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Formation of Porosities during Spot Laser Welding: Case of Tantalum Joining

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Nd : YAG spot laser welding ➔ weak workpieces distortions

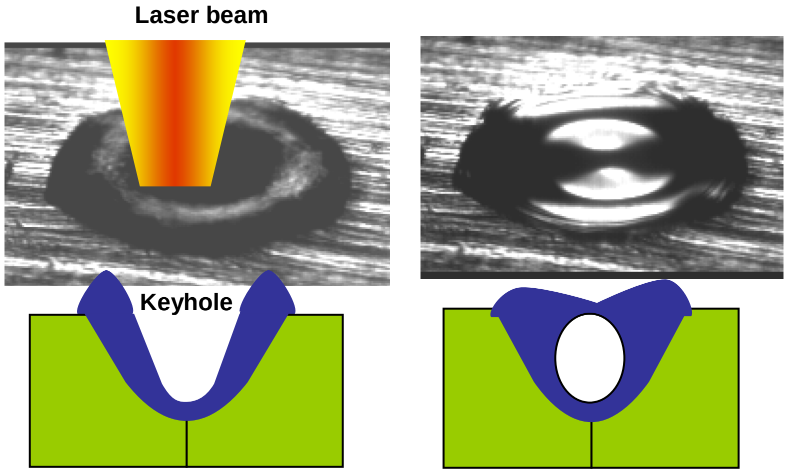
But welded joins can be polluted by micro or macro pores defects

Aim of the study:

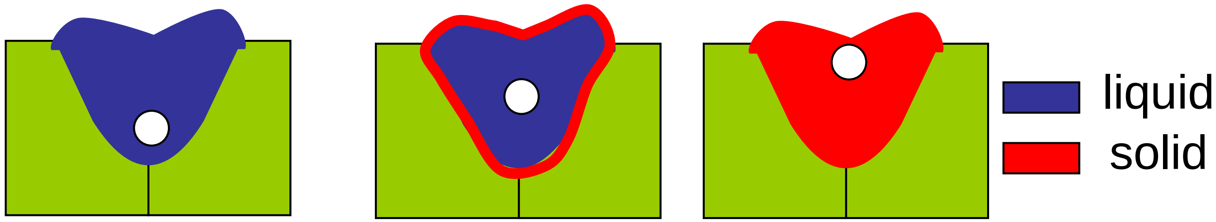
predict the formation of porosities in the case of tantalum joining

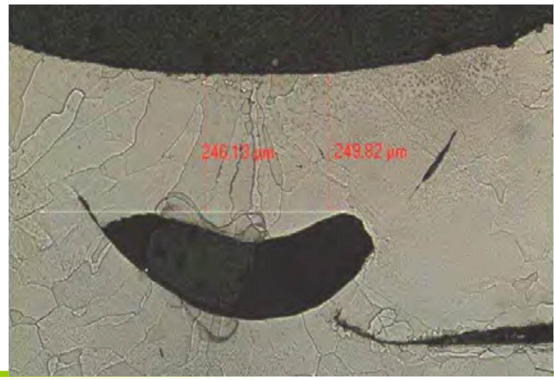
Physical mechanisms (identified during K. Girard‘s PHD)

Gas bubble trapping



Solidification front progress ➔ residual porosities



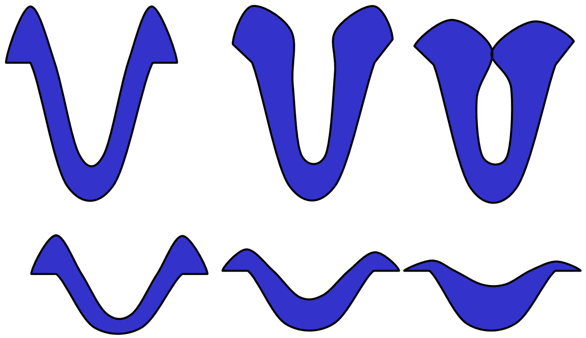


Physical models

Predictive approach of the whole process : complex
➔ Simulation of the cooling stage only

keyhole shape ➔
mechanisms of collapse

1st model



Hydraulic

2nd model

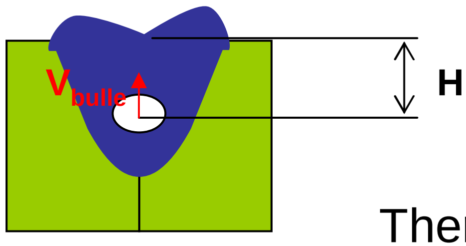
Gas bubble diameter

+

Solidification time

=

Porosity ?



Thermo-hydraulic

Laminar Flow

$$\mathrm{Re} = \frac{\rho V L}{\eta} = 175$$

Capillary effects >>viscous effects

$$Ca = \frac{\mu V}{ts} = 2.10^{-3}$$

Gravity neglected

$$Bo = \frac{\rho g.L^2}{ts} = 8.10^{-4}$$

Material properties :

Density ρ = 15630 kg/m^3

Dynamic viscosity μ = 8.032^e-3 Pa·s.

Surface tension coefficient σ = 2.168 N/m.

Interface tracking : Level Set and Phase Field methods

Level Set

$$\frac{\partial\phi}{\partial t} + \mathbf{u}\cdot\nabla\phi = \gamma\nabla\cdot\left(\varepsilon\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right)$$

u (m/s) fluid velocity, γ (m/s) and ε (m) stabilization parameters

Phase Field

$$\frac{\partial\phi}{\partial t} + \mathbf{u}\cdot\nabla\phi = \nabla\cdot\frac{\gamma\lambda}{\varepsilon^2}\nabla\psi$$

$$\psi = -\nabla\cdot\varepsilon^2\nabla\phi + (\phi^2-1)\phi$$

u fluid velocity (m/s), γ mobility parameter (m3·s/kg), λ mixing energy density (N), and ε (m) interface thickness parameter

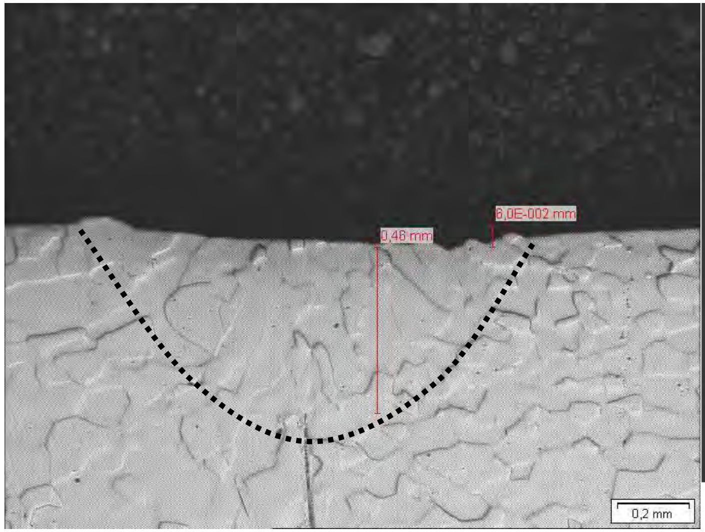
Incompressible Navier-Stokes equations

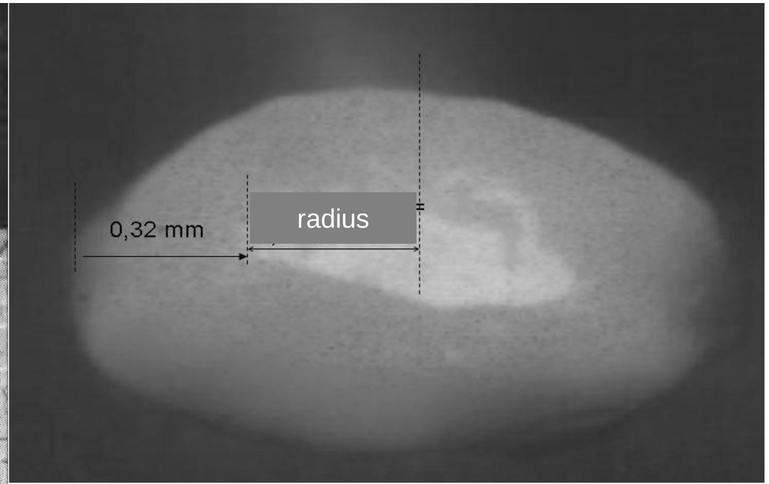
$$\nabla\cdot\mathbf{u} = 0$$

$$\rho\left(\frac{\partial\mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \nabla\cdot\eta(\nabla\mathbf{u} + \nabla\mathbf{u}^T) + \rho\mathbf{g} + \mathbf{F}_{st}$$

ρ (kg/m3) density, u velocity (m/s), t time (s), p pressure (Pa), η denotes dynamic viscosity (Pa·s).

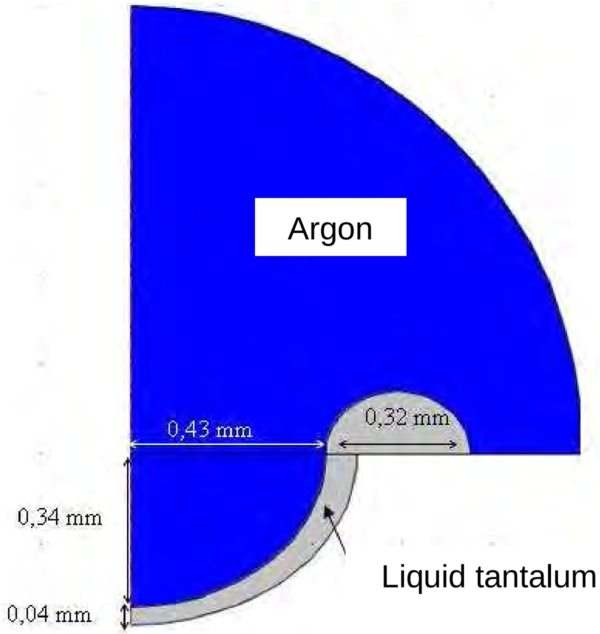
Keyhole collapse: initial state



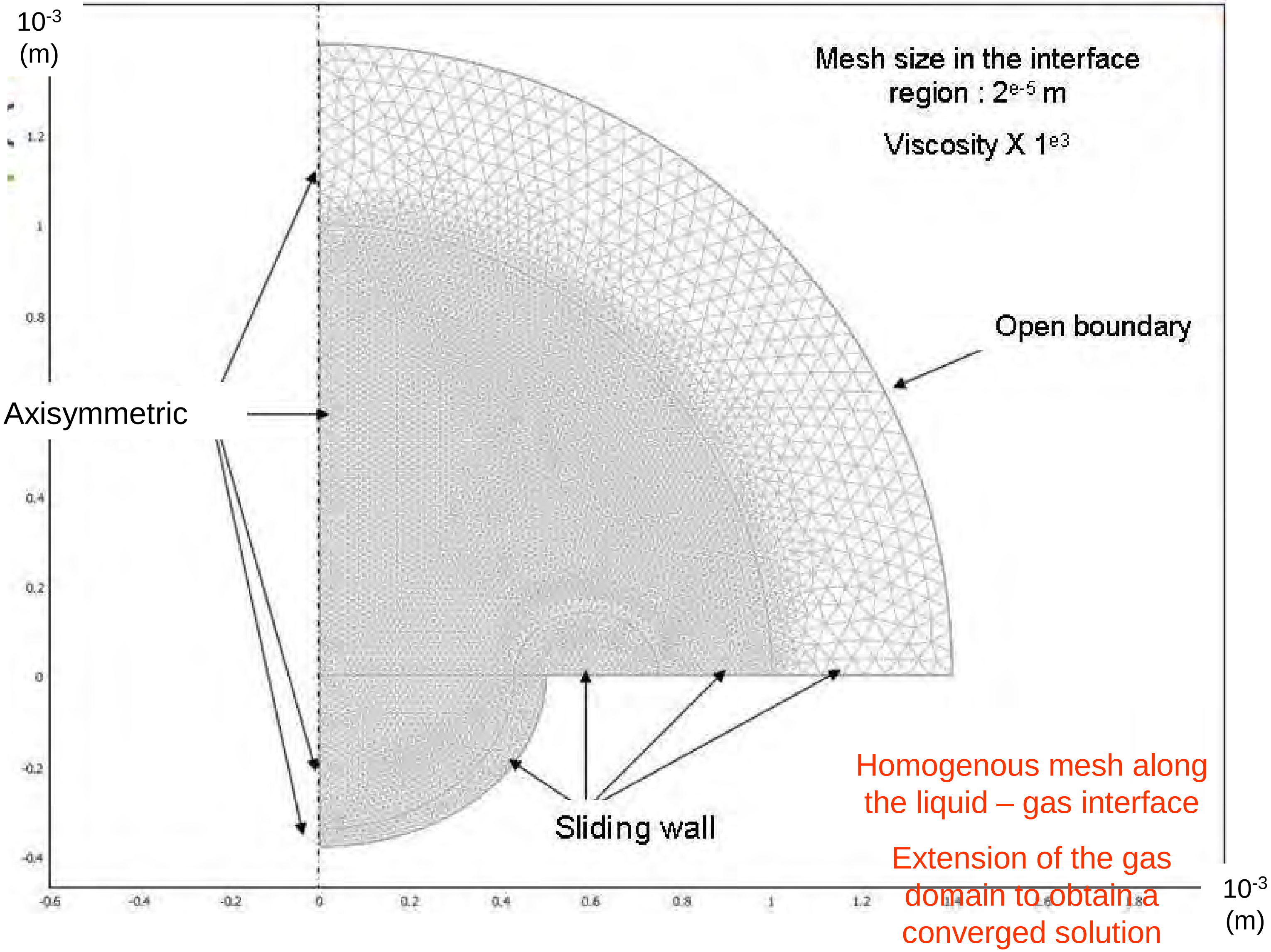


Keyhole ½ elliptic

Metal accumulated at the surface ➔ toric



Keyhole collapse: boundary conditions and meshing



Homogenous mesh along the liquid – gas interface

Extension of the gas domain to obtain a converged solution

Keyhole collapse: stabilization parameters

Level Set : ε = 1e-5 m (= mesh size / 2),
$\gamma = 1\ m.s^{-1}$ (experimental estimation of the fluid velocity)

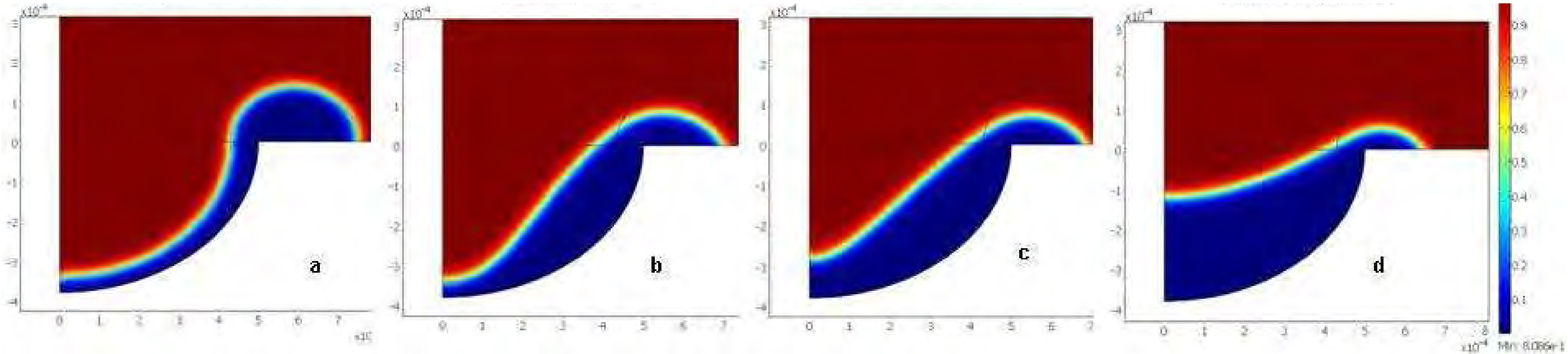
The initialization time is fixed to 5ε/γ (ε=mesh size/2).

Phase Field :

ε = 5e-6 m, $\chi = 1\ m^2.s^{-1}$ (successive tests)

The phase field initialization time is 5ε for χ=1 (ε=mesh size/2).

Keyhole collapse: results and discussion



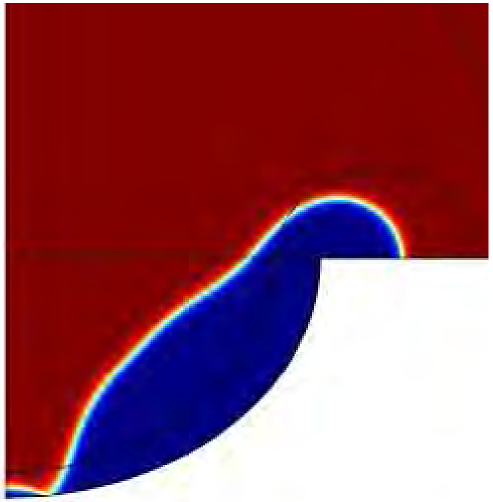
Detachment stage

Filling stage

For high viscosity (1000µ): same results with the Level Set and the Phase Field methods (filling >10 ms)

Spatial convergence mesh size < 2e-5 m

For the real viscosity (8e-3 Pa.s)



Level Set ➔ thinning of the liquid film
(not correct)

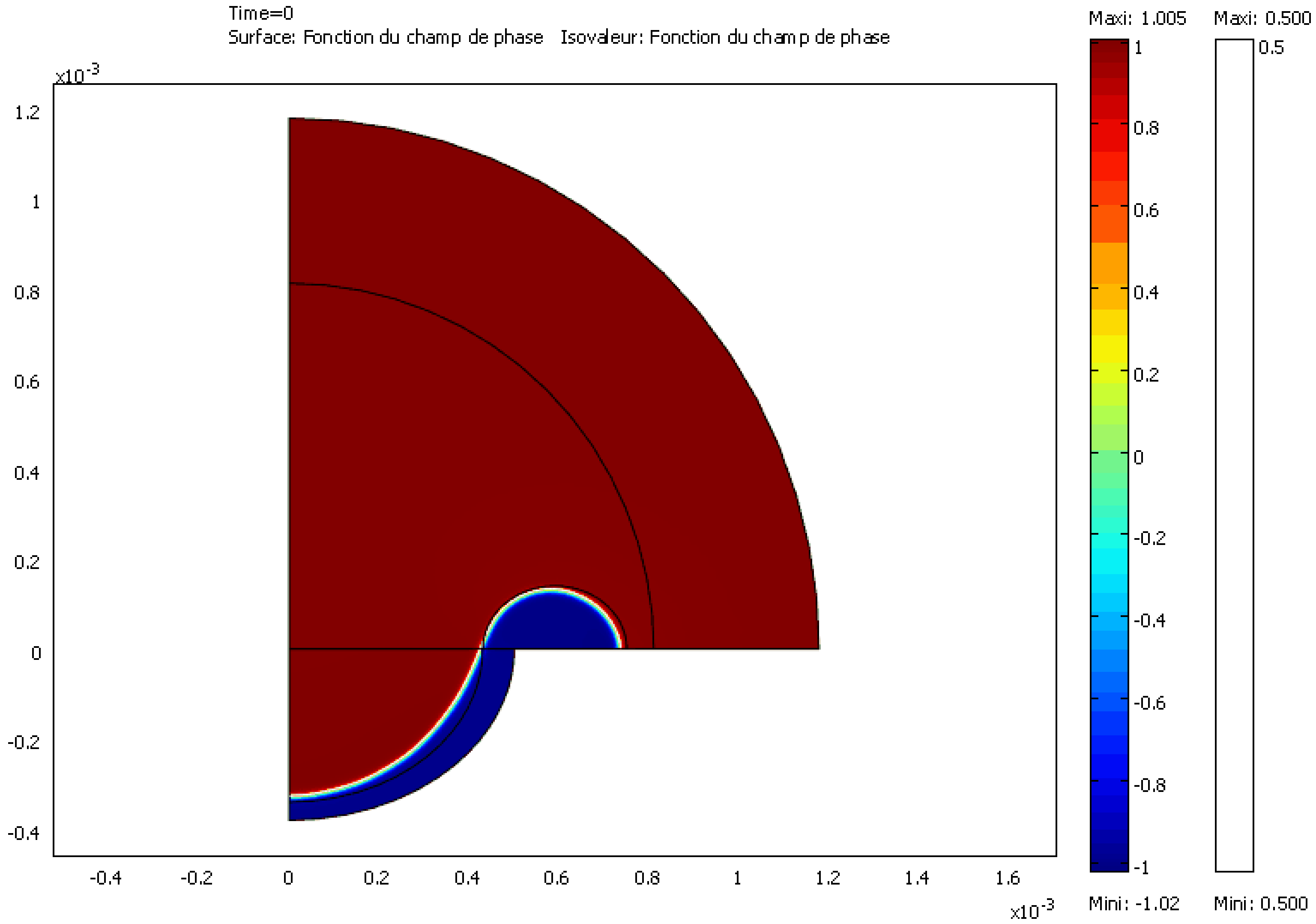
Phase Field ➔ correct interface shape

Complete filling time : > 8 ms

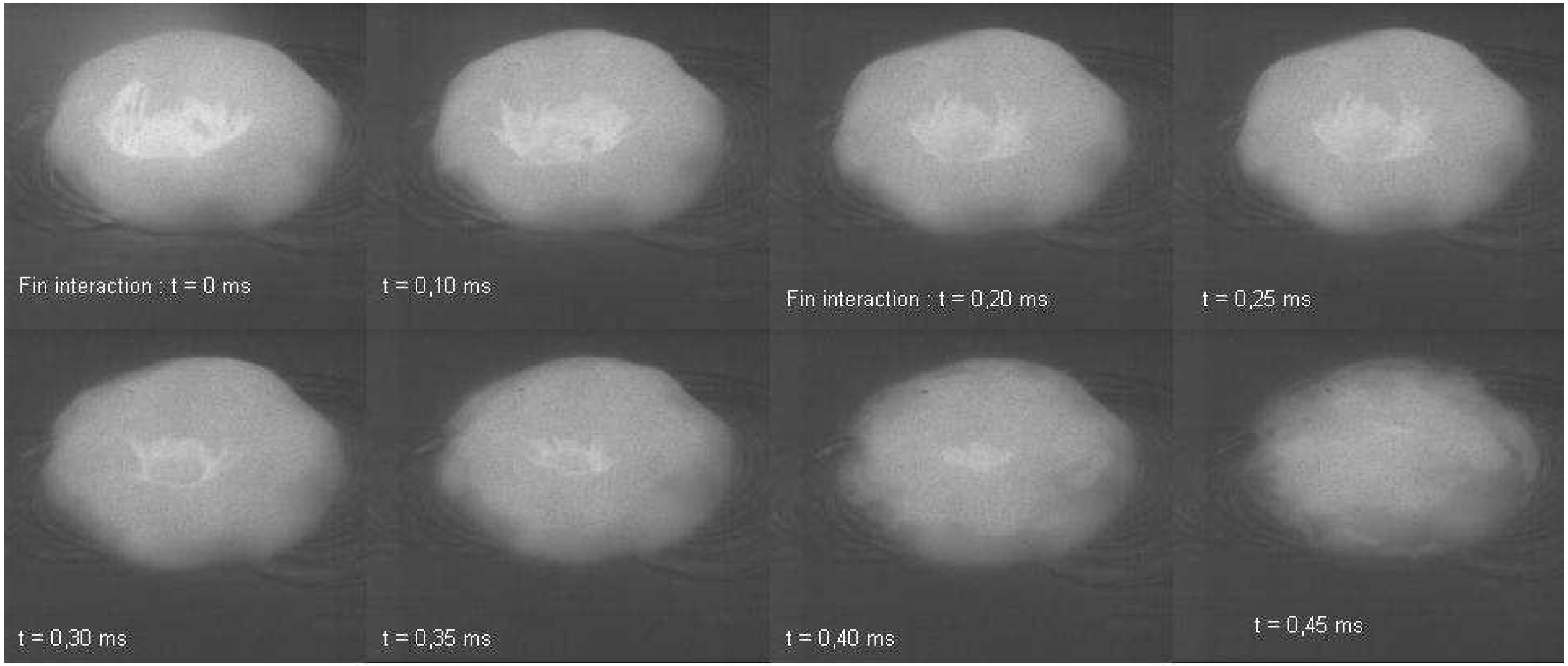
Solver BDF

calculation of the Jacobien at each iteration

Keyhole's collapse: results and discussion (Phase Field)



Experimental filling time ….



Numerical filling time longer than expected … Dependence between materials properties and the temperature field ?

Only an hydraulic approach

Model close to “Bubble rising” (COMSOL documentation)

Same equations as in the “keyhole’s collapse” model.

Same material’s properties as in the “keyhole’s collapse” model

Laminar Flow

$$\mathrm{Re} = \frac{\rho V L}{\eta} = 40$$

Capillary effects >>viscous effects : Ca

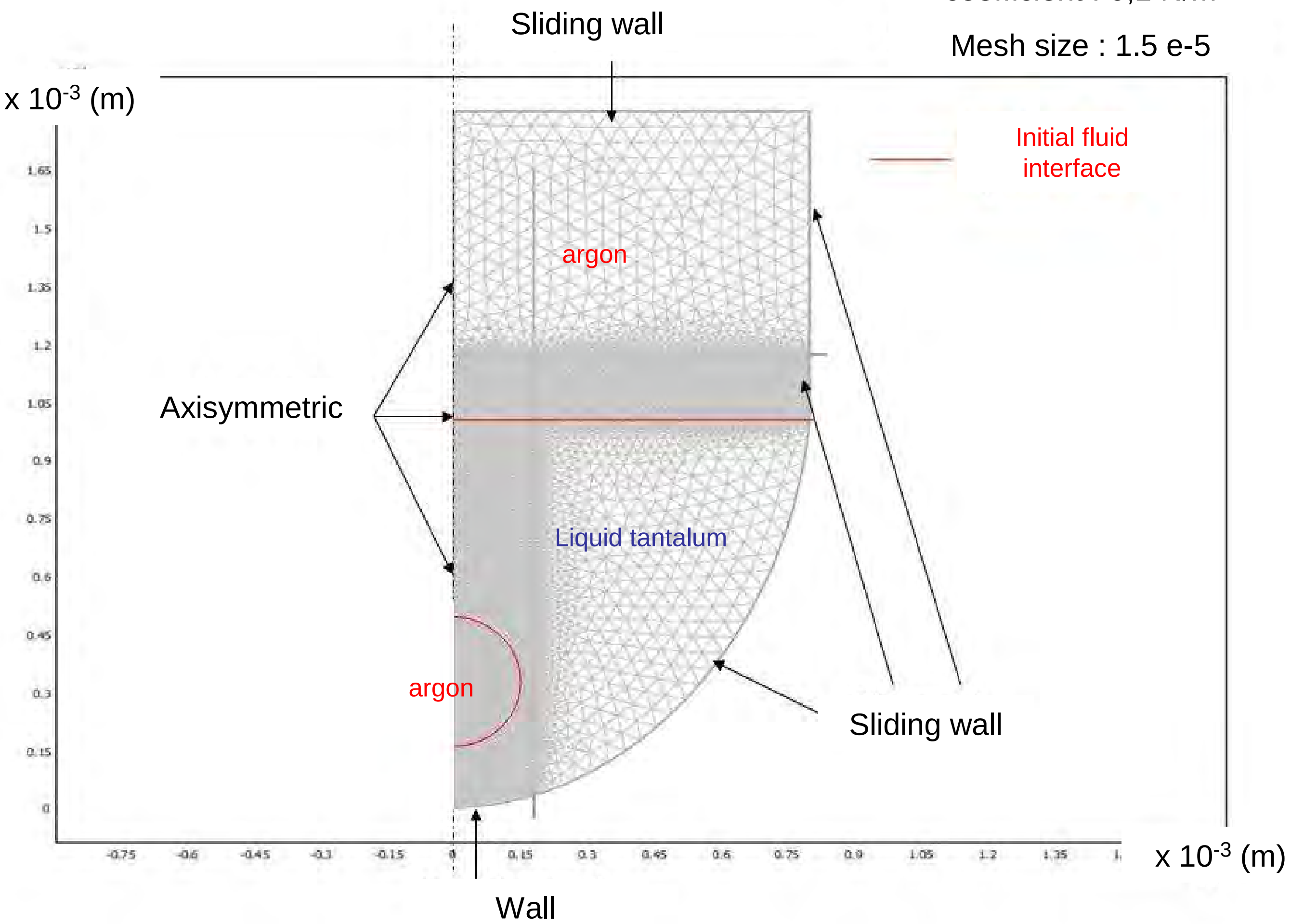
$$Ca = \frac{\eta V}{\sigma} = 2.10^{-4}$$

Gravity ➔ Archimedes's force

Gas bubbles rising: initial state, meshing and boundary conditions

Surface tension coefficient : 0,1 N/m

Mesh size : 1.5 e-5



Gas bubble diameter : 0.3^{e}-3 m

Surface tension coefficient highly influence the fluid flow

For σ~1e-3 N/m, same results with level set and Phase Field method

Ovalisation of the bubble

Up rising duration : 17 ms

For σ~1e-1 N/m , convergence with the 2 methods
(BDF + Jacobien calculation at each iteration)

Refinement of the mesh (2e-5 m)

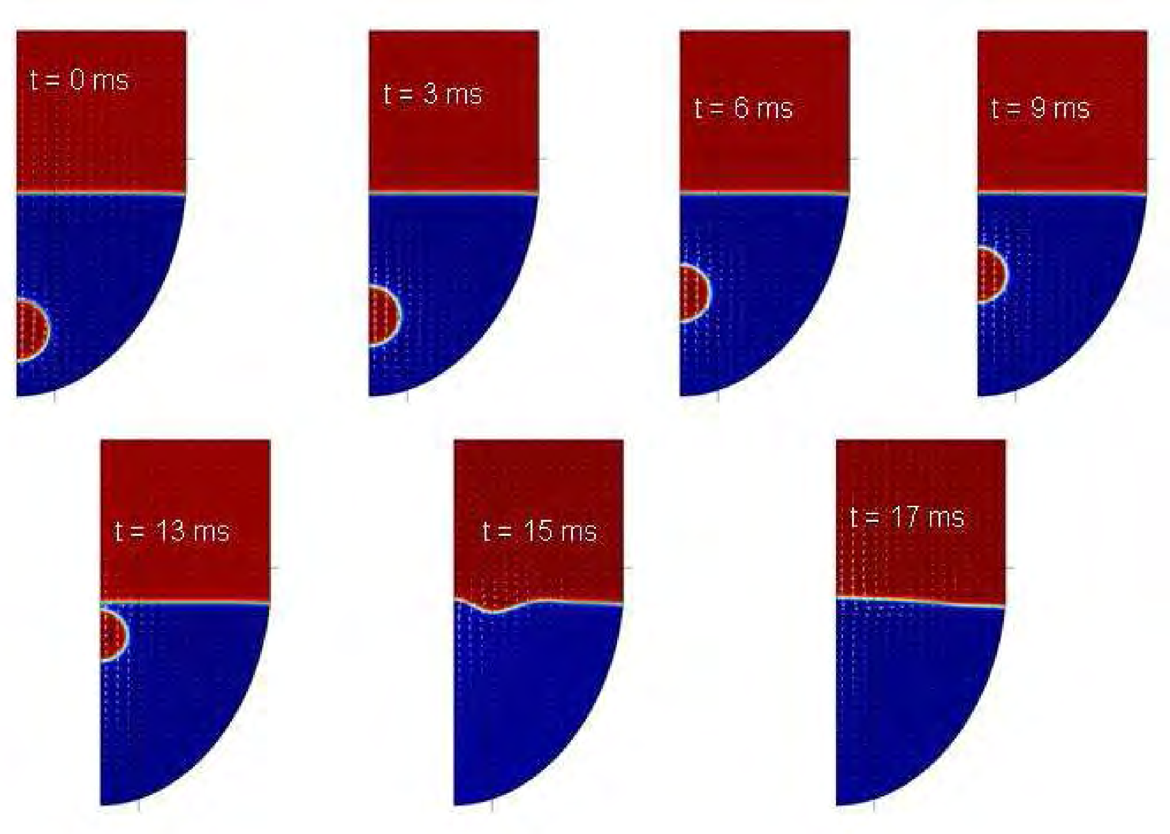
Up rising duration : 14 ms

For σ=5e-1 N/m, convergence with the Phase Field method only
(BDF + Jacobien calculation at each iteration)

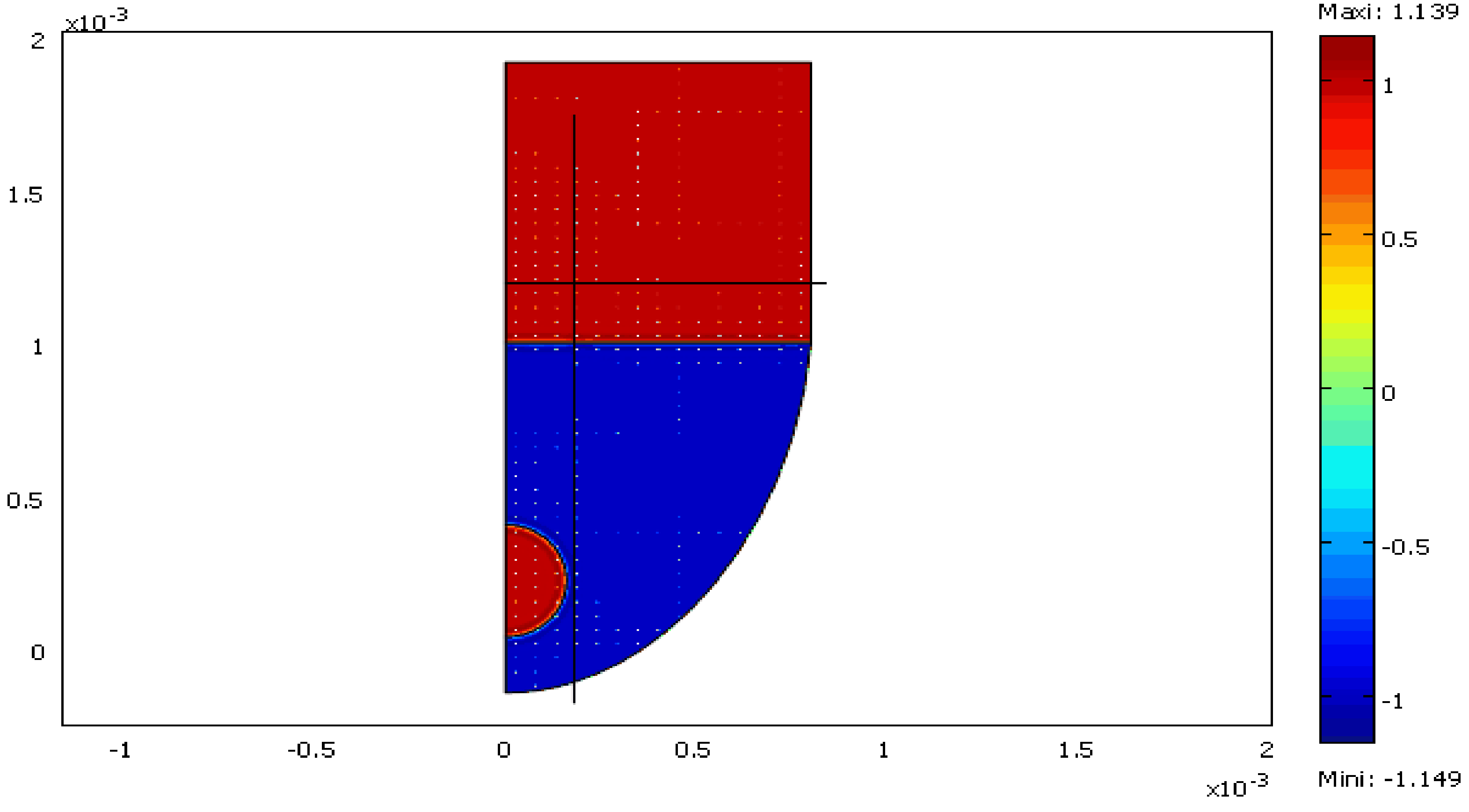
Refinement of the mesh (2e-6 m)

Up rising duration : 12 ms

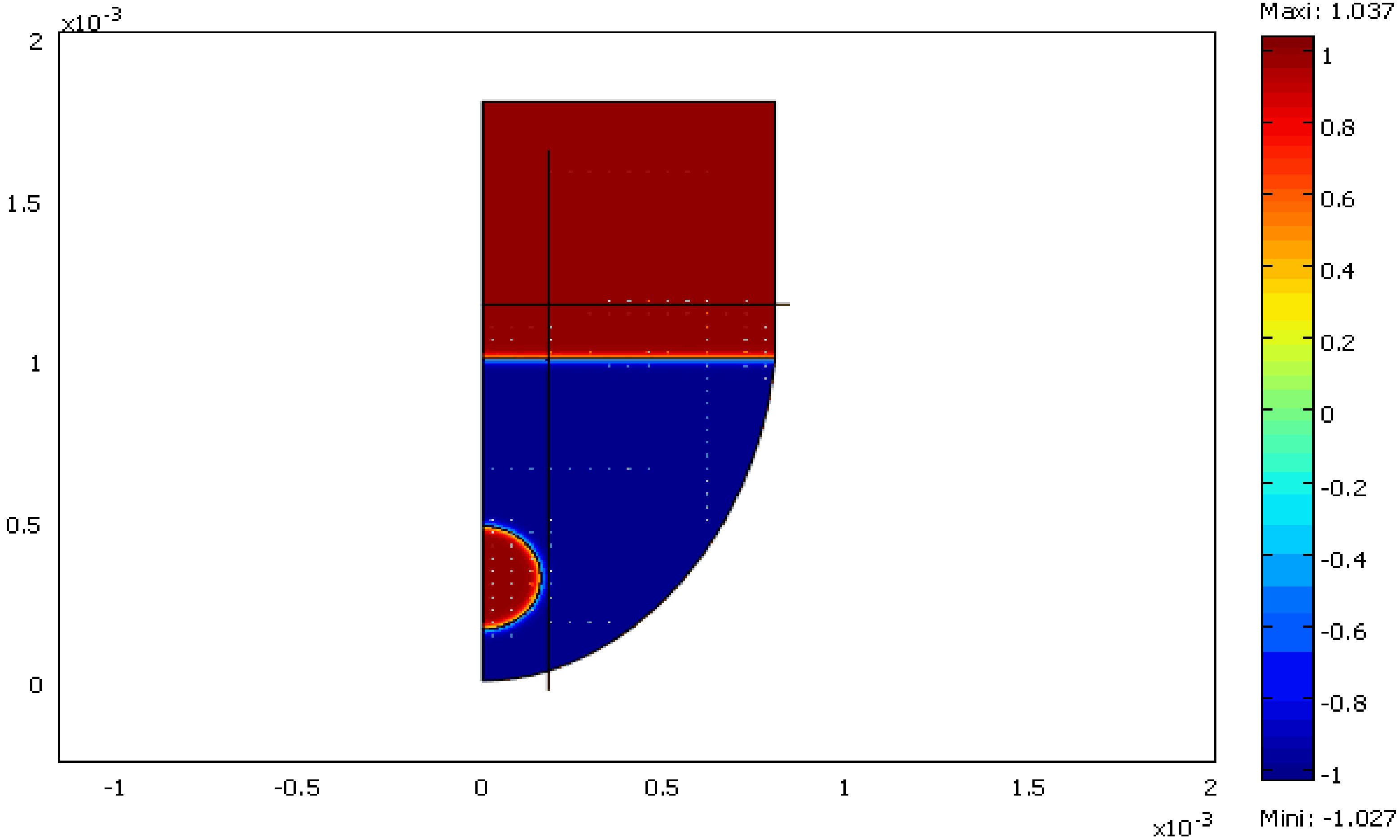
Results for
σ~1e-1
N/m



Gas bubbles rising: results and discussion: without surface tension



Gas bubbles rising: results and discussion: surface tension = 0.1 N/m



At the fusion temperature, σ=2.1 N/m➔ The mesh will have to be consequently refined (reduction of ε)

Progression of the solidification front :

Coupling with a solidification/melting model
➔ thermo hydraulic approach

Conclusions

2 models have been developed to increase our understanding of the porosities formation during spot laser welding.

1st model ➔ collapse of the keyhole,

2nd model ➔ up rising of gas bubble.

For the 2 cases :

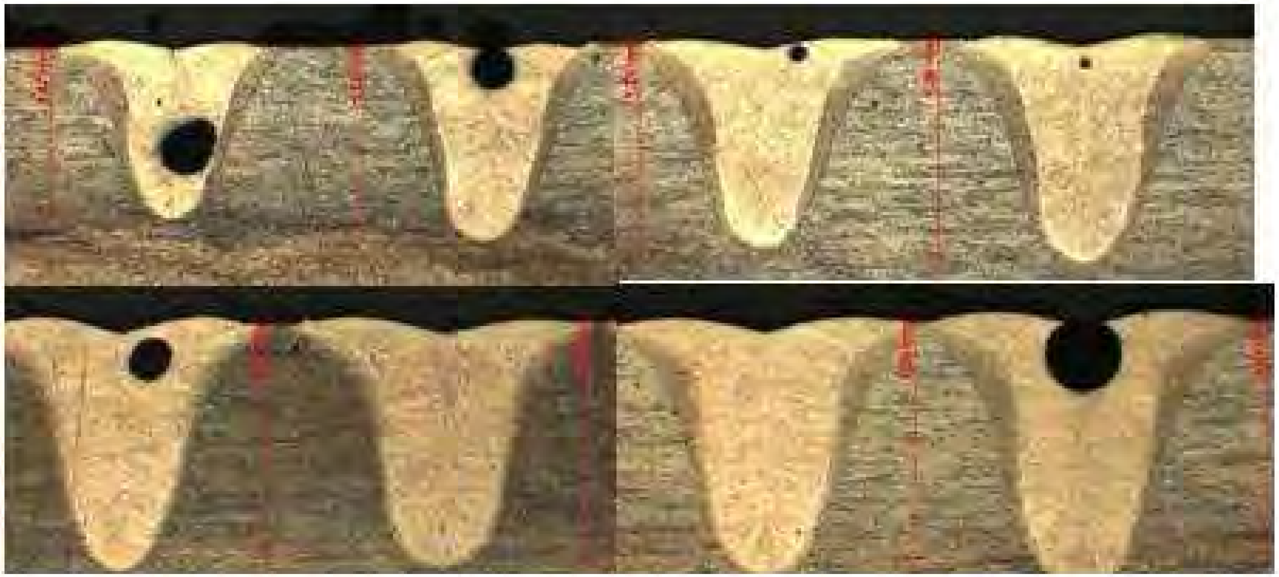
Application modes : Level Set and Phase Field

Better convergence with the Phase Field method, solver BDF, calculation of the Jacobien at each iteration – Especially for important surface tension coefficients ..

Importance of materials properties

Experimental confrontations are needed to analyze the simulations hypothesis

Metallurgical characterizations to valid the position of the bubbles after the cooling stage (complete problem)



Example : TA6V

Thanks to :

M. PETIT (COMSOL): *model of "keyhole's collapse" with a high viscosity*

M. NAMY (SIMTEC): *advices concerning the "Rising Bubble" model*

M. Fabbro and H. Koji (PIM Laser/ CNRS): *Visualization of the keyhole*

All the COMSOL Support team