Laser welding process – a review of keyhole welding modelling

FTF conference 2016
Abstract ID 25078

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Introduction

High power laser beam $5 \times 10^4 - 10^7$ W/cm²

**Ex. specific properties**

- 10 µm or 1 µm wavelength

**General properties**

- Melting and vaporization
- High vapor pressure (recoil pressure)
- Large depth to width ratio

**Advantages**

- Large welding speed
- Low energy input
- Small HAZ
- Narrow bead

**Disadvantages**

- Humping
- Lack of fusion (gap)
- Spatter
- Porosity

Comparison of the size of weld beads
(a) laser-beam (b) TIG

Pores in weld generated by YAG-laser in Ti-alloy

American Welding Society Welding Handbook Ed. 8
Motivation

- Understand how to reduce some defects: pores and too narrow waist
- Supplement experimental observations
- Gain process understanding

Nd:YAG, IN-alloy
\[ L_t, L_b > L_w \]


Physics of keyhole laser welding

• **Beam-matter interaction**
  - Direct Fresnel
  - Multi-Fresnel
  - Inverse Bremsstrahlung
  - Mie- and Rayleigh-scattering

• **Thermal fluid**
  - multi-scale:
    - kinetic (Knudsen layer)/hydrodynamic
  - multi-phase
    - melting/solidification, vaporization
  - surface deformation

Non-linear and multi-physical problem

Thermal fluid

**Knudsen layer** – a vapor layer with a thickness of some mean free paths

Jump relations on temperature, pressure and density according to Knight (1979) is a simple way of implementing the **Knudsen layer**.

Keyhole laser welding - modelling

Can distinguish 2 approaches:

1. Laser beam:
   Beam/material interaction: 1 way
   Metal: heat conduction (+ convection via boundary conditions)

2. Laser beam:
   Beam material interaction: 1 or 2 way
   Metal: fluid flow in molten pool (based on CFD techniques)
Modelling the beam

Electromagnetic theory of optics

**Assumptions:**
- Linear optics is valid (small emg. fields)
- Homogeneous, isotropic and non-dispersive media,
- Locally neutral media at the scale considered \((L > \text{Debye})\)
  - Physical wave optics (Helmholtz eq.)

**With additional assumptions:**
- Non-conduction media
- Simple harmonic plane waves for laser light
  - Geometrical wave optics (Wave eq. & Fresnel laws of optics, ray-tracing method)
Ray-tracing

Absorption/reflection:
function of wavelength, polarization, angle of incidence, surface temperature

Application:
- One way coupling
  pre-defined keyhole heat input
- Two ways coupling (ex. Na et al)
  With keyhole geometry CFD calculation and ray-tracing method iteratively applied

### Models with beam-matter interaction and thermal fluid flow

<table>
<thead>
<tr>
<th>Author</th>
<th>Domain of study</th>
<th>Main properties of model</th>
<th>Some other properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ki et al. (2001), (2002)</td>
<td>cw CO₂ laser, steel</td>
<td>2 cF L p_r, h_{fg}</td>
<td>1st model</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Narrow band LS</td>
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<tr>
<td>Lee et al. (2002)</td>
<td>mild steel</td>
<td>2 cF V h_{fg}</td>
<td>Assume sonic flow in Knudsen layer</td>
</tr>
<tr>
<td>Chen and Wang</td>
<td>cw CO₂ laser, iron</td>
<td>3* FB* p_r, h_{fg}</td>
<td>*Cylindrical keyhole cavity</td>
</tr>
<tr>
<td>Wang and Chen (2003)</td>
<td></td>
<td></td>
<td>Only gas flow; no thermal aspect</td>
</tr>
<tr>
<td>Cho et al. (2006)</td>
<td>pulsed Nd:YAG S304 steel</td>
<td>3 cF V p_r, h_{fg}</td>
<td>Constant surface tension</td>
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<tr>
<td></td>
<td></td>
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<td>Radiative cooling cavity-room</td>
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<tr>
<td>Zhou et al. (2006)</td>
<td>pulsed Nd:YAG</td>
<td>2 cFB V p_r, h_{fg}</td>
<td>Vapour included (absorbing-emitting media; no flow)</td>
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<td></td>
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<td></td>
<td>*with diffraction</td>
</tr>
<tr>
<td>Cho et al. (2012)</td>
<td>fibre laser, carbon steel</td>
<td>3 cF* V p_r, h_{fg}</td>
<td>Vapour flow included</td>
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<td></td>
<td>*with Beer’s law</td>
</tr>
<tr>
<td>Otto et al. (2012)</td>
<td>Pulsed, 304 Stainless steel</td>
<td>3 cF V p_r, h_{fg}</td>
<td>Sharper Surface Force VOF, vapour flow included</td>
</tr>
<tr>
<td>Tan et al. (2013)</td>
<td>Nd:YAG, DP600 steel</td>
<td>3 cFB* L S_p, h_{fg}</td>
<td>Vapour flow included</td>
</tr>
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<td>*Eikonal equation</td>
</tr>
</tbody>
</table>

D – number of space dimensions, B-M – beam-matter interaction with beam and flow coupled (c), multiple Fresnel absorption (F), iB-absorption (B), S – surface deformation using Level Set (L) or VOF (V), V – vaporization modeled through: mass source (S_p), recoil pressure (p_r), latent heat of vaporization (h_{fg}), H – heat source in relative motion with the base metal (if ×), M – Marangoni force modeled (if ×), B – buoyancy modeled (if ×), K – Knudsen layer modeled (if ×).
Common Assumptions

Beam-matter interaction

- Fresnel
- Multiple Fresnel in most models

Modelling of thermal fluid

- Newtonian and laminar fluids
- Constant thermodynamic and transport properties in most models
- At least two phases (liquid and solid)
- Solidification and melting (mushy zone model)
- Vaporization (seldom as mass source term)
- Surface deformation in most models
Differences

**Beam-matter interaction**
- Inverse Bremsstrahlung not always considered
- Physical/optical wave optics
- Ray tracing: One way or two way coupling

**Modelling of thermal fluid**
- Few models consider vapour phase
- Recoil pressure (through mass source or force)
- Knudsen layer
- Marangoni
- Buoyancy
- T-dependent thermodynamic properties, ...
Conclusion

- Several models have been developed in the past 15 years, First by Ki et al. (2001).
- Field still under development.
- Comparison of existing models and assumptions would be of interest

Physical models may need further improvements:
- Temperature dependent material properties are often neglected. Sometimes not available over complete range.
- Metal plasma modelled as a gas and not yet a plasma.
- ...

Important issue is the need for experimental data for validation of models.
Ongoing modelling work

Includes in 1st step:

• T-dependent material properties
• Fresnel, multi-Fresnel, iB,
• Solid, liquid, vapor
• Solidification, melting, vaporization
• Surface deformation
• Marangoni, buoyancy
• Ray tracing with one way coupling

Probably not yet sufficient for modeling surface instability and pore formation

fullWeld200um.avi
Test case model

Numerical test case model
  • 3D model of 6 mm plate
  • Argon shielding gas flow
  • Welding speed 15 mm/s and 9 mm/s
Volumetric heat source
Thermophysical properties assumed constant in each phase – mixture properties are used
Experimental measurements
Thank you for your attention!