Additive Manufacturing for Large Structures

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TU Delft

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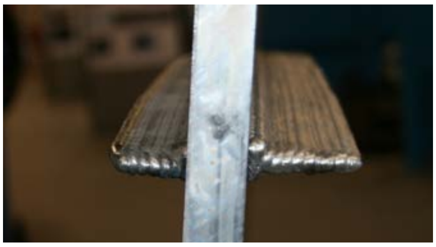

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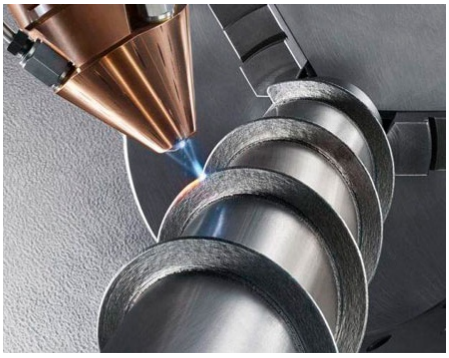
Metal Additive Manufacturing

Very Simply

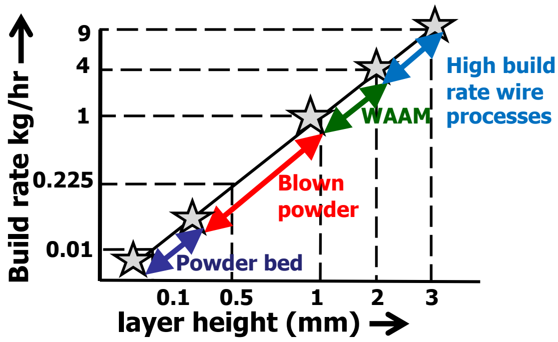


Melting ⇒ Welding

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 cladding
- Laser Engineered Net Shaping (LENS)
- Lasform
- Laser melting
- (Metal) Rapid Prototyping
- Net shape manufacture
- Net shape engineering
- Shaped deposition manufacturing
- Shaped melting
- Selective Laser Melting (SLM)
- Shaped Metal Deposition (SMD)
- Shape Melting Technology (SMT)
- Shape welding
- Solid freeform fabrication (SFF)

Basics of metal AM systems



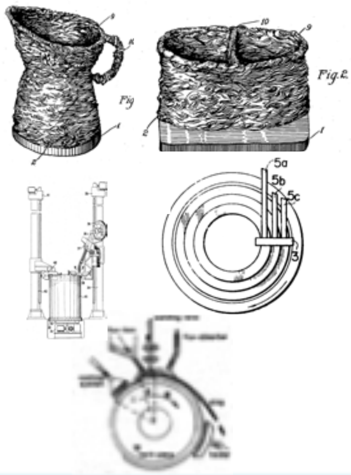
For a single axisymmetric energy source at maximum melting efficiency **build rate depends on the square of the layer height**

Resolution depends on the exact width to height ratio and on several other factors **but is usually about 1.5 times the layer height**

Metal Additive Manufacture - History

This idea 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"
- 1971 Ujiie (Mitsubishi) Pressure vessel fabrication using SAW, electroslag and TIG, also multi-wire with different wires to give functionally graded walls
- 1983 Kussmaul used Shape Welding to manufacture high quality nuclear structural steel (20MnMoNi5 5) parts – deposition rate 80kg/hr – total weight 79 tonnes



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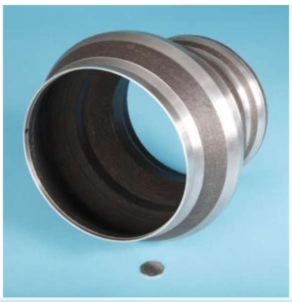
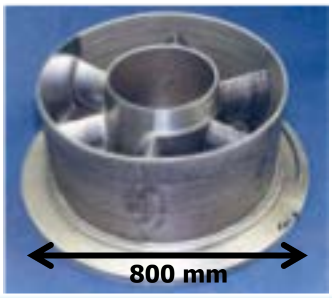
Metal Additive Manufacture - History

- 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 – still in production





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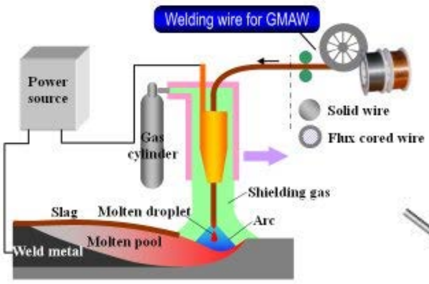
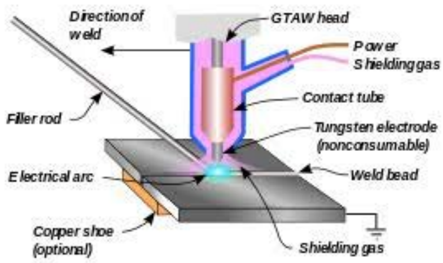
Arc Based Deposition Processes

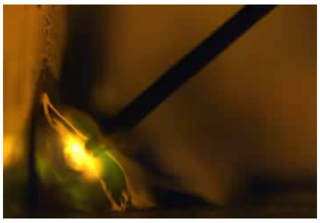


Gas Metal Arc

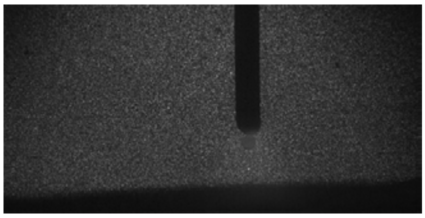
Gas Tungsten Arc



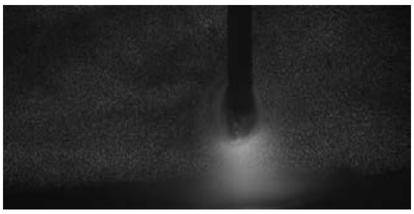
Deposition Gas Metal Arc Welding



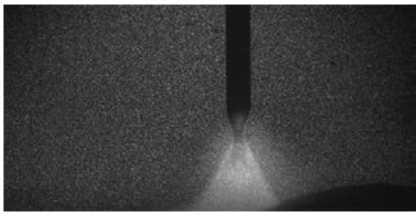
Short circuiting transfer



Pulsed transfer



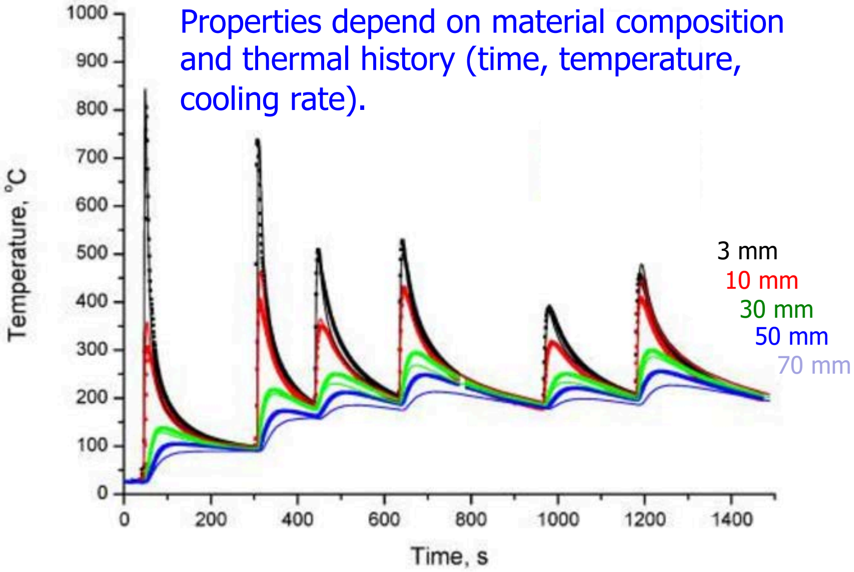
Globular transfer



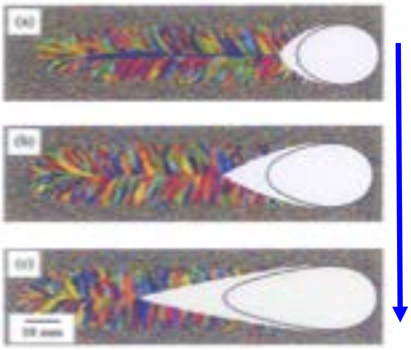
Streaming transfer

Thermal History

Properties depend on material composition and thermal history (time, temperature, cooling rate).



Microstructure field



Increased travel speed

Cross section, steel weld
Fusion Zone, Heat Affected Zone

Seijffers

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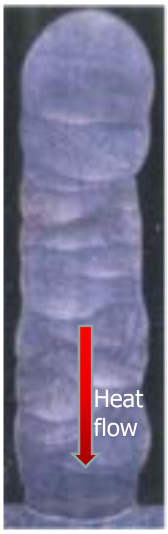
Microstructure field

- Solidification
- Uni-directional heat flow
- Metallurgical effects (solidification microstructure, segregation, solid state transformations, grain size, precipitation, tempering, etc..)



R. Seijffers
AISI316L/GTAW

Transverse cross Section

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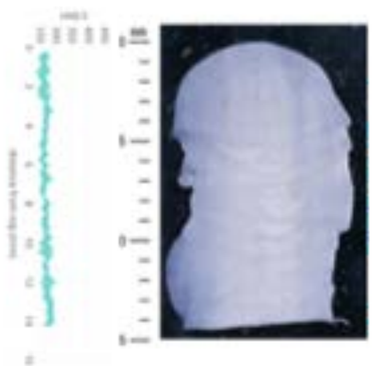
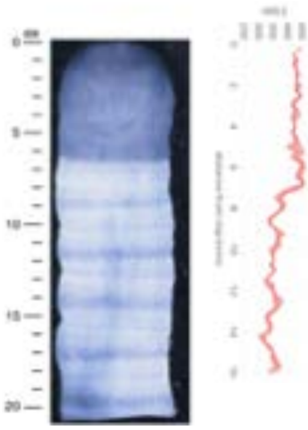
Cooling during deposition



No cooling

Interpass time 7 s, 16 layers



Cooling

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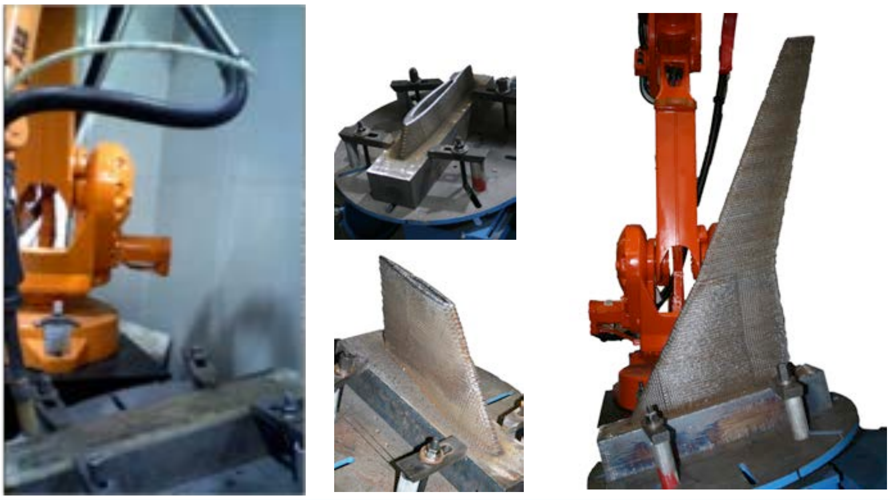
Wire Arc Additive Manufacturing (WAAM)



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Video & Images courtesy Cranfield University

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WAAMpeller Project

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Courtesy: DAMEN & RAMLAB

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WAAMpeller Project

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Courtesy: RAMLAB

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WAAMpeller project

Total weight: 410 kg

- Weight Hub/Cap/Shaft/: 48kg/~5kg/~20kg = 73 kg
- Total welded wire ~ 337 kg
- Total build time: ~300 hours at ~1,6 kg/hour

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Courtesy: RAMLAB

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WAAMpeller Project

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Courtesy: DAMEN & RAMLAB

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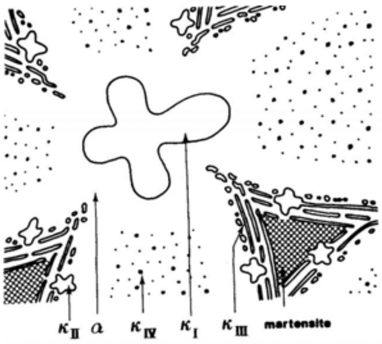
Nickel Aluminum Bronze - Microstructure

- *α phase: Cu-rich, FCC*
- *β phase: Cu-rich, BCC (HCP-martensite)*



H. Meigh, Cast and wrought aluminium bronzes, properties, processes and structure. Leeds: Maney Publishing, 2000.

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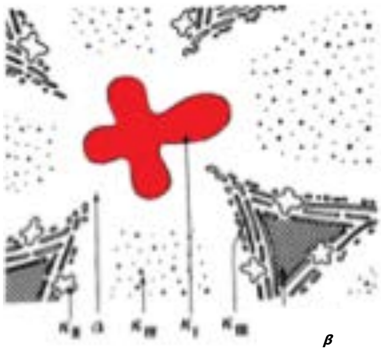
Nickel Aluminum Bronze - Microstructure

- *α phase: Cu-rich, FCC*
- *β phase: Cu-rich, BCC (HCP-martensite)*
- *κ_1 : 20-50 μm*



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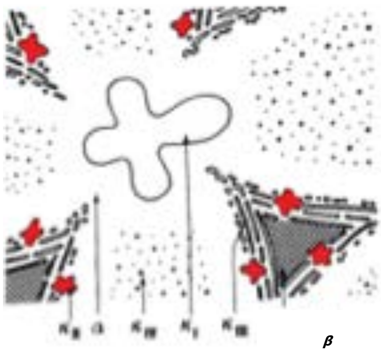
Nickel Aluminum Bronze - Microstructure

- *α phase: Cu-rich, FCC*
- *β phase: Cu-rich, BCC (HCP-martensite)*
- *κ_1 : 20-50 μm*
- *κ_2 : 5-10 μm*



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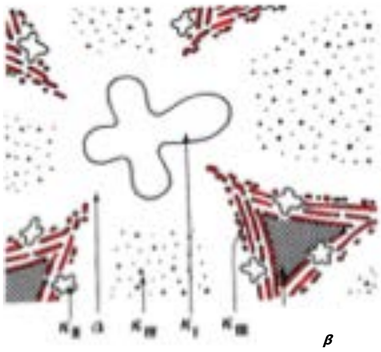
Nickel Aluminum Bronze - Microstructure

- α phase: Cu-rich, FCC
- β phase: Cu-rich, BCC (HCP-martensite)
- κ_1 : 20-50 µm
- κ_2 : 5-10 µm
- κ_3 : lamellar form



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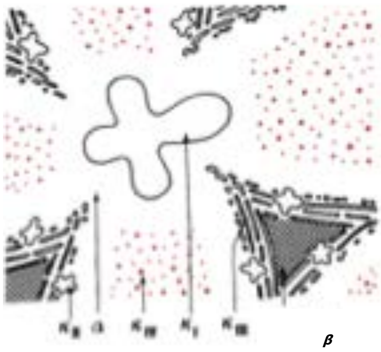
Nickel Aluminum Bronze - Microstructure

- α phase: Cu-rich, FCC
- β phase: Cu-rich, BCC (HCP-martensite)
- κ_1 : 20-50 µm
- κ_2 : 5-10 µm
- κ_3 : lamellar form
- κ_4 : 2 µm



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WAAM CuAl8Ni6 - Microstructure

As Cast

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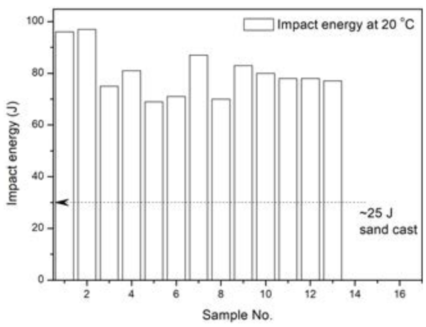
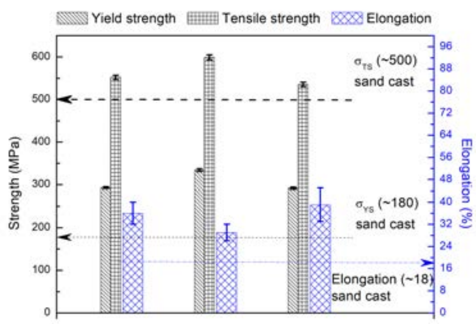
Anisotropy in mechanical properties of 3D-Printed Bronze





TD WD BD
Directions

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Case: Large offshore crane hooks

- Hooks: critical part of large offshore construction cranes
- Safe Working Loads (SWL): ranging from 100 – 10000 tons
- Conventional production: forging, casting
- Size range: 1m – 5.5m

Cast Ramshorn (2-prong) hook

- With size, both delivery time and material quality challenges increase

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Case: Large offshore crane hooks

Cast 4-prong hook

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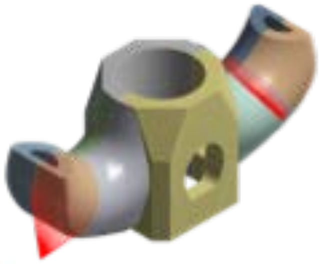
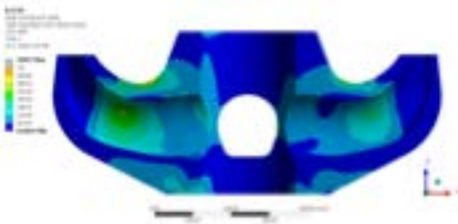
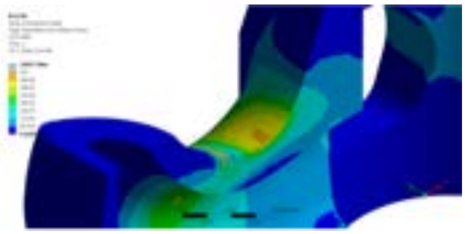
Case: Large offshore crane hooks



Weight approx. 1000 kg

Width approx. 1.1 m





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AM Technical Challenges

- Control of defects
- Extended models for more complex shapes
- Improved process monitoring and error prediction
- Improve process accuracy at smaller length scales
- Integrated machining
- Commercial software
- Commercial hardware
- Turn-key operation

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AM Scientific Challenges

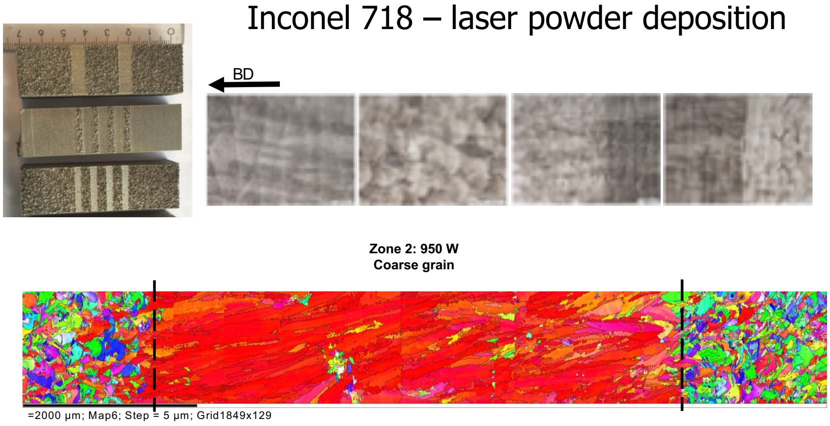
- Predict temperature and stress fields
  - Influence of energy source
  - Influence of fluid flow
- Predict and control microstructures
  - Multiple heating and cooling cycles
- On the basis of the microstructure and thermal-mechanical history, predict mechanical properties
- Build the predictions into the optimisation models to determine build process, strategy *etc*.

Additive Manufacturing for Extra Large Components (AiM2XL)

- Offer a **new** materials-centric approach to additive manufacturing, focusing on large-scale components
- Integrate design, microstructure and material properties through physically based models, delivering a **unique capability** to produce properties on demand
- Provide the **fundamental knowledge** necessary for development and exploitation at the large scale

Controlled and Graded Microstructures

Inconel 718 – laser powder deposition



Popovich *et al.* 2017

The AiM2XL Programme

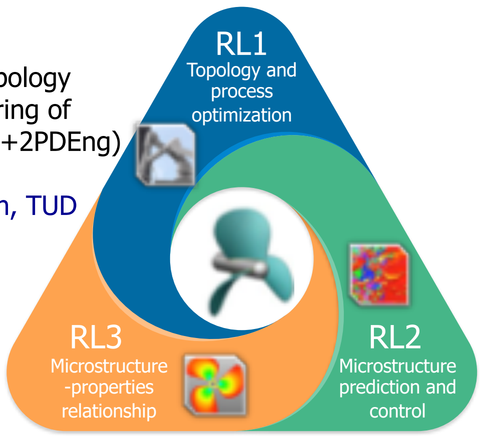
RL1

Project 1: Microstructure based topology optimisation for additive manufacturing of very large metal components (1PhD+2PDEng)

prof. van Keulen, TUD

Project 5: Sensing and adaptive Control for quality assurance during large scale additive manufacturing of metal components (1PhD+2PDEng)

prof. Römer, U. Twente



Perspectief

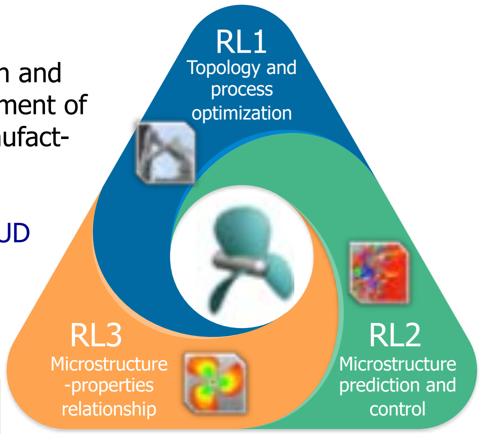
The AiM2XL Programme

RL2

Project 3: Microstructure prediction and composition control for the development of tailored properties in additively manufactured metallic components (2PhD+1 PDEng)

dr. Hermans, TUD

Project 4: Local and global scale prediction and control of residual stresses and distortion in additively manufactured components (2PhD)



prof. van den Boogaard, U. Twente

The AiM2XL Programme

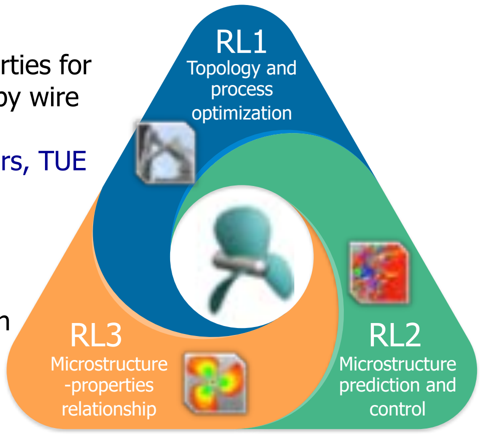
RL3

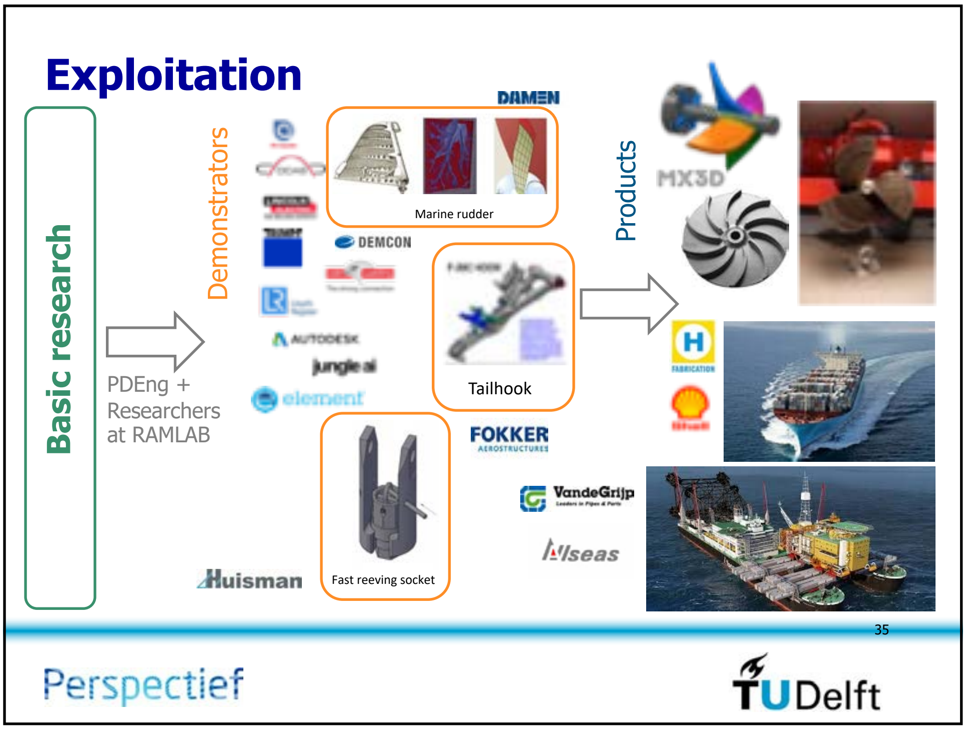
Project 2: From structure to properties for large-scale additive manufacturing by wire deposition (2PhD)

prof. Geers, TUE

Project 6: From structure to Properties for large-scale additive manufacturing by powder deposition (1PD)

prof. Pei, U. Groningen




Exploitation
Basic research
PDEng +
Researchers
at RAMLAB
Demonstrators
DAMEN
Marine rudder
DEMCON
Tailhook
AUTODESK
jungle ai
element
FOKKER
Fast reeving socket
Huisman
Products
MX3D
VandeGrijp
Allseas
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Thank you for your attention!
Questions?

Scientific Challenges

1. Properties on demand

Account for path, speed and power variations at the design optimisation stage

Develop gradient deposition conditions (composition / properties) to avoid sharp interfaces

2. Topology optimization

Develop optimisation strategies for multiple criteria, including process flow and post processing treatments

Control properties by adapting thermal-mechanical conditions

3. Enhance local microstructures and properties

4. Tailor graded microstructures

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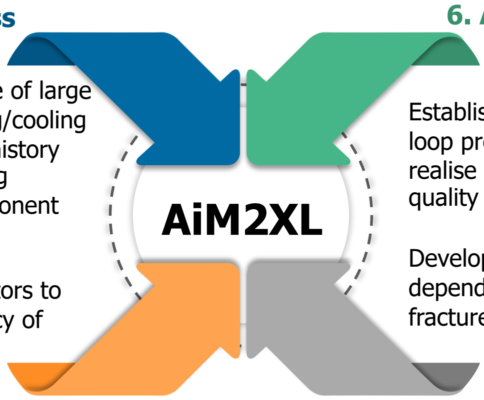
Scientific Challenges

5. Control stress and distortion

Model the influence of large numbers of heating/cooling cycles on thermal history and work hardening throughout a component

Produce demonstators to explore the accuracy of model predictions

8 Demonstrators



6. Adaptive closed loop process control

Establish adaptive closed loop process control to realise on-line product quality control

Develop orientation-dependent strength and fracture behaviour models

7. Investigate material and component properties

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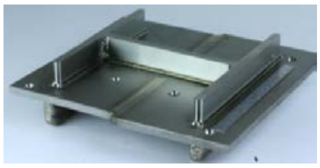
WAAM - Process features (1)

Inclined torch (CMT)

Angled and horizontal walls

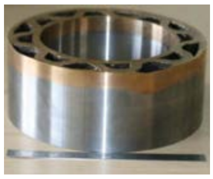
Straight near net shape Ti thin wall



Machined intersections

Medium complexity 2D part

Weight efficient structure



With mixed materials

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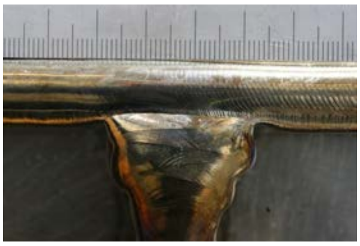
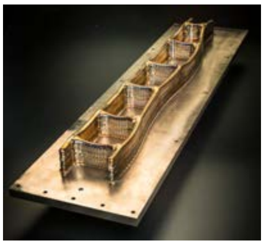
WAAM Example part - Titanium Spar



- 1.2 m long, welded titanium spar
- 37 hours from digital model to completed part



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Images courtesy Cranfield University

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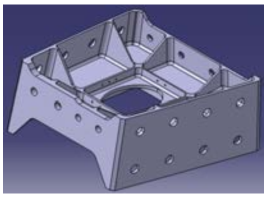
WAAM - Example part - Landing gear rib



	Before (kg)	After (kg)	Buy-to-fly	Waste
Machining	240	21	11.6	91%
AM	24	21	1.15	13%

Deposition time - 24 hours

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Images courtesy Cranfield University

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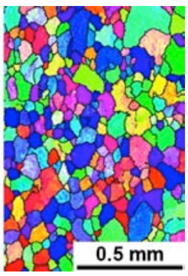
Additive Manufacturing

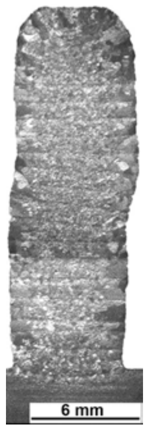
Met. & Mater. Trans. A, [1073-5623] 44A(2), 968 -977, 2013. Courtesy Cranfield University & UMIST

Titanium deposit

No mechanical deformation

75 kN mechanical deformation





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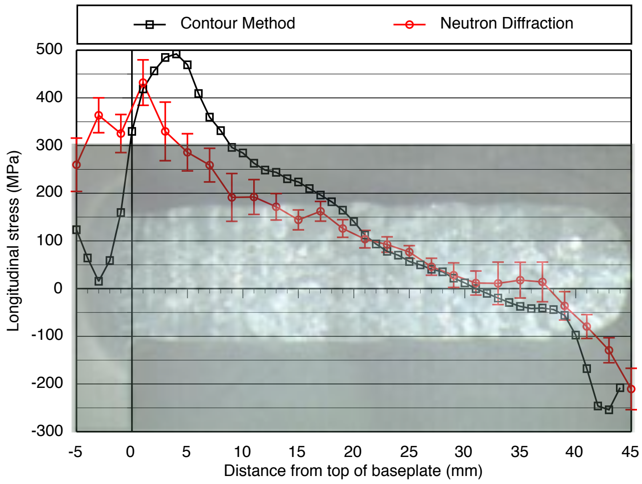
Residual Stresses



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Courtesy Cranfield University

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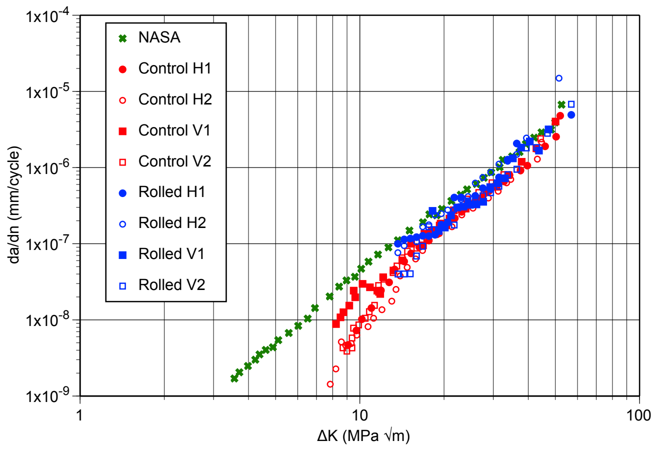
Fatigue crack growth rate (Ti alloy)



- Rolling has no negative influence on damage tolerance
- Fatigue crack growth rate is isotropic

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Courtesy Cranfield University

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Additive Manufacturing - challenges

AM construction is currently process driven and many limitations exist, including:

Porosity Control

Poor Repeatability

High Residual Stresses

Anisotropy

Excessive Distortion

Lack of Predictability

Lack of Feedstock homogeneity

Absence of Process – Property Models

Lack of Reliable Property Control

Variable Process Stability

Difficulties with Up-scaling

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WAAMpeller Project

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Courtesy: DAMEN & RAMLAB

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