# Laser welding process – a review of keyhole welding modelling

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# Introduction

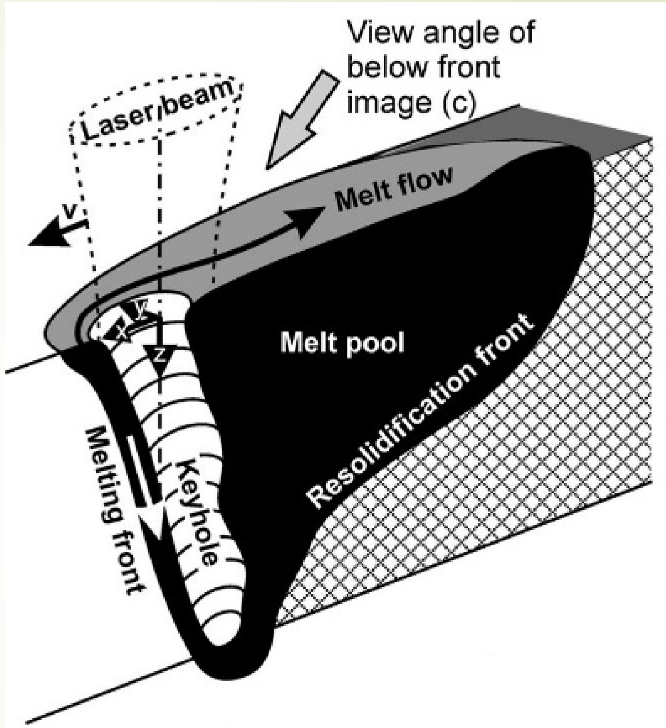
High power laser beam $5 \times 10^4$ - $10^7$ W/cm$^2$

**Ex. specific properties**

- 10 µm or 1 µm wavelength

**General properties**

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



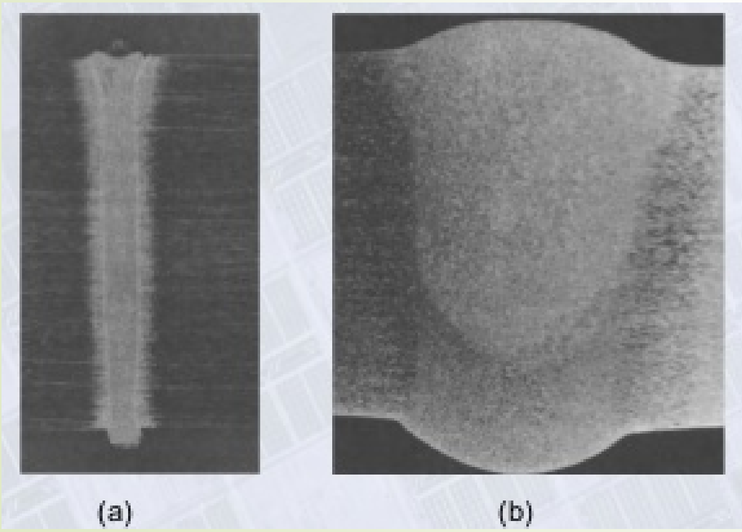

Kaplan, A., (2012.). Appl. Physics Letters 101, 151606.

**Advantages**

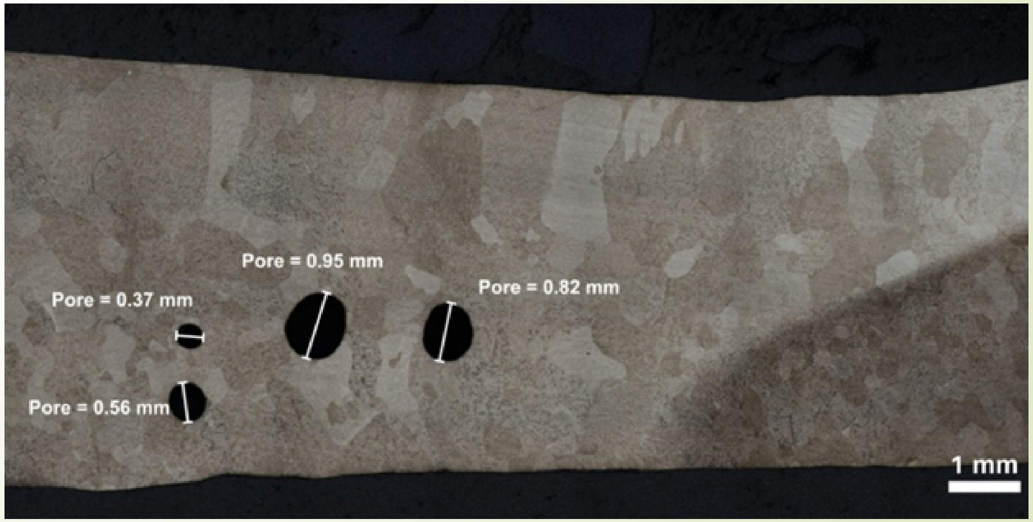
- Large welding speed
- Low energy input
- Small HAZ
- Narrow bead

**Disadvantages**

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



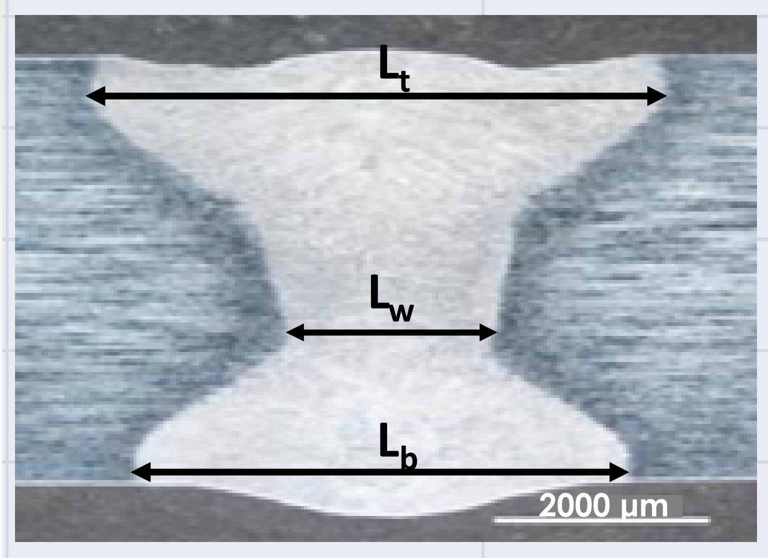

Comparison of the size of weld beads
(a) laser-beam (b) TIG
American Welding Society Welding Handbook Ed. 8




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

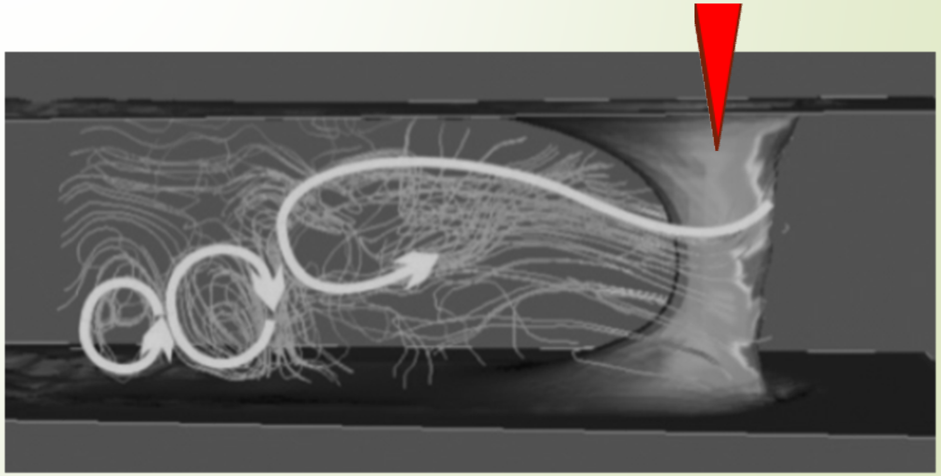
# Motivation

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




**Nd:YAG, IN-alloy**
**$L_t, L_b > L_w$**


Eriksson et al. (2014), J. laser. Appl. 26, 012006.

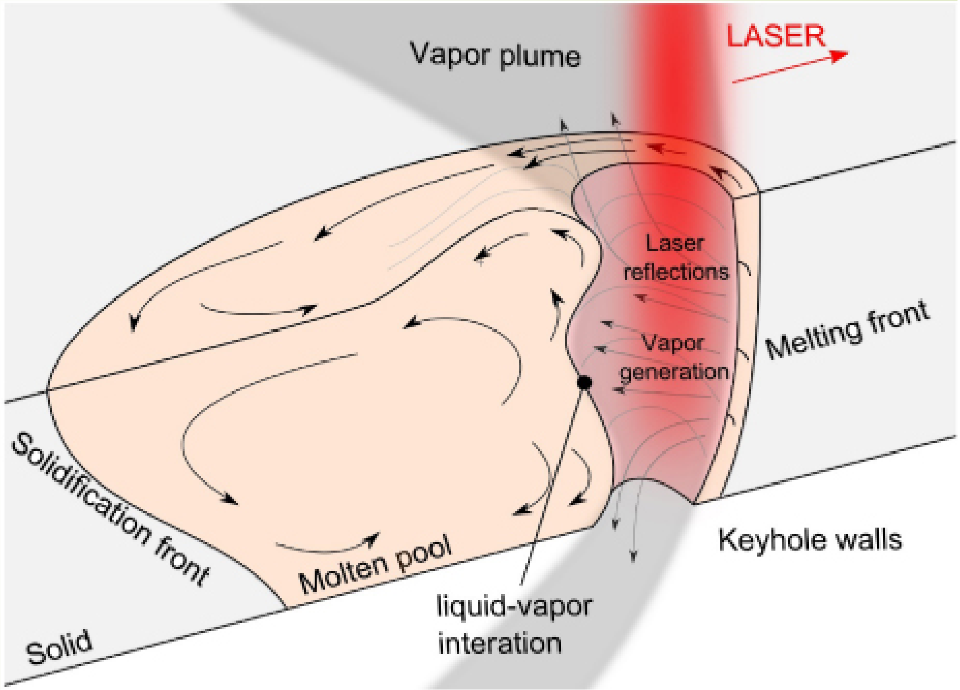


Otto et al. (2011), Phys. Proc.., 12, 11-20.

# 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



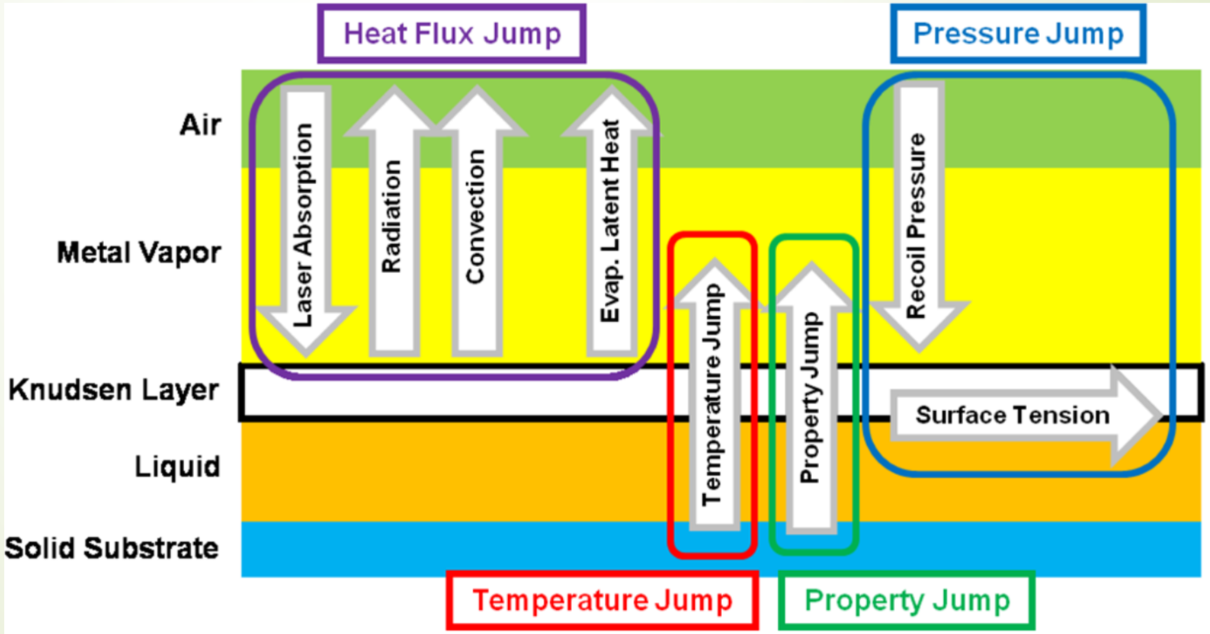

Non-linear and multi-physical problem

Courtois, M. et al. (2013). J. Physics D: Appl. Physics **46**(50), 505305.

# 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**.




Tan, W. et al. (2013). J. of Physics D: Appl. Physics **46**(5), 055501.

# 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 > Debye)

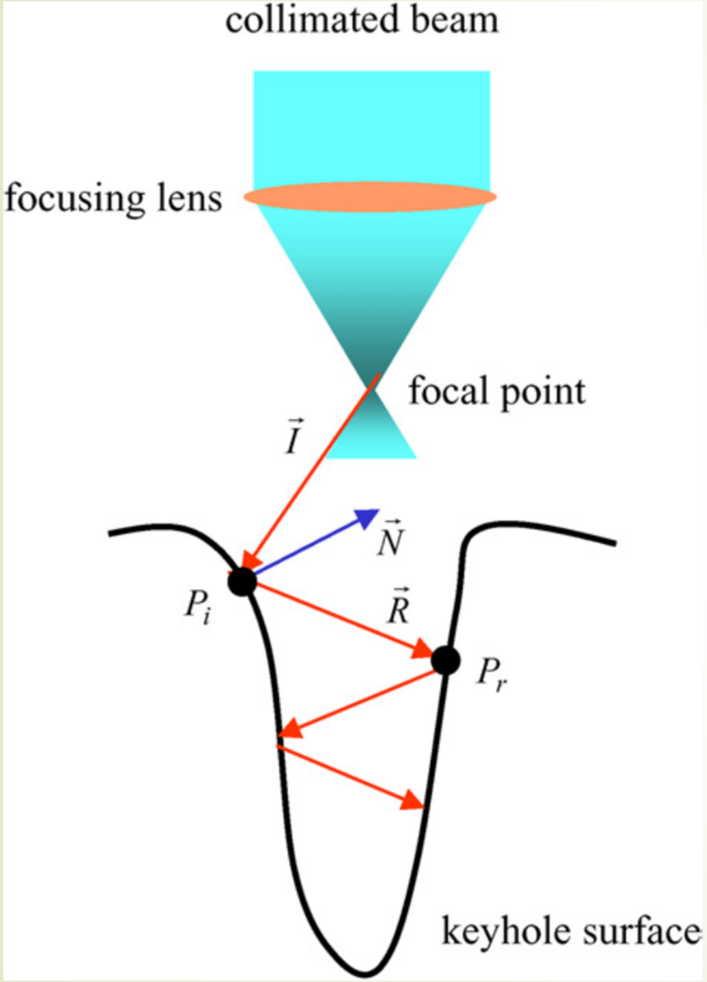
➡ Physical wave optics (Helmholtz eq.)

**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




Cho, J.H., Na, S.J., 2006 J. Phys. D: Appl. Phys. **39**(24), 5372-5378.

**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

| Author | Domain of study | Main properties of model | | | | | | | | Some other properties |
|---|---|---|---|---|---|---|---|---|---|---|
| | | D | B-M | S | V | H | M | B | K | |
| Ki et al. (2001), (2002) | cw $CO_2$ laser, steel | 2 | *cF* | *L* | $p_r$, $h_{fg}$ | × | × | | × | 1st model<br>Narrow band LS |
| Lee et al. (2002) | mild steel | 2 | *cF* | *V* | $h_{fg}$ | | × | × | × | Assume sonic flow in Knudsen layer |
| Chen and Wang<br>Wang and Chen (2003) | cw $CO_2$ laser, iron | 3* | *FB** | | | | | | | *Cylindrical keyhole cavity<br>Only gas flow; no thermal aspect |
| Cho et al. (2006) | pulsed Nd:YAG<br>S304 steel | 3 | *cF* | *V* | $p_r$, $h_{fg}$ | | | | | Constant surface tension<br>Radiative cooling cavity-room |
| Zhou et al. (2006) | pulsed Nd:YAG | 2 | *cFB* | *V* | $p_r$, $h_{fg}$ | | × | × | × | Vapour included (absorbing-emitting media; no flow) |
| ⋮ | ⋮ | | | | | | | | | ⋮ |
| Cho et al. (2012) | fibre laser, carbon steel | 3 | *cF** | *V* | $p_r$, $h_{fg}$ | × | × | × | | Vapour flow included<br>*with diffraction |
| Otto et al. (2012) | | 3 | *cF* | *V* | $p_r$, $h_{fg}$ | × | | | | Sharper Surface Force VOF, vapour flow included |
| Tan et al. (2013) | Pulsed,<br>304 Stainless steel | 3 | *cFB** | *L* | $p_r$, $h_{fg}$ | | × | × | × | Vapour flow included<br>*with Beer's law |
| Courtois et al. (2013) | Nd:YAG,<br>DP600 steel | 2 | *cF** | *L* | $S_\rho$, $h_{fg}$ | | | × | × | *Eikonal equation<br>Vapour flow included |

**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 ($S_\rho$), recoil pressure ( $p_r$), latent heat of vaporization ( $h_{fg}$),* **H** *–heat source in relative motion with the base metal (if ×),* **M** *–Marangoni force modelled (if ×),* **B** *–buoyancy modelled (if ×),* **K** *–Knudsen layer modelled (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

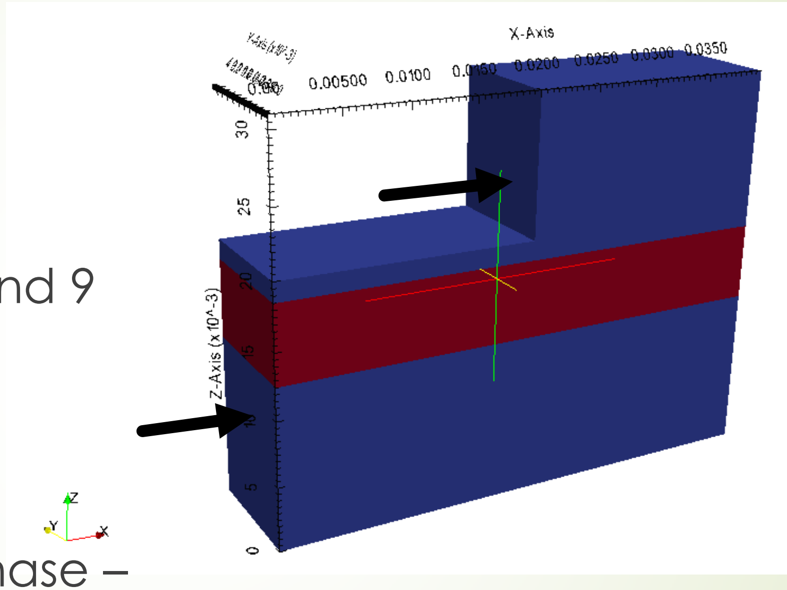
# Test case model

Numerical test case model

- 3D model of 6 mm plate
- Argon shielding gas flow
- Welding speed 15 mm/s and 9 mm/s

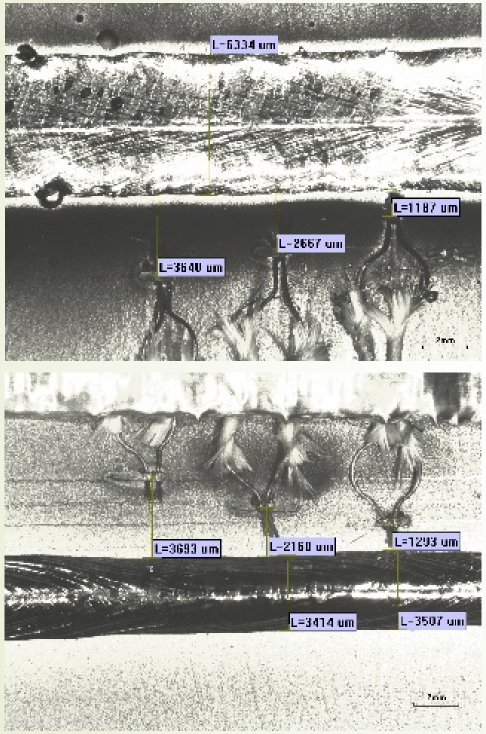
Volumetric heat source

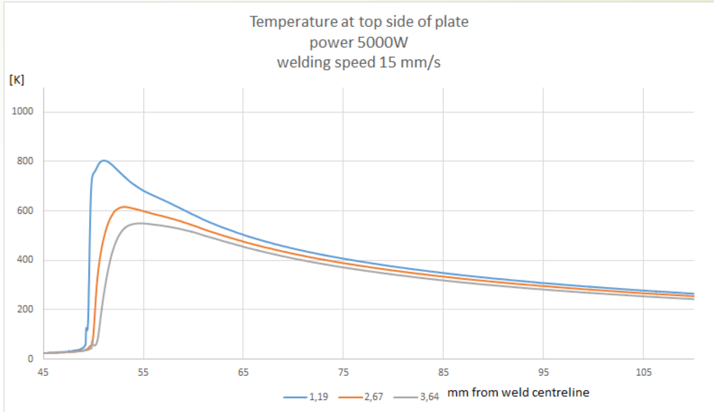
Thermophysical properties assumed constant in each phase – mixture properties are used

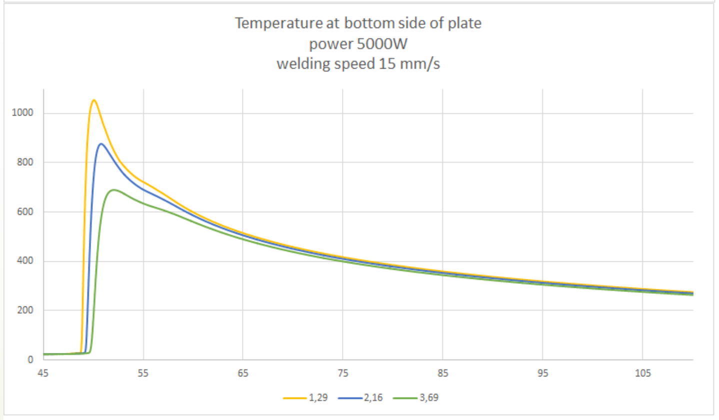



Calculation domain

# Experimental measurements



*Thank you for your attention!*