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

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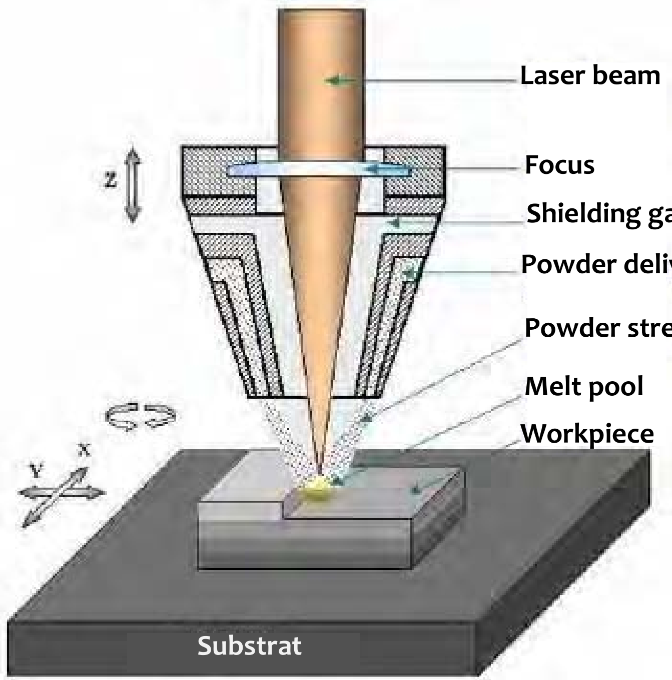
ASPECT project context

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.



DMLD process

Three operating parameters :

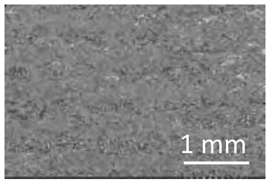
- laser power (W)
- powder mass flux ($kg.s^{-1}$)
- travel speed ($m.s^{-1}$)

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

Two surface finish criteria :

Waveness (Wa)

Roughness (Ra)



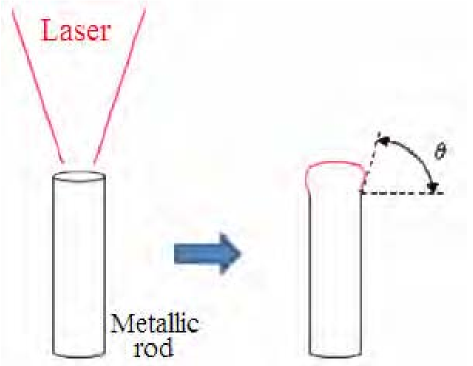
Project goals :

- 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



Unknown data :

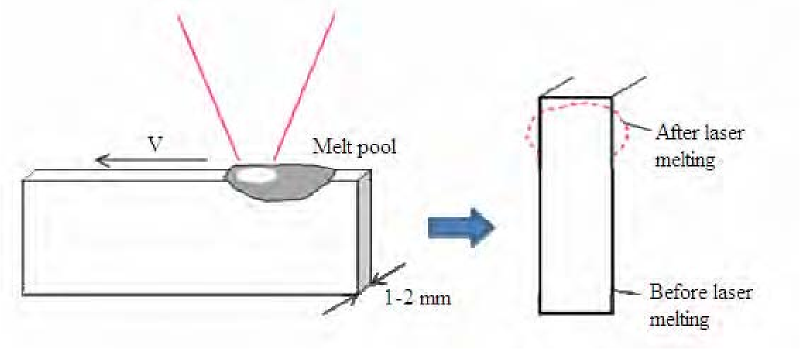
- L/G and L/S interfaces

- Temperature field

-Velocity field

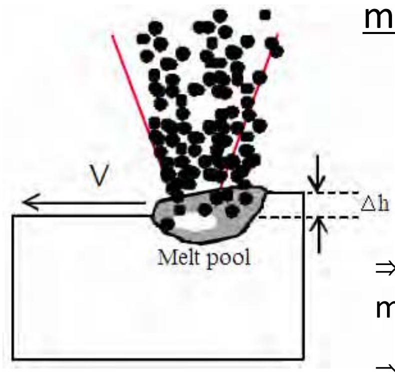
⇒ validation of the surface tension and input parameters

3D model for heat transfer and fluid flow



⇒ validation of the surface tension in 3D

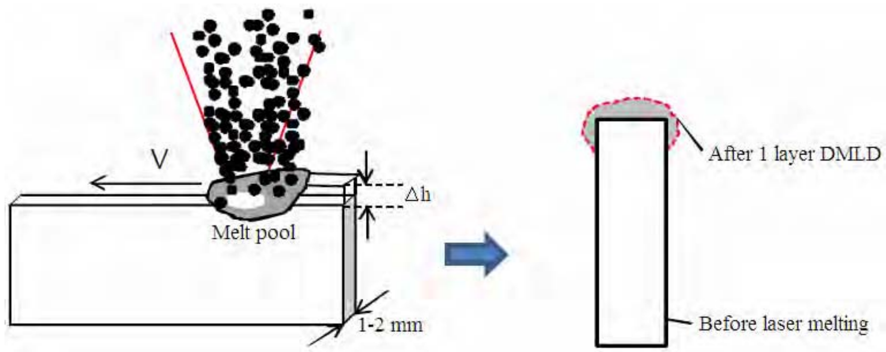
2D model for heat transfer and fluid flow with filler material



⇒ validation of the analytical filler material model

⇒ study of the melt pool behavior

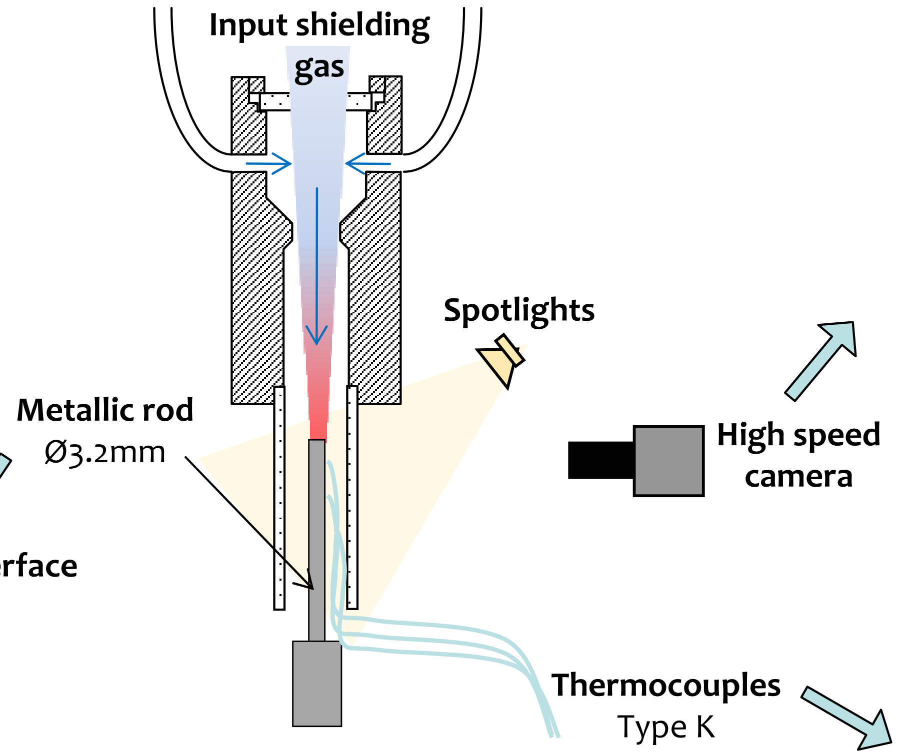
3D DMLD process modeling



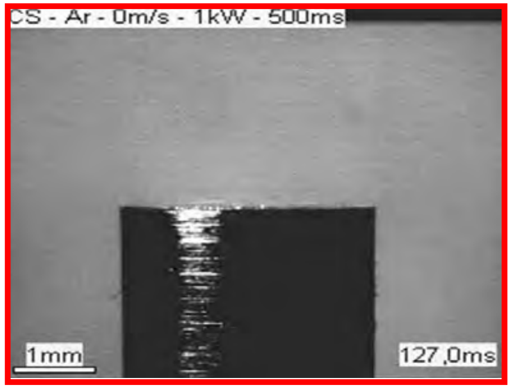
⇒ study of the waveness (Wa)

Study of local melting of a vertical rod

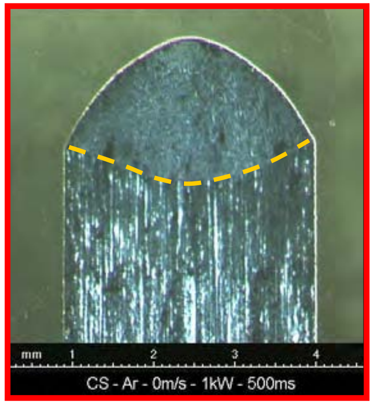
Experimental set-up :



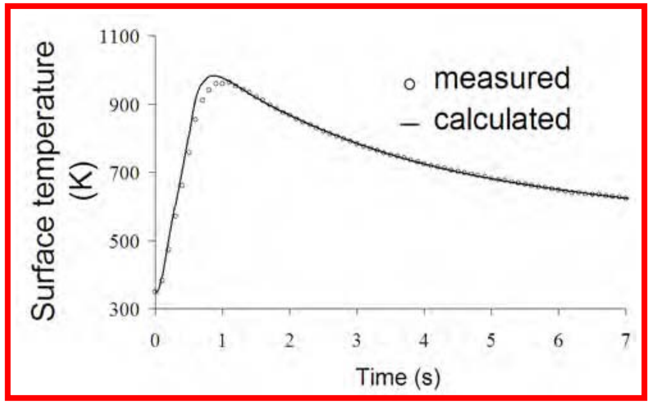
Dynamic shape of the melt zone



Location of the liquid/solid interface

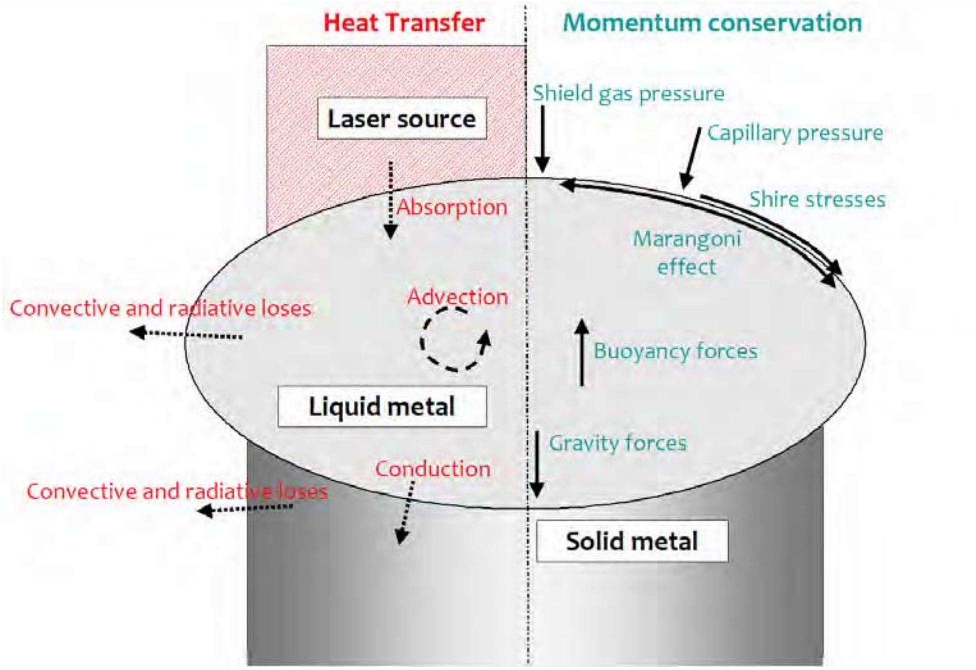


Thermal cycles

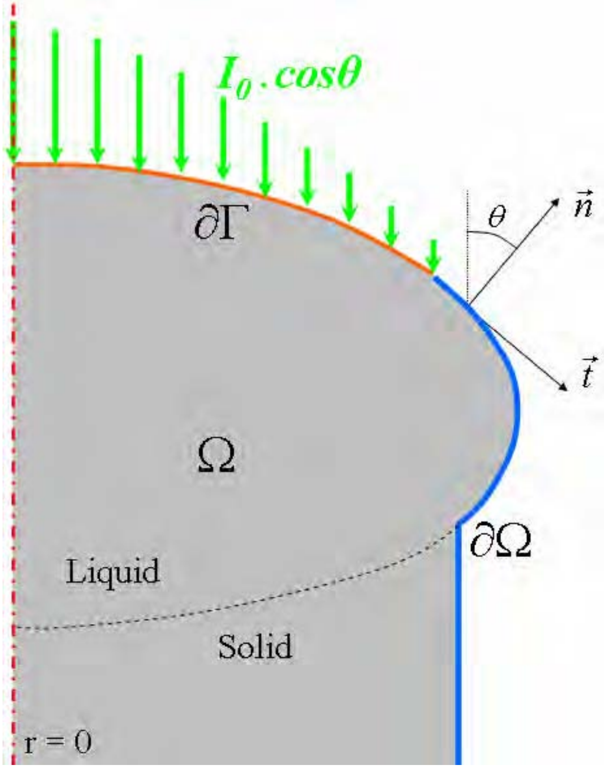


2D axial symmetry

- The model needs to describe several phenomena…



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



<u>2Daxi model :</u>

- fluid flow → NS
- heat transfer → HT
- moving mesh → ALE

Equations

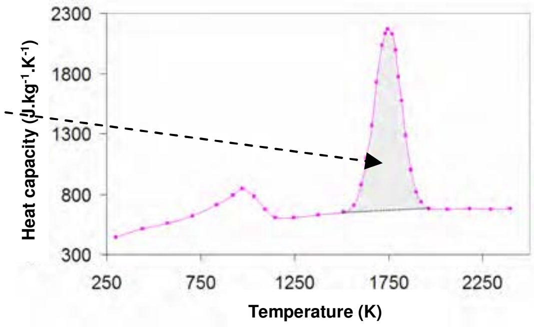
Heat transfer equation

$$\rho(T)c_p^{app}(T)\left[\frac{\partial T}{\partial t}+\vec{\nabla}.(\vec{u}T)\right]-\vec{\nabla}\cdot(\lambda(T)\vec{\nabla}T)=0$$

- equivalent c_p method

$$c_p^{app}(T)=c_p(T)+\Delta H_f\cdot\frac{df_L}{dT}$$

latent heat



Momentum conservation equation

$$\rho_0\left[\frac{\partial\vec{u}}{\partial t}+\vec{u}.(\nabla\vec{u})\right]=\vec{\nabla}.\left[-pI+\mu(T)\left(\vec{\nabla}\vec{u}+(\vec{\nabla}\vec{u})^T\right)\right]+\vec{S}_u+\vec{F}_v$$

(incompressible Newtonian fluid)

- Darcy condition (liquid/solid interface)

$$\vec{S}_u=-C\frac{(1-f_L)^2}{(f_L^3+b)}\vec{u}$$

$$f_L=\begin{cases}0 & T\leq T_S\\ \dfrac{T-T_S}{T_L-T_S} & T_S<T\leq T_L\\ 1 & T>T_L\end{cases}$$

- Volume forces (Buoyancy, gravity)

$$\vec{F}_V=\rho_0.(1-\beta.(T-T_0)).\vec{g}$$

Continuity equation

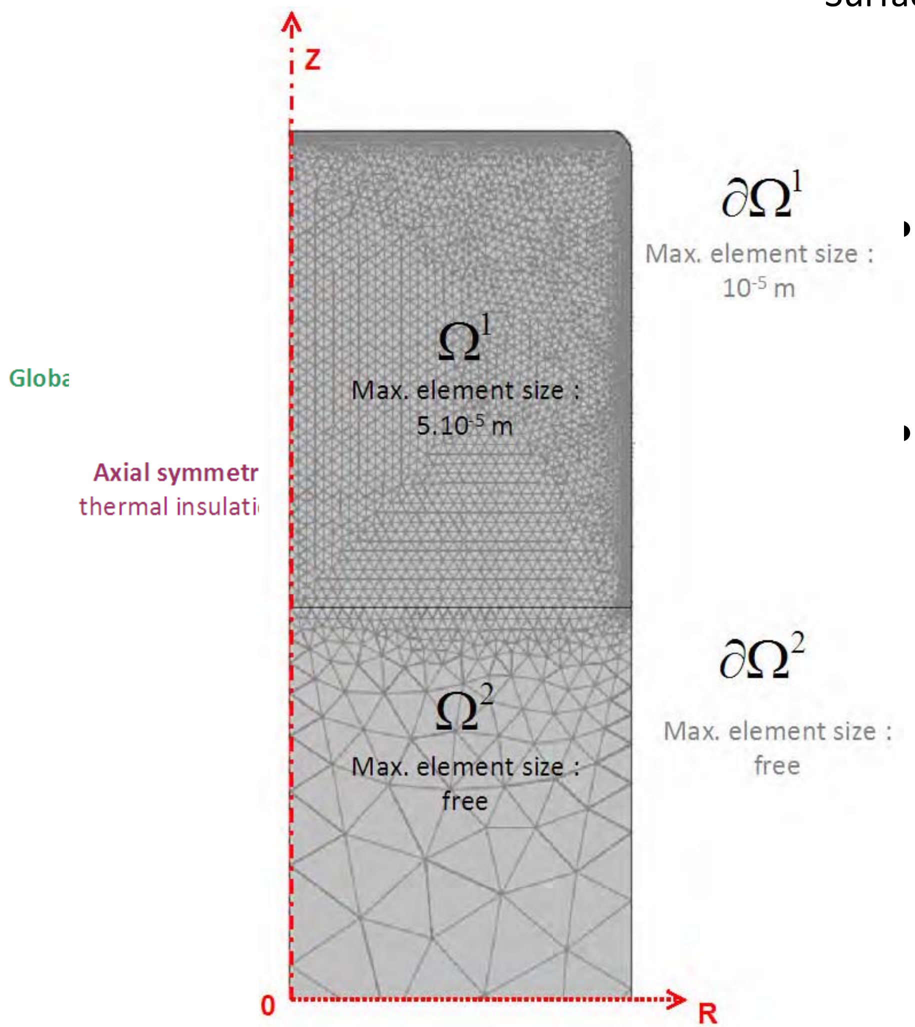
$$\vec{\nabla}\cdot\vec{u}=0$$

Moving mesh

→ ALE method (Winslow smoothing method)

Mesh & boundary conditions

- Mesh element size



- Fluid flow conditions

Surface tension : $\sigma_n \vec{n} = -P_a \vec{n} + \gamma(T).\kappa \vec{n} \qquad (\partial\Omega^1)$

Marangoni : $\sigma_t = \dfrac{\partial\gamma}{\partial T}(T, S\%)\vec{\nabla}T \cdot \vec{t} \qquad (\partial\Omega^1)$

- Moving mesh condition

$$U_{mesh}.\vec{n} = U_{material}.\vec{n} \qquad (\partial\Omega^1)$$

- Heat transfer conditions

$$q_{imp} = \begin{cases} \alpha(\theta)I_0(r,t) - h_c(T - T_0) - \varepsilon\sigma(T^4 - T_0^4) & (\partial\Omega^1) \\ -h_c(T - T_0) - \varepsilon\sigma(T^4 - T_0^4) & (\partial\Omega^2) \end{cases}$$

with : $I_0(r,t) = \begin{cases} \dfrac{P_l}{\pi r_l^2}\delta(t) & r \leq r_l \\ 0 & r > r_l \end{cases}$

$$\alpha(\theta) = \alpha_0.\cos(\theta)$$

Numerical results

Input parameters :

Material

Properties for liquid phase ?

$$\left(\rho, c_p, \lambda, \mu, \gamma, \frac{\partial \gamma}{\partial T}, \varepsilon\right)$$

Laser

Heat source

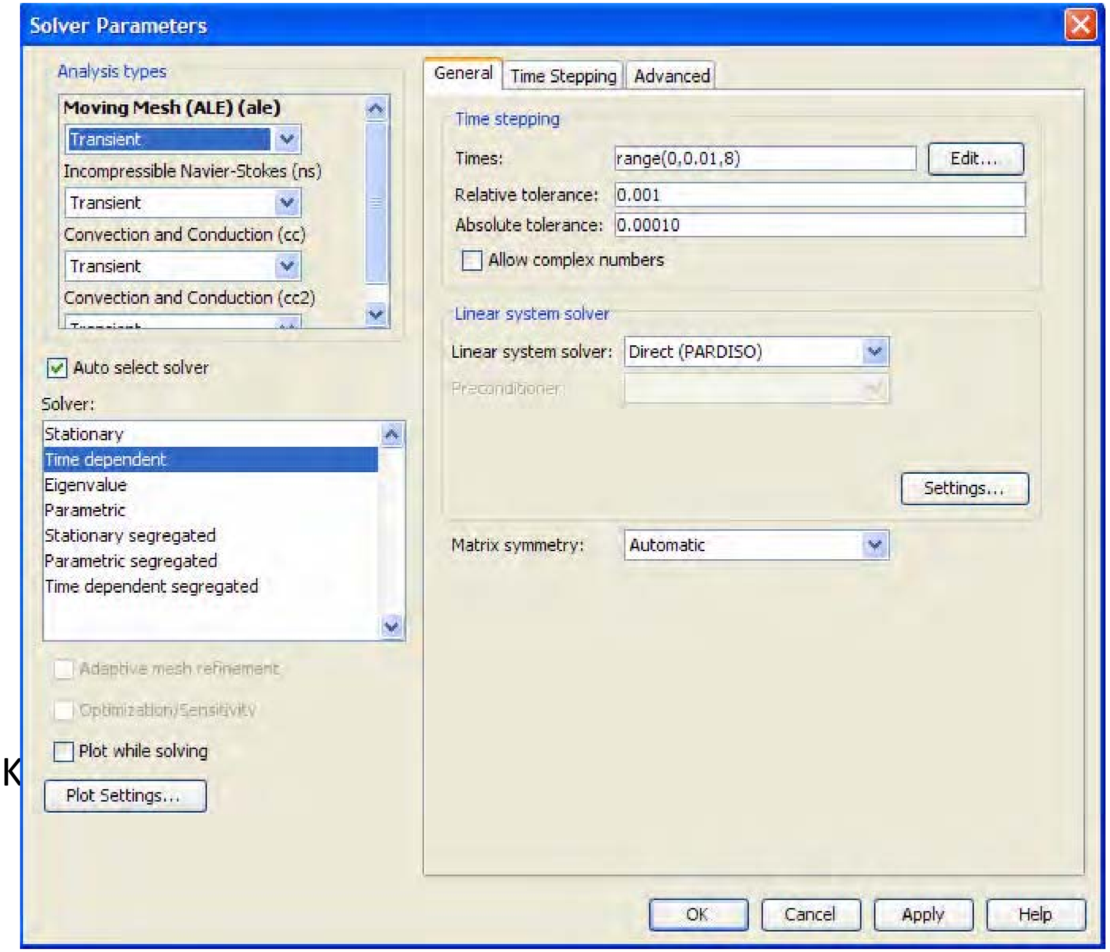
- Incident laser power : 962 W
- Laser beam radius : 1.57 mm
- Interaction time : 500 ms
- Absorptivity coefficient : α_0 ?

Heat losses

Convective and radiative loss

- Convective coefficient : 15 W.m^{-2}.K
- Emissivity coefficient : 0.5

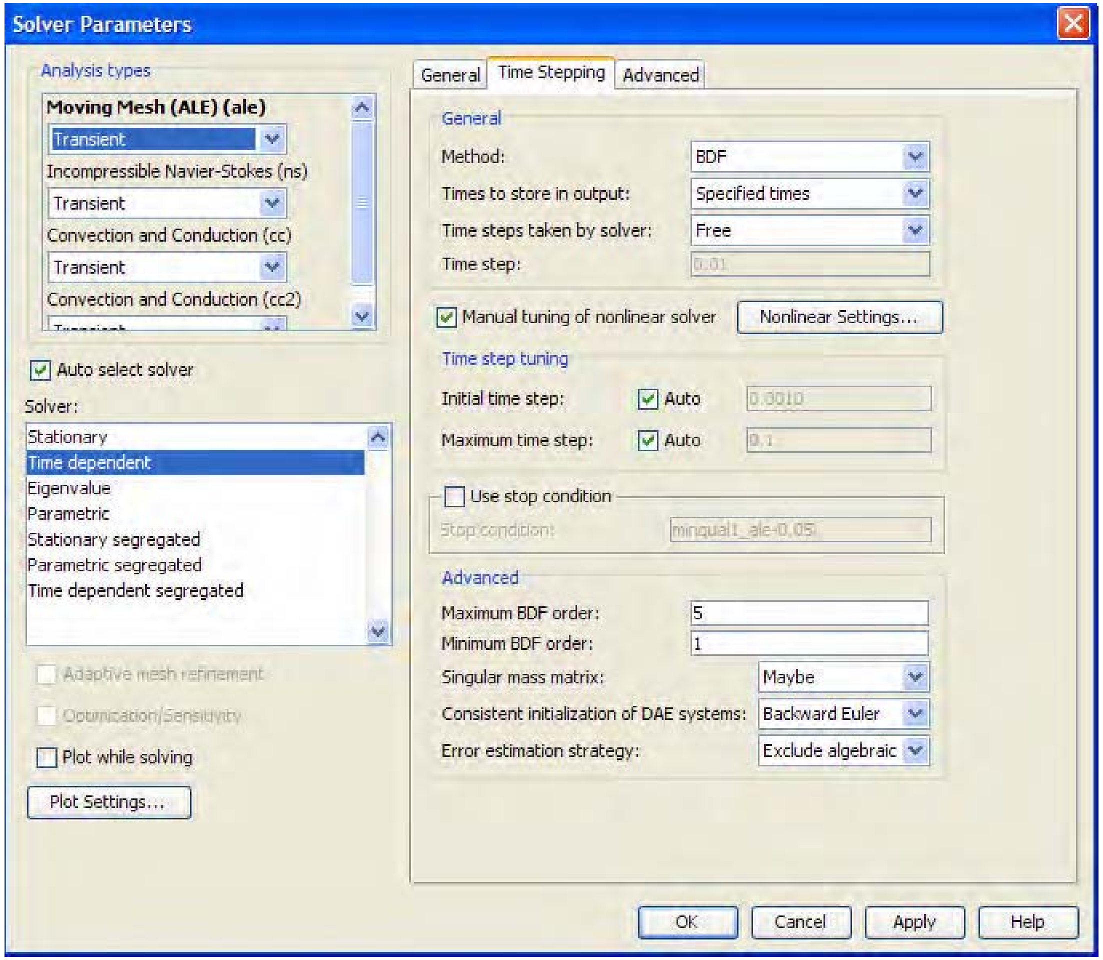
Linear solver parameters



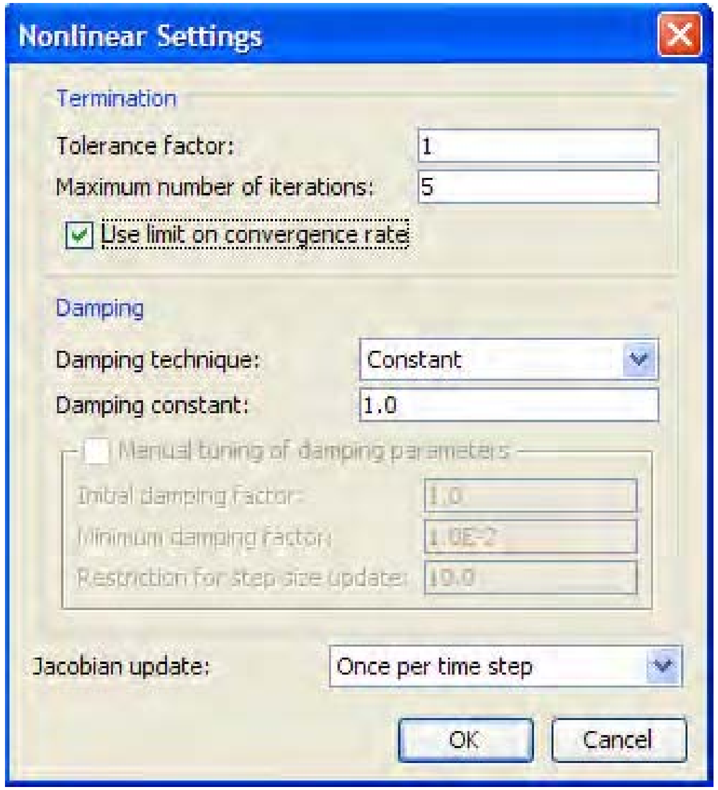
Numerical results

Input parameters :

Non linear solver parameters



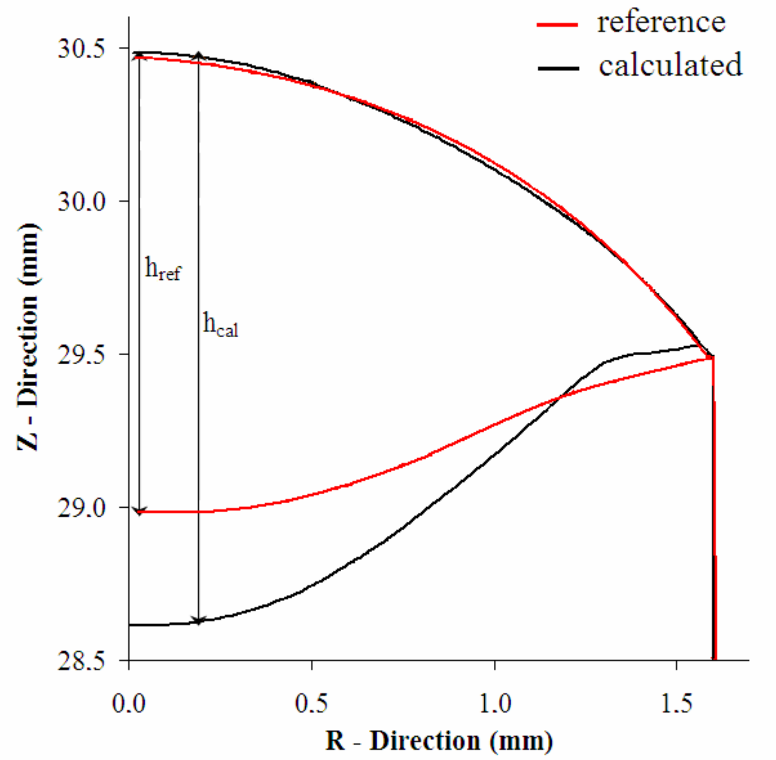
Non linear parameters



Sensitivity analysis

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

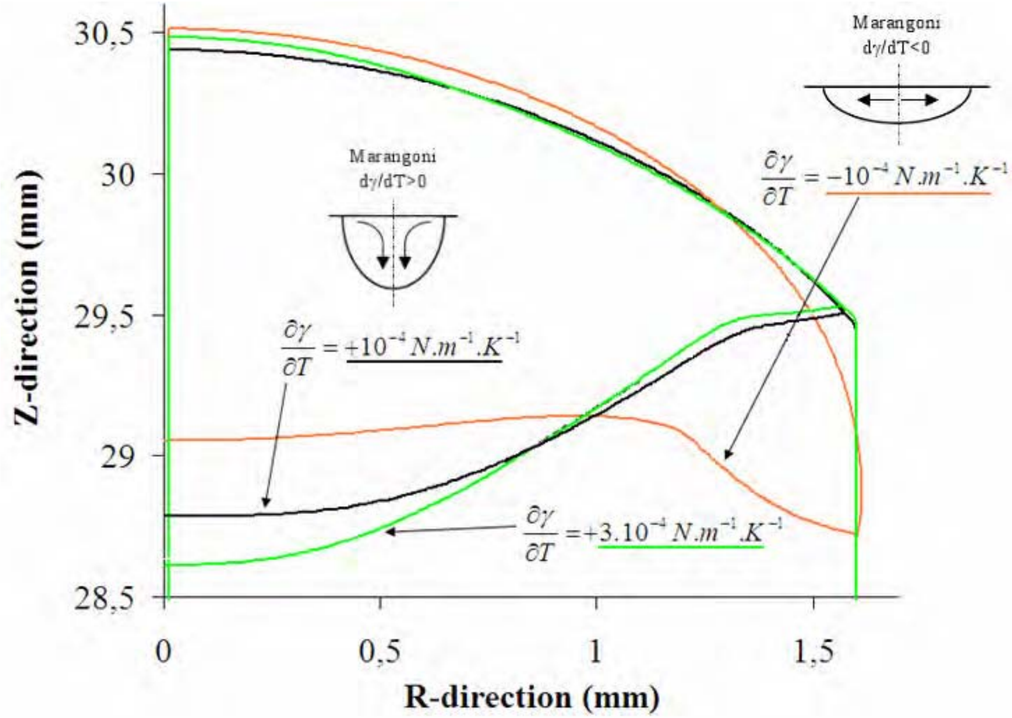
Each parameter is independently increased by 25% to evaluate his sensibility on the melt pool depth.



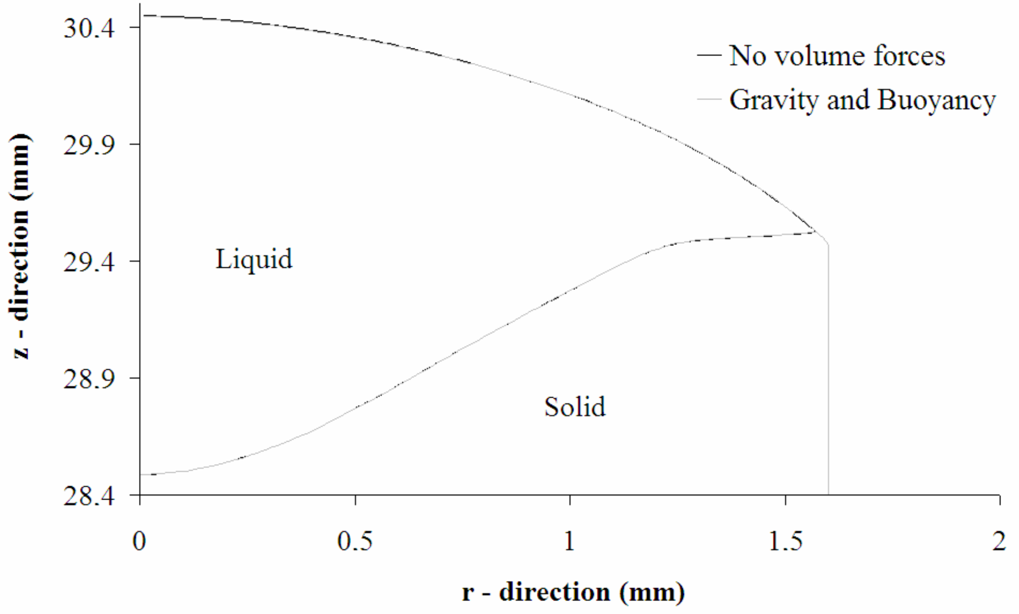
Conclusions from sensitivity analysis :

- Input data very influent on melt pool geometry : thermal diffusivity and absorptivity
- Thermocapillary forces strongly control melt pool geometry
- Gravity and Buoyancy forces can be neglected

Sensitivity analysis



$$\vec{F}_V = \rho_0.\vec{g}.-\rho_0\beta.(T-T_0).\vec{g}$$



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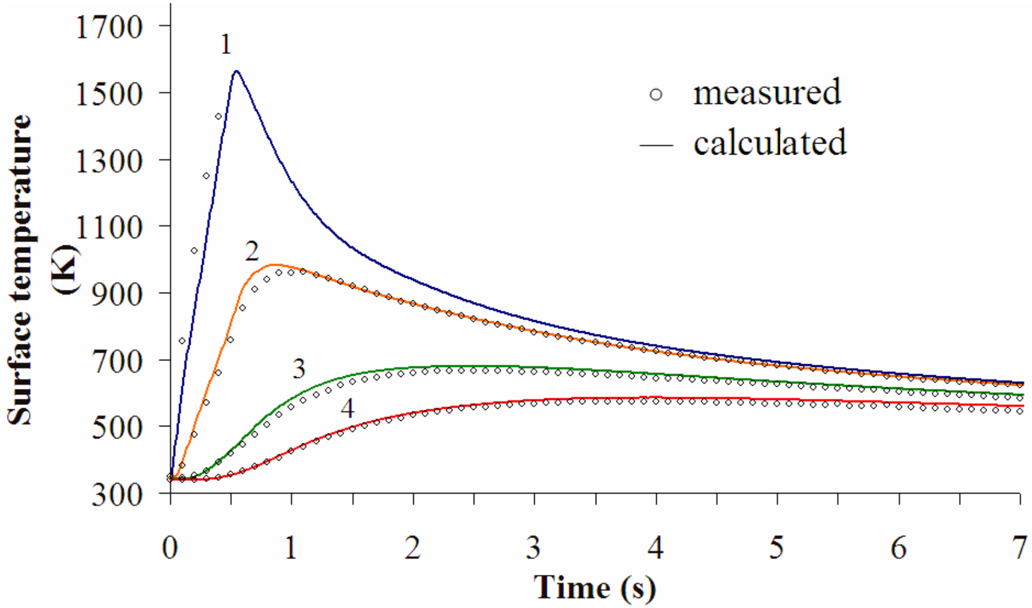
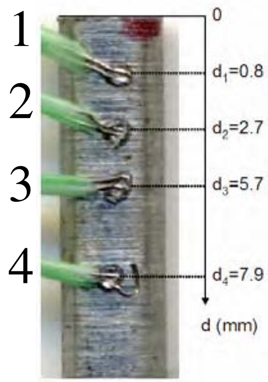
Experimental validation

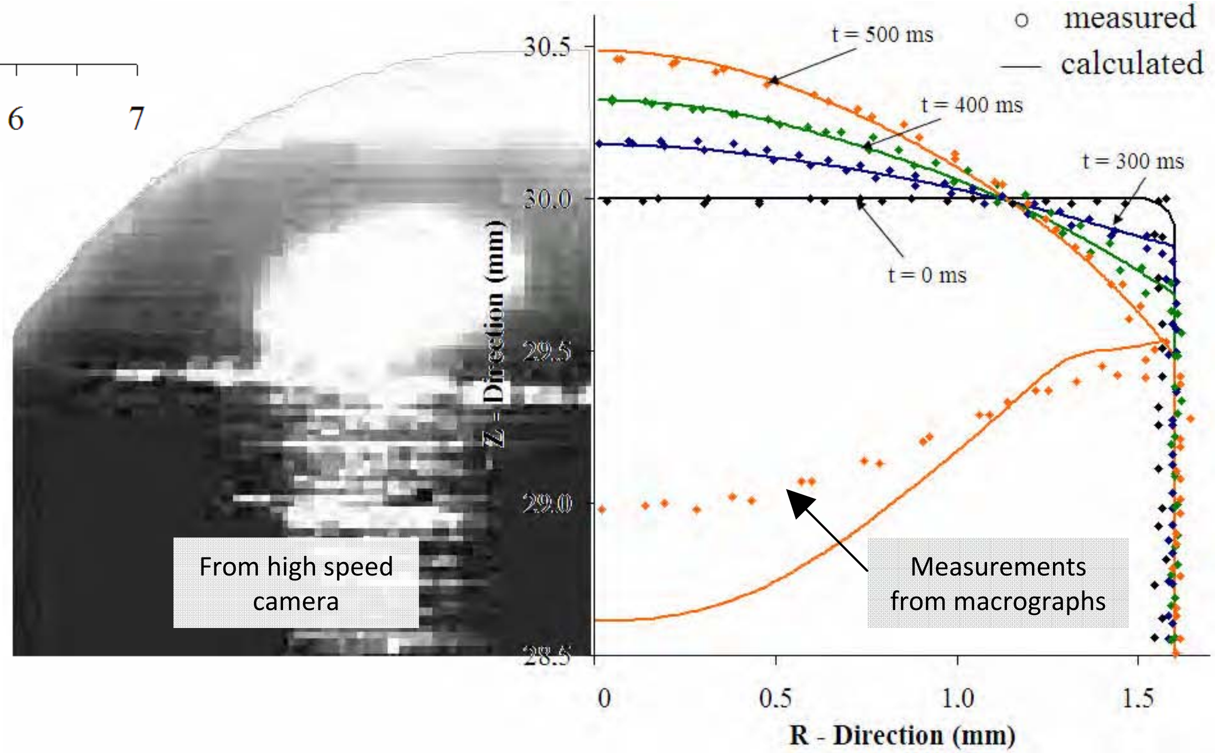




Conclusions :

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



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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