Large Scale Metal Wire + Arc Additive Manufacturing of Structural Engineering Parts

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Topics

- Brief summary of Wire + Arc Additive Manufacture process in relation to other AM processes
- WAAM Materials
- WAAM Systems
- Future plans
Metal Additive Manufacture - Background

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”
Metal Additive Manufacture - Background

This has been around awhile!

- 1947 Carpenter – weld based cladding using SAW
- 1964 White – Roller coating using SAW
- 1971 Ujiie (Mitsubishi) = Pressure vessel fabrication using SAW, electroslag and TIG, also multiwire with different wires to give functionally graded walls
- 1974 Thyssen produced components of any dimension and shape made only of weld metal instead casting, forging or rolling using SAW
1983 Kussmaul used Shape Welding to manufacture high quality large nuclear structural steel (20MnMoNi5 5) parts – deposition rate 80kg/hr – total weight 79 tonnes
Wire + Arc Additive Manufacture (WAAM) Process

Deposition time 24 hours
Additive manufacturing landscape

Heat sources
- Beam
  - Laser
  - Electron beam

Feedstock
- Wire
- Powder
  - Powder bed
  - Blown powder
- Powder
- Wire
- Wire

Cranfield University

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Where we are aiming - HELP!

**Aluminium:**
- 14 months for forging
- 4 months for machining
- 90% waste

**Titanium:**
- 10 times worse problems
Basics of metal AM systems – What process or hardware should you use?

For a single axisymmetric energy source build rate depends on the square of the layer height.

Optimum for finish machining ± 1mm

Resolution depends linearly on the layer height

Surface finish also depends linearly on the layer height
Basics of metal AM systems – Cost of depositing material

Specific cost approaches the material cost for high build rates
Optimum cost saving based on build rate

Example for 1-3 m part with BTF of 10 for machining and weight of 30 kg and minimum feature size of 2 mm
Benefits and limitations

- **Powder-bed**
- **Blown-powder**
- **WAAM**
- **Hi. Dep. Wire-fed**

**Note – our assessment**

- Build rate
- Complexity
- Part size
- Platform flexibility
- Post-processing requirement
- Accuracy
- Cost savings
- Mech. properties
- Material utilisation
Key WAAM process features

- Build rates 0.5 - 4 kg/hour – **typical 1kg/hr titanium**
- Unlimited build volume
- **Buy to fly ratio** – typical 1.5 but always <2
- Fully dense materials with excellent mechanical properties
- Minimum feature size 2 mm
- **No commercial systems available – yet**
WAAM - Business Drivers

- WAAM business drivers are
  - Cost and material saving compared to current manufacturing methods
  - Greatly reduced lead times
  - Application to large engineering structures
  - In field applications

GKN Ti demonstrator part – typical features
### WAAM business driver – cost saving case studies - Bombardier rib

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<th>Design option</th>
<th>Mass (kg)</th>
<th>BTF</th>
<th>Cost (£k)</th>
<th>Cost red.</th>
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<td>20</td>
<td>12</td>
<td>16.2</td>
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<td>WAAM + machining</td>
<td>20</td>
<td>2.3</td>
<td>5</td>
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<th>Mass (kg)</th>
<th>BTF</th>
<th>Cost (£k)</th>
<th>Cost red.</th>
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<td>12</td>
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<td>WAAM + machining</td>
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<td>2.3</td>
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What we’ve deposited so far

- **Ti-6Al-4V**
  - Grade 5
  - Grade 23

- **Aluminium**
  - 2024
  - 2319
  - 4043
  - 5087

- **Refractories**
  - Tungsten
  - Molybdenum
  - Tantalum

- **Steels**
  - ER60
  - ER80
  - ER90
  - ER120
  - Maraging grade 250
  - Maraging grade 350
  - Stainless (17-4 PH, 316L)

- **Inconel**
  - 625
  - 718

- **Bronze**

- **Copper**
Unique features // High pressure rolling
- Reduction in prior $\beta$ grain size
- Reduction in $\alpha$ lamellae thickness
- Possibly some work-hardening effects still left in the structure
Ti64 // Static properties (isotropy)

- **Cast ASTM F1108**
- **Wrought AMS 4928**

**Ultimate tensile strength (MPa)**
- 850
- 900
- 950
- 1000
- 1050
- 1100

**Elongation (%)**
- 8
- 10
- 12
- 14
- 16
- 18
- 20
- 22
- 24
- 26

**Proof strength (MPa)**
- 750
- 800
- 850
- 900
- 950
- 1000
- 1050

**Single V.**
- 50 kN V.
- 75 kN V.

**Single H.**
- 50 kN H.

**Plate**
- 75 kN H.
There is no porosity in the rolled + heat treated sample.
Aluminium properties (2024 – 2319 – 5087 (average))

![Graph showing aluminium properties](image-url)
Steel (average)
Low alloy steels-Tensile testing

Direction-specific results of tensile test. Error bars indicate 95% confidence intervals.
Stainless steel 17-4 PH - Tensile test results

Direction-specific results of tensile test. Error bars indicate 95% confidence intervals.
WAAM Process features (4) – deposit composition control using multiple feeds

Multi wire approach

Wire + Powder

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

3 wire (Al8%Cu1.5%Mg – 140HV)
WAAM process features (5) - mixed materials - copper and steel

Steel/bronze (CuSi3%) parts

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

Copper on steel with WC ceramic added
Refractory metal WAAM

13 Layers W

7 Layers Mo

Tantalum walls
Graded Structure Ta/Mo/W (Chemical Analysis and Hardness)
Topological Optimisation for WAAM

Original part

Freeform topological optimisation

WAAM Optimisation

Weight saving
7.5 kg – 3.9 KG – 33%
Also much to make than the original
The systems

Robot option

Tent + part rotator option

Gantry option

3 Axis CNC milling system with WAAM

Open architecture systems
Rolling Assisted WAAM

Wire Feeder and Spool

Tool Holder

Roller

Torch

Argon Shield
Research results - Local shielding

Oxygen contour plot of the AP/PWP Local Shielding Device
Unique features - local shielding solution
Visual aspect comparison of parts built in a chamber and using the AP/PWP Local Shielding Device
Coordinate motion deposition

Thin wall revolving structures: ARA beanie
Building time: 2.5 hours
Wall thickness: around 5mm
Material: Al5087
WAAM Software

Two major challenges:

- Avoiding defects, especially lack of fusion defects
- Achieving and maintaining the specified layer height

Reverse machining strategies or powder bed additive path planning are not suitable.

Four main functions of the automatic WAAM path planning software

- Intelligent partitioning
- Build path strategies
- Process parameter database
- Manufacturing strategy
Two routes

Cranfield WAAMSoft
- Internal process development mainly
- Development of a feature based WAAM software
- Development of automatic path planning method
- Can be customised and supplied to WAAMMat partners if requested
- Development of process data base

Rhinoceros cad platform + Grasshopper development + Robot simulation environment
Two routes

Delcam Commercial Software
- Commercial software provider
- CAD + CAM +CAR
- Software maintenance and training
  - Cranfield will support the software development
  - Will provide updated process data base
  - Will provide developed path planning methods and algorithms

PowerShape + PowerMill + Robot Plugin + ‘Build style’ development environment
Where are we heading?
World’s largest metal AM parts:

- 6 m aluminium bulkhead
- 7 m steel cantilever beam (1500 kg)
Next 3 years

- Software
- Control

Tool path automation

Commercialisation of the technology

Cranfield Development route

- WAAMSoft
  - WAAM basic features
  - Process database basics
  - WAAM advanced features
    - Process database interface
  - Automatic feature recognition
    - Process database advanced

Commercial route

- 1st stage WAAM software
- 2nd stage WAAM software
- 3rd stage WAAM software

Selected beta audience
Available to everyone

May 2016
Nov. 2016
Feb. 2018
Next 3 years

- **Qualification** for aerospace (civil + defence)
- **Parallel** processing

- **High-strength** aluminium > 500 MPa
- **Mixed** materials, graded structures (f.i. aluminium MMCs)
Next 5 years

- **Commercialisation:**

  - **Robotic** manipulation
    - Medium size ~ 1m$^3$ → £100k
    - Large size ~ 6-10m → £200k up to £700k depending on accuracy requirements

  - **CNC** manipulation
    - Low cost ~ 0.5m x 0.5m x 0.5m → £30k
    - Medium size ~ 2m x 1m x 1m → £300k
    - Extended capability including cold-work ~ 6m x 3m x 1m → £2M

  - + whatever: the software being developed should be able to drive any manipulation system – great for retrofitting
Beyond 8 years

- **Very large** parts – Ti (local shielding), Al, Steel

- Full **industrial implementation** as No. 1 process

LASIMM
6M€ EU project
3 years
Starts this October
New website – launched April 1st.

waammat.com

THANK YOU FOR YOUR ATTENTION😊

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WAAMSoft: Demonstration