Modelling of Transport Phenomena in Laser Welding of Steels

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Laser Welded Blanks

Butt Joining > No overlap > Weight reduction

Overlap of approx. 20 mm

Butt laser weld line without any overlap

Thickness optimization (Best material at the best place) > Weight reduction

Overlap spot welding

20% mass saving

Butt laser welding

Hard steel

Soft steel
Problematic

Understand and control the mixing process in the weld between dissimilar steels

Multiphysical modelling of full penetrated laser welding

Use of tracer material to validate convection paths (Ni)
I – Generalities
II – Mathematical formulation
III – Results and discussion
IV – Conclusion and prospects

Model

Heat transfer in fluids

Turbulent flow

Transport of diluted species

3D model
Pseudo-stationary formulation
Strong coupling

Taking into account of:

• Phase change
• Gravity
• Marangoni effect
• Vapour plume shear stress
Assumptions

- a steady keyhole with a conical geometry (full penetration)
- temperature inside the keyhole is assumed to be uniform
  \[ T_{\text{keyhole}} = T_{\text{vaporization}} \]
- top and bottom surfaces of the weld are assumed to be flat
- liquid metal is assumed to be Newtonian and incompressible

Reduction of computational resources

**Workstation**
- 32 cores
- 128 GB RAM
Material properties

<table>
<thead>
<tr>
<th>Thermal properties</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion temperature</td>
<td>1808</td>
<td>K</td>
</tr>
<tr>
<td>Vaporization temperature</td>
<td>3300</td>
<td>K</td>
</tr>
<tr>
<td>Latent heat of fusion</td>
<td>$2.7 \times 10^5$</td>
<td>J·kg$^{-1}$</td>
</tr>
</tbody>
</table>

Uniform thermo-physical properties over all domain: 100 µm insert of Ni is neglected ($T_f = 1728$ K).
Heat transfer

**Energy equation:** \[ C_p \mathbf{u} \cdot \nabla T + \nabla (k \nabla T) = 0 \]

\[
C_p = C_p^*(T) + \alpha L_{\text{fusion}} = \frac{1}{T} \cdot \sqrt{T_fusion - T} \cdot e^\left( \frac{T_fusion - T}{T} \right)
\]

\[
\alpha = \frac{k \cdot v \cdot d^2}{P}
\]

Laser spot \( \varnothing = 600 \mu m \)

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Reynolds-averaged Navier-Stokes Turbulent flow:

Mass continuity:  \( \nabla \cdot (\mathbf{u}) = 0 \)

Momentum equation:
\[
(u \cdot \nabla)u = \nabla \cdot \left[ \rho (1 + \frac{1}{2} T) \left( \nabla u + (\nabla u)^T \right) \right] + g + F_{\text{Marangoni}} + F_{\text{Plume}}
\]

Turbulence kinetic energy:
\[
(u \cdot \nabla)k = \nabla \cdot \left[ \left( 1 + \frac{1}{2} k \right) \nabla k \right] + p_k
\]

Specific dissipation rate:
\[
(u \cdot \nabla) = \nabla \cdot \left[ \left( 1 + \frac{1}{2} T \right) \nabla \right] + p_k
\]

\[
T = \frac{k}{k}, \quad p_k = T \left[ \nabla u : \left( \nabla u + (\nabla u)^T \right) \right]
\]

Wilcoxon modified k-\(\omega\) model

\[
F_{\text{Marangoni}} = \frac{g \times T}{T}
\]

Closure Coefficients:

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>13/25</td>
</tr>
<tr>
<td>(\sigma_k^*)</td>
<td>1/2</td>
</tr>
<tr>
<td>(\sigma_\omega)</td>
<td>1/2</td>
</tr>
<tr>
<td>(\beta_0)</td>
<td>9/125</td>
</tr>
<tr>
<td>(\beta_0^*)</td>
<td>9/100</td>
</tr>
<tr>
<td>(\kappa_v)</td>
<td>0.41</td>
</tr>
<tr>
<td>(B)</td>
<td>5.2</td>
</tr>
</tbody>
</table>
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Transport of diluted species

**Fick’s law:**

\[ \nabla \cdot \left( D_i \nabla c_i + uc_i \right) = 0 \]

\[ D_i = \frac{k_B T e^{-\frac{T}{Sc_T}}}{6 r_i} \]

Diffusion coefficient in liquid metal + turbulent diffusion

\[ D_{Ni}^T = \begin{bmatrix} 3 \times 10^9; 6 \times 10^9 \end{bmatrix} \]
Laminar diffusion isn’t enough to obtain numerical and experimental results in good agreement. Underestimation of mixing!

Turbulent mixing is essential to have an important exchange of matter between 2 vortexes.
**k-ε ↔ k-ω**

- **k-ε** model
- **k-ω** model

**Ni X-map**

**k-ω model provides better agreement with experimental results**
Marangoni effect

Marangoni convection and solid phase modelling

\[ M = 1 \times 10^{-4} < 0 \]

Stream lines and velocity magnitude in cross section
I – Generalities

II – Mathematical formulation

III – Results and discussion

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Liquid entering into solid

\[ M = 1 \times 10^{-4} < 0 \]

\[ M(T) \]
## Weld geometry

<table>
<thead>
<tr>
<th>Dimensions (µm)</th>
<th>Laser offset (µm)</th>
<th>ε (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Exp</td>
<td>858</td>
</tr>
<tr>
<td></td>
<td>Calc</td>
<td>935</td>
</tr>
<tr>
<td>L2</td>
<td>Exp</td>
<td>659</td>
</tr>
<tr>
<td></td>
<td>Calc</td>
<td>791</td>
</tr>
<tr>
<td>L3</td>
<td>Exp</td>
<td>1033</td>
</tr>
<tr>
<td></td>
<td>Calc</td>
<td>897</td>
</tr>
</tbody>
</table>

\[ P = 4 \text{ kW}; \quad V_s = 6 \text{ m.min}^{-1} \]

\[ \varepsilon < 20 \% \]
Stream lines and velocity field

The maximum velocity is observed on top and bottom surfaces

Simulation with and without plume shear stress (200 μm offset)
Nickel mass fraction in cross-section

- centred
- 200 μm off-set

Numerical

Experimental

(a) Top surface

(b) Middle weld

(c) Bottom surface

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Nickel mass fraction in cross-section

Numerical  Experimental

(a)

Top surface

- analysis line
- initial Ni foil
- weld shape
Nickel mass fraction in cross-section

**Numerical**

**Experimental**

![Graph comparing numerical and experimental data for nickel mass fraction in cross-section.](image)
Nickel mass fraction in cross-section

Numerical

Experimental

Bottom surface

Numerical

Experimental

(c)

(c)
Conclusion

Model predicts macroscopic chemical composition in the laser weld between dissimilar steels

- Turbulent Mixing
- Convective Mixing
- Macroscopic scale

- Good agreement of the weld geometry
- Modelled convection paths validated with Ni tracer
- Next step: Welding dissimilar steels
Prospects

In front of the keyhole and in the mushy zone, the velocity field divergence isn’t calculated well.

➢ Fix it ...

Bad calculation of U divergence!
THANK YOU FOR YOUR ATTENTION!

$U \text{ (m/s)}$

200 µm beam offset