



Thermal Plasmas for Metal Additive Manufacturing

Online Low Temperature Plasma Seminar, 5 April 2022

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David G Thomas², Joshua Kim¹

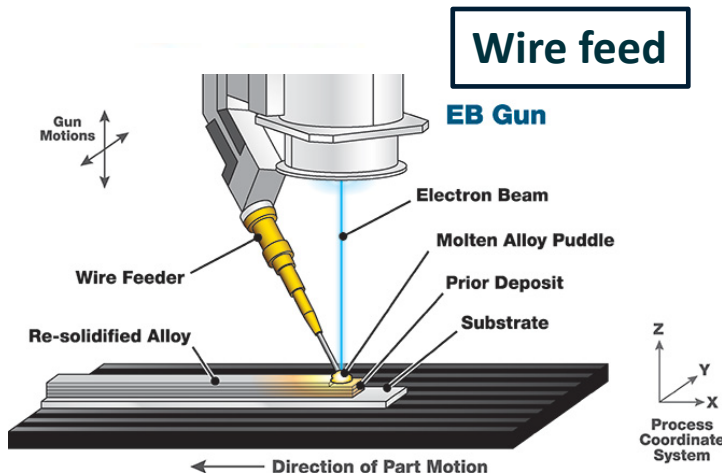
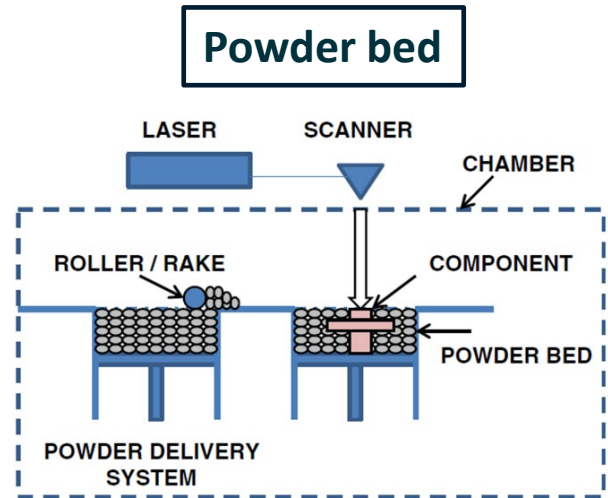
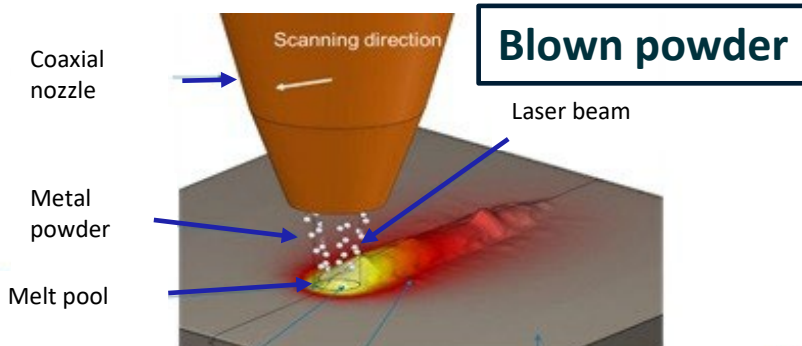
¹ CSIRO Manufacturing ² CSIRO Data61

Metal additive manufacturing (3D printing) produces metal parts layer-by-layer



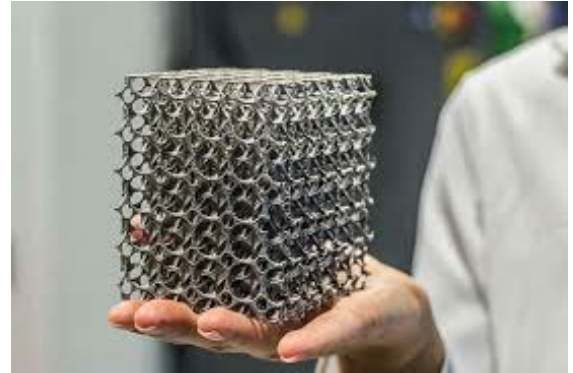
Laser powder-bed fusion

Metal additive manufacturing uses metal powder or wire, and a power beam (laser, e-beam, arc)



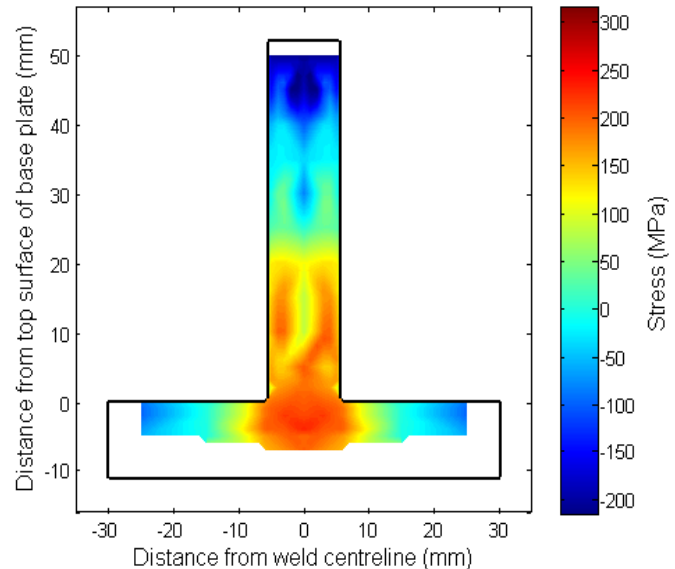
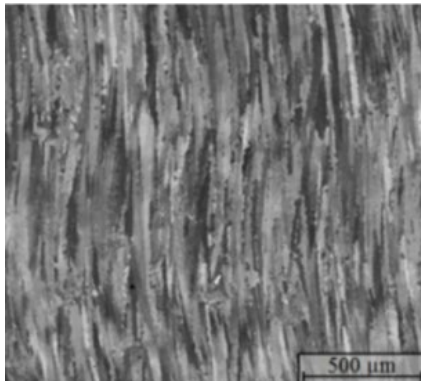
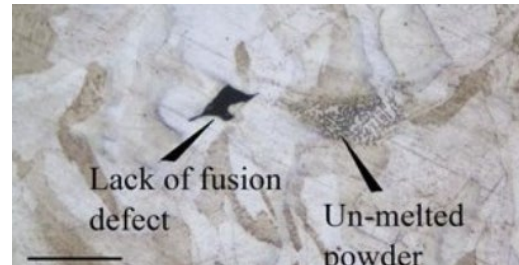
Metal additive manufacturing has many advantages

- Customised designs
- Reduced weight
- Low waste
- Novel structures
- Porous structures (e.g. implants)



However, there are also disadvantages

- Powder-bed processes are slow and the machines are expensive
- Defects (lack of fusion, porosity) can occur
- Repeated heating and cooling cycles can cause large residual stresses
- Metal microstructures can be difficult to control



What does metal additive manufacturing have to do with plasma?

1. The powder precursors are widely produced using thermal plasma technologies
2. Wire-arc additive manufacturing (WAAM) is a thermal plasma process

Low-pressure plasmas



Semiconductor etching
Fluorescent lighting
Thin-film deposition

Atmospheric-pressure non-equilibrium plasmas



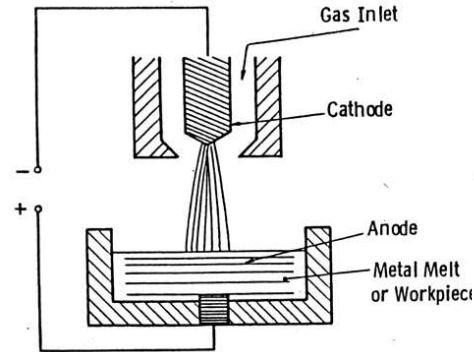
Ozone production
Electrostatic precipitation
Polymer treatment
Gas cleaning
Sterilisation / medicine
Plasma TVs

Thermal plasmas

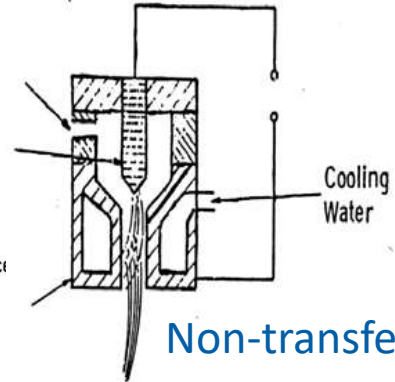


Arc welding
Plasma spraying
Plasma cutting
Mineral processing
Waste treatment
Arc lamps

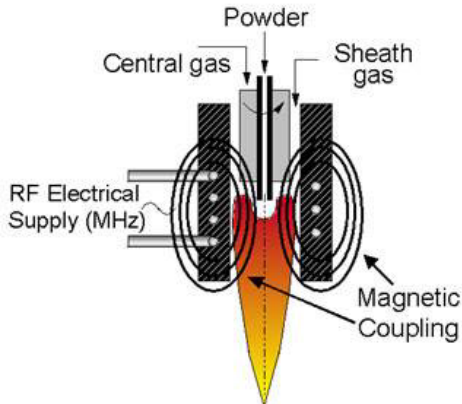
There are three main types of thermal plasma



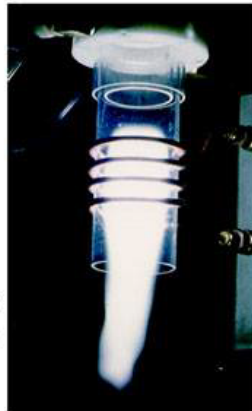
Transferred arc



Non-transferred arc



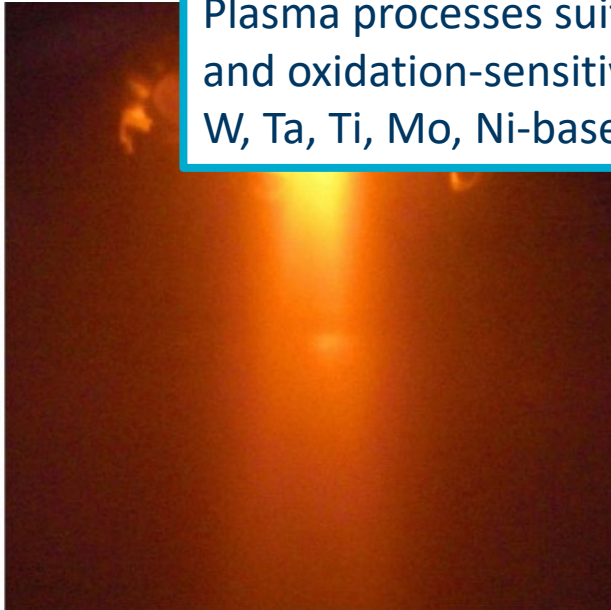
RF inductively coupled plasma



Powder production for additive manufacturing

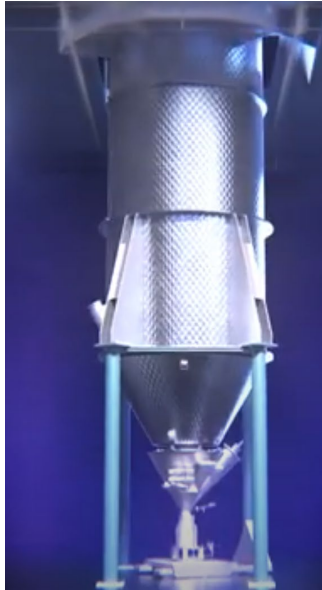
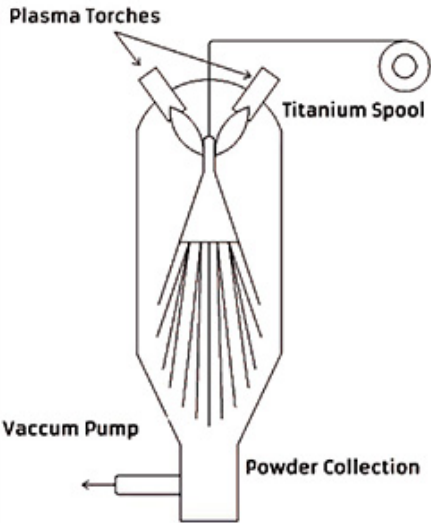
Powder production for metal additive manufacturing

- Gas atomisation
- Induction melted bar atomisation
- Water atomisation
- Plasma atomised wire process
- Plasma rotating electrode process
- Plasma spheroidisation

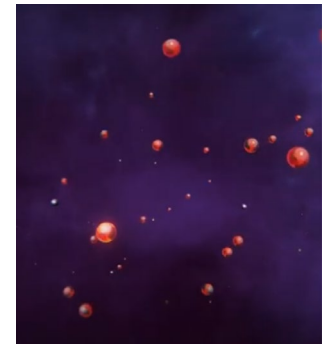
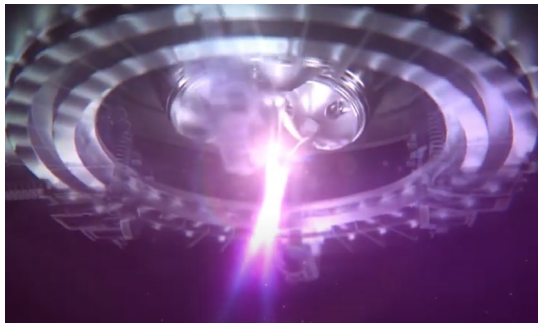
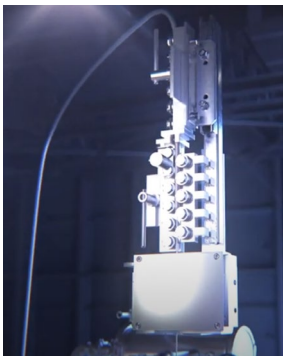


Plasma processes suit high-melting-point and oxidation-sensitive materials:
W, Ta, Ti, Mo, Ni-based superalloys, WC, ...

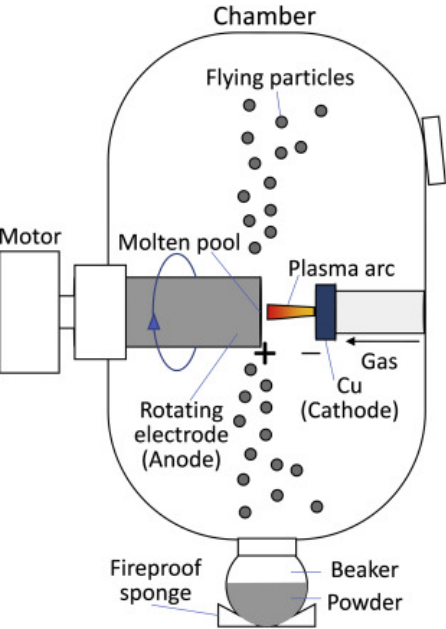
Plasma atomised wire process



AP&C Powder (GE) (USA)
Pyrogenesis (Canada)



Plasma rotating electrode process



Electrode diameter \ Rotation speed	15mm		25mm	
7000rpm				
9000rpm				
11700rpm				

Y. Cui et al., Powder Technol. **376** (2020) 363

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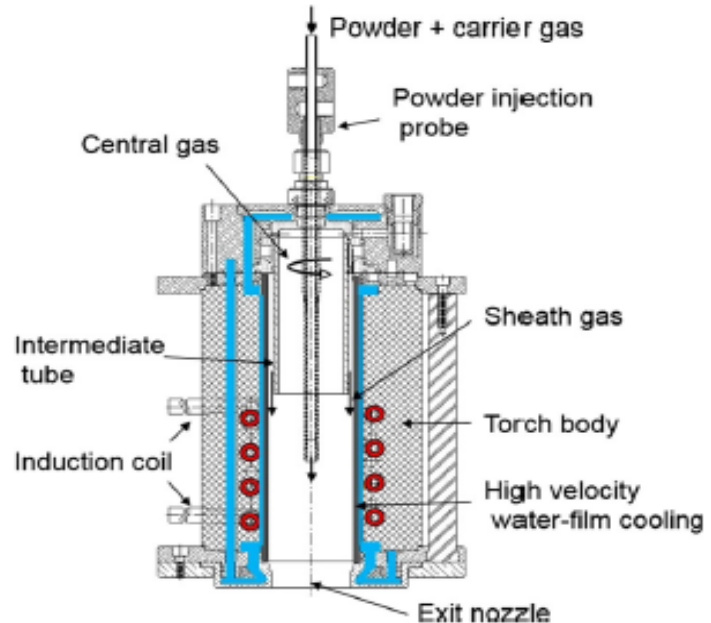
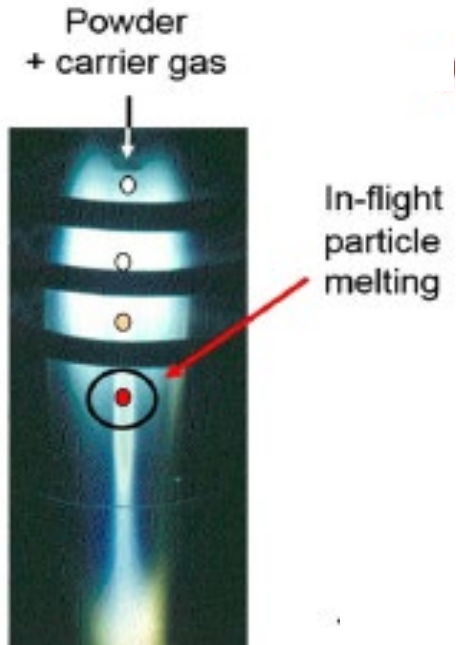
Fukuda Metal Foil & Power Co. (Japan)

Shanghai Truer Industrial Development Co. (China)

MTI Co. (China)



Plasma spheroidisation

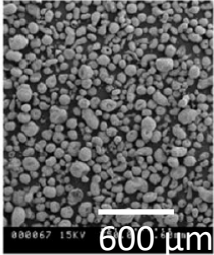


Tekna (Canada)

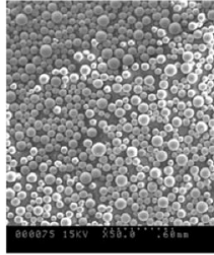
Advanced Metallurgy Technology (China)

Powder sphericity decreases with increasing feed rate

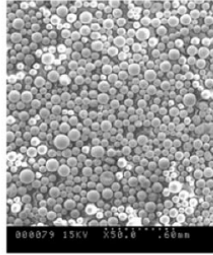
Feed powder



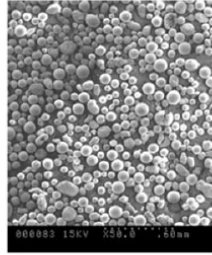
7kg/h



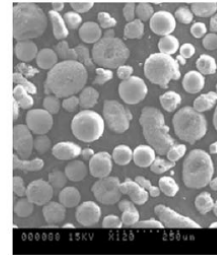
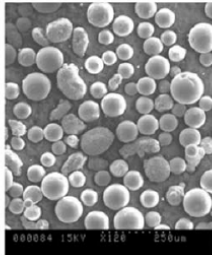
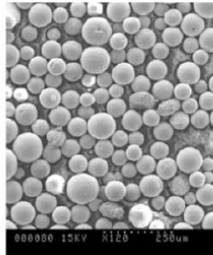
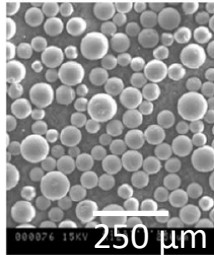
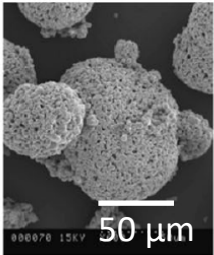
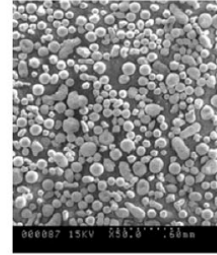
15kg/h



20kg/h



25kg/h



Tap Density 3.2 g/cc
Hall Flow 36 s

6.35 g/cc
13.0 s

6.25 g/cc
14.0 s

5.8 g/cc
16.0 s

5.0 g/cc
19.0 s

Mo powder

Tekna PS-70 torch, 100 kW, 110 kPa, Ar + H₂

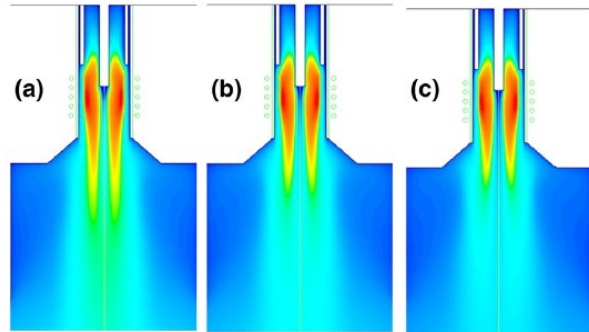
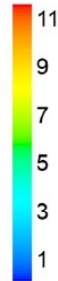
M I Boulos, Plasma Chem. Plasma Process. **36** (2016) 3

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Increasing the powder feed rate decreases the plasma and powder temperature

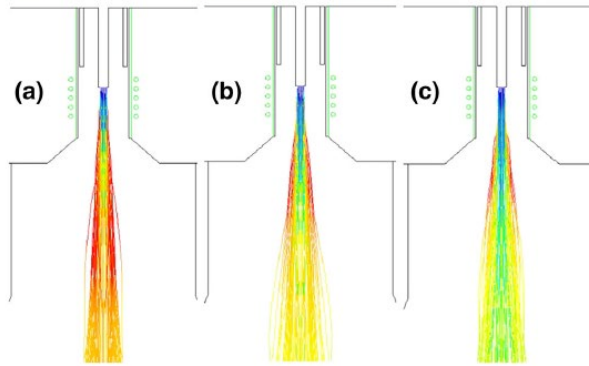
Plasma temperature

$T(10^3 \text{ K})$



Powder temperature

$T_p(10^3 \text{ K})$

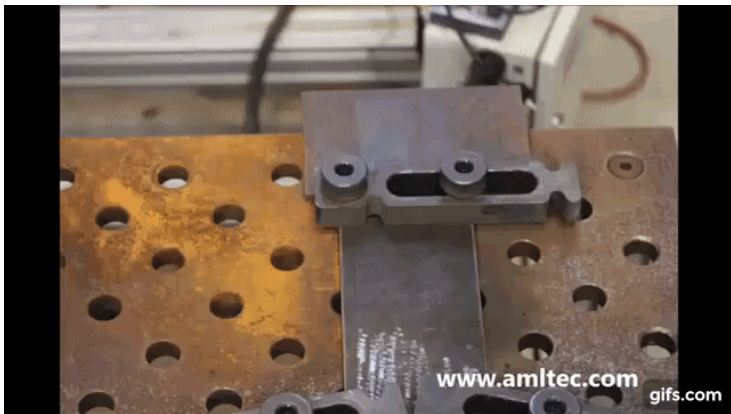
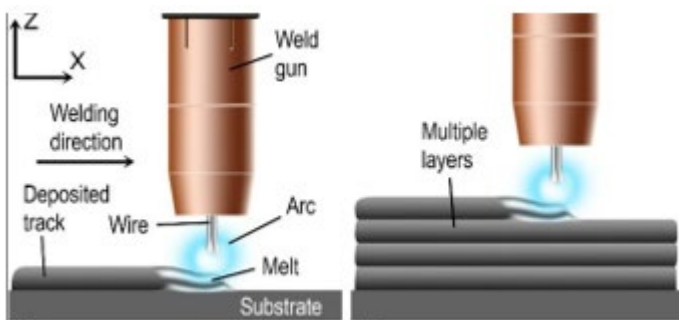
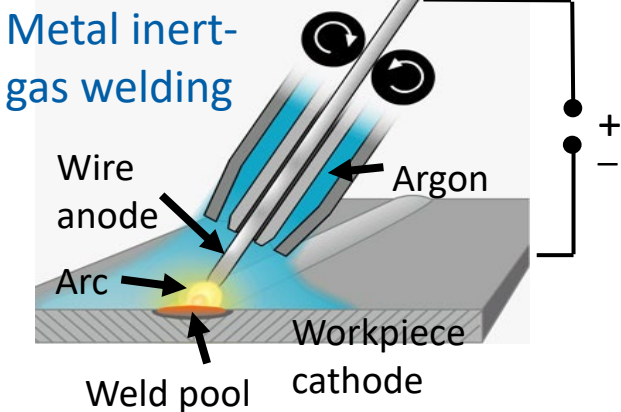


Mo powder
Tekna PS-70 torch
100 kW, 110 kPa
Ar + H₂

Feed rate	=7.5 kg/h	15 kg/h	25 kg/h
Melted fraction	=100.0%	100.0%	67.0%
Evap. Fraction	= 5%	1.7%	0.7%

Wire-arc additive manufacturing

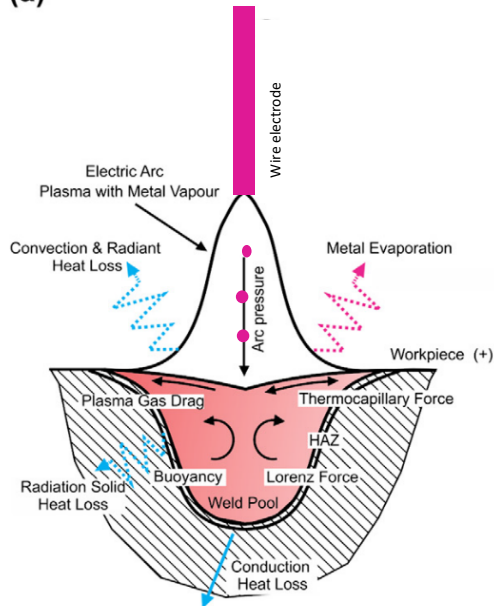
Wire-arc additive manufacturing is based on arc welding, and is used for producing large components



There are two main approaches to modelling of wire-arc additive manufacturing and arc welding

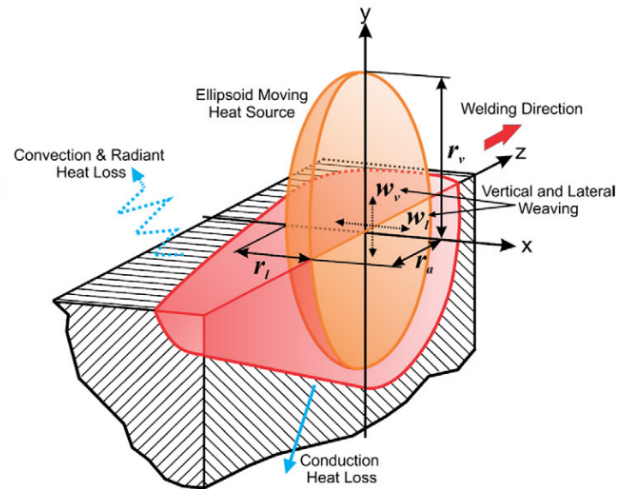
**Computational fluid dynamic
(+ electromagnetic) model of
melt/weld pool and arc**

(a)



**Finite-element
thermomechanical model of
workpiece (the metal part
being built or welded)**

(b)



O. Muransky et al., Int. J. Solids Structures **49** (2012) 1045

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Computational fluid dynamics

Advantages

- Contains all important physics (fluid flow, electromagnetics, heat transfer – conductive, convective and radiative)
- Provides detailed information

Disadvantages

- Complex and relatively slow
- Limited to small components
- Can run in steady-state mode to speed up – but this can only handle
 - Straight line builds
 - Complete cooling between each layer

Finite element analysis

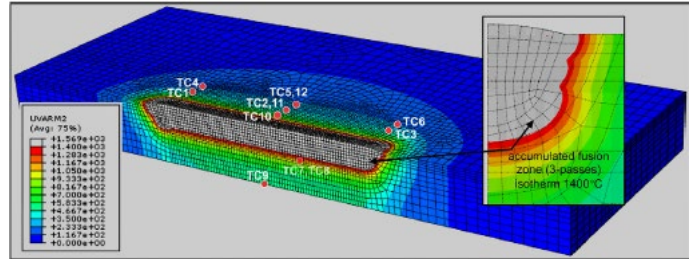
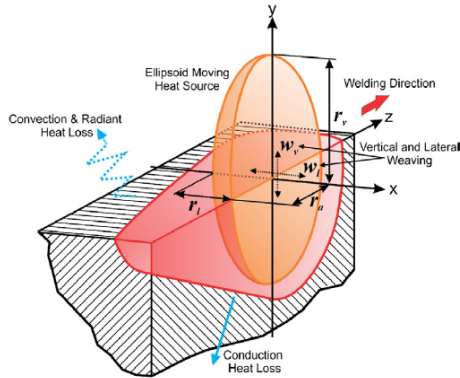
Advantages

- Relatively simple and fast
- Multiple layers straightforward
- Large components can be modelled
- Can predict residual stress and distortion
- Commercial software widely available

Disadvantages

- Fluid flow, electromagnetics, radiative heat transfer neglected
- Layer geometry is approximate
- See next slide

In finite element analysis, detailed experiments are required to determine the heat source

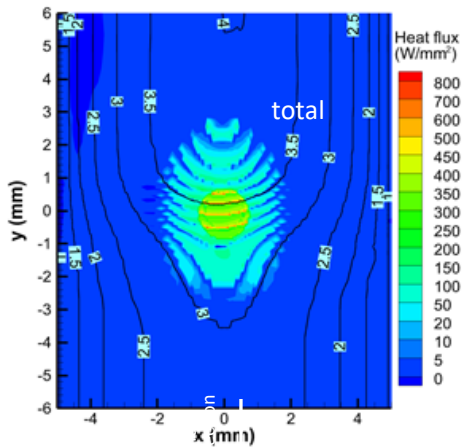


The free parameters (ϵ , a , b , c) are determined by fitting predicted thermal histories to thermocouple measurements

$$q = \epsilon VI \exp \left[-\left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2 - \left(\frac{z}{c}\right)^2 \right]$$

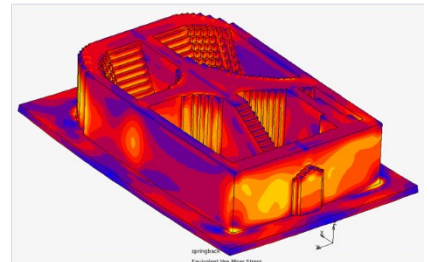
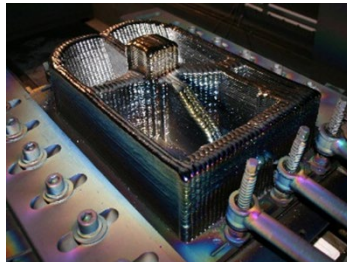
The free parameters change when the WAAM parameters (current, travel speed, wire angle, workpiece geometry, ...) are altered

We are adopting a hybrid approach to model wire-arc additive manufacturing



Use our ArcWeld software (a CFD/EM model of the arc plasma and weld pool) to calculate the shape of each layer and the heat flux to the workpiece

Use this data as the input to commercial finite element software to calculate the temperature and residual stress distributions



ArcWeld models the arc, electrodes & weld pool with CFD equations + **plasma & electromagnetic** effects

$$\text{Mass: } \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\text{Momentum: } \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla P - \nabla \cdot \boldsymbol{\tau} + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g}$$

$$\text{Energy: } \frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \mathbf{v} h) = \frac{\mathbf{j}^2}{\sigma} - U - \nabla \cdot \left(\frac{k}{c_p} \nabla h \right) + \frac{5k_B}{2ec_p} \mathbf{j} \cdot \nabla h$$

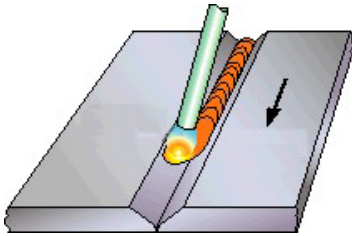
$$\text{Charge: } \nabla \cdot \mathbf{j} = 0$$

$$\text{Also: } \mathbf{j} = -\sigma \nabla \phi, \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$

- Three-dimensional Cartesian geometry, usually steady-state
- Internal heat transfer boundary conditions imposed at arc-metal interfaces
- In-house code using a finite-volume approach

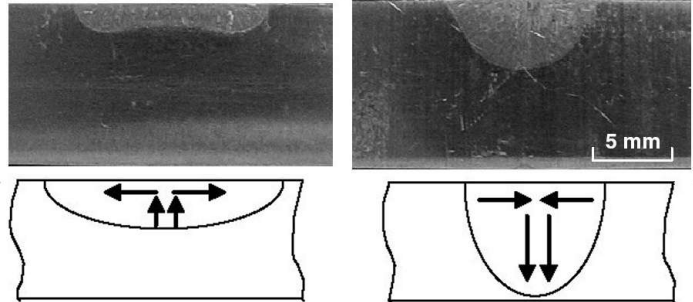
Important complications have to be treated

Wire motion along weld seam

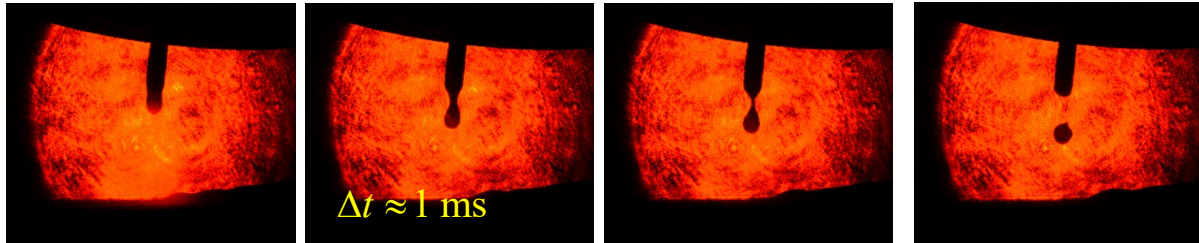


Transform equations into frame of reference of moving wire & arc

Weld pool flow has to be tracked



Calculate flow, considering Marangoni force, droplet momentum, magnetic pinch force, arc drag force and buoyancy

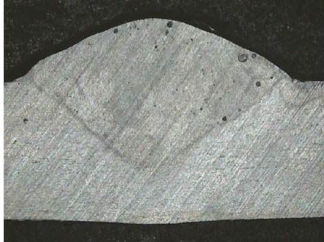


Transfer by **droplets** of momentum and energy to the weld pool

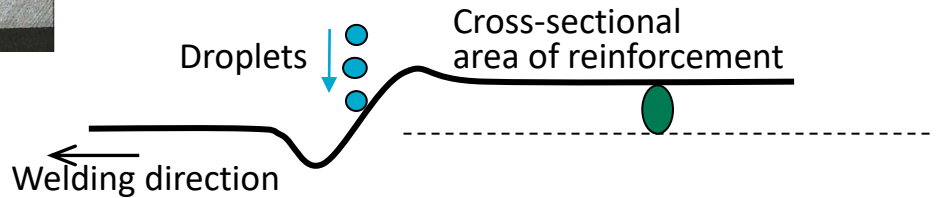
Average the transfer of momentum and energy from arc and to weld pool over time and over droplet cross-sectional area

Important complications have to be treated

The weld pool **surface profile** is not flat



Calculate the surface profile of minimum energy, taking into account surface tension, arc pressure, droplet pressure, buoyancy and volume of metal transferred by droplets



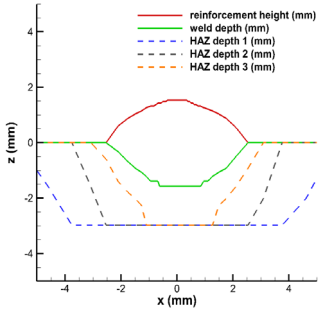
Production of **metal vapour** from the wire, droplets and weld pool



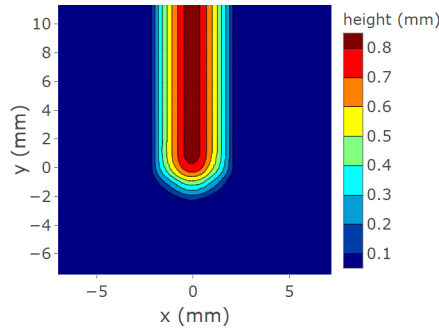
Calculate the rate of vaporization of wire, droplets and weld pool, and solve equation for conservation of metal vapour mass

Three sets of results are produced

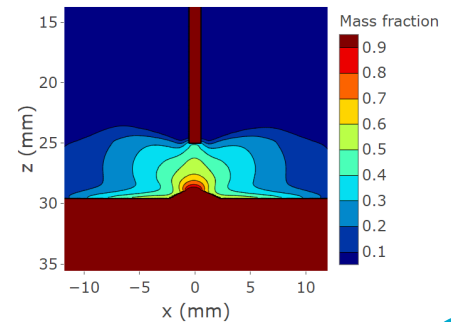
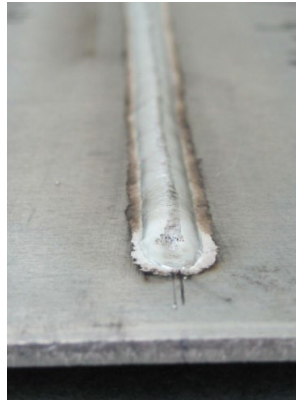
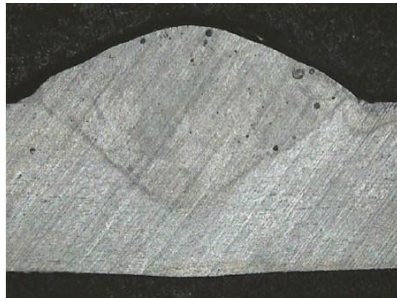
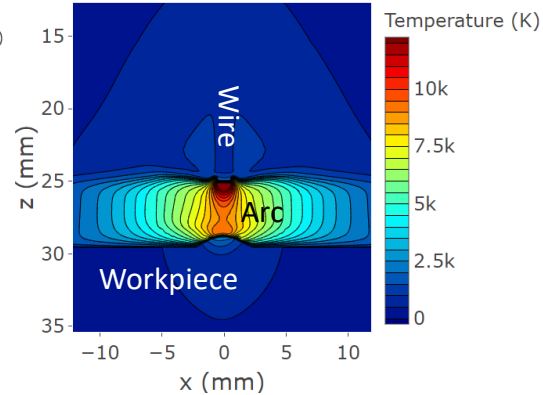
Weld cross-sections



Surface profile during weld

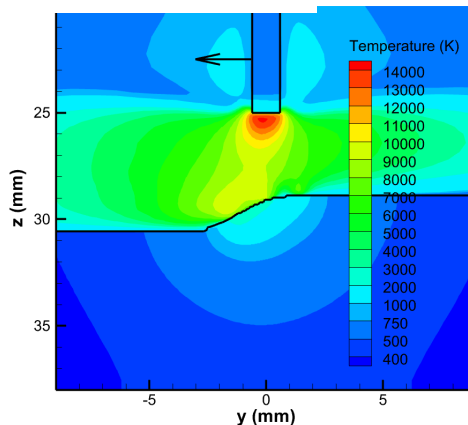
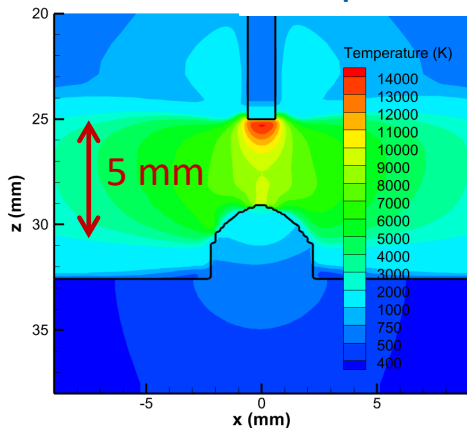


Temperature, velocities, current density, metal vapour fraction, etc., during weld



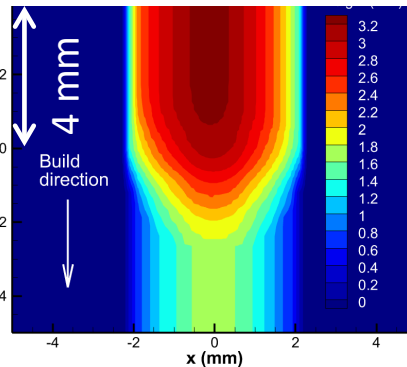
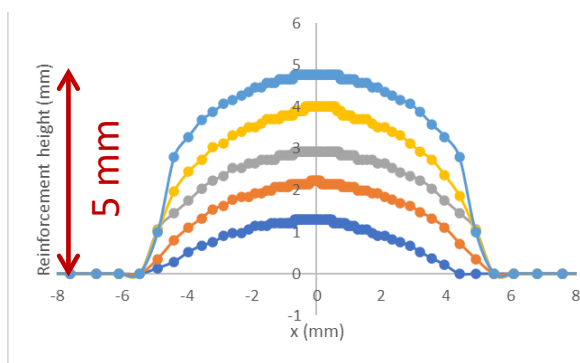
The model has been extended to treat several layers

Temperature (400 - 14,000 K)



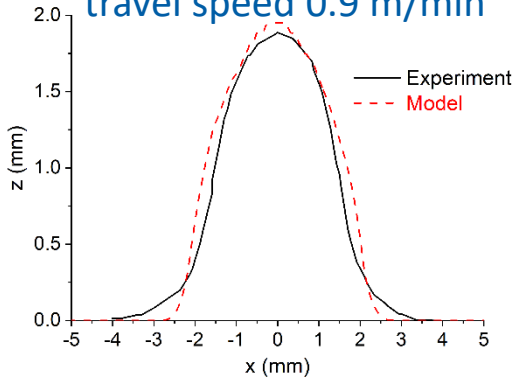
2nd layer

Cross-sections of first five layers Workpiece height (0 - 3.2 mm)



Benchmarking against measurements 1

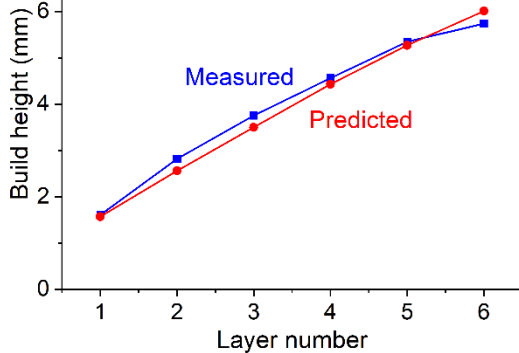
Initial layer cross-section,
travel speed 0.9 m/min



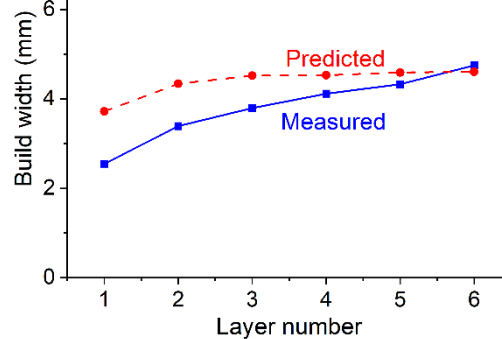
A. Gomez Ortega et al., *Sci. Tech. Weld. Join.*
23 (2018) 316

- Cold-metal transfer
- Current: 2 ms @ 150 A peak, 9 ms @ 70 A base , 6 ms @ 40 A short-circuit
- Arc length: 5 mm peak, 3 mm base
- Wire feed rate: 5.15 m/min
- 1.2 mm AA4043 wire, 6 mm Al base plate

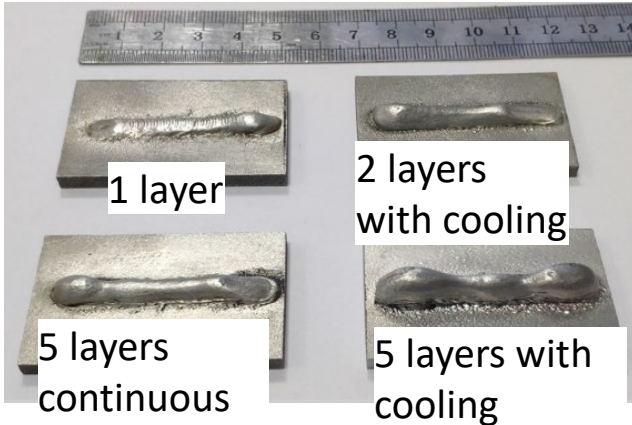
Height vs layer number
travel speed 1.2 m/min



Width 0.5 mm above base plate
vs layer number, 1.2 m/min

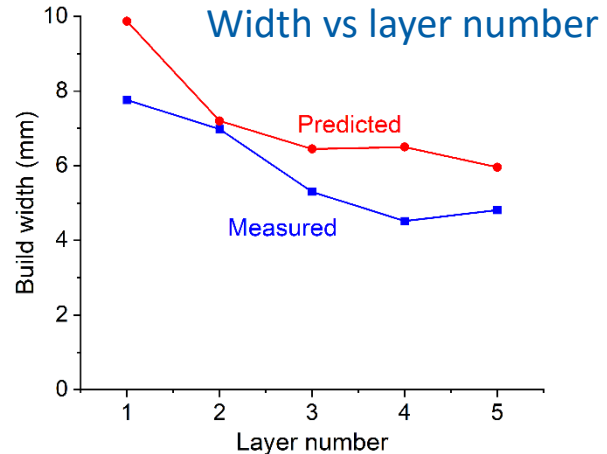
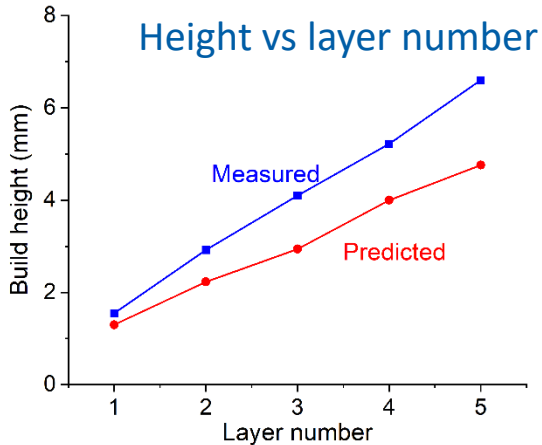


Benchmarking against measurements 2

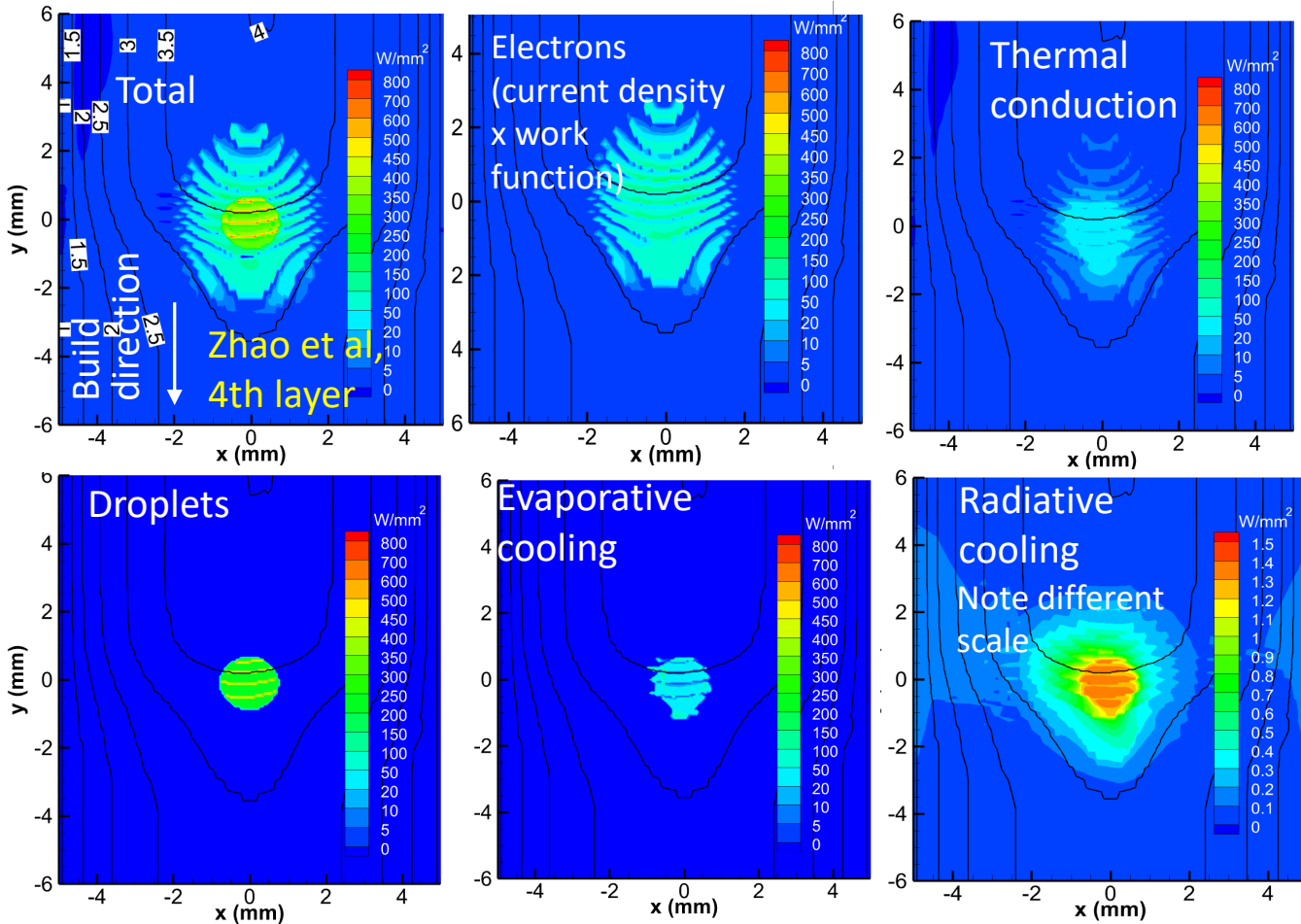


W. Zhao et al., *Weld. World.* **65** (2021) 1571

- Free-flight transfer
- Current: 135 A
- Arc length: 5 mm
- Wire feed rate: 9 m/min
- Travel speed 1.2 m/min
- 1.2 mm ER5356 wire, 4 mm 5A05 base plate (both Al-Si-Mg alloys)



Five heat transfer mechanisms are considered

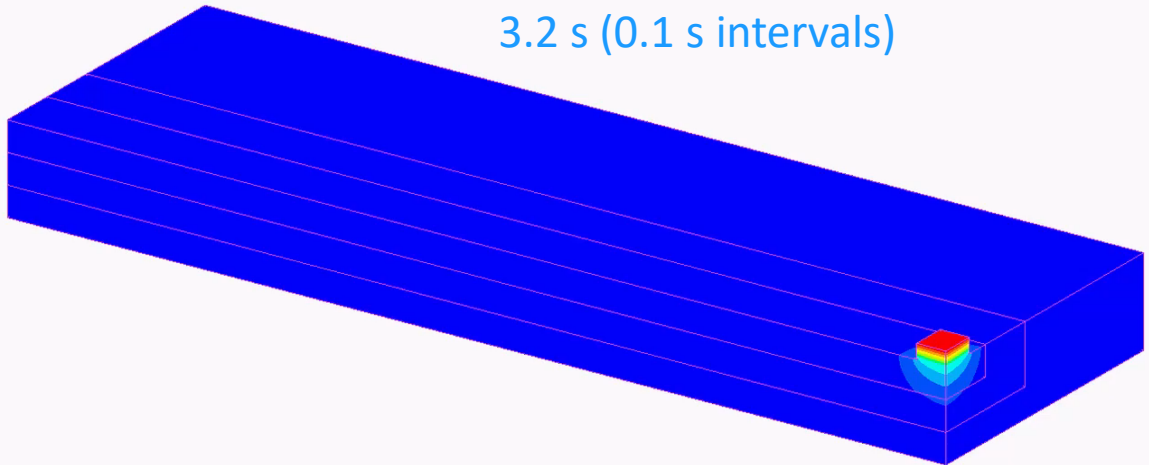


Finite element heat transfer model – initial layer

Input from ArcWeld: droplet temperature, heat flux, layer height and width

T (K)

51 mm long x 21 mm half-width x 6 mm thick
3.2 s (0.1 s intervals)



Max: 1.971e+03 @Node 265
Min: 3.000e+02 @Node 571687

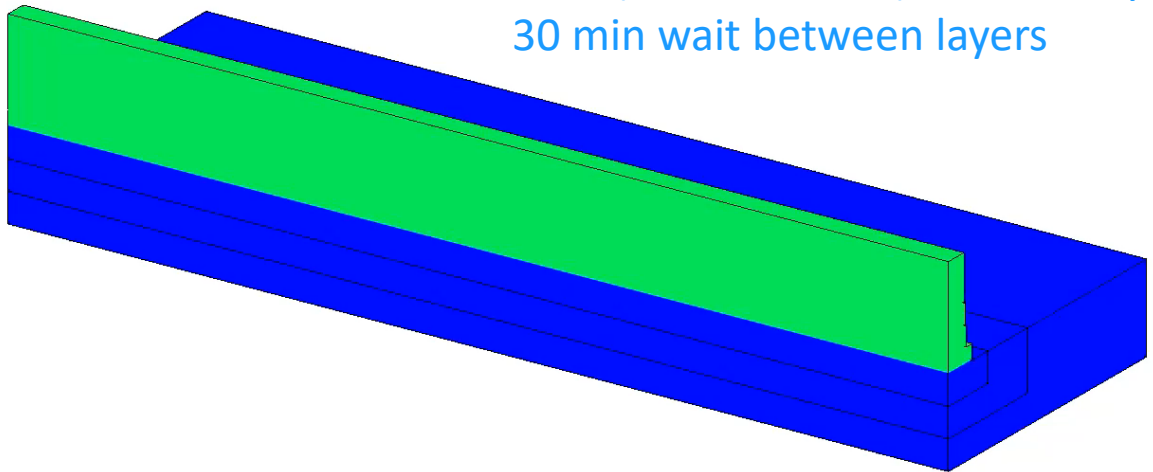
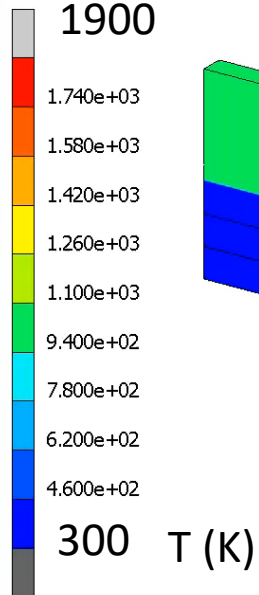
Welding
Temperature

Finite element heat transfer model – five layers

Input from ArcWeld: droplet temperature, heat flux,
layer height and width

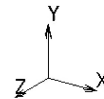
Inc: 0
Time: 0.000e+00

51 mm long x 21 mm half-width x 6 mm thick
3.2 s (0.1 s intervals) for each layer
30 min wait between layers

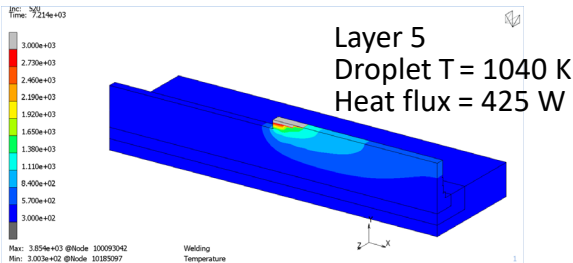
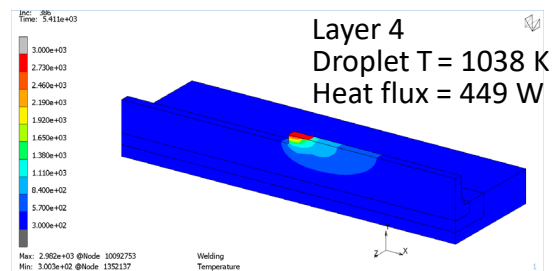
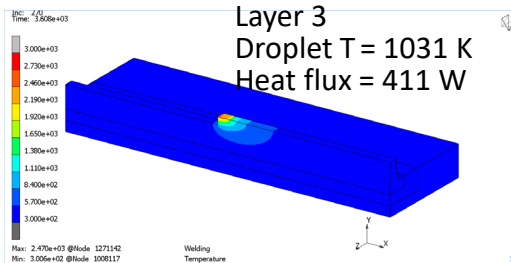
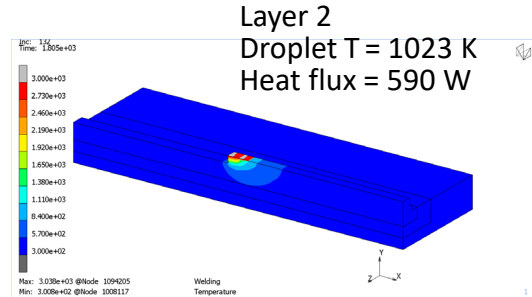
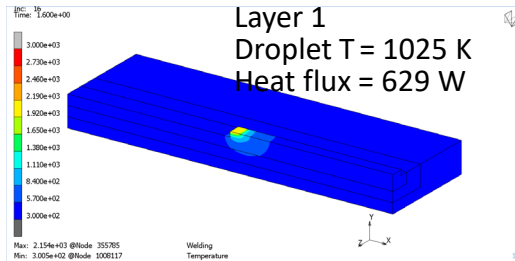
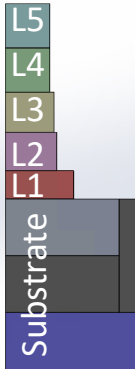


Max: 3.000e+02 @Node 318
Min: 3.000e+02 @Node 318

WAAM_thermal_only_with_L1_&_L2
Temperature



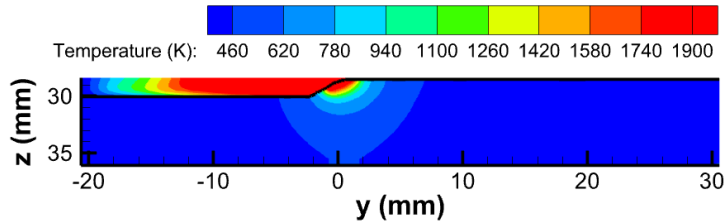
We have so far modelled five layers with the finite element model



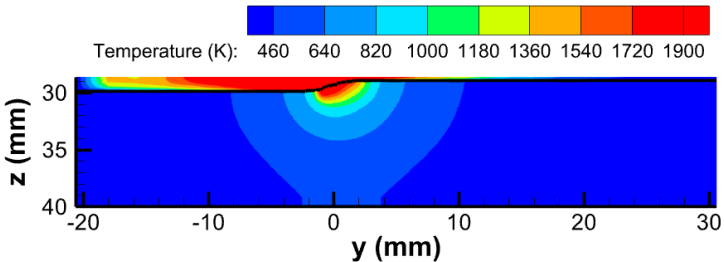
Rest time between deposition of layers = 1800 s (30 min)

Agreement between ArcWeld and finite element model temperature distributions is only fair

ArcWeld prediction

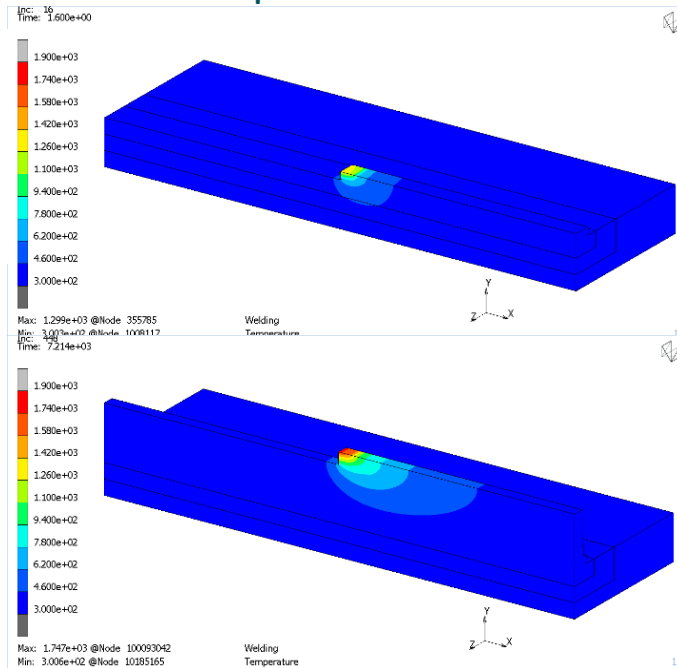


Layer 1

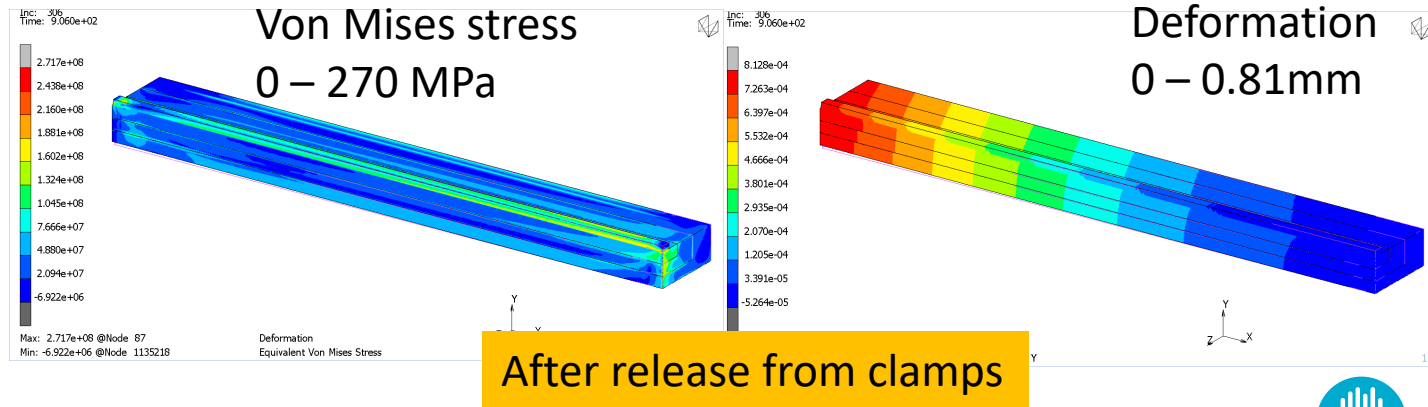
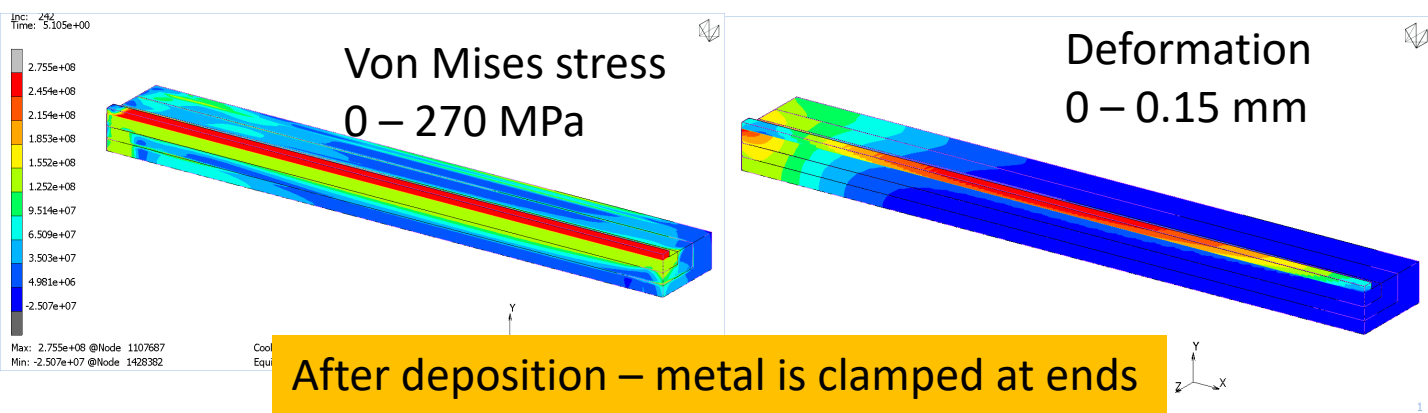


Layer 5

Finite element prediction



Residual stresses lead to deformation



Conclusions

- Metal additive manufacturing has several properties that make it attractive in industries including aerospace, biomedical, energy, ...
- Thermal plasma approaches are used for production of powders for metal AM, particularly for high-melting point or oxygen-sensitive metals
- Wire-arc additive manufacturing is suitable for rapid production of large parts
- We are extending our computational fluid dynamic / electromagnetic (CFD/EM) model of arc welding to wire-arc additive manufacturing
- The CFD/EM model is limited to small components and (for reasonable running time) steady-state operation
- We are therefore developing a hybrid CFD/EM – finite element model
- The CFD/EM model predicts the layer geometry and heat flux to the metal
- The finite-element model can calculate time-dependent temperature and residual stress distributions in large, complex components

Thank you

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