2D axial-symmetric model for fluid flow and heat transfer in the melting and resolidification of a vertical cylinder

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Direct Metal Laser Deposition (DMLD) is an original technique from rapid prototyping, part repairing and surface treatment of metals. This process involves injecting metal powder through a coaxial nozzle into a melt pool obtained by a moving laser beam.

Three operating parameters:
- laser power (W)
- powder mass flux (kg.s\(^{-1}\))
- travel speed (m.s\(^{-1}\))

Main current limitations of DMLD processes: **surface finish**

Two surface finish criteria:
- Waveness (Wa)
- Roughness (Ra)

Project goals:
- Provide a real physical understanding of the melt pool behaviour in DMLD
- Develop a predictive model of DMLD process

Improve surface finish to obtain surface state near surface machining
Proposed approach

2D-axi heat transfer and fluid flow model

⇒ validation of the surface tension and input parameters

3D model for heat transfer and fluid flow

⇒ validation of the surface tension in 3D

3D DMLD process modeling

⇒ study of the waveness (Wa)

2D model for heat transfer and fluid flow with filler material

⇒ validation of the analytical filler material model
⇒ study of the melt pool behavior

Unknown data:
- L/G and L/S interfaces
- Temperature field
- Velocity field
Study of local melting of a vertical rod

Experimental set-up:

- Metallic rod Ø3.2mm
- Input shielding gas
- Spotlights
- High speed camera
- Location of the liquid/solid interface
- Thermocouples Type K
- Dynamic shape of the melt zone
- Thermal cycles
2D axial symmetry

- The model needs to describe several phenomena...

...coupled to the evolution of the laser/melt pool interaction and free surface deformation.

2Daxi model:
- fluid flow → NS
- heat transfer → HT
- moving mesh → ALE
**Equations**

**Heat transfer equation**
\[
\rho(T) c_p(T) \left[ \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right] - \nabla \cdot (\lambda(T) \nabla T) = 0
\]

**Momentum conservation equation**
\[
\rho \left[ \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right] = -\nabla p + \mu(T) \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) + \mathbf{F}_T + \mathbf{F}_v
\]

(\text{incompressible Newtonian fluid})

**Continuity equation**
\[
\nabla \cdot \mathbf{u} = 0
\]

**Moving mesh**
- ALE method (Winslow smoothing method)

- equivalent \( c_p \) method
\[
c_p(T) = c_p(T) + \Delta H_f \frac{df_f}{dT}
\]

- Darcy condition (liquid/solid interface)
\[
\mathbf{f}_{\text{d}} = \begin{cases} 
\frac{T - T_s}{T_s - T_q} & T \leq T_s \\
\frac{T_s - T_q}{T_q} & T_s < T \leq T_q \\
1 & T > T_q
\end{cases}
\]

- Volume forces (Buoyancy, gravity)
\[
\mathbf{F}_v = \rho \left( 1 - \beta (T - T_0) \right) \mathbf{g}
\]

- Latent heat

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Simon Morville, PhD
Mesh & boundary conditions

- **Mesh element size**

- **Fluid flow conditions**
  
  Surface tension: \( \sigma_n \vec{n} = -P_a \vec{n} + \gamma(T) \kappa \vec{n} \)  
  
  Marangoni: \( \sigma_r = \frac{\partial \gamma}{\partial T}(T, S\%) \, \vec{V}T \cdot \vec{n} \)

- **Moving mesh condition**
  
  \( U_{\text{mesh}} \cdot \vec{n} = U_{\text{material}} \cdot \vec{n} \)

- **Heat transfer conditions**
  
  \( q_{\text{rad}} = \begin{cases} \alpha(\theta) I_0(r, t) - h_c (T - T_0) - \varepsilon \sigma (T^4 - T_0^4) & (\partial \Omega^1) \\ -h_c (T - T_0) - \varepsilon \sigma (T^4 - T_0^4) & (\partial \Omega^2) \end{cases} \)

with: \( I_0(r, t) = \begin{cases} \frac{P_I}{\pi r_i^2} \delta(t) & r \leq r_i \\ 0 & r > r_i \end{cases} \)

\( \alpha(\theta) = \alpha_0 \cos(\theta) \)
Input parameters:

**Material**

Properties for liquid phase: 
\[ \rho, c_p, \lambda, \mu, \gamma, \frac{\partial y}{\partial T}, \varepsilon \]

**Laser**

Heat source
- Incident laser power: 962 W
- Laser beam radius: 1.57 mm
- Interaction time: 500 ms
- Absorptivity coefficient: \( \alpha \)?

**Heat losses**

Convective and radiative loss
- Convective coefficient: 15 W.m\(^{-2}\).K
- Emissivity coefficient: 0.5
Numerical results

Input parameters:

Non linear solver parameters

Non linear parameters
**Sensitivity analysis**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference values</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (S-L)</td>
<td>40-32 W.m(^{-1}).K(^{-1})</td>
<td>-13.5</td>
</tr>
<tr>
<td>Heat capacity (S-L)</td>
<td>500-710 J.kg(^{-1}).K(^{-1})</td>
<td>-23.8</td>
</tr>
<tr>
<td>Density (S-L)</td>
<td>7800-7290 kg.m(^{-3})</td>
<td>-22.1</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>5.10(^{-3}) Pa.s</td>
<td>-1.6</td>
</tr>
<tr>
<td>Capillary coefficient</td>
<td>1.5 N.m(^{-1})</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Thermocapillary coefficient</td>
<td>10(^{-4}) N.m(^{-1}).K(^{-1})</td>
<td>2.1</td>
</tr>
<tr>
<td>Absorptivity coefficient</td>
<td>0.3</td>
<td>32.4</td>
</tr>
<tr>
<td>Emissivity coefficient</td>
<td>0.5</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Latent heat of fusion</td>
<td>2.5.10(^{5}) J.kg(^{-1})</td>
<td>1</td>
</tr>
</tbody>
</table>

Each parameter is independently increased by 25% to evaluate his sensibility on the melt pool depth.

**Conclusions from sensitivity analysis:**

- Input data very influential on melt pool geometry: thermal diffusivity and absorptivity
- Thermocapillary forces strongly control melt pool geometry
- Gravity and Buoyancy forces can be neglected
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- Input data very influential on melt pool geometry: thermal diffusivity and absorptivity
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\[ \vec{F}_v = \rho_0 \cdot \vec{g} - \rho_0 \beta \cdot (T - T_0) \cdot \vec{g} \]
Experimental validation

Conclusions:

Good correlation between numerical and experimental results for thermal cycles and liquid/gas interface location.

Best fit for liquid/solid interface by adjusting $\frac{\partial \gamma}{\partial T}$ as shown by the sensibility analysis.
Conclusions & Perspectives

- 2D axial-symmetric model well describes physics thermohydraulic phenomena involved in local metallic rod melting:
  - Good correlation for:
    - thermal cycles
    - Dynamic shapes of liquid/gas interface
    - Liquid/solid interface location
- Simplifying assumptions are validated:
  - Gravity and Buoyancy forces negligible in our case
- Thermal properties, absorptivity coefficient and thermocapillary coefficient are key parameters for the prediction of the geometry

Next steps:
- Validation of TA6V titanium alloy and 316L steel properties
- Implementation of a 2D thermohydraulic model with powder feeding
- Computation in a 3D framework for DMLD process modeling