Simulation and Visualisation of Wire-Arc Additive Manufacture

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Overview

Background
previous work, WAAM process

MHD flow modelling
Plasma arc welding torch model

Schlieren imaging
Validation through optical diagnostics

Ongoing work
Trail shield, torch optimisation
Pressure validation


Wire – Arc Additive Manufacture (WAAM)

HiVE Chamber @ Cranfield University: gantry-based motion

Plasma arc welding torch

Ar supply (up to 195 lt/min)

Trailing shield

Printed part Ti-6Al-4V
PAW torch simulation layout

Plasma gas inlet

Shielding gas inlet

Ti-6Al-4V workpiece (Wall/substrate)

Ar-air thermal plasma in LTE

Highly non-linear multiphysics problem

Ar - air mixture properties $f(T, \omega)$
Plasma arc welding: Magneto-hydrodynamics
Simulating MHD flow with COMSOL

\[ \rho (u \cdot \nabla u) = \nabla \cdot \left[ -p + \mu (\nabla u + (\nabla u)^T) \right] + F \]

\[ \nabla \cdot (\rho u) = 0 \]

\[ -\nabla \cdot (k \nabla T) + \rho c_p (u \cdot \nabla T) = J \cdot E + \frac{5k_b}{2e} J \cdot \nabla T - 4\pi\varepsilon_N \]

\[ \nabla \times \left( \frac{1}{\mu_0} \nabla \times A \right) + \sigma \nabla V = 0 \]

\[ \nabla \cdot \sigma \nabla V = 0 \]

\[ -\nabla \cdot \left( \rho D_i^o \nabla \omega_i + \rho \omega_i D_i^o \frac{\nabla M_n}{M_n} + D_i^T \frac{\nabla T}{T} \right) + \rho (u \cdot \nabla) \omega_i = 0 \]

Implicit & explicit physics couplings

Compressible flow
(SST turbulence model)

Heat transfer
(Solids & Fluids)

Electric & Magnetic fields
(gauged)

Transport of concentrated species
(Ar & air)
Plasma jet – shield gas stream interaction

Temperature field partly constricted by nozzle
Arc pinches shield gas flow
Convective recirculation
Steady-state air entrainment

Lorentz force \((F_L = J \times B)\) high near electrodes
Stronger pull but similar air levels with higher current
\(~4k\ ppm air transported near melt pool (\!)\)
Deposited wall geometry: Temperature

Side jet inclination changes with wall width
Heat transfer to wall influenced by convective action
Also relevant to torch positioning during builds
Heat transfer to wall

Flow along wall enhances heat transfer

Inner and outer vortex structure
Wall geometry – $O_2$ concentration

Inert environment changes with wall geometry
Schlieren imaging

Light collimated between M1 & M2

Flow information = Refracted rays

Cut-off highlights $\frac{\partial n}{\partial x} \propto \frac{\partial \rho}{\partial x}$

Band pass filter at 633 ± 10 nm
Torch gas shield gradients

\[ \frac{\partial n}{\partial x} \propto \frac{\partial \rho}{\partial x} \]

Nozzle position relative to wall determines side jet angle

Turbulence increases with current & plasma gas flowrate
Ongoing work

Pressure measurements to further validate model

Momentum transfer in arc critical in understanding interaction with melt pool

No steady-state level set!
Results summary

MHD flow features validated from schlieren

Schlieren interpretation facilitated by simulation

Allows optimisation of WAAM process

Torch – Shielding – Manufactured part
HiVE local shielding system

- Inner vortex
- Outer vortex
- Trail shield bulk flow
- Fast boundary flow along wall, substrate
- Travel speed only affects thermal gradient
- Gas recirculation between side jet and built wall (inner vortex)
- Torch gradients interact with trail shield flow creating outer vortex
MHD modelling: Turbulent jets

- Enthalpy probes
- Thomson scattering
- Laser-induced fluorescence

Comparison with simulation, including k-ε turbulence model


TIG torch in WAAM wall

- Step towards more representative plasma torch model
- MHD physics identical with PAW, steady-state flow patterns similar
- 2D axisymmetric geometry: ~15 mins solution time per case
Air contamination

Increased accuracy in boundary layer due to wall functions (SST turbulence model)
Parametric sweeps

- Stagnation pressure increases non-linearly with arc current
- Air entrainment doubled for 200 A compared to 100 A
- Theoretical analyses to complement future measurements
Turbulence intensity

- As current increases, the side jets contract but also push out and downwards with more momentum
- Overall greater turbulence levels
- Relatively higher air content on top of solidifying metal expected

Rv: torch + trail shield/PAW_trail_shield_7
The high wall problem

- As the physical constraint of the substrate is no longer there, the inner area becomes more exposed
- The outer vortex stretches to the extent that it loses effectiveness
- Air contamination increases proportionally to standoff from substrate

Rv: torch + trail shield/PAW_trail_shield_9
Background: MIG welding process optimisation


d\frac{n}{dr} \propto \frac{\partial \rho}{\partial r}

Observed flow features predicted by simulation

Qualitative validation through schlieren
Arc welding simulations

Air entrainment more severe at 6 l/min

Availability for air absorption on weld surface

15 l/min nozzle flow constrains jet circa 3000 K isotherm

Arc plasma temperature, velocity similar

10,000+ ppm O₂
## Radiographic cross-examination

### Ar Flowrate (l/min)

<table>
<thead>
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<th>Nozzle standoff (mm)</th>
<th>6 l/min</th>
<th>9 l/min</th>
<th>12 l/min</th>
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<td>10</td>
<td>SW16</td>
<td>SW17</td>
<td>SW18</td>
<td>SW19</td>
</tr>
</tbody>
</table>

**Porosity**

**Acceptable welds**

**Film**

DH36 Sample

**X-ray source**

Representative films & bead on plate welds