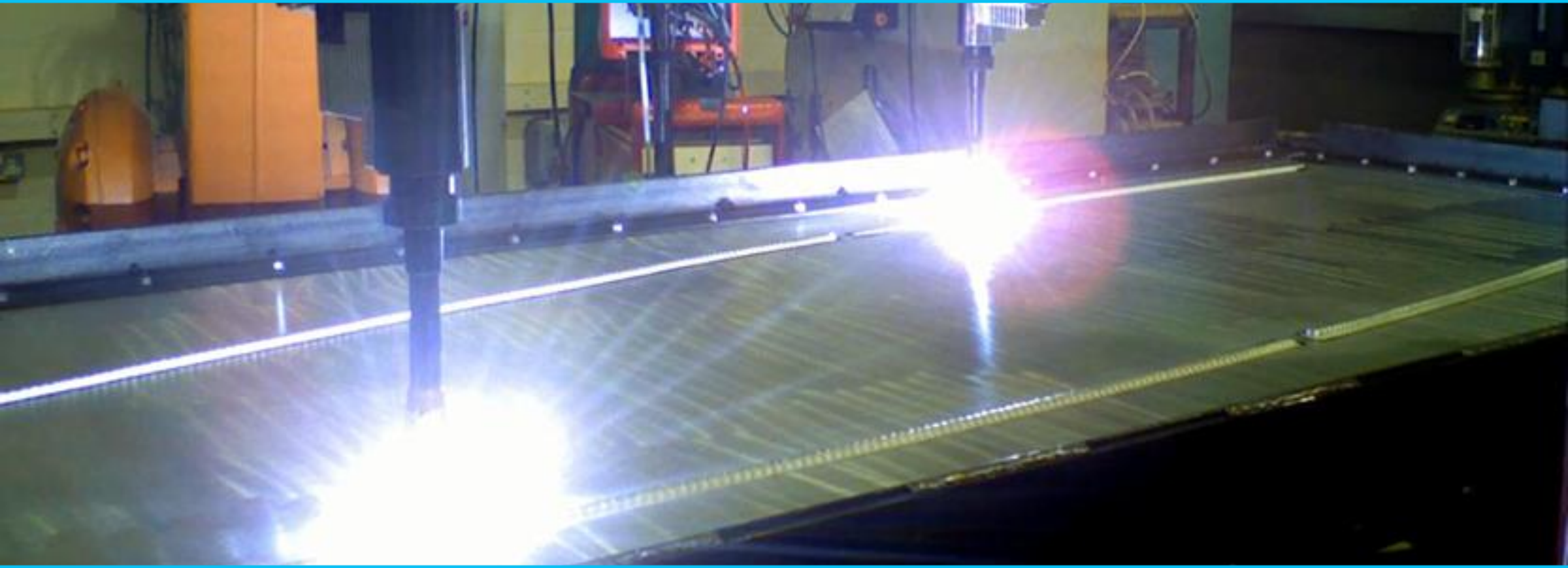
Wire + Arc Additive Manufacturing: properties, cost, parts



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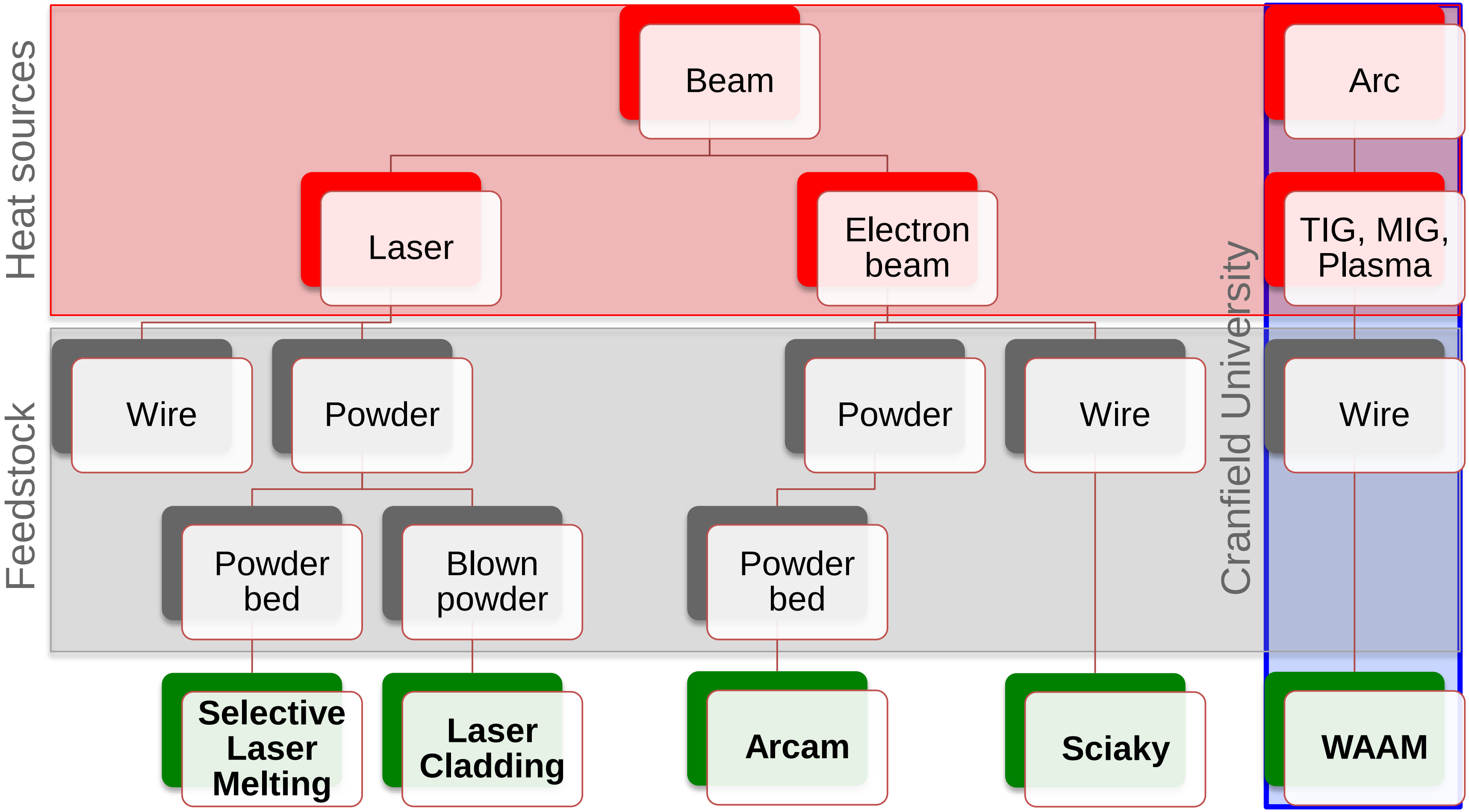
Agenda

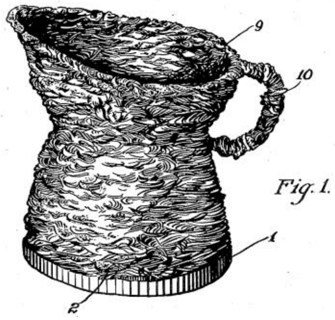
- Wire + Arc Additive Manufacturing (WAAM) history
- WAAM features and systems
- Steel
- Aluminium
- Titanium
- Graded / new / multi materials
- Challenges

Metal AM processes

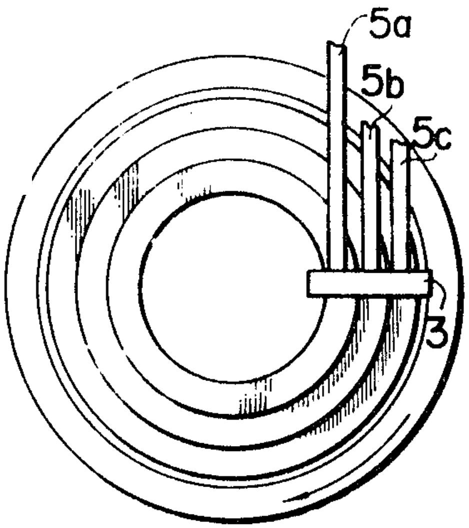


WAAM // History

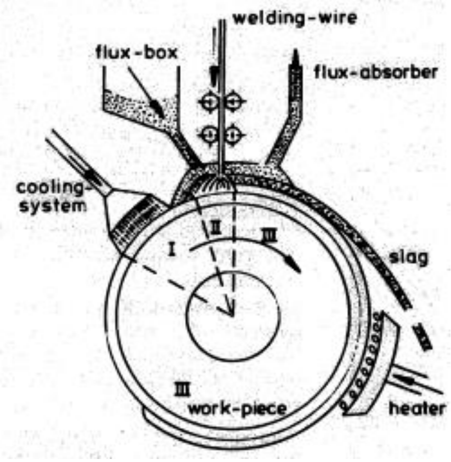
- **1926** Baker patented “The use of an electric arc as a heat source to generate 3D objects depositing molten metal in superimposed layers”



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

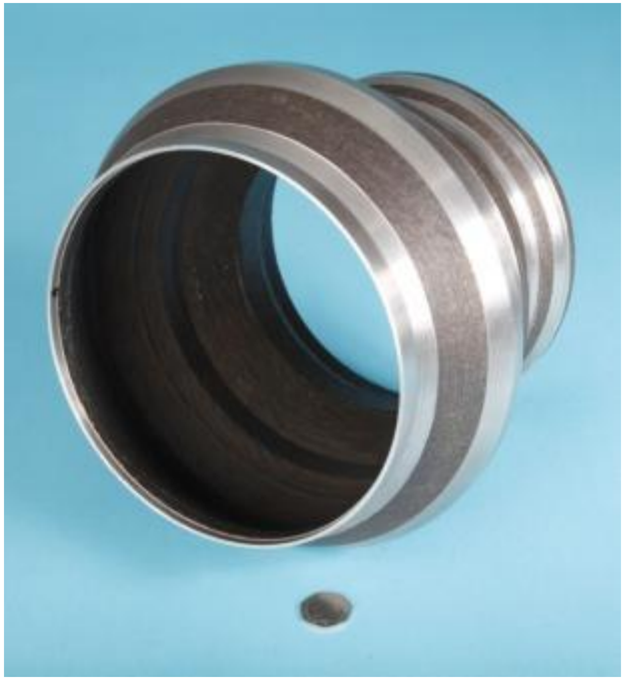


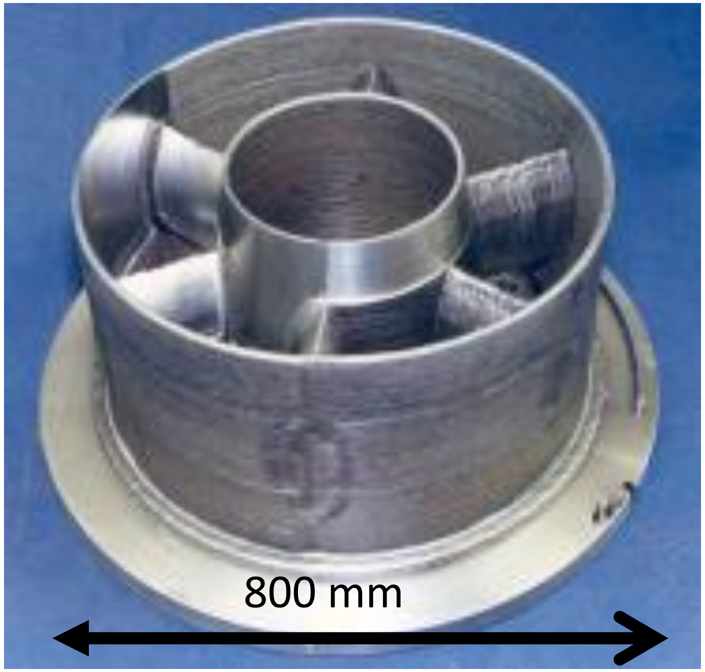
- **1983** Kussmaul used Shape Welding to manufacture high quality large nuclear structural steel (20MnMoNi5 5) parts – deposition rate 80kg/hr – total weight 79 tonnes



WAAM // History

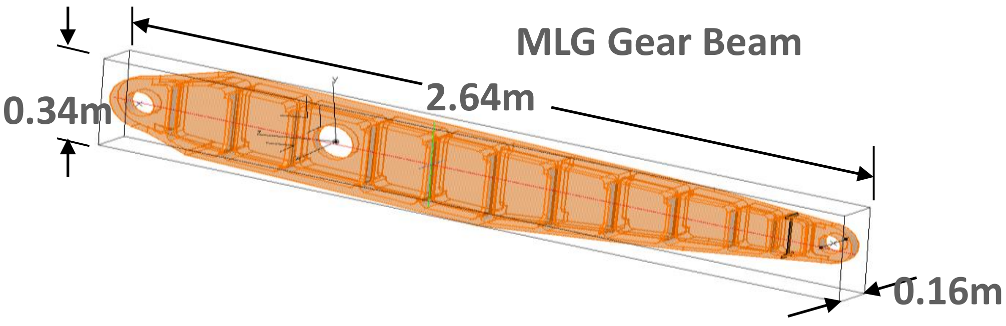
- **1993** Prinz and Weiss patent combined weld material build up with CNC milling → Shape Deposition Manufacturing (SDM)
- **1994-99** Cranfield University develop Shaped Metal Deposition (SMD) for Rolls Royce for engine casings, various processes and materials were assessed – still in production

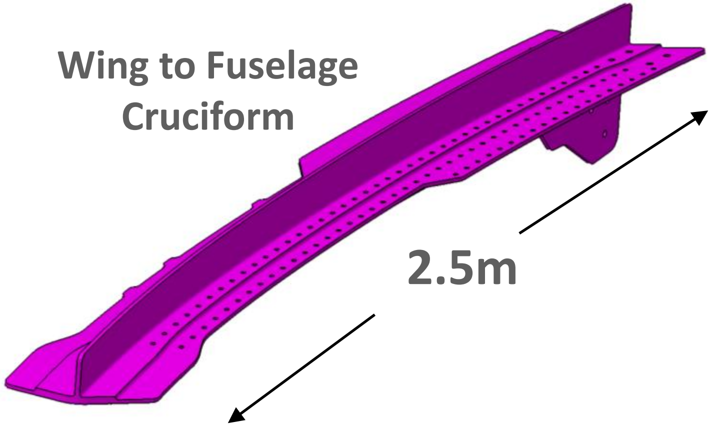




WAAM at Cranfield // History

- **2006** Airframe companies talk to Cranfield about high deposition rate for **titanium** parts
- Target is **metre** scale parts of relatively simple geometries





- The process is aimed at **replacing unsustainable machining** from billet or forgings:
  - projected requirement for Ti in aircraft over the next 20 years is **18 million tonnes**
  - Average buy-to-fly ratio for airframes is 5
  - meaning **15 million tonnes** would be scrap or low value swarf

Business drivers for AM

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- Reduction in **manufacturing cost**
  - Reduction in **lead time**
  - Reduction in **material waste**

- Reduction in **design constraints**
- Reduction in **complex assembly** efforts
- Increase in **design flexibility**

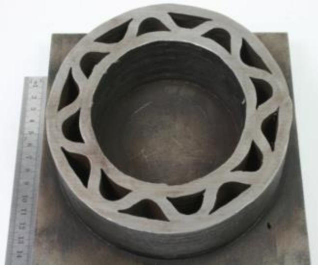
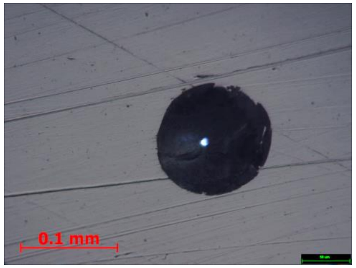
- **Distributed manufacturing** (f.i. on the Moon)

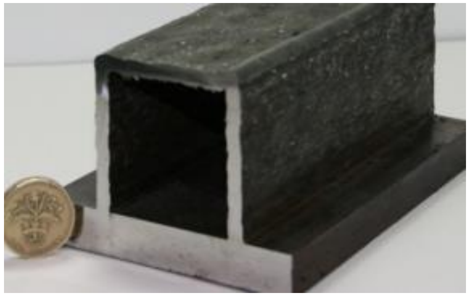
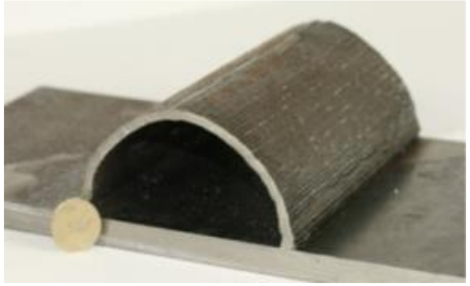
- Improvement in parts performances (f.i strength/weight, multifunctional, graded)

WAAM // Features

- Build rates **0.5 - 4 kg/h** (titanium ~ 1 kg/h)
- **Unlimited** build volume
- **BTF** typical **1.5, always < 2**
- 100% dense parts as deposited with no defects
- Specific deposition cost (dependant upon BTF):
  - **Ti:** £300/kg
  - **Al:** £20/kg
  - **Mild steel:** £25/kg

- Freedom of design? **Not** so much

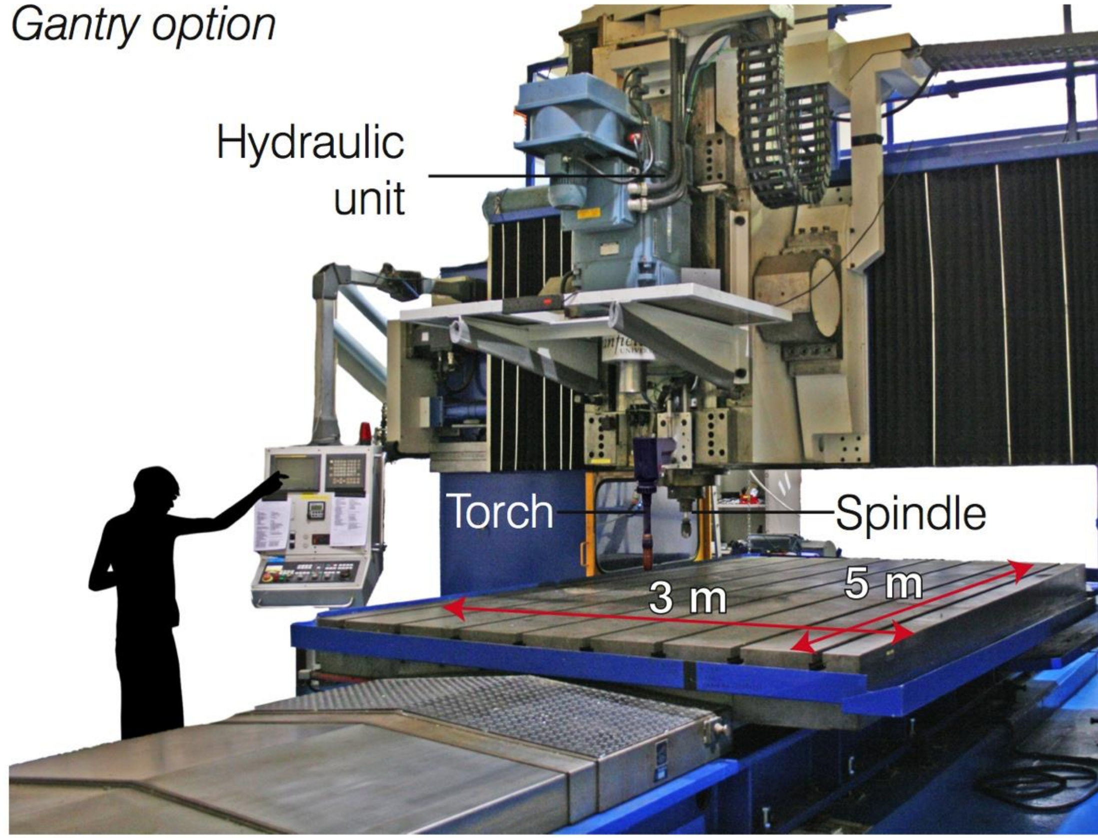




WAAM // Systems

Robot option

Tent + part rotator option

Gantry option

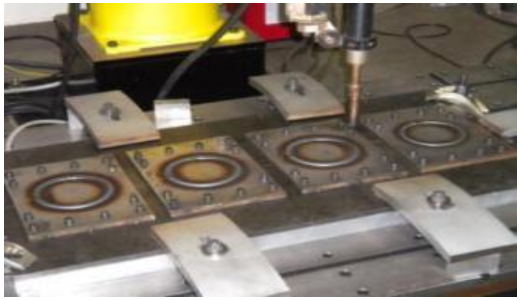


3 Axis CNC milling system with WAAM

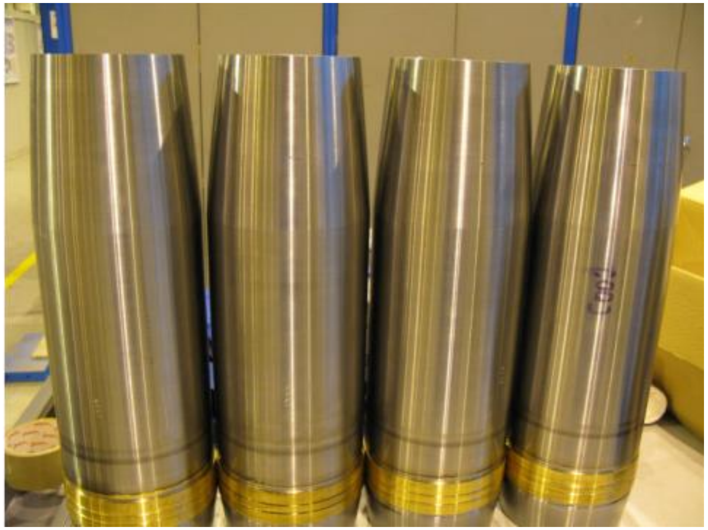
<u>Open architecture systems</u>

STEEL

Projectiles



Mass 32 kg each // Deposition rate 4 kg/h



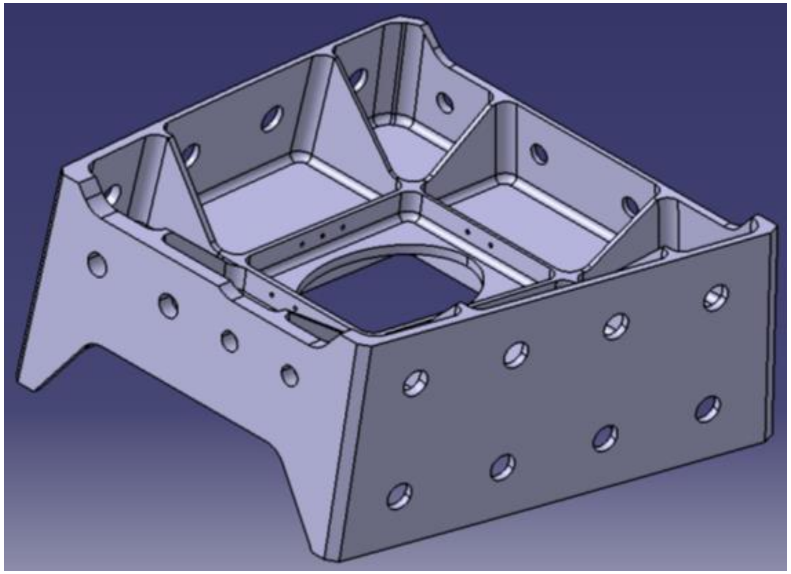
After machining

After assembly and just before firing

Wind tunnel model

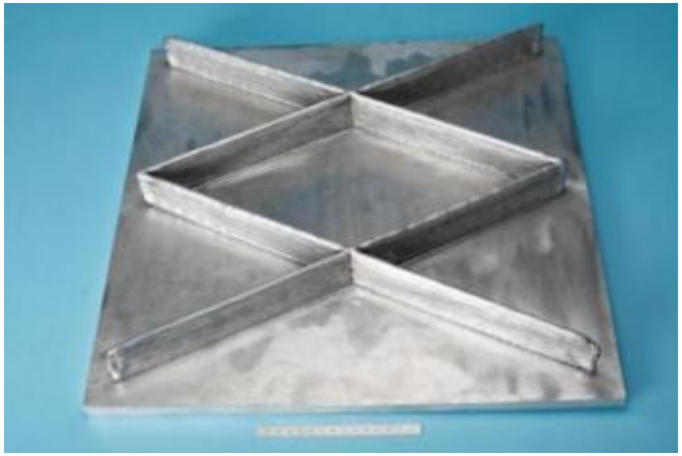
Bombardier landing gear rib

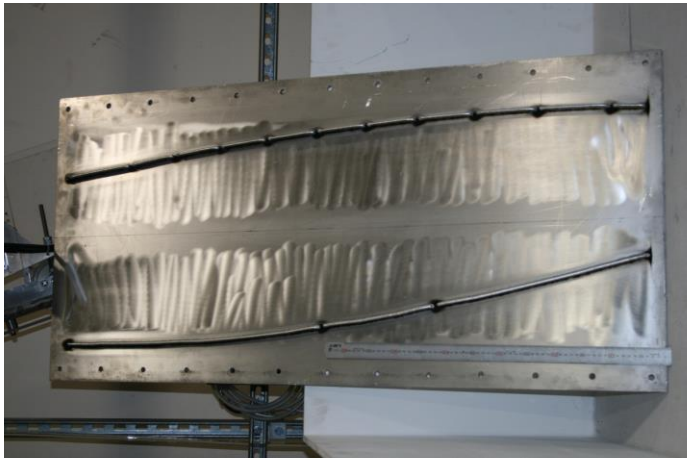
Manufacturing option	Mass (kg)	BTF	Cost (£k)	Cost red.
Original, machined	36	12	1.6	-
Original, WAAM	36	2.3	0.7	55%



ALUMINIUM

Aluminium parts

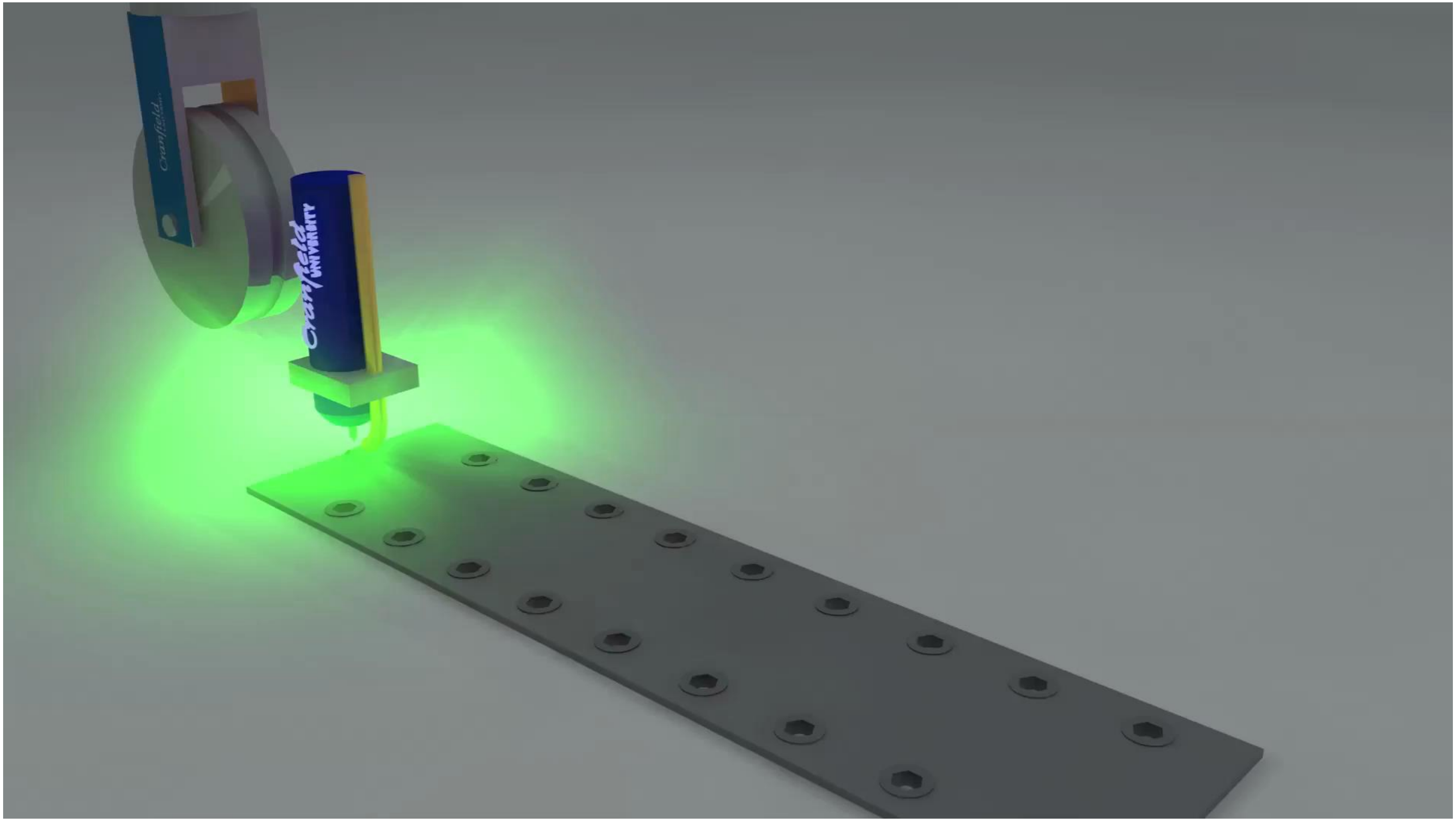




Aluminium // Deposition

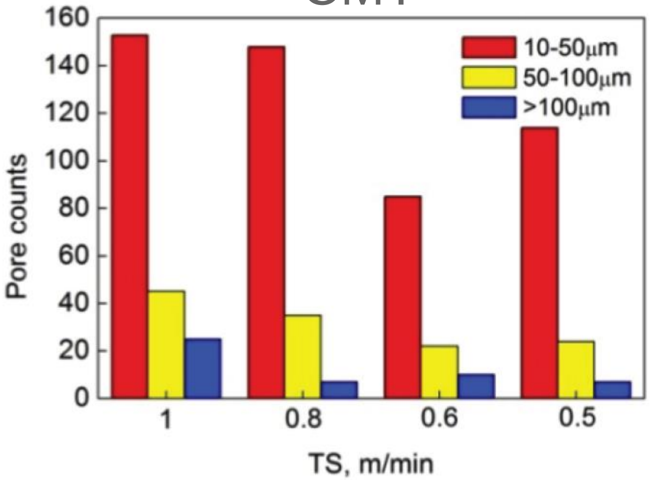
- **Issues:**
  - **Defect** control
    - Porosity
    - Cracking
  - Achieving **high strength**
    - Most high strength alloys are heat treatable
    - Very limited range of **binary** filler wires
      - AlCu, AlMg, AlSi
- **Solutions:**
  - **Waveform:** control of bead shape and microstructure
  - **Wires** selections
  - **Heat** treatments
  - High pressure interpass **rolling**

Rolling of AM parts

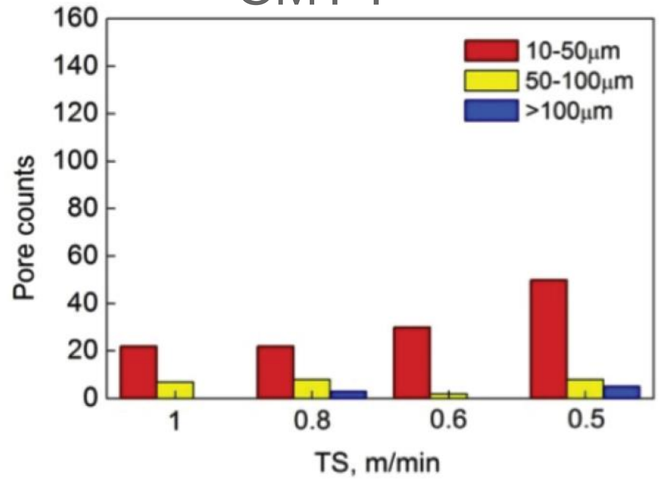


2319 // Effect of MIG variants on porosity

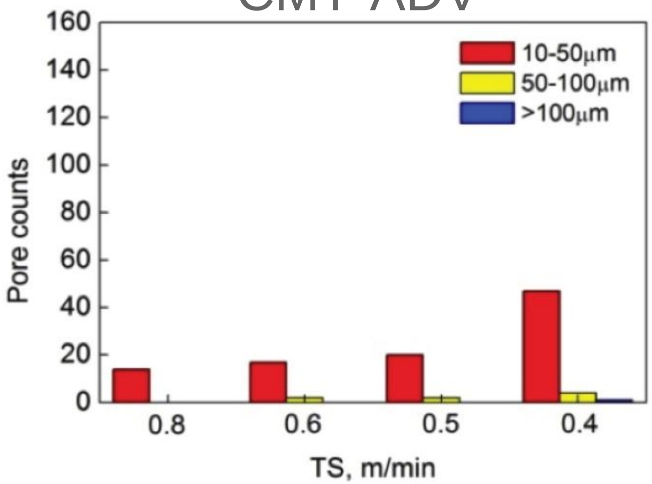
CMT



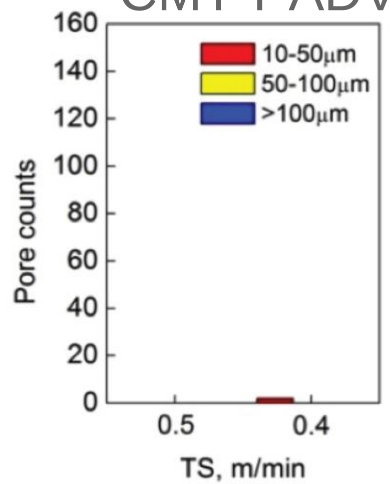
CMT-P



CMT-ADV



CMT-PADV



Single layer deposits

2319 // Effect of rolling + HT on porosity

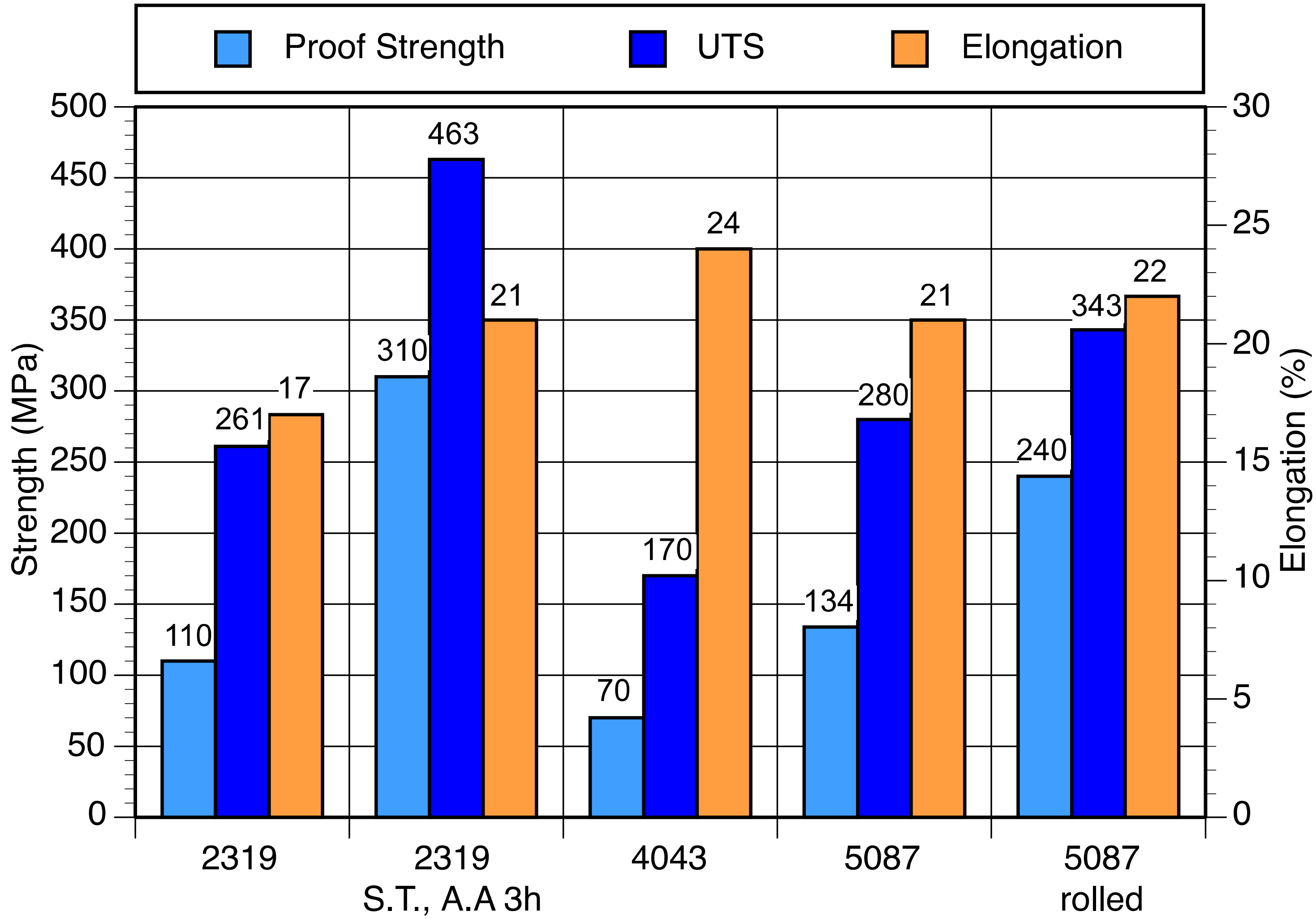
As deposited

ST+AA

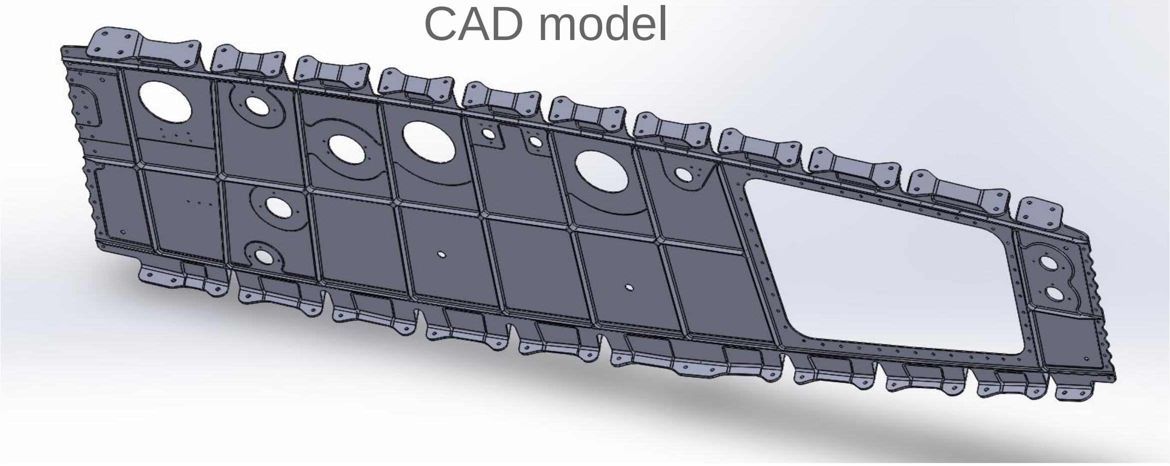
Rolled +
ST + AA

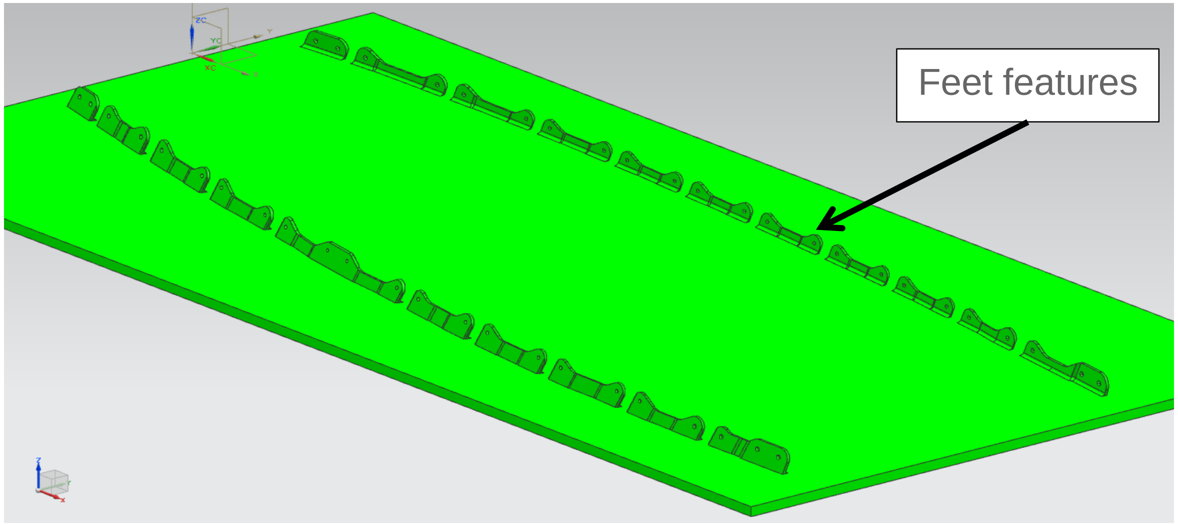
There is no porosity in the rolled + heat treated sample.

Aluminium // Tensile properties



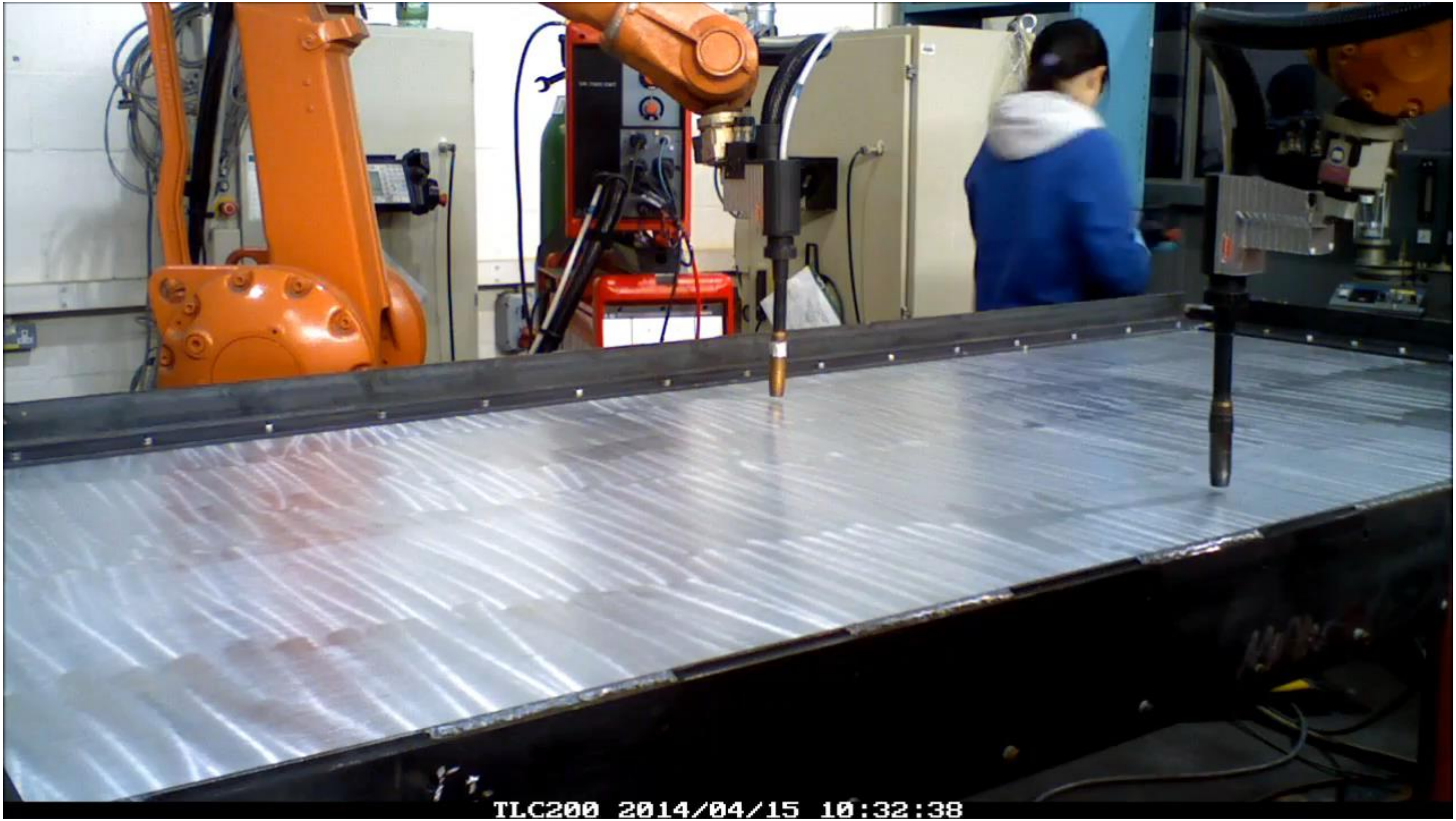
Bombardier wing rib





- **Material:** Al4043
- **Length:** ~2.5 m
- BTF = **45**
- BTF WAAM = **12** (minimum = 2.7)
- Savings > **500 kg**

Bombardier wing rib



Bombardier wing rib

Bombardier wing rib

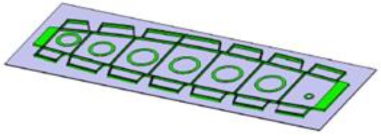
15 kg aluminium wing rib (DR = 1kg/h)

Design option (MRR = 65 kg/h)	BTF	Cost (£k)	Cost red.
Machined from solid	45	4.9	-
WAAM option 1	2.9	1.7	65%
WAAM option 2	12.3	2	58%

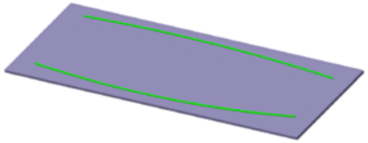
Design option (MRR = 323 kg/h)	BTF	Cost (£k)	Cost red.
Machined from solid	45	4.4	-
WAAM option 1	2.9	1.7	61%
WAAM option 2	12.3	1.9	56%

CAD:

Option 1:



Option 2:



TITANIUM

Ti–6Al–4V // Deposition

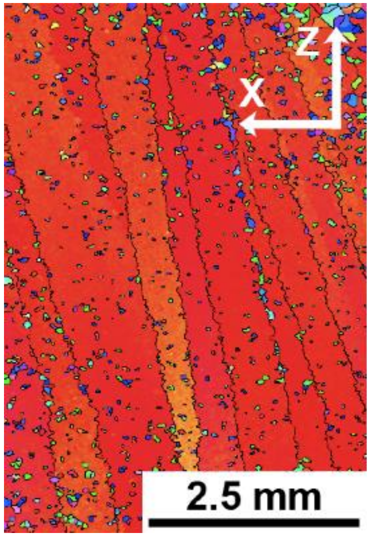
- **Issues:**
  - Anisotropy
  - Strength of AM parts **<** Strength forged/machined parts
  - Residual stress / distortion

- **Solution:**
  - High pressure interpass rolling
  - Build strategy

Ti–6Al–4V // Effect of rolling on microstructure

Ti–6Al–4V // Effect of rolling on microstructure

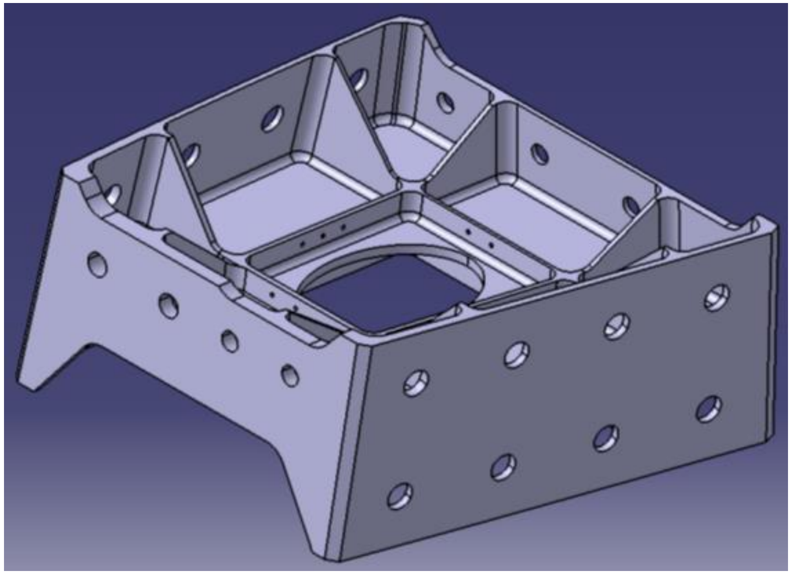
Control

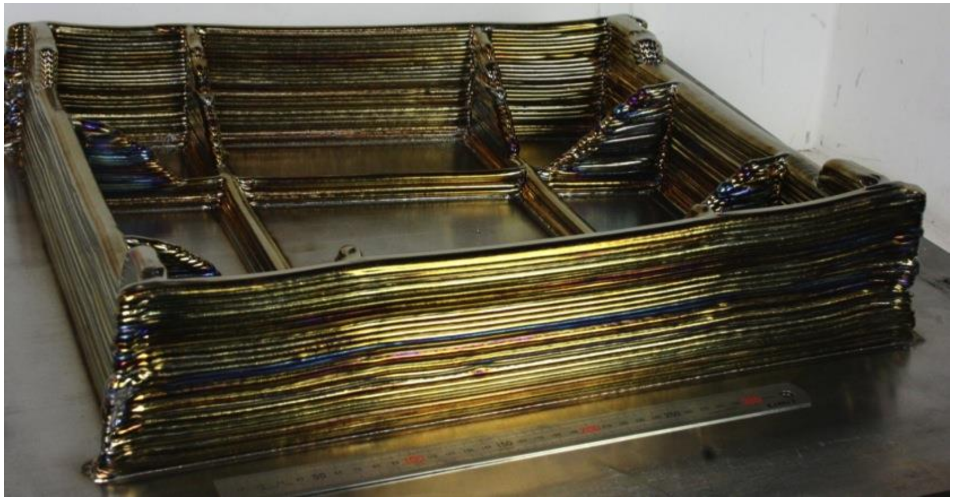


- Isotropy a
- Strength
  - Proof

Bombardier landing gear rib

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





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BAE Systems spar

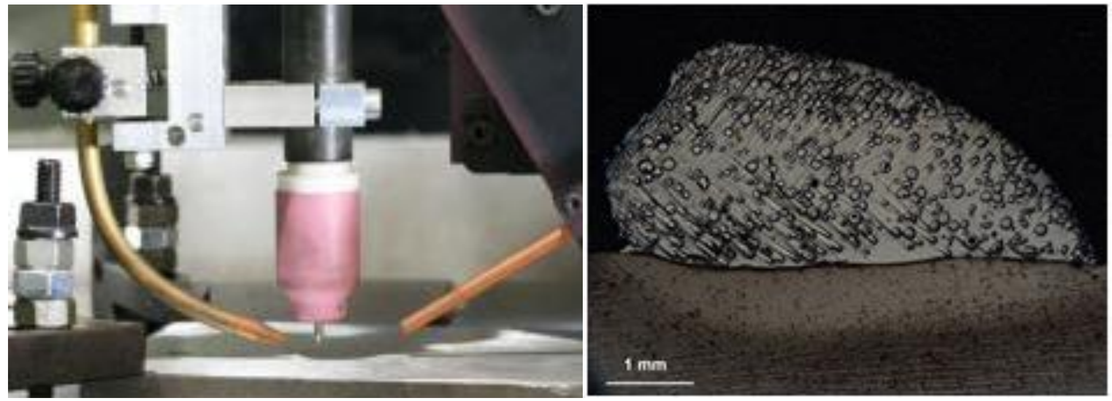
- Demonstrates the features of a **fighter-jet** wing spar
- Double sided deposition
- **BTF** reduced to **2.2**
- **40 h** manufacturing time (20 h per part)

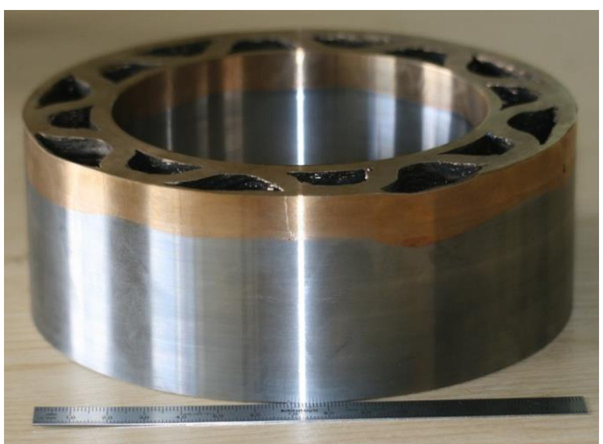
Manufacturing option	Mass (kg)	BTF	Cost (£k)	Cost red.
Original, machined	17	6.5	7.2	-
Original, WAAM	17	2.2	5.1	29%

Graded/new/multi materials

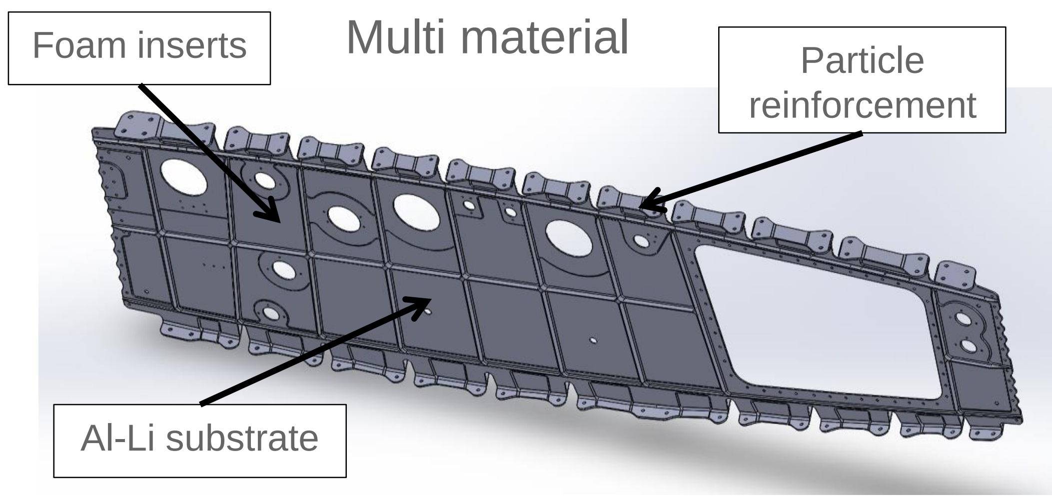
Local alloying

Wire + powder





Multi material



Challenges // WAAMMAt programme, £1.6 million

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- Development of **control system** and full automation → **Commercialisation** of a platform for OEMs and Tier 1 suppliers
- In process **NDT**:
  - Shape
  - Porosity
  - Grain size
- Hardware development:
  - local **shielding**
  - process **monitoring**
  - fault **detection**
- Stress and distortion management
- **Net shape finishing** – integrated machining or multiple robots:
  - Finish part within same setup
  - Correction of errors (shape, porosity)

Thanks for your attention!

- Williams, S.W., Martina, F., Addison, A.C., Ding, J., Pardal, G., and Colegrove, P., 2015. ***Wire + Arc Additive Manufacturing***, Materials Science and Technology, in press.
- Martina, F., 2014. ***Investigation of methods to manipulate geometry, microstructure and mechanical properties in titanium large scale Wire+Arc Additive Manufacturing***, PhD thesis, Cranfield University.
- Colegrove, P.A., Martina, F., Roy, M.J., Szost, B., Terzi, S., Williams, S.W., Withers, P.J., Jarvis, D., 2014. ***High pressure interpass rolling of Wire + Arc Additively Manufactured titanium components***. Advanced Materials Research 996, 694–700.
- Colegrove, P.A., Coules, H.E., Fairman, J., Martina, F., Kashoob, T., Mamash, H., Cozzolino, L.D., 2013. ***Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling***. Journal of Materials Processing Tech. 213, 1782–1791.
- Martina, F., Menhen, J., Williams, S.W., Colegrove, P.A., Wang, F. 2012. ***Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V***. Journal of Materials Processing Tech. 212, 1377–1386.

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