Heat and fluid flow modeling of keyhole formation in laser welding

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I – Introduction
  - Physics of laser welding

II – Definition of the heat and fluid flow model
  - Equations
  - Level-set method

III – Results and discussion
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IV – Conclusion and future work
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Keyhole laser welding

Mains phenomena influencing the melt pool geometry and the appearance of defects:

Energy:
- Conduction
- Convection
- Radiation

Fluid mechanic:
- Liquid and gas flows
- Vaporization
- Recoil pressure
- Surface tension
- Marangoni effect

4 kW 11 m/min spot of 600µm (PIMM lab.)
Axisymmetric approach  →  Stationary spot laser welding

Goal: model the keyhole formation in order to improve understanding

- recoil pressure
- gravity
- surface tension
- Marangoni effect
- Multiple reflection of laser rays

LEE 2002

MEDALE 2007

TOUVREY-XHAARD 2006

Experimental approach
Setting up the model

Assumptions:
- Axisymmetric geometry
- Incompressible Newtonian fluids
- Laminar flows
- Constant thermophysical properties
- Gaussian distribution of energy

Equations solved:
- Energy conservation
- Momentum conservation
- Mass conservation
- Transport equation of Level Set variable

Taking into account of:
- gravity
- surface tension
- solid phase (Darcy condition)
- recoil pressure
- vapor plume

Neglected (here):
- Marangoni effect
- Latent heats
- Laser reflections

Code: Comsol Multiphysics® v4.3 (+ CFD module)
Conservation equations for each phase

Mass conservation:

\[ \nabla . u = \dot{m} \delta(\phi) \left[ \frac{\rho_l - \rho_v}{\rho_v^2} \right] \]

Away from the interface \( \nabla . u = 0 \)

Momentum conservation: Navier-Stokes equations

\[ \rho \left( \frac{\partial u}{\partial t} + u. (\nabla u) \right) = \nabla \left[ -PI + \mu (\nabla u + (\nabla u)^T) \right] - \rho (1 - \beta (T - T_{fusion})) g + K(T) u + F_{ts} \]

With: \( F_{ts} = (\gamma.n \kappa - \nabla_s \alpha t) \delta(\phi) \)

Energy conservation:

\[ \rho c_p \left[ \frac{\partial T}{\partial t} + \nabla .(u T) \right] = \nabla . (\lambda \nabla T) + I(r) \]

with \( I(r) = P_{max} \frac{\exp \left( -\frac{r^2}{R_g^2} \right) \delta(\phi)}{\pi R_g^2} \)
Level Set method

Fixed mesh

Definition of a variable $\phi$ in all the elements

Transport of this variable using the fluid flow calculation

Engine: Laser energy at liquid / vapor interface:

$$ I(r) = \frac{P_{\text{max}}}{\pi R_g^2} \exp \left( -\frac{r^2}{R_g^2} \right) \delta(\phi) $$
Level Set method

Fixed mesh

Definition of a variable $\phi$ in all the elements

Transport of this variable thanks to fluid mechanic calculation

**Engine:** Energy application on liquid / vapor interface

$$I(r) = \frac{P_{\text{max}}}{\pi R_g^2} \exp\left(-\frac{r^2}{R_g^2}\right) \delta(\phi)$$
Operating parameters:

- P = variable
- Øfocal = 600 µm
- Heating time = 20 ms
- Cooling time = 5 ms

Increase power with the drilling velocity

\[ P_{\text{laser}} < 800 \text{ W} \Rightarrow \text{no porosity} \]

Thermophysical properties:

\[ \begin{align*}
\rho_{\text{liquid}} &= 7000 \text{ kg.m}^{-3} \\
\lambda_{\text{liquid}} &= 40 \text{ W.m}^{-1}.\text{K}^{-1} \\
C_p_{\text{liquid}} &= 400 \text{ J.kg}^{-1}.\text{K}^{-1} \\
\mu_{\text{liquid}} &= 5 \times 10^{-3} \text{ Pa.s}^{-1} \\
\rho_{\text{vapor}} &= 10 \text{ kg.m}^{-3} \\
\lambda_{\text{vapor}} &= 10 \text{ W.m}^{-1}.\text{K}^{-1} \\
C_p_{\text{vapor}} &= 373 \text{ J.kg}^{-1}.\text{K}^{-1} \\
\mu_{\text{vapor}} &= 1 \times 10^{-5} \text{ Pa.s}^{-1}
\end{align*} \]
**Velocity fields**

- **Ejection of matter**
  - $V_{\text{max}} > 10 \text{ m/s}$

- **Main vortex**
  - $V_{\text{max}} = 0.1 \text{ m/s}$

Relatively low power => stable keyhole, steady state establishment

Vapor plume => interaction with the melt pool

Velocity field **with** buoyancy (no Marangoni)

Velocity field **without** buoyancy (no Marangoni)
Creation of porosity possible with the level set method

Presence of porosities from 900 W

Important sensibility to the heating time:

\[ t_{\text{heat}} = 24 \text{ ms} \quad 25 \text{ ms} \quad 26 \text{ ms} \]

↑ \( P_{\text{laser}} \)

↑ vaporization

↑ depth & inclination of liquid

↑ porosities presence probability

Computation performed in 6 h (8 cores X5690 and 8 gb ram)
Experimental validation

Disk Laser $\lambda = 1.06 \ \mu m$, $D_{\text{focus}} = 600 \ \mu m$, DP 600 steel, thickness 1.8 mm

$P_{\text{laser}} = 1500 \ W$

- Rate of porosity > 50%
- Axisymmetric shape well verified (except porosities)
- Depth penetration of model is satisfying
- Width over-estimated but with good tends
Conclusion 2D axisymmetric model

- Promising approach, possibility to take into account many phenomena and configurations:
  - Recoil pressure, gravity effects, vapor plume…
  - Liquid collapsing, porosity capturing…

Medium term objectives

- Considering:
  - latent heats
  - Marangoni effect
  - Laser beam reflections and energy concentration

Long term outlook? 3D?
Main goal of the project 3D configuration with laser movement

Is that the transition to 3D is possible (with reasonable computation time)?

Static laser – 2D (axi.)

Laser in movement – 3D
3D configuration -> material sustainability ok

Temps=0 s

Scrolling materiel direction
(Fixed Laser)

- $P_{\text{laser}} = 1000 \text{ W}$
- Thikness = 0.9 mm
- $V_{\text{laser}} = 6 \text{ m/min}$

400 000 DDL; 63 000 cells; Calculation on 33 ms
Calculation time 4 days
(around 8 cores & 15 gb ram)
General conclusion

- Promising approach:
  - Mains physical phenomena treated
  - Prediction of different defects possible (porosities, collapsing, partial penetration…)
  - large number of possible configurations (tailored blanks with gap, by transparency…)

Medium and long term objectives

- Finish to improve 2D axisymmetric model (laser reflections…)
- Transpose to 3D, use the model in industrial configurations
… Thanks for your attention …