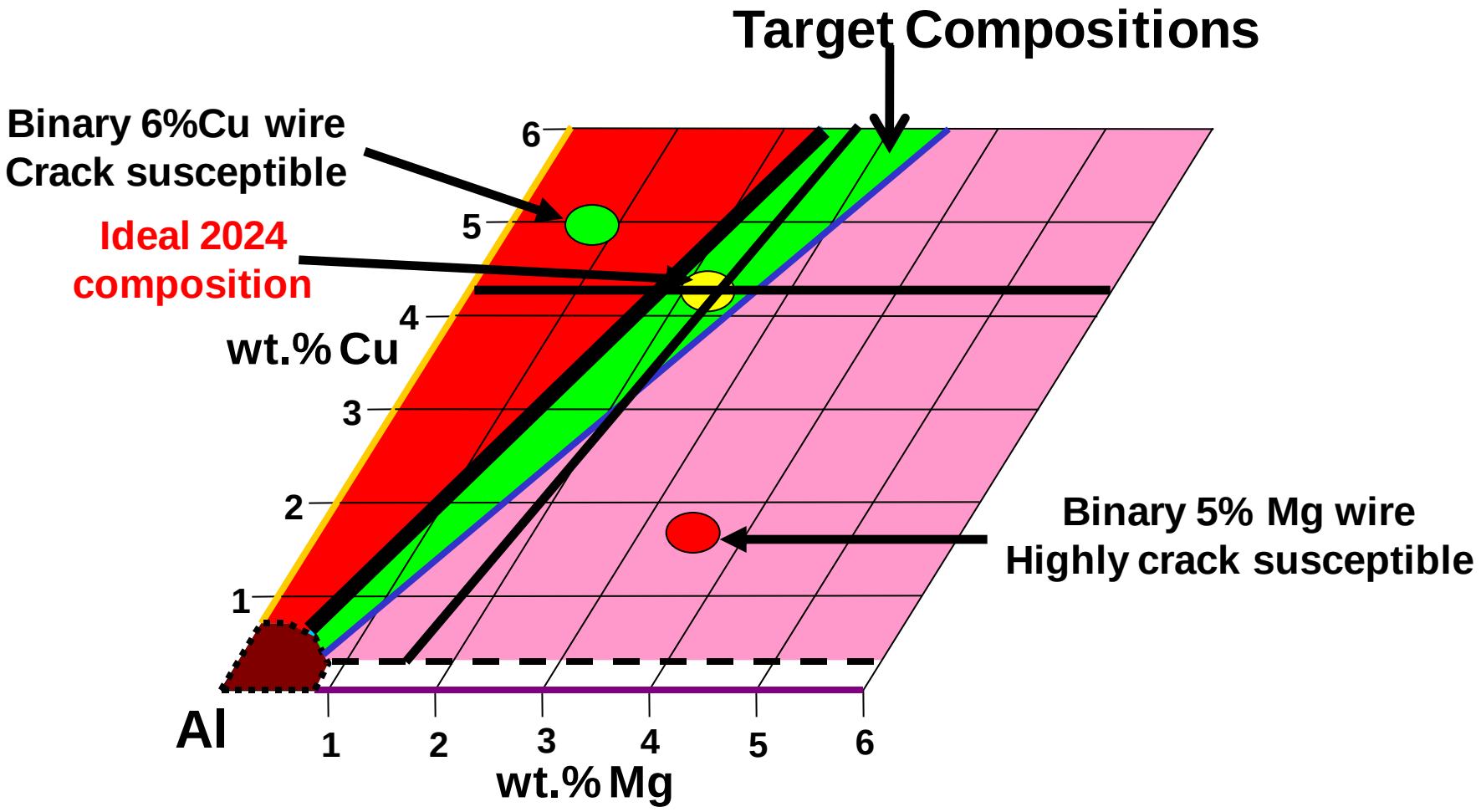
Solution – Combine modern developments in materials modelling with technological welding advances to provide a quick and cost effective method of defining near optimum weld compositions

Avoidance of Cracking - Microstructural Modelling



Large freezing range or small fraction of Eutectic liquid leads to the likelihood of cracking

Summary compositions of Al/Cu/Mg alloy System (2xxx series)



2024 mid range composition - 4.3% Cu, 1.5% MG

Weld metal engineering using a tandem torch with different wire compositions, sizes and feed rates

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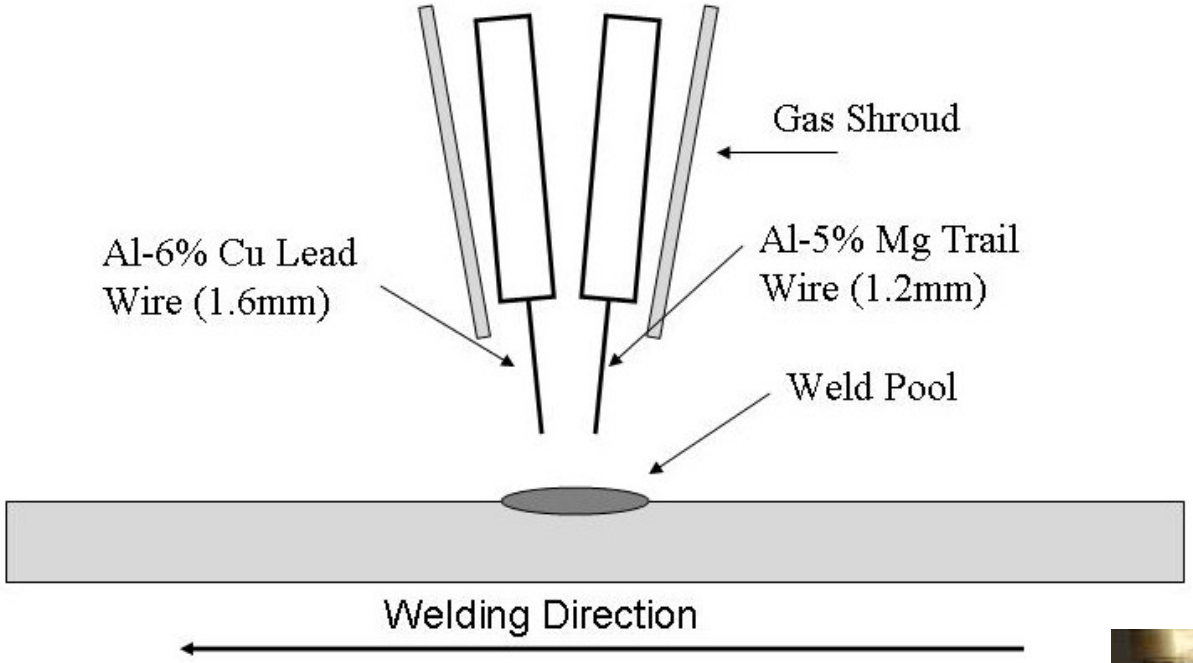

Fusion Welding – Avoidance of Cracking – Multiple Wires

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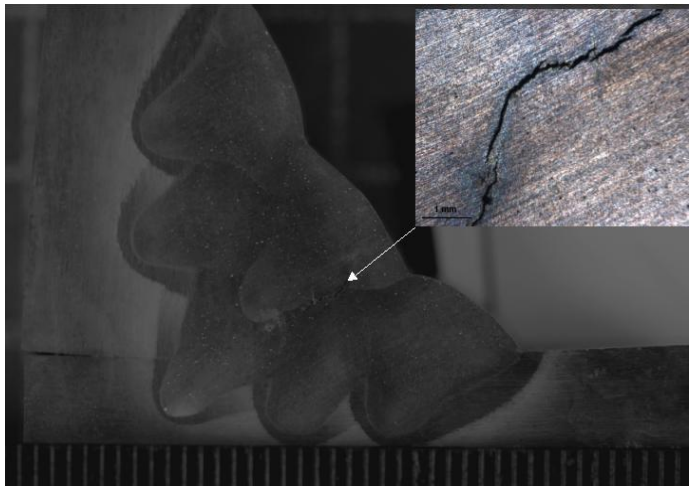
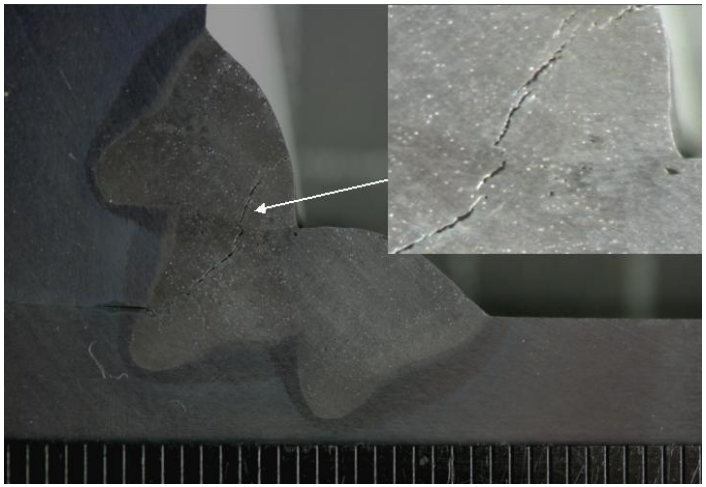
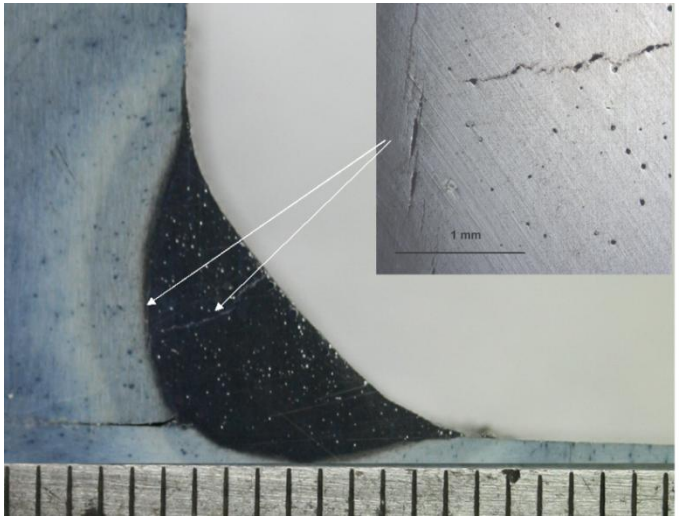


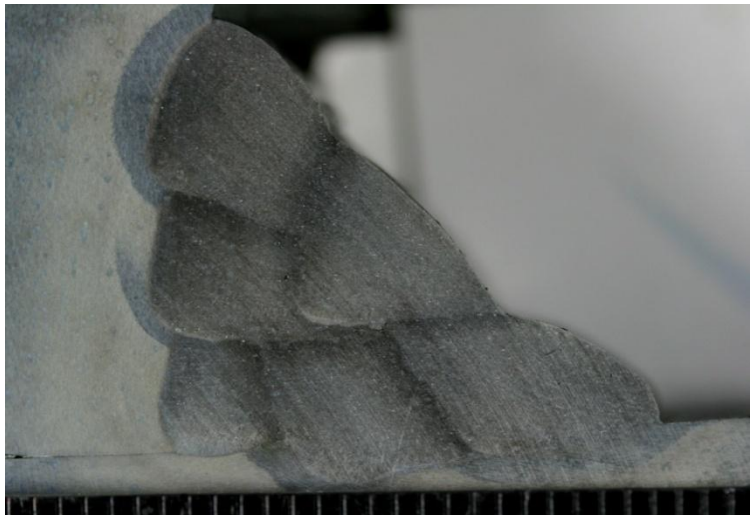
Binary 6% Cu wire – cracks in sequence



Binary 6% Cu wire – cracks in weld 2 & 3

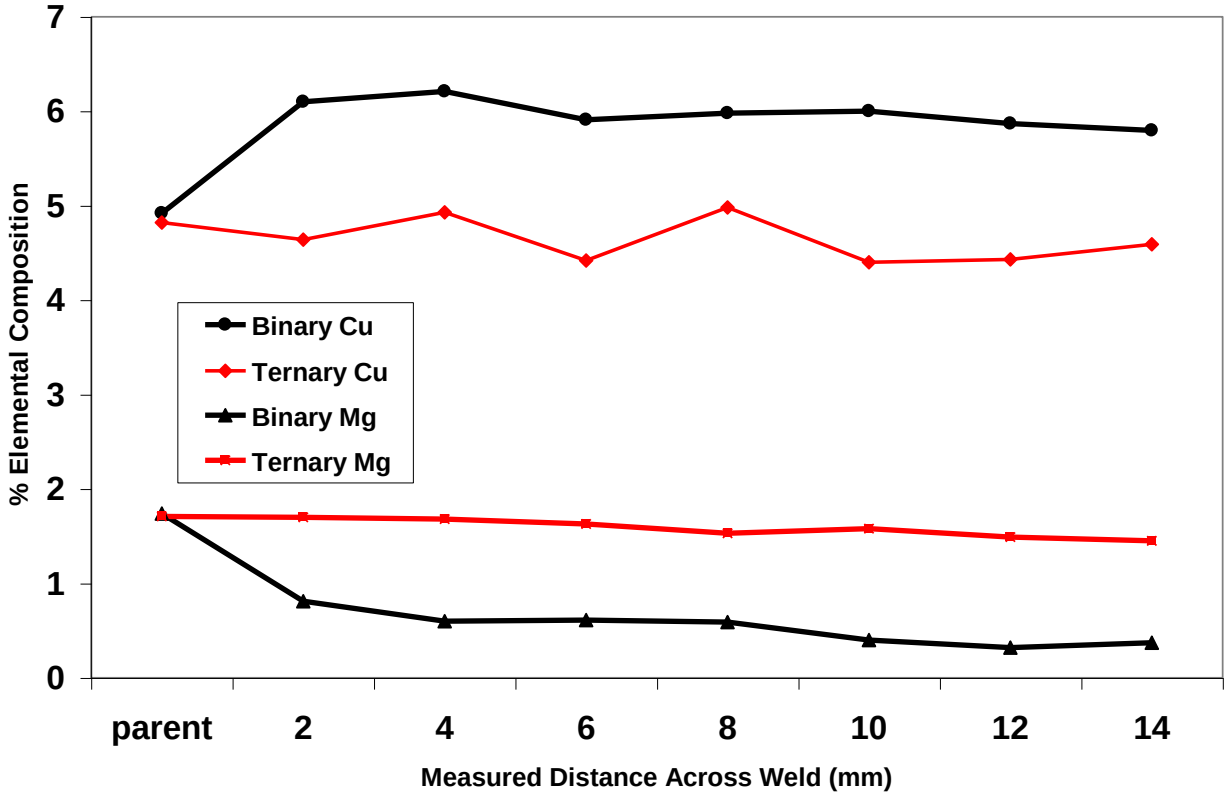


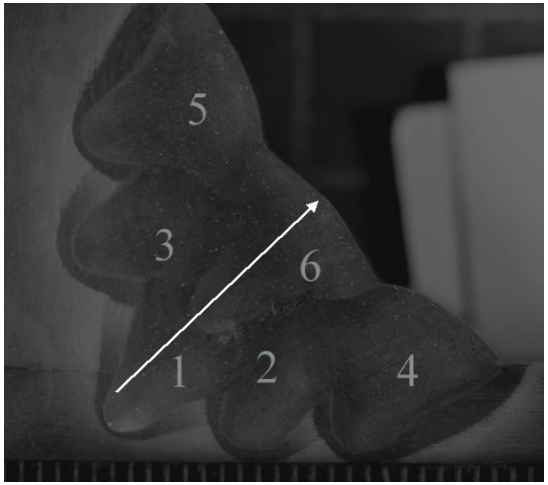
Binary 5% Mg wire – severe cracking



Mixed wire – no cracking in sequence

Maintenance of weld metal composition throughout a multipass weld

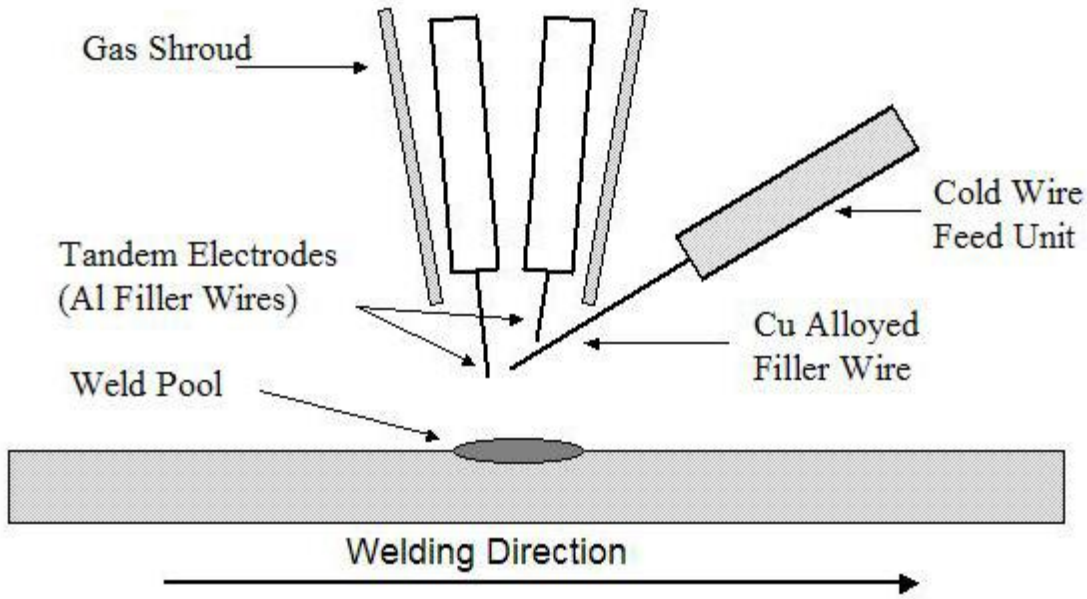




Black – Binary wire – rapidly becomes Cu rich and Mg depleted – result is cracking

Red – Ternary mix – stable composition throughout weld – result is no cracking

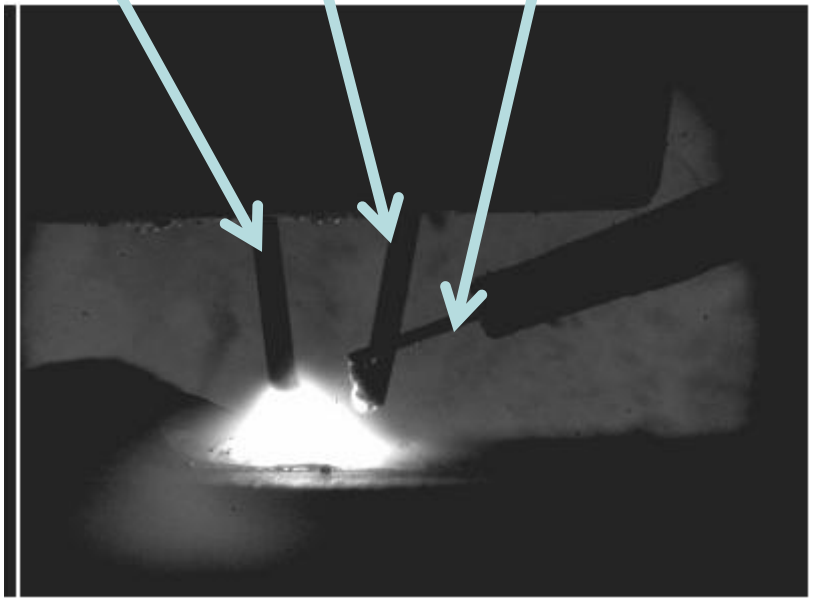
Three wire configuration



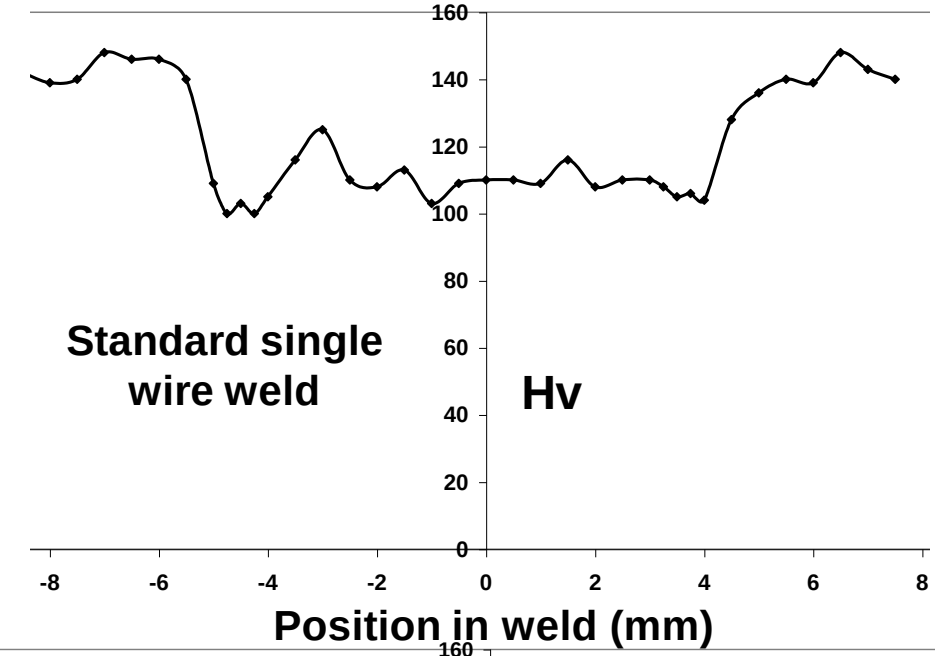
6% Cu Wire

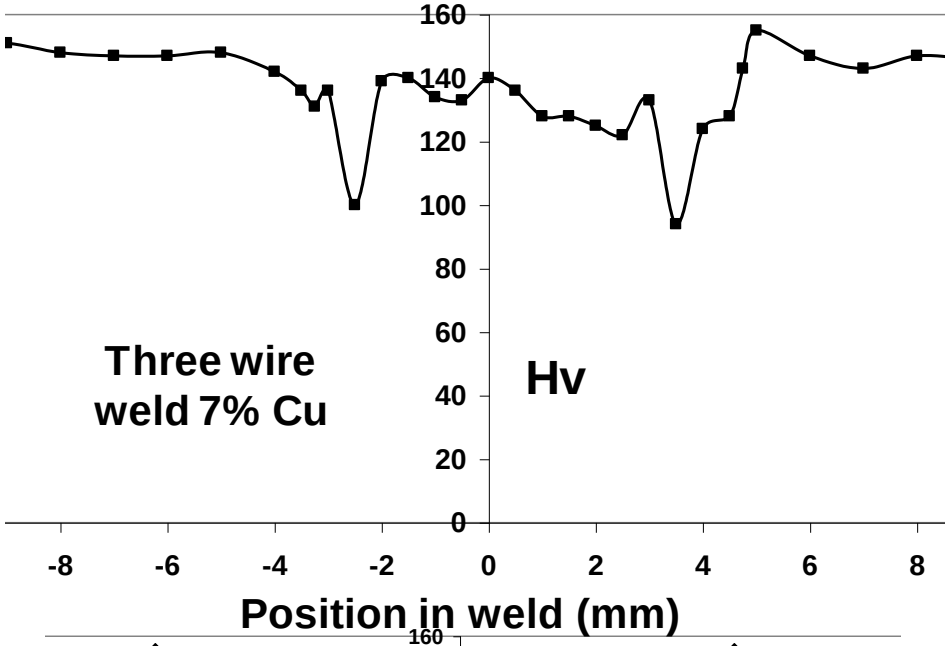
5% Mg Wire

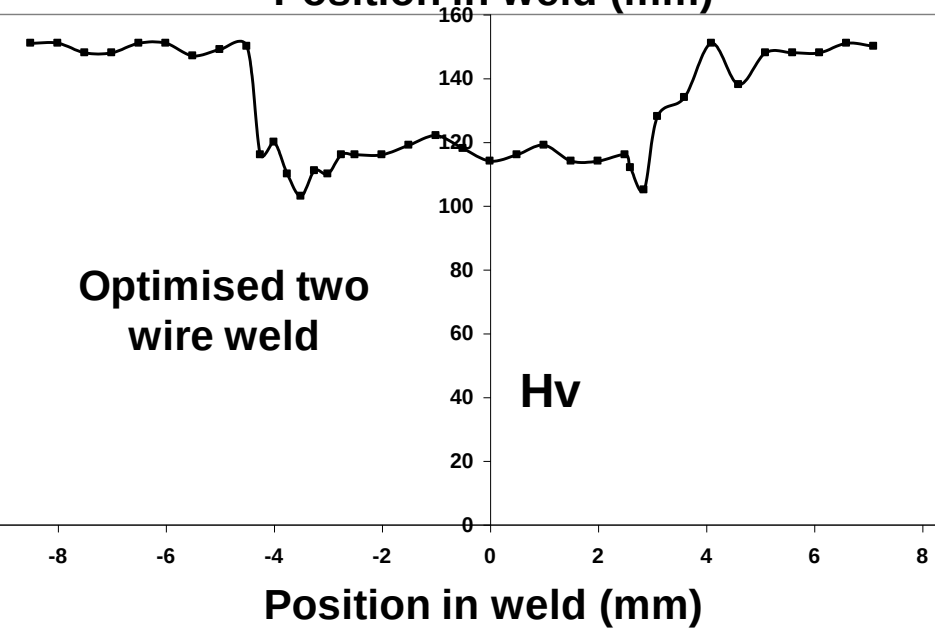
$CuSi_3$ Wire

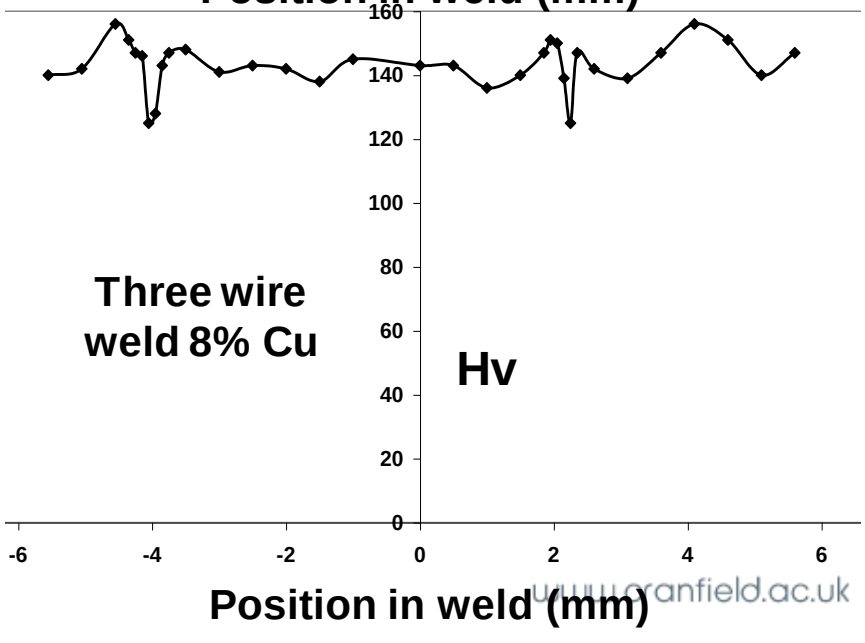


Fusion Welding – Improving Weld Metal Properties – Three Wires







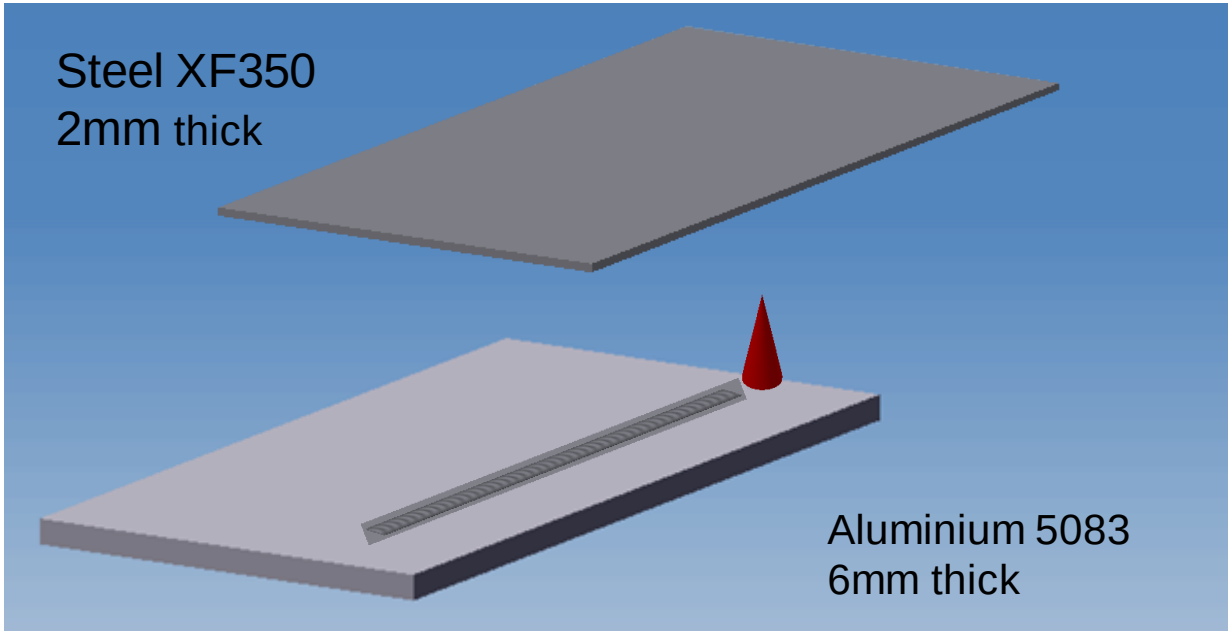


Summary of fusion welding of high strength aluminium

- Microstructural modelling can be used to determine optimum weld metal compositions – in this case to avoid cracking
- Tandem welding methods can be used to explore different weld metal chemistries
- By using an optimum composition with 2024 alloy crack free welds are obtained
- By adding a 3rd wire an even wider range of compositions is possible
- From this welding wire compositions can be specified for either welding or additive manufacture applications

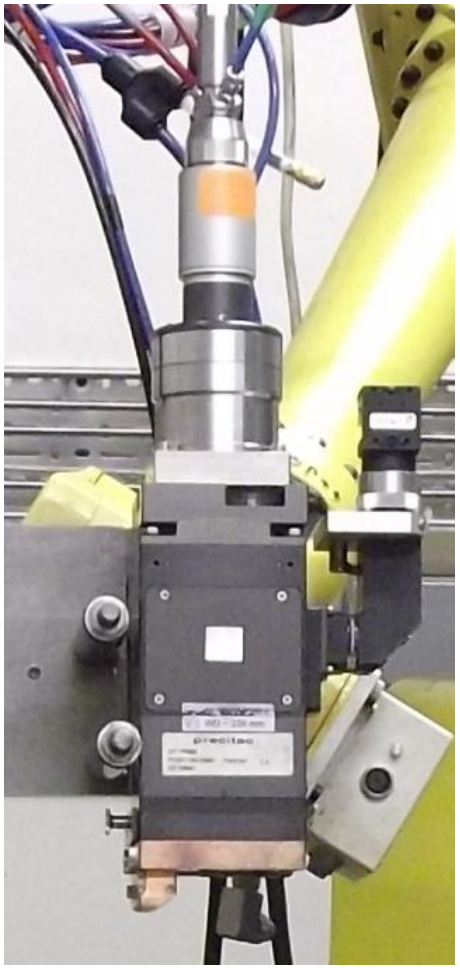
Joining of aluminium to steel – seam welding

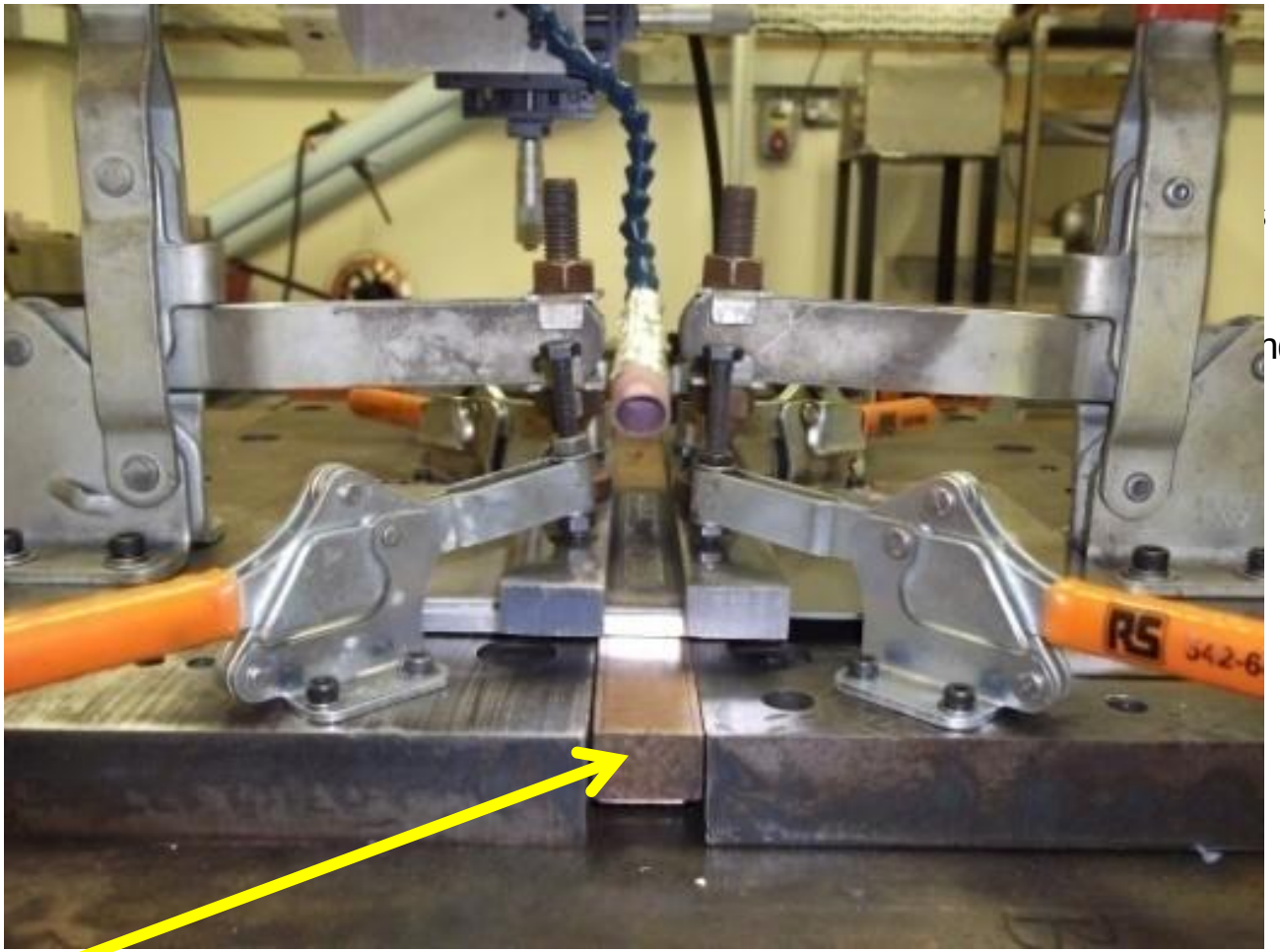
- Objective is to use the laser in conduction mode
- A correlation is sought between the intermetallic layer thickness and the fundamental laser interaction parameters
  - Power density - power/area
  - Interaction time – beam diameter/travel speed
  - Specific process energy – Power Density X interaction time X area
- Correlate the intermetallic layer thickness with joint strength



•Plate dimensions
138 x 150 mm

Experimental setup





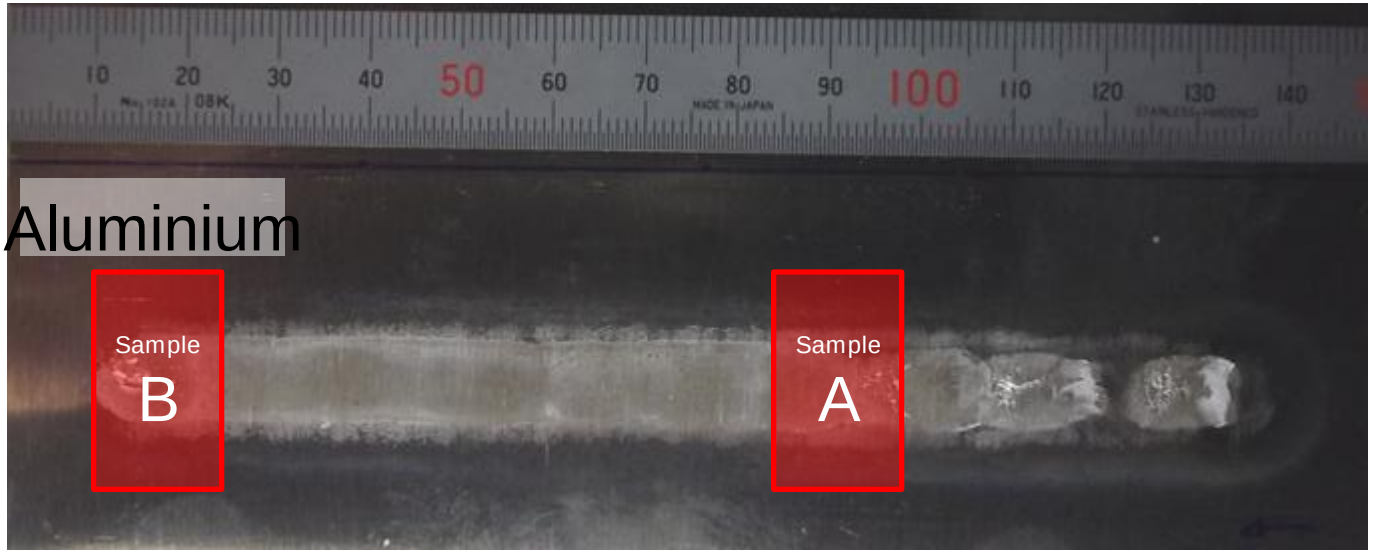
8kW Fibre Laser

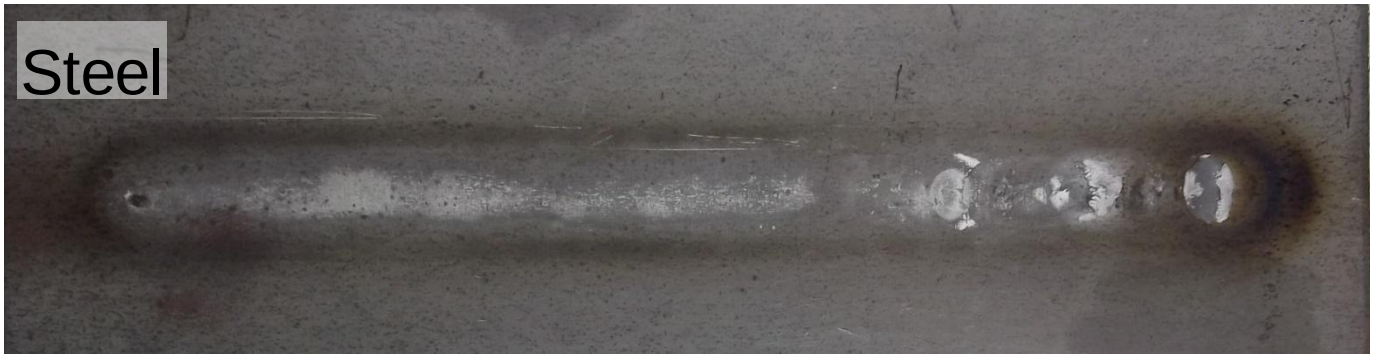
Cu bar

Samples clamped always with the same load

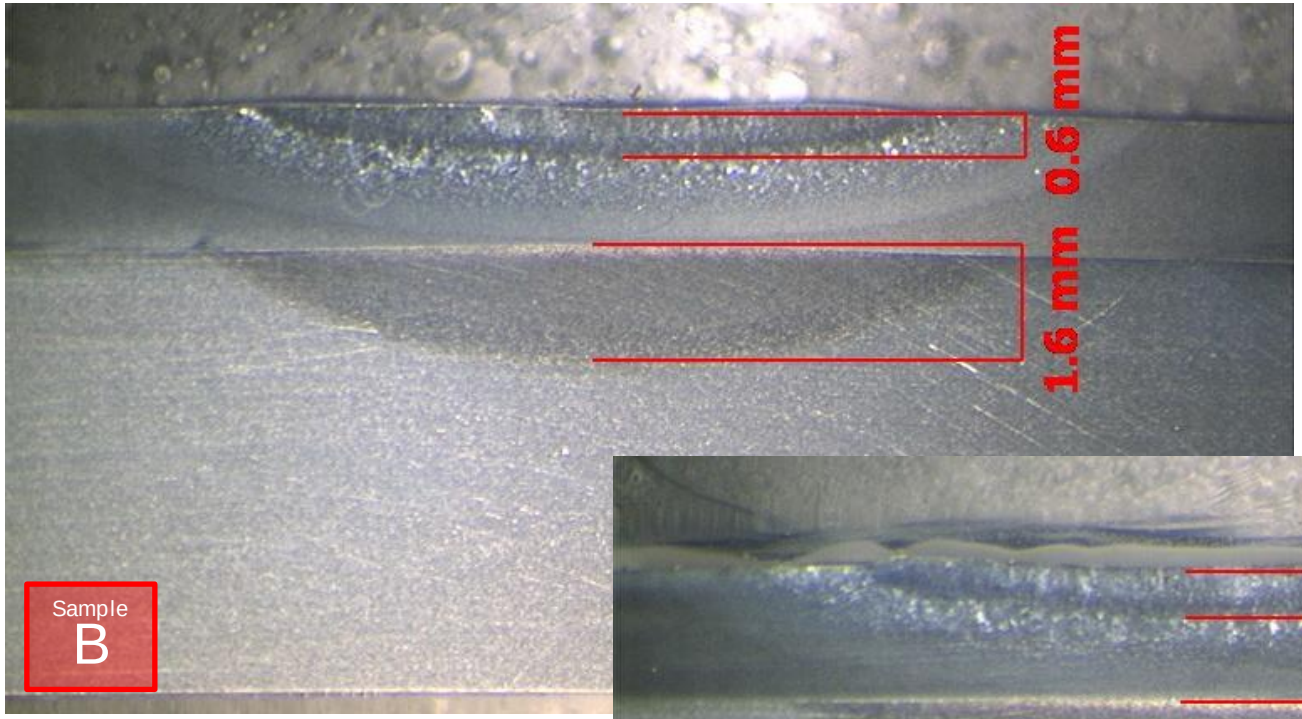
Results

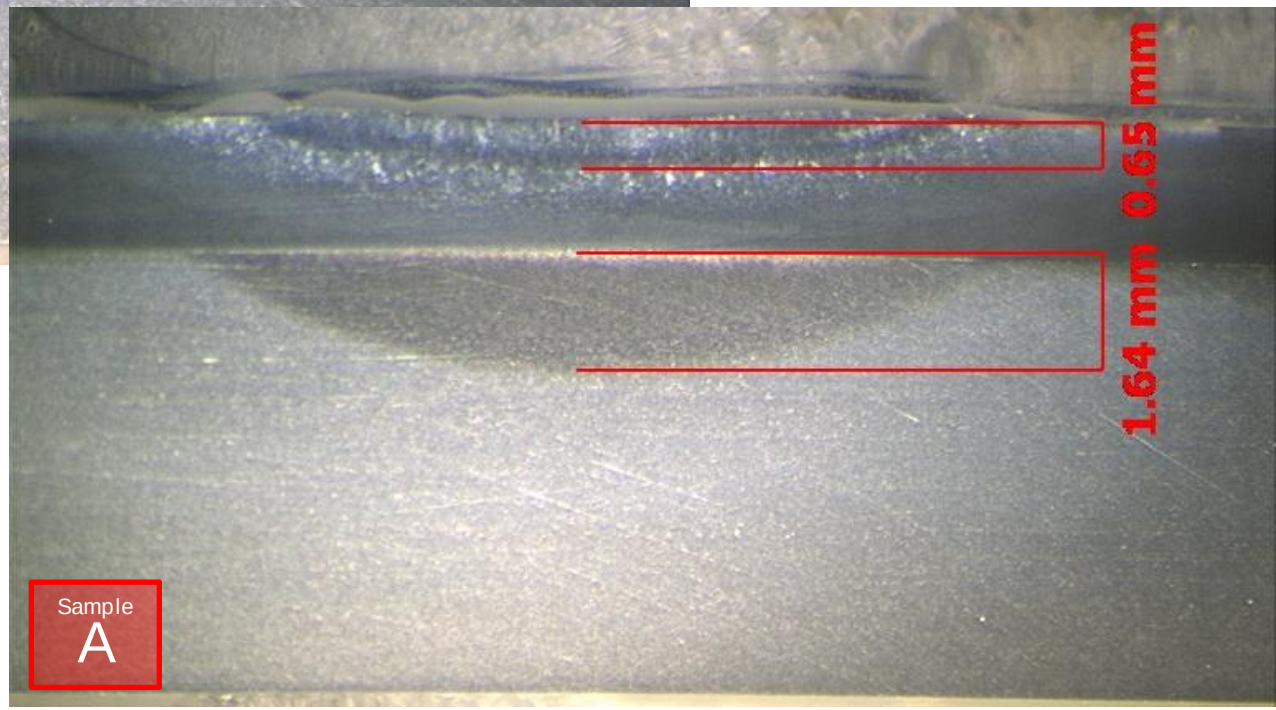
• Samples were cut in two different positions to check if penetration and IML thickness were constant along the





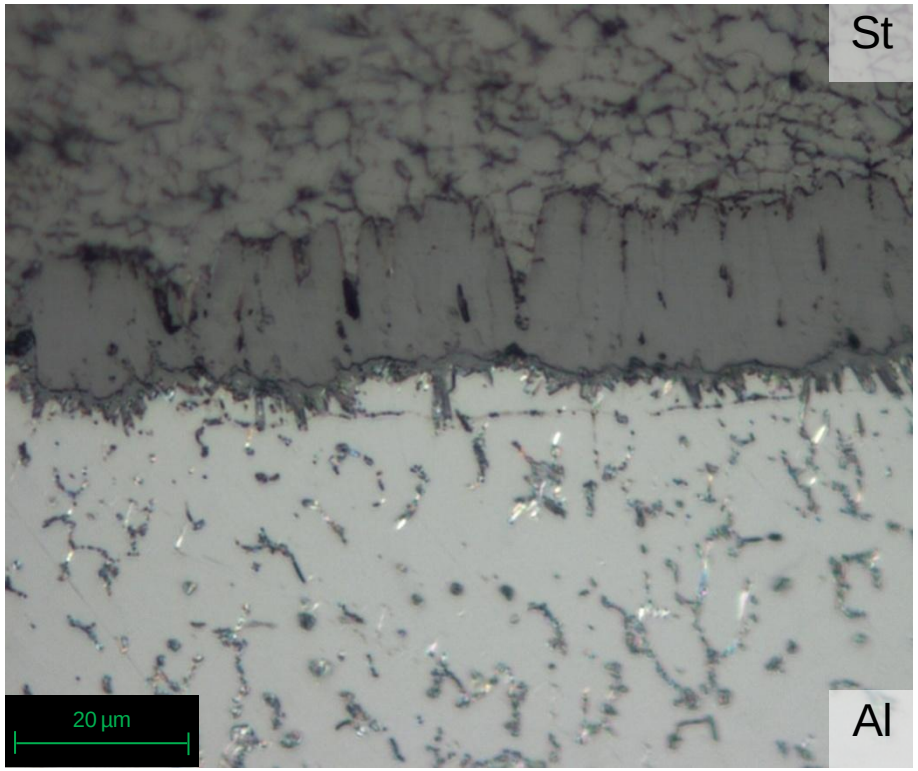
Results





No difference observed between the ends

Results – Intermetallic compounds



Intermetallic layer

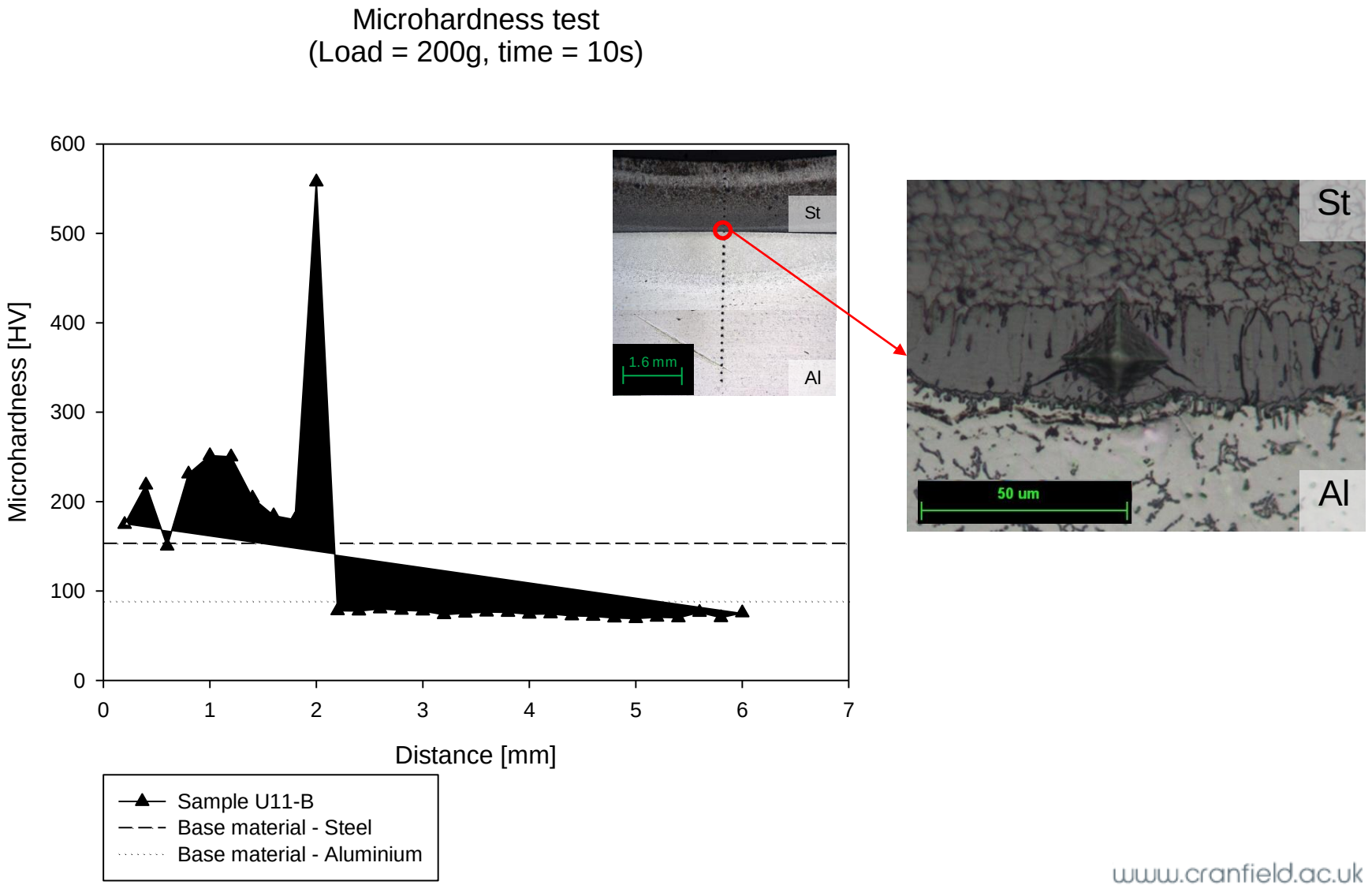
Fe_2Al_5

$FeAl_3$

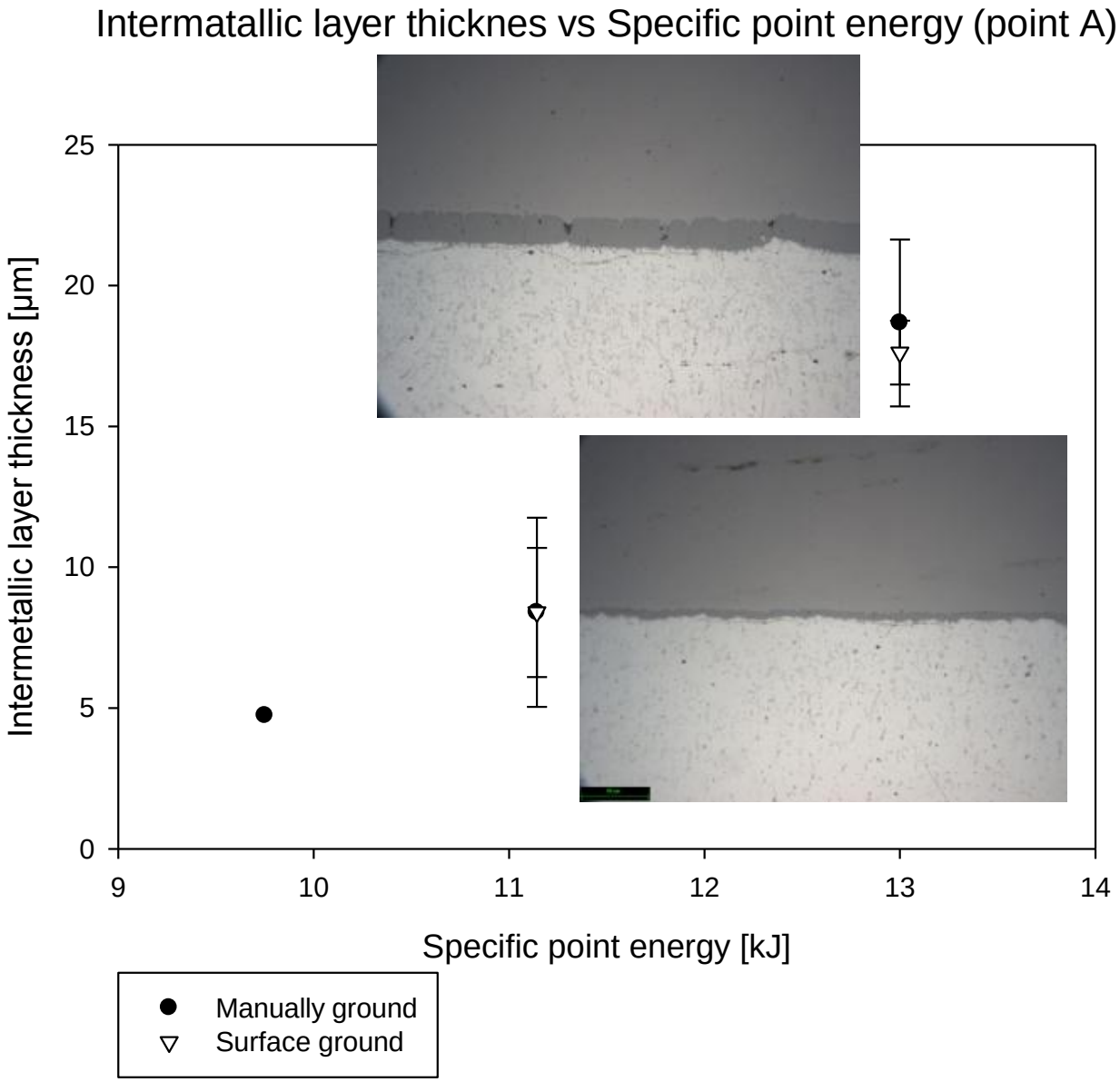
Sample U11 B

Welding parameters:
Power = 4.0 kW; Interaction time = 3.9 s; Travel speed = 20 cm/min;
Spot size = 13 mm

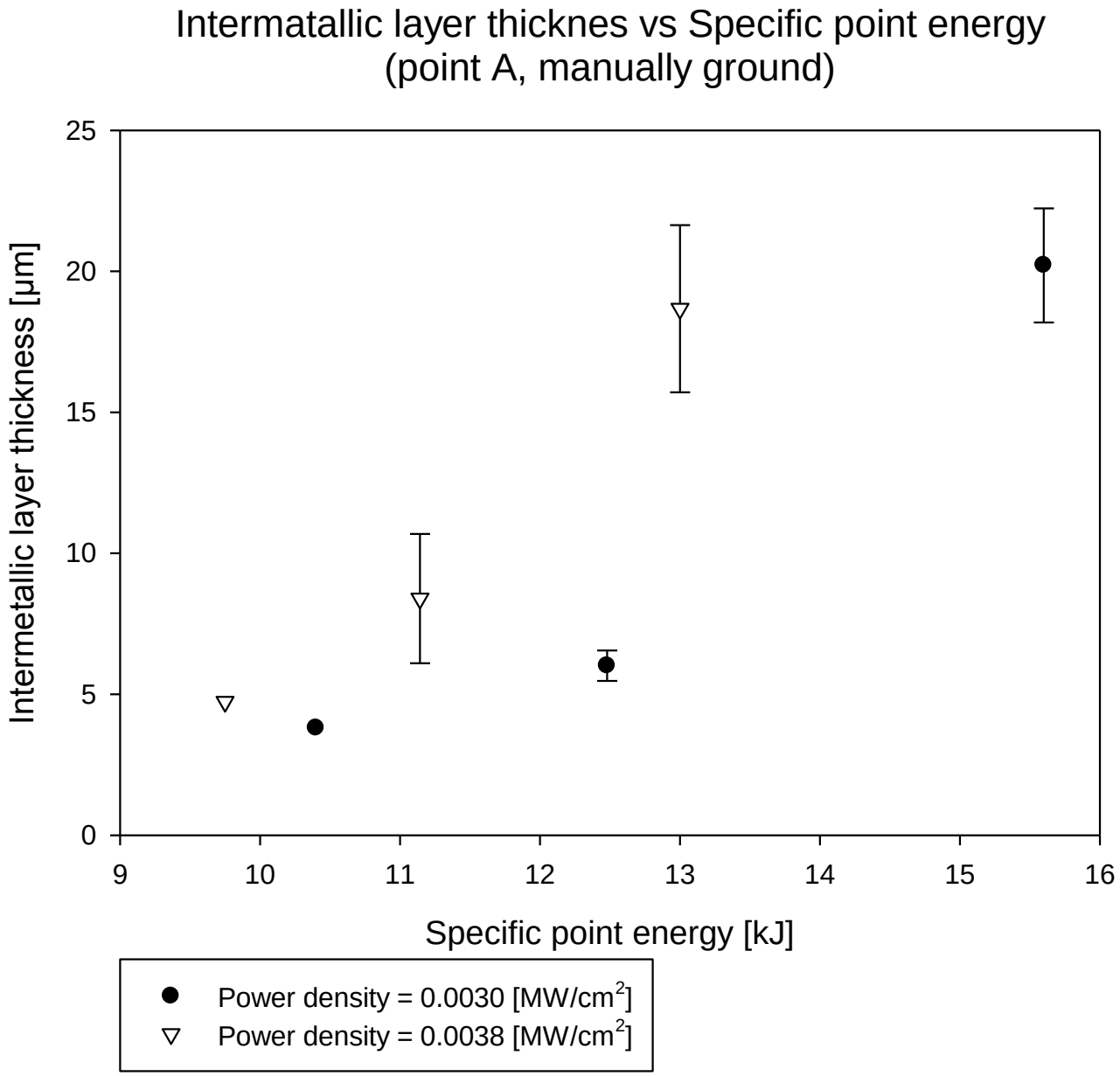
Results – Vickers microhardness test



Results: Intermetallic layer thickness evolution



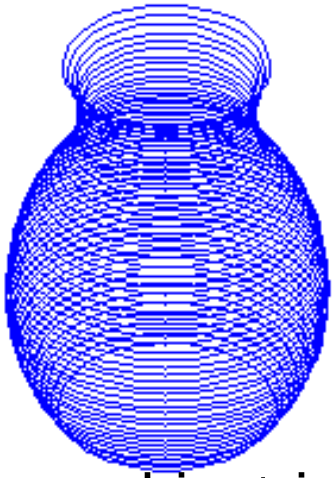
Results: Intermetallic layer thickness evolution



Summary aluminium to steel joining

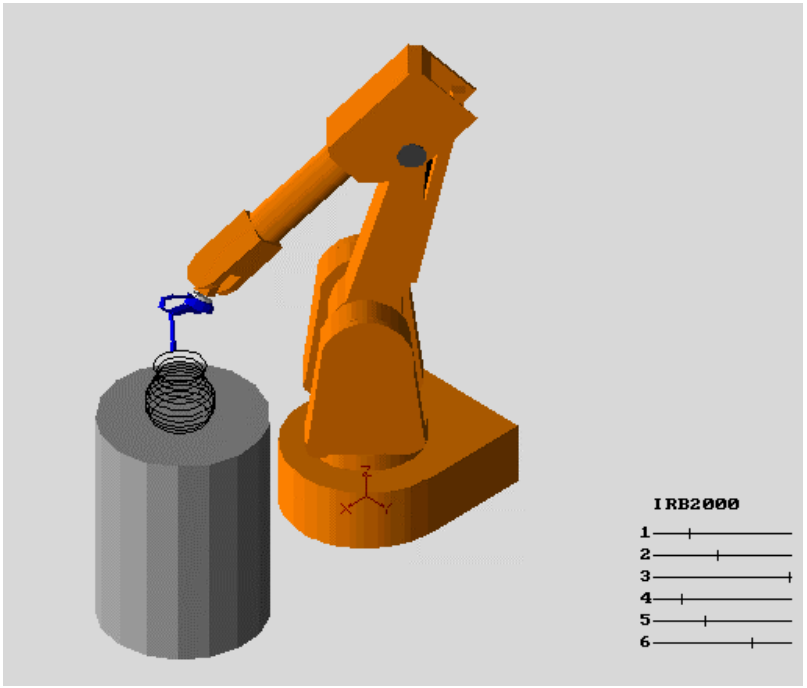
- By using the laser fundamental interaction parameters a good understanding and control of the intermetallic layer can be obtained
- Continuous seam welds can be produce without porosity or defects
- Properties are yet to be determined

What is Metal Additive Manufacture - Basic Process



Slice an object into layers

Programme a robot or machine tool to trace out the layers



Using a deposition tool to build up your part

What is a (metal) deposition tool

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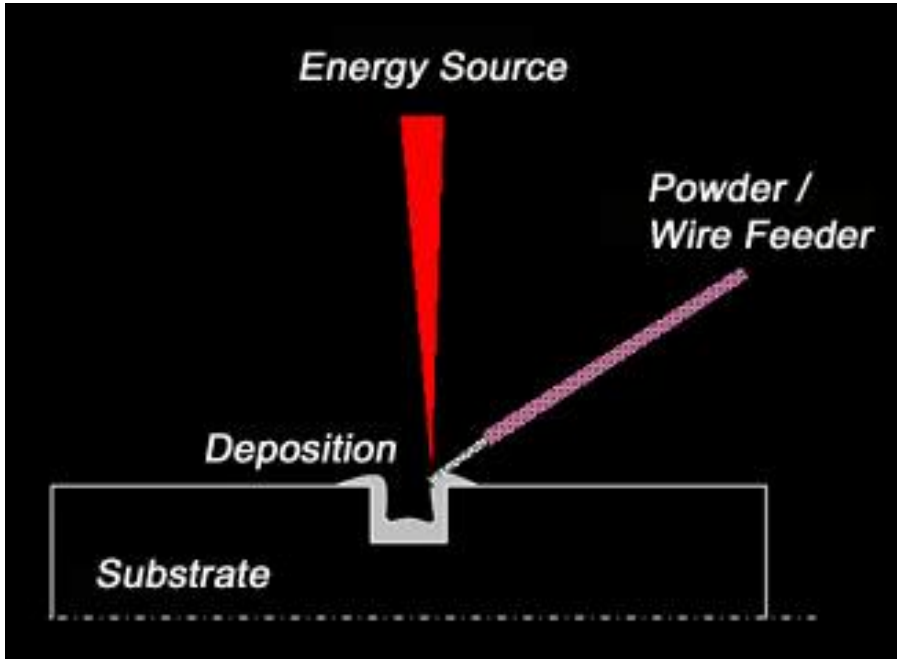
Very Simply



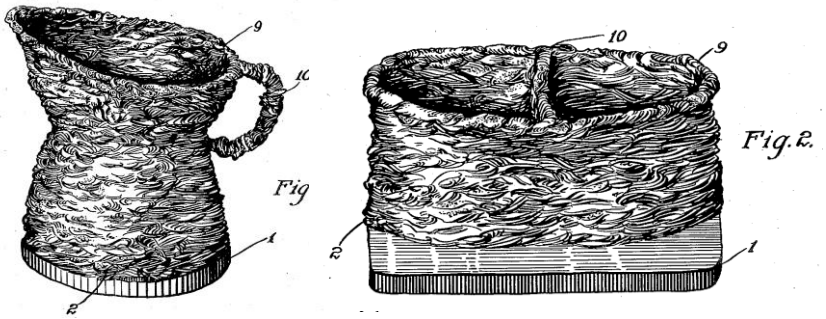
And we have ours
Wire + Arc Additive Manufacture
WAAM

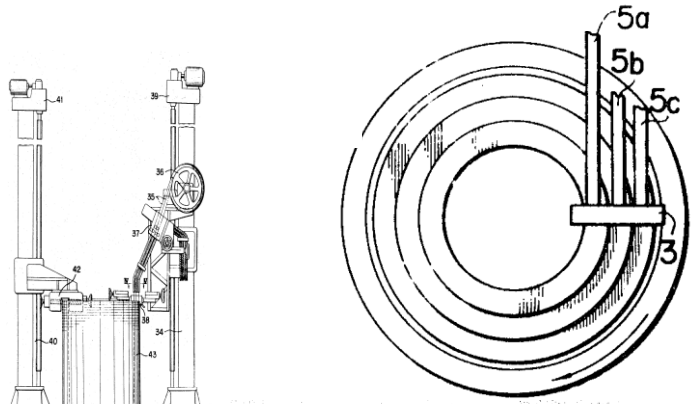
- **Also known as**
  - **Additive (Layer) Manufacture (A(L)M)**
  - **(Laser) Cladding**
  - **Buttering**
  - **Digital manufacture**
  - **Direct Light Fabrication**
  - **Direct Metal Casting (DMC)**
  - **Direct Metal (Laser) Deposition (DM(L)D)**
  - **Laser Direct Casting or Deposition**
  - **Laser casting**
  - **Laser clad casting**
  - **Laser consolidation**
  - **Laser cusing**
  - **Laser Engineered Net Shaping (LENS)**
  - **Lasform**
  - **(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**

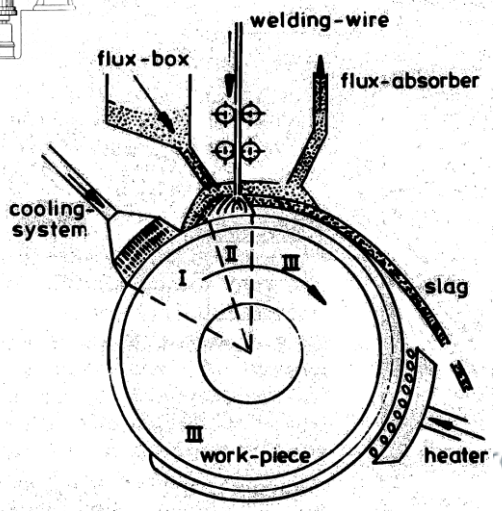
Metal Additive Layer Manufacture - History

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

- 1994-99 Cranfield University develop Shaped Metal Deposition (SMD) for Rolls Royce for engine casings, various processes and materials were assessed

MALM – Process Options

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Weld based Additive Layer Manufacturing - METALS

Powder based

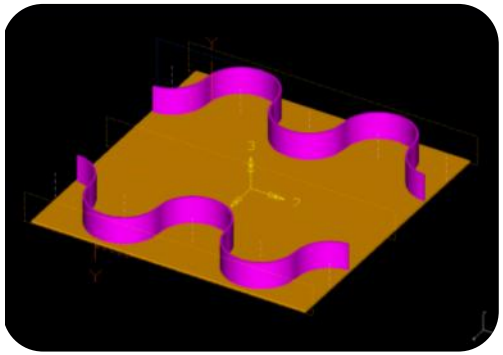
X Low deposition rates (0.1-0.2 kg/h)
X Low material efficiency (10-60%)
X Quality and flaw issues
X Very high part cost
✓High level of complexity

Wire based

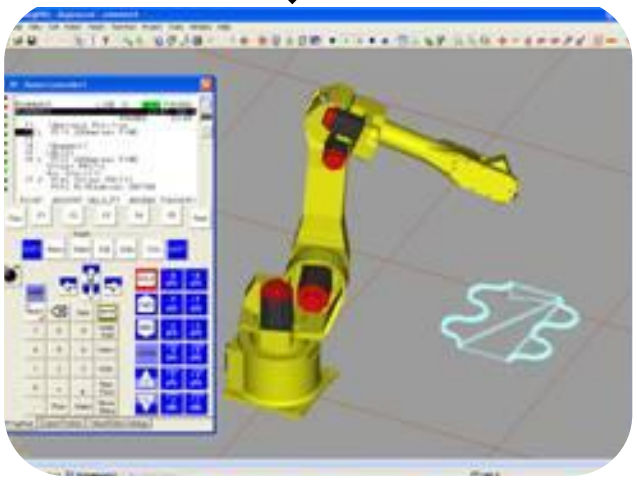
✓High deposition rates (several kg/h)
✓High material efficiency (90%)
✓No defects
✓Low part cost
x Medium to low level of complexity

Primary Objective:
large scale structural components

WAAM Process



CAD STL

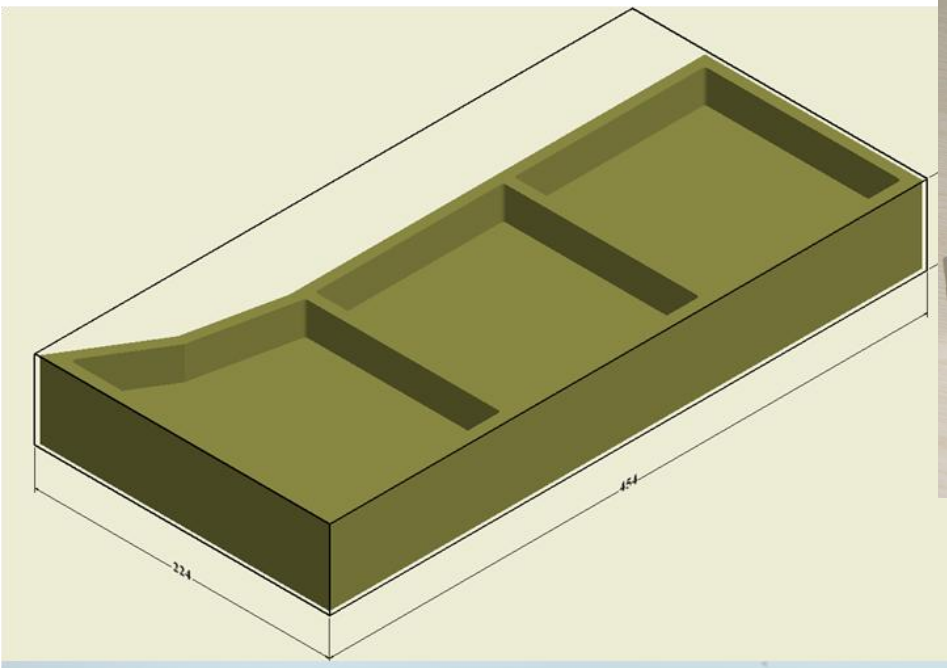


RUAMRob 2.0
Slicing and path generation
(within a couple of minutes)

WAAM
machine

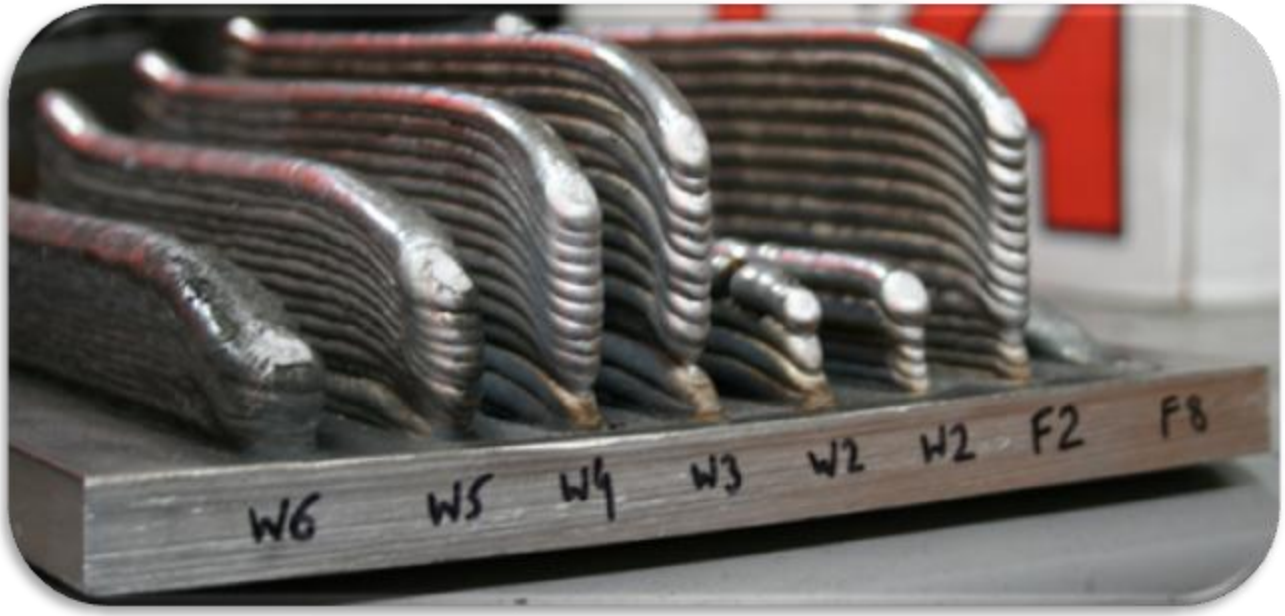
WAAM
workpiece

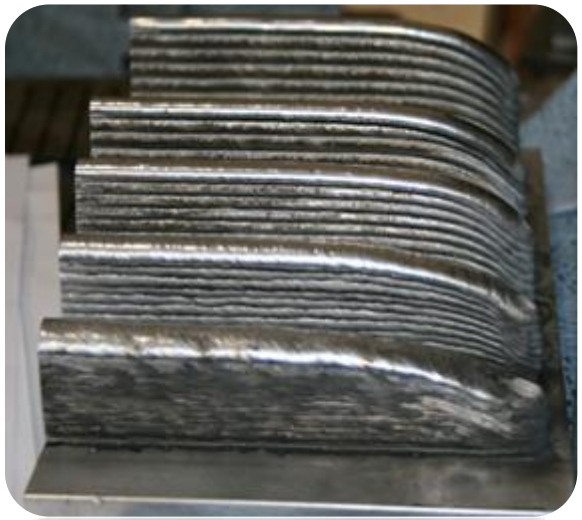
Example application - Ti Stiffened panel



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

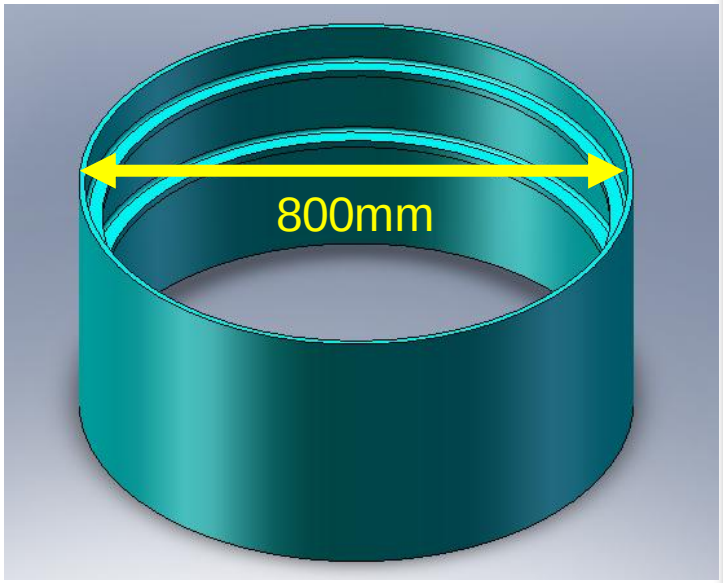
Development of aluminum CMT process algorithms

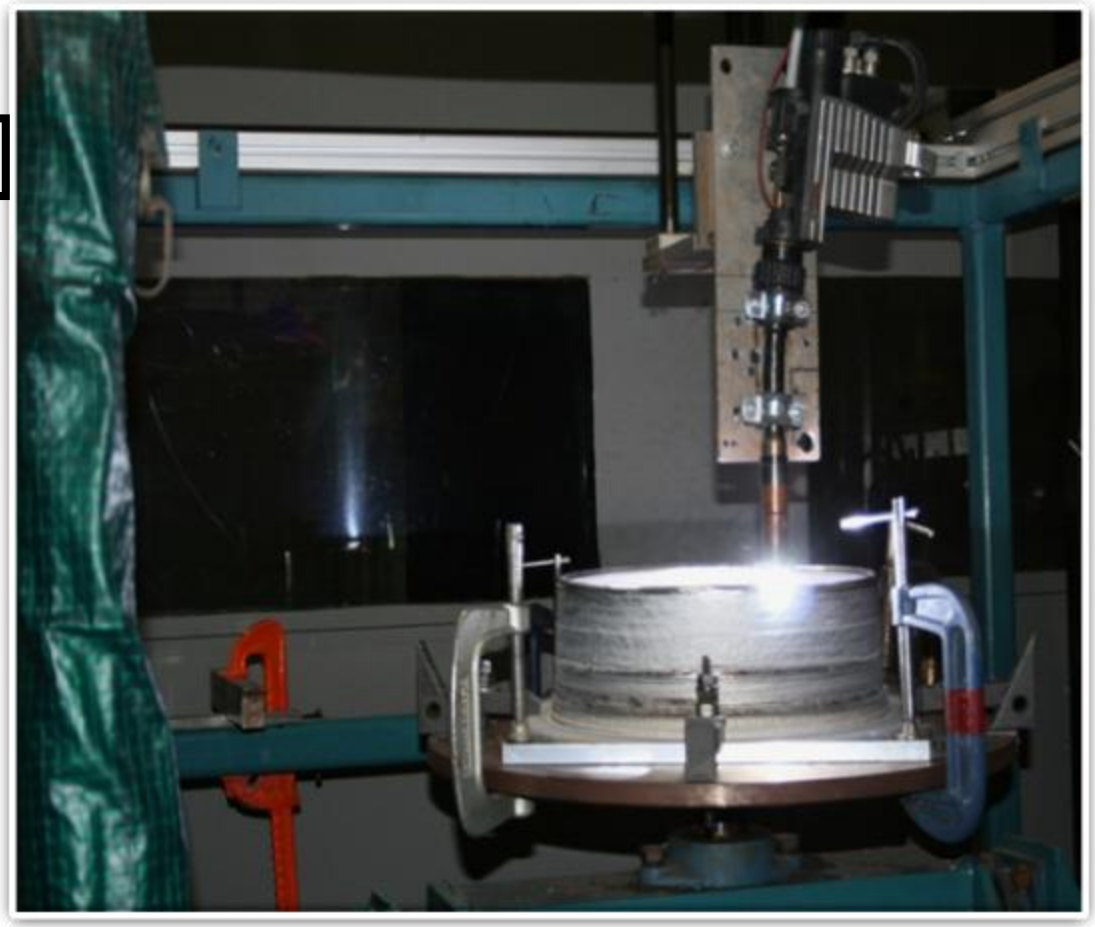




Example aluminum application – satellite launch vehicle component

Variable wall thickness 6-8mm





Building cylinder on a 5 Axis system

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

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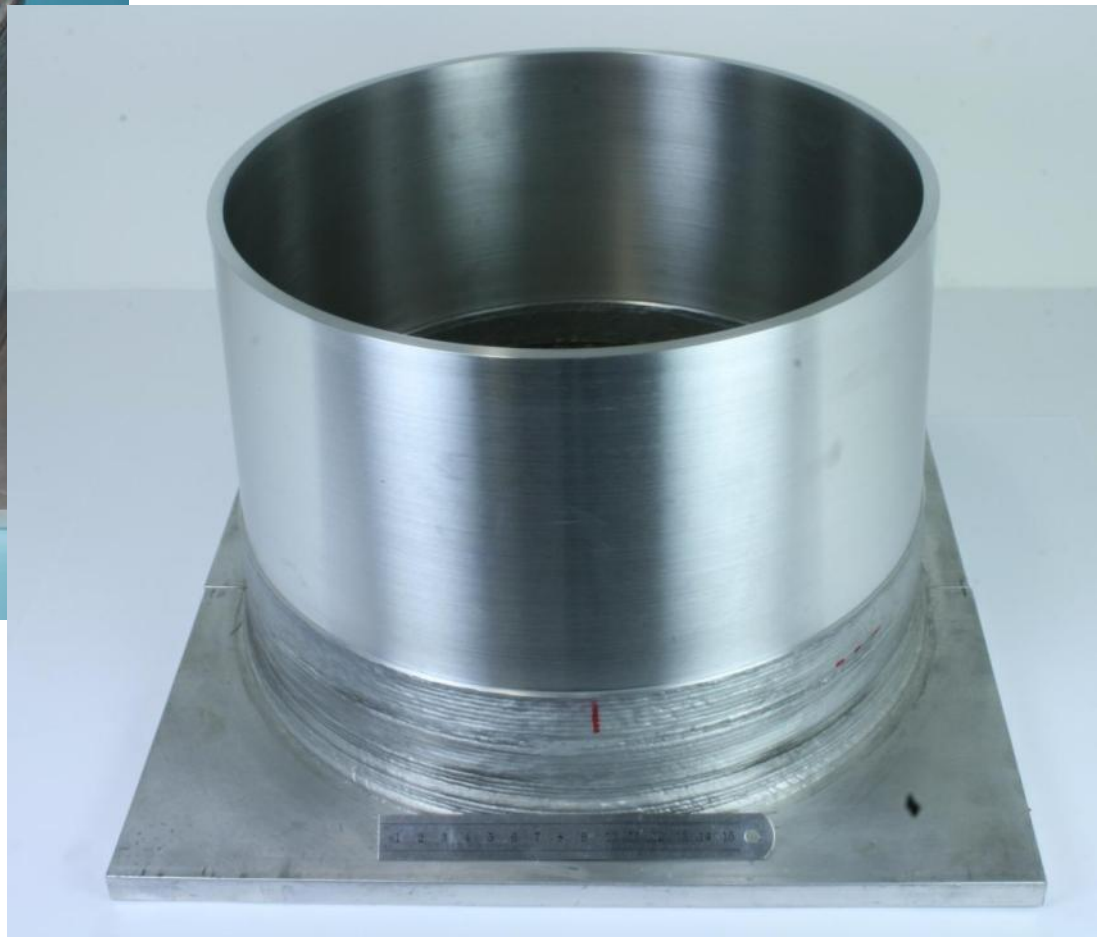
As deposited – 6 hours

After machining



WAAM - Large parts Intersecting Stiffened Panels

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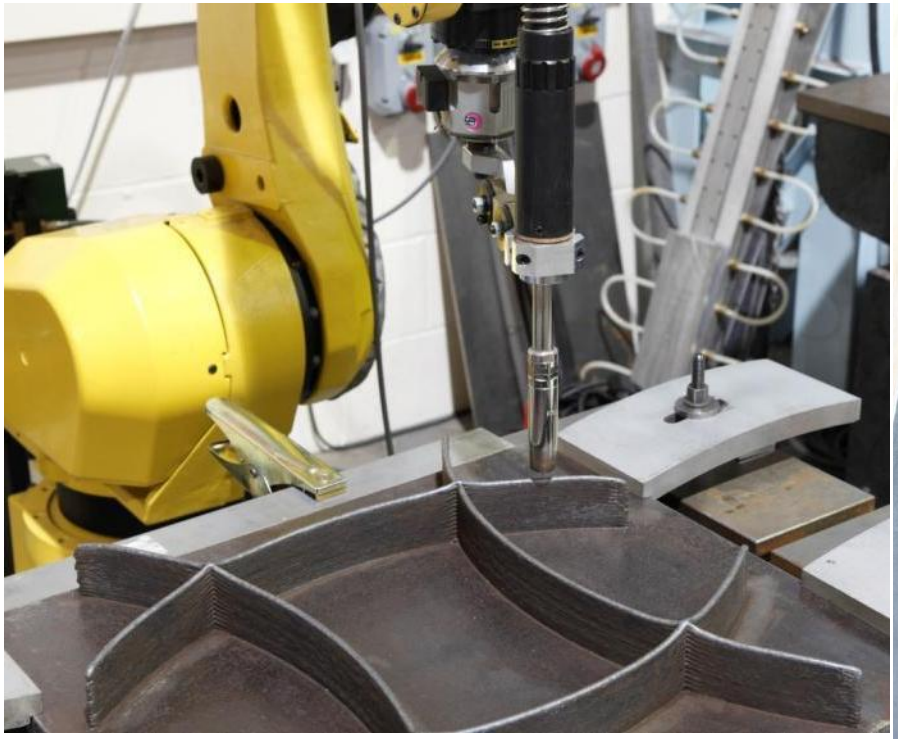

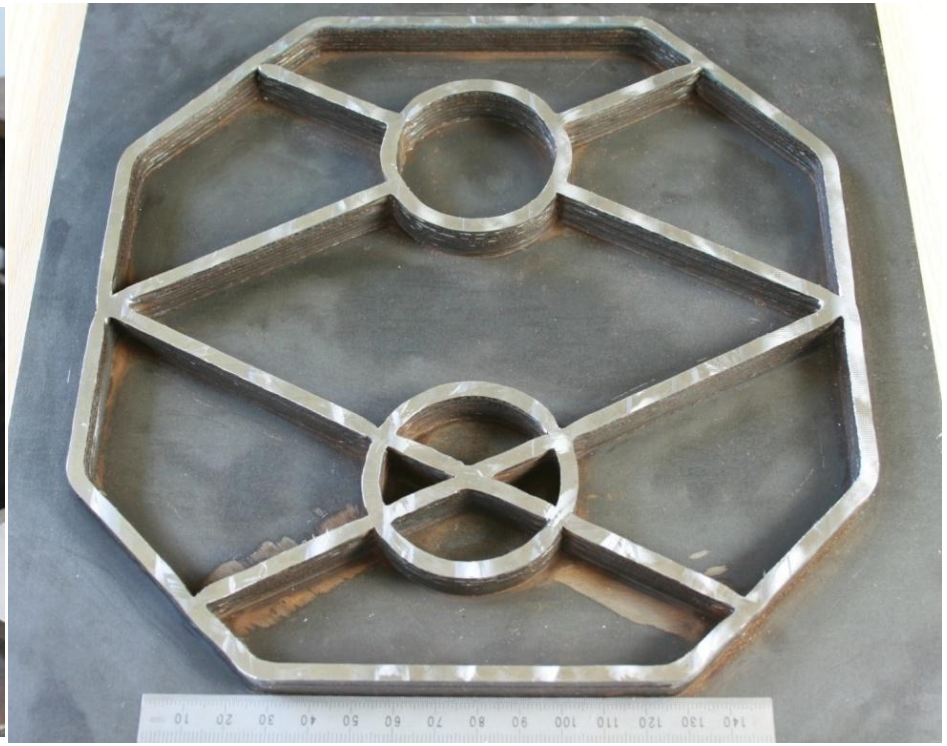

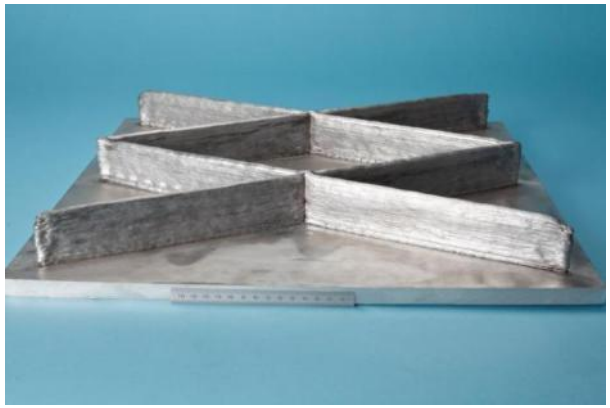

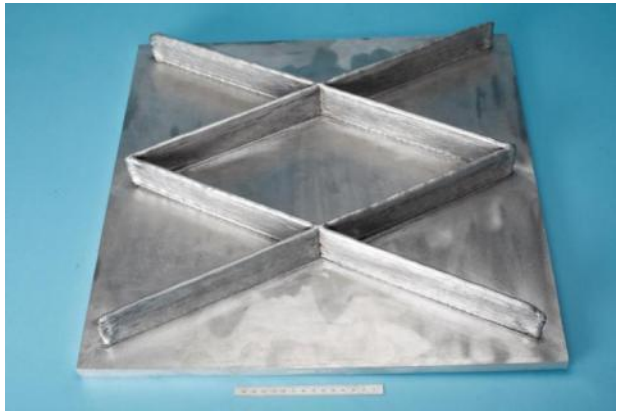

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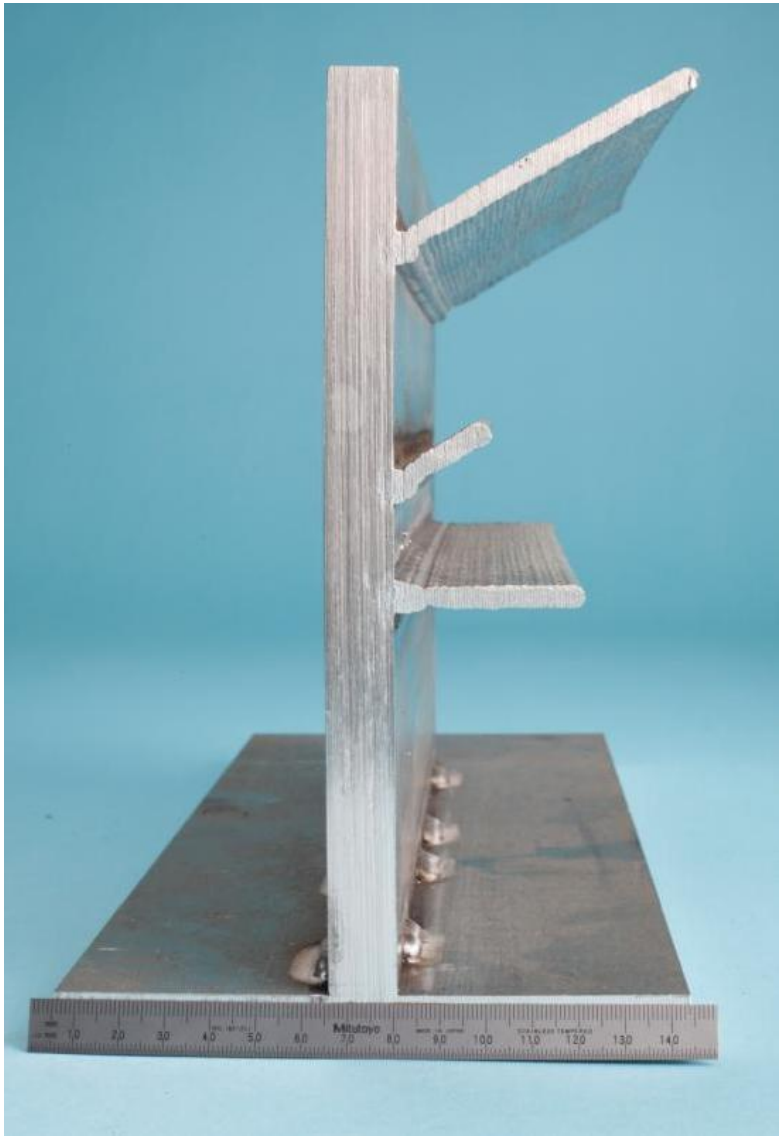
Aluminium

Design Handbook - Horizontal Unsupported walls -aluminium

Enclosed structure (steel)



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

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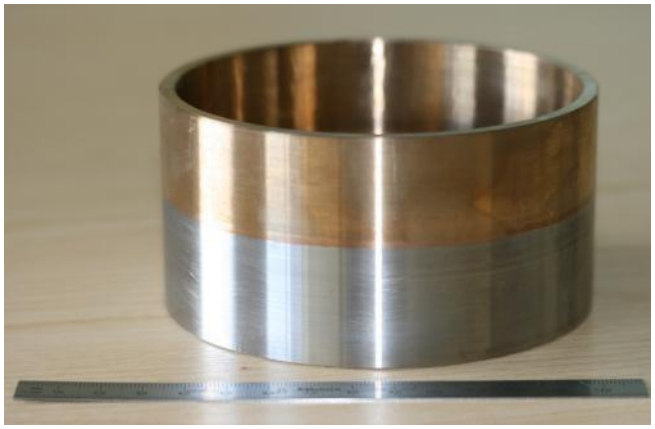
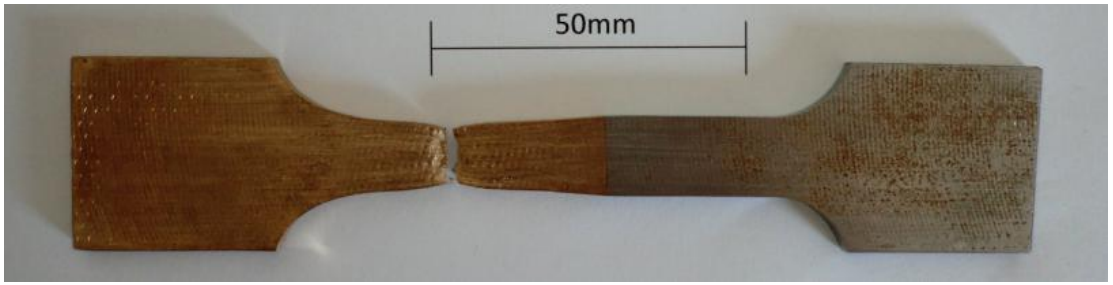
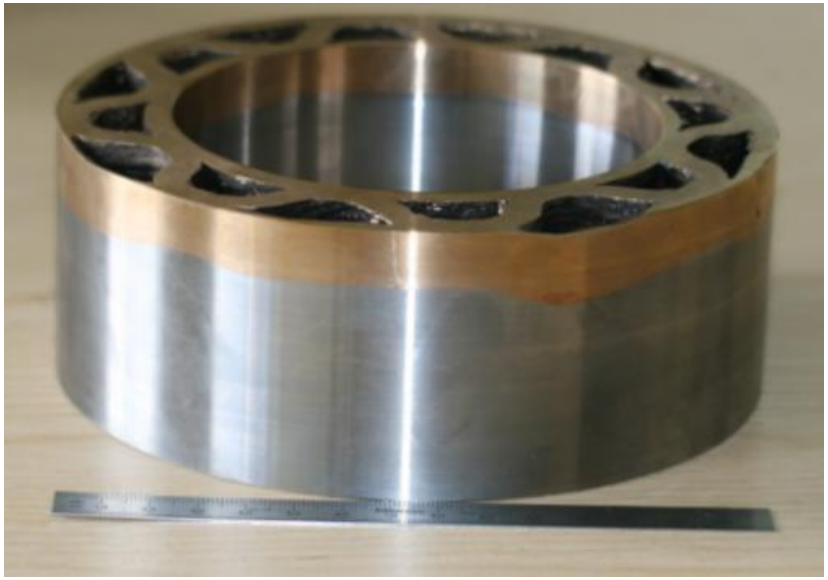
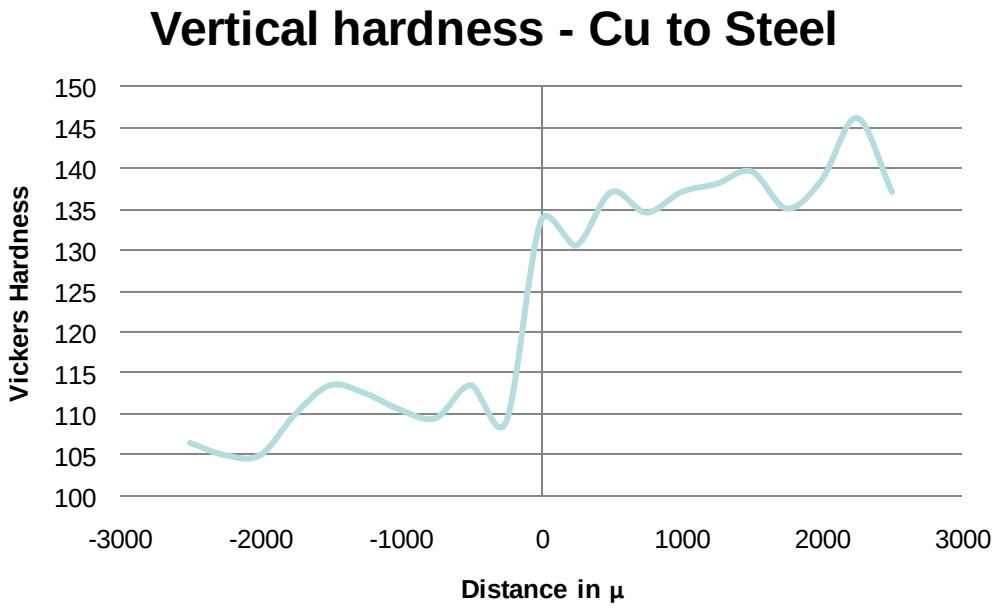


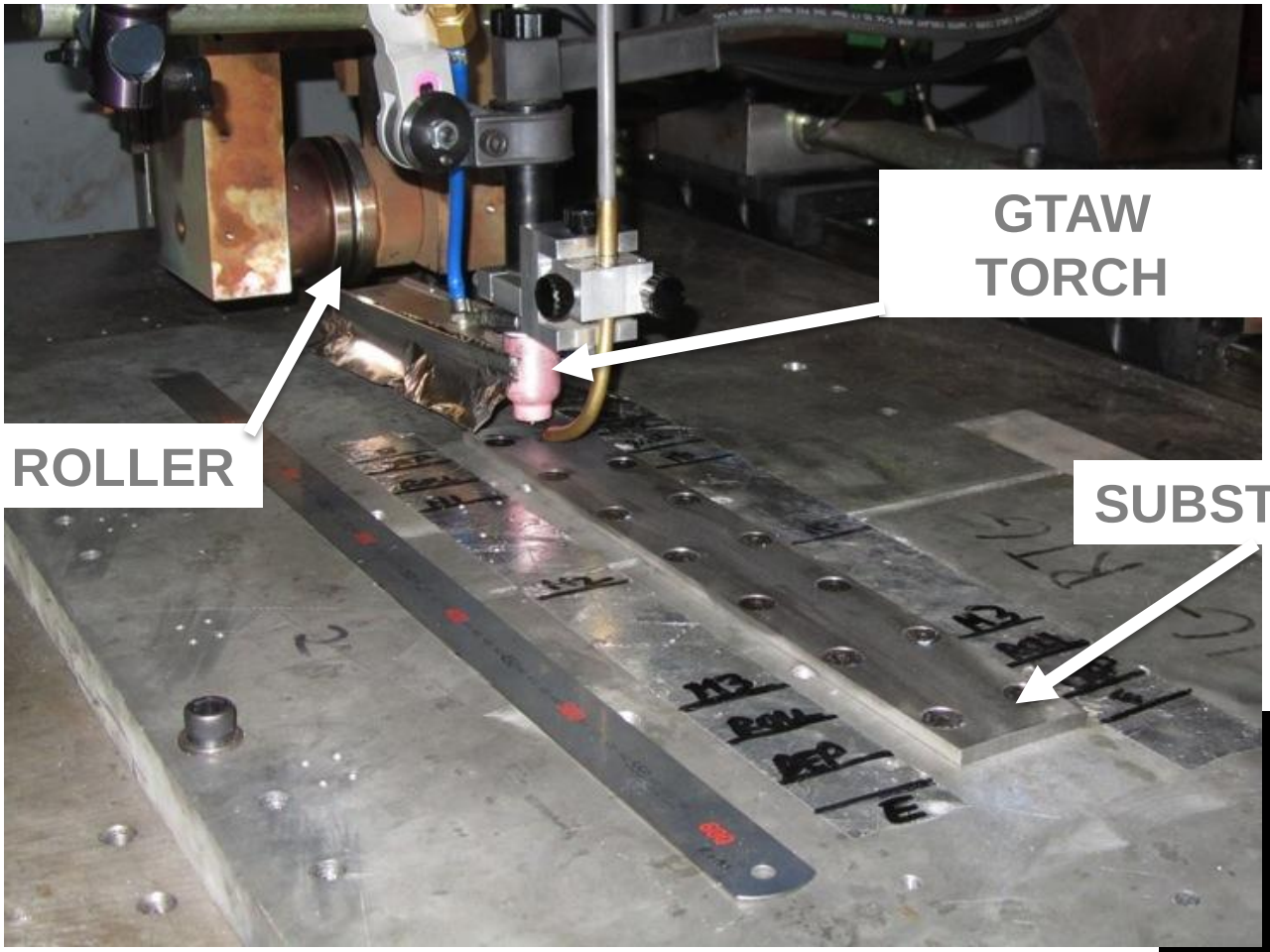


Yield 140 MPa, UTS 300 MPa, elongation 12%, failure in bronze



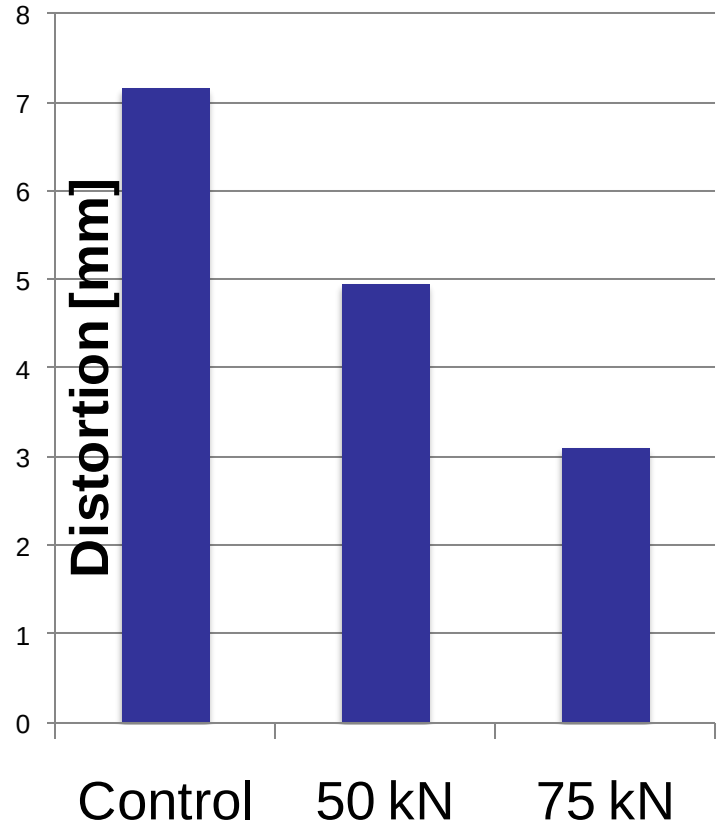


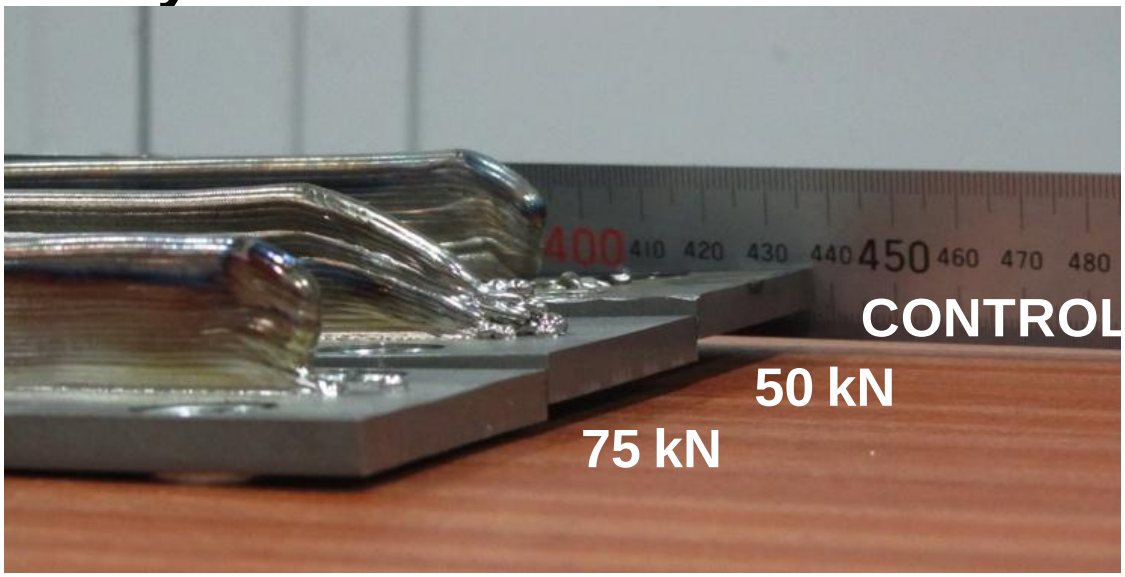
WAAM – latest results – rolling* - setup



*Patent applied for

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





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

- Plates are 450 mm long

Rolling improves process repeatability

WAALM – latest results – rolling - effect on microstructure

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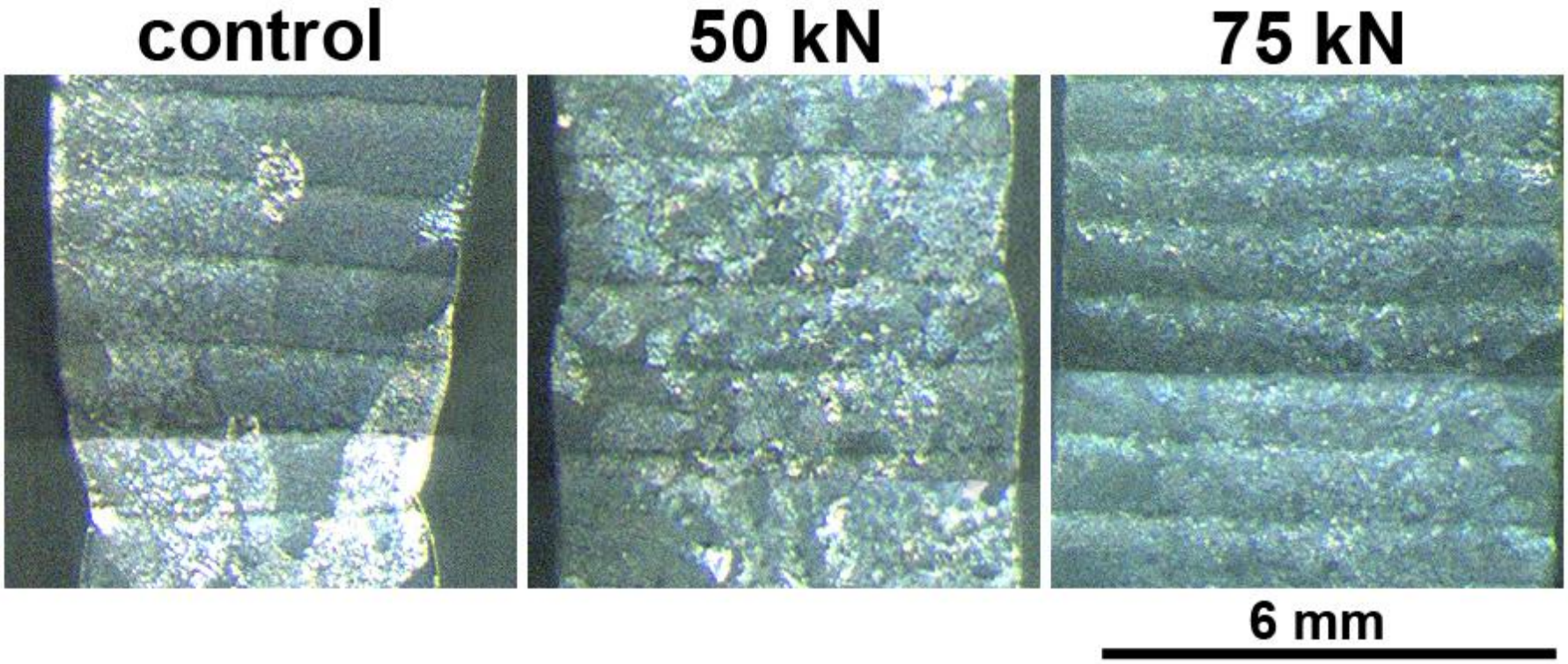
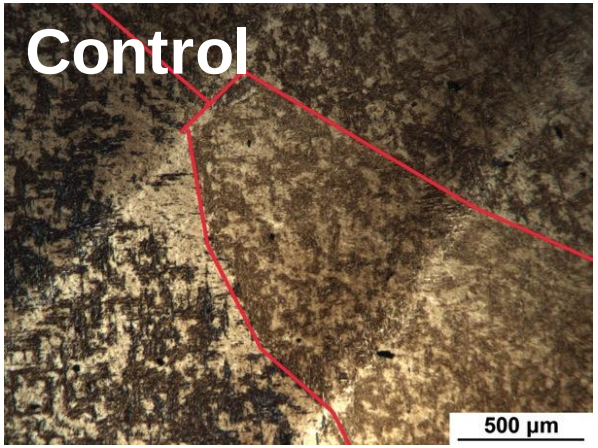
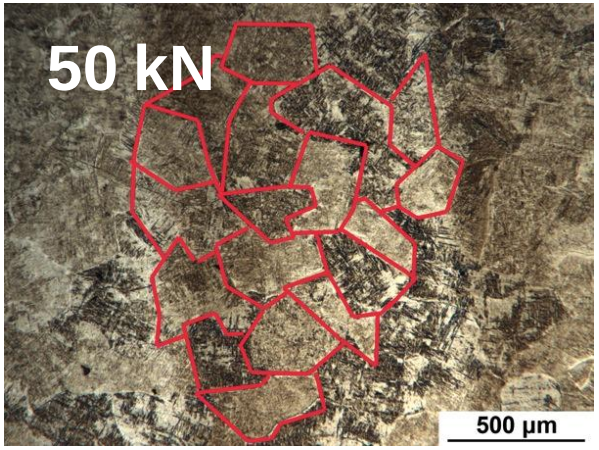
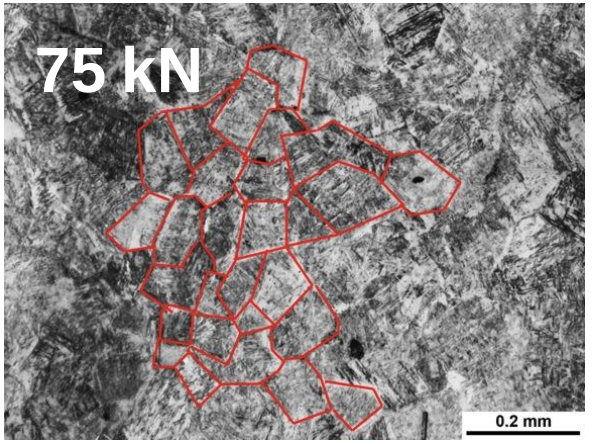


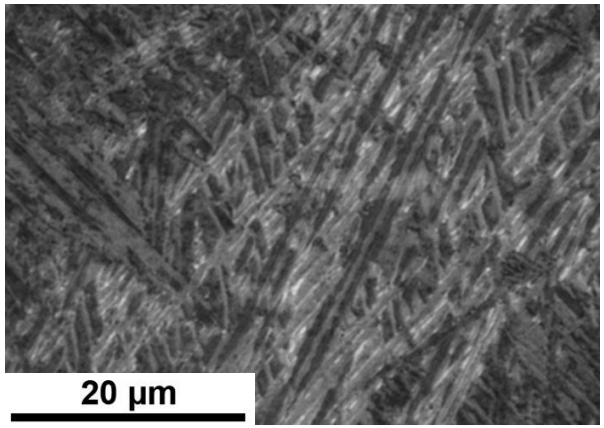
Rolling introduces **deformation**, **nucleation sites** and **stored energy** into the large beta grains, thus inducing **recrystallisation** when layers are reheated during the subsequent deposition

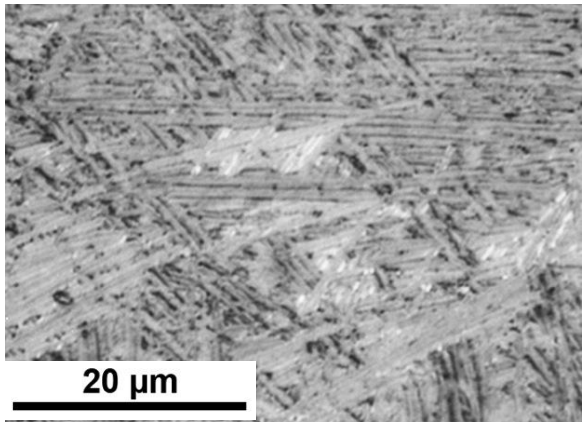
Reduction in grain size

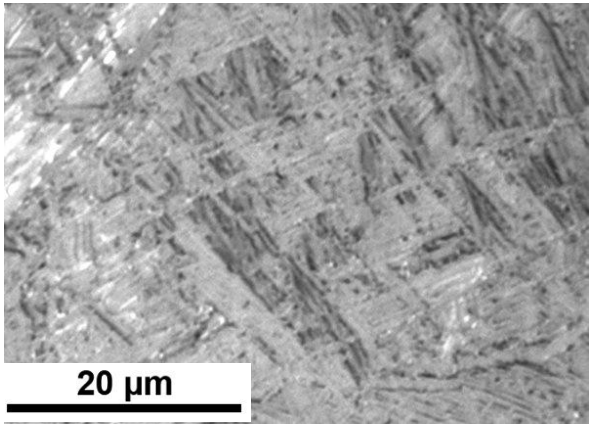








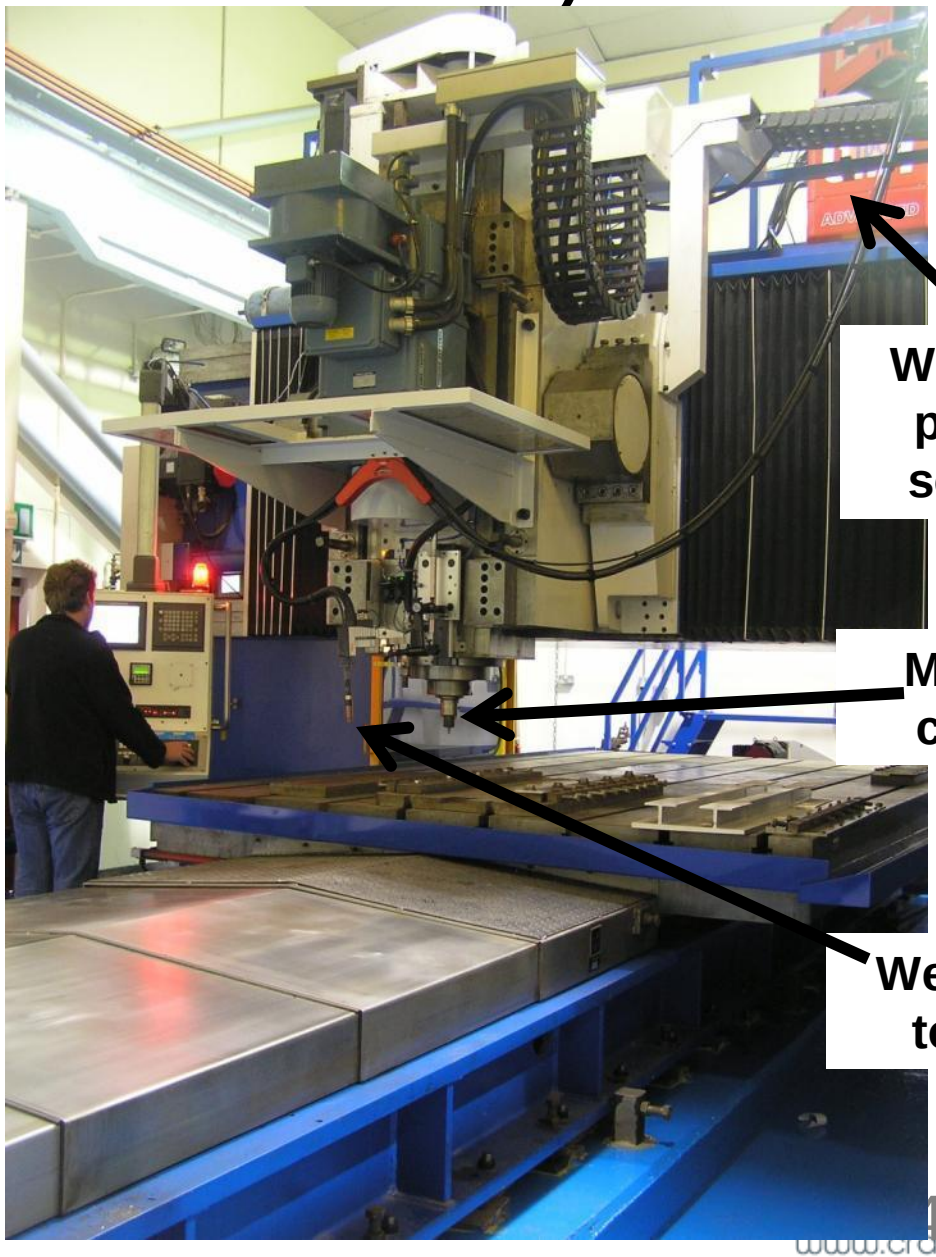




Grain size	Control	50 kn	75 kN
Primary grains	3 x 30 mm	240 µm	83 µm

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 (to be completed)



Large scale WAAM – 1st part

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

Summary additive manufacture

- Wire + arc based additive manufacture is suitable for producing large structural metal parts in a very cost effective manner
- It can used for a wide variety of materials including aluminium titanium and tool steel
- New developments such as rolling, mixed materials and integrated machining are rapidly evolving
- This will be a very important technology for high value manufacturing

Thanks you for your attention

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