Modeling of Expanding Metal Foam

B. Chinè[1,3] and M. Monno[2,3]
[1]Instituto Tecnológico de Costa Rica, Costa Rica; [2]Politecnico di Milano, Italy;
[3] Laboratorio MUSP, Macchine Utensili e Sistemi di Produzione, Piacenza, Italy.

bchine@itcr.ac.cr

TEC Tecnológico de Costa Rica

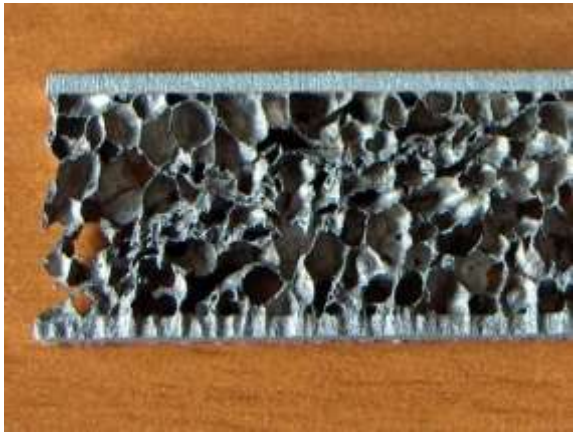
POLITECNICO MILANO

MUSP
Macchine Utensili e Sistemi di Produzione

COMSOL CONFERENCE 2014 CAMBRIDGE

September 17-19

Presentation overview



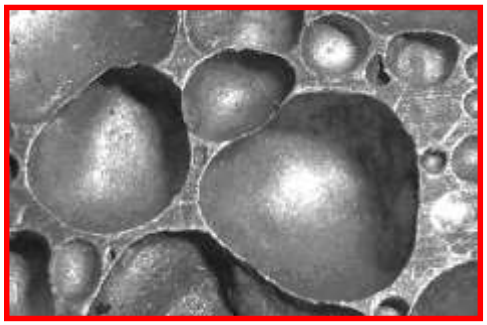
- Introduction
- Metal foams
- Bubble expansion
- Expanding a metal foam
- Modeling the disjoining pressure
- Conclusions

Indirect foaming via precursor: physical phenomena

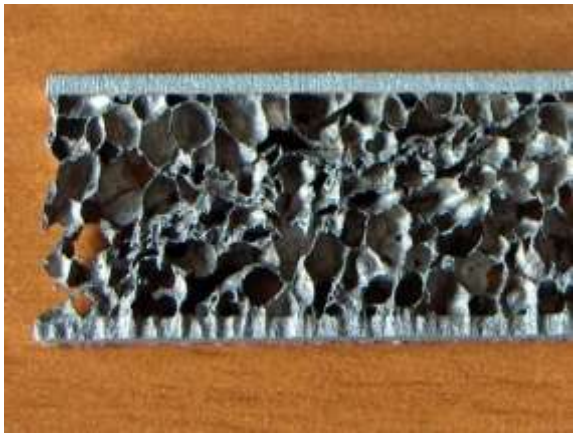
Foaming [1,2,3] is a complex phenomena:

- simultaneous mass, momentum and energy transfer mechanisms
- several physical phenomena on interfaces, interface motion
- **bubble expansion**, dynamics, coarsening, rupture
- other aspects (drainage, mould filling, geometry)
- difficulty for experimental measurements (foams are hot, opaque, etc.)

melted Al and H_2 gas



solidified metal foam

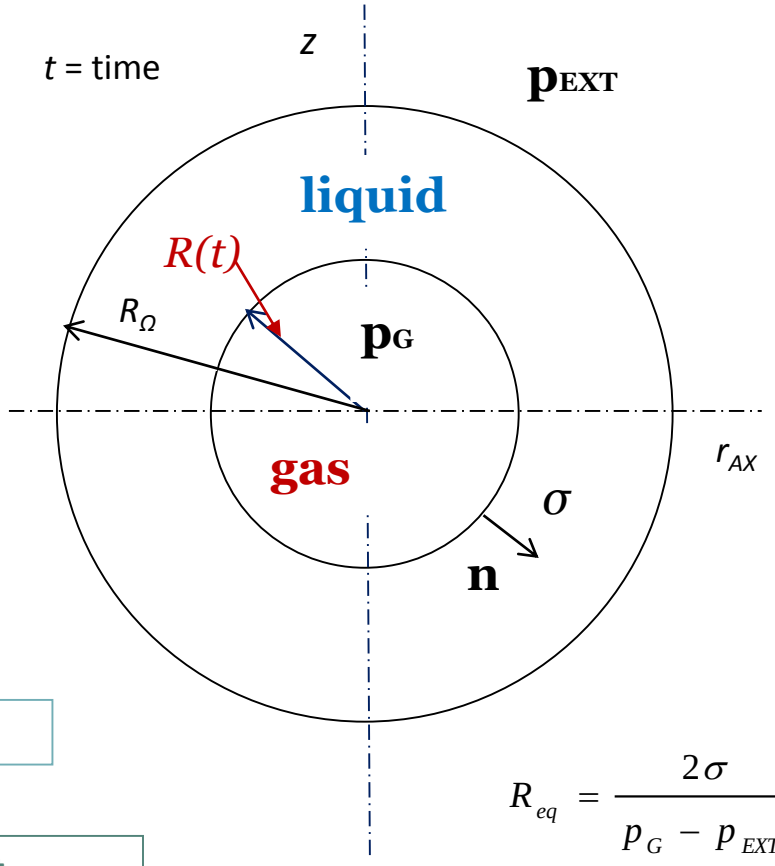


Bubble expansion: model

Two Phase Flow, Level Set interface, Weakly-Compressible [4]

t = time

σ = surface tension coefficient



$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

continuity

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - (\frac{2\eta}{3} - \kappa_{DV})(\nabla \cdot \mathbf{u})\mathbf{I}] + \mathbf{F} + \rho \mathbf{g} + \mathbf{F}_{ST}$$

momentum

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

level set

$$R_{eq} = \frac{2\sigma}{p_G - p_{EXT}}$$

without flow at time t

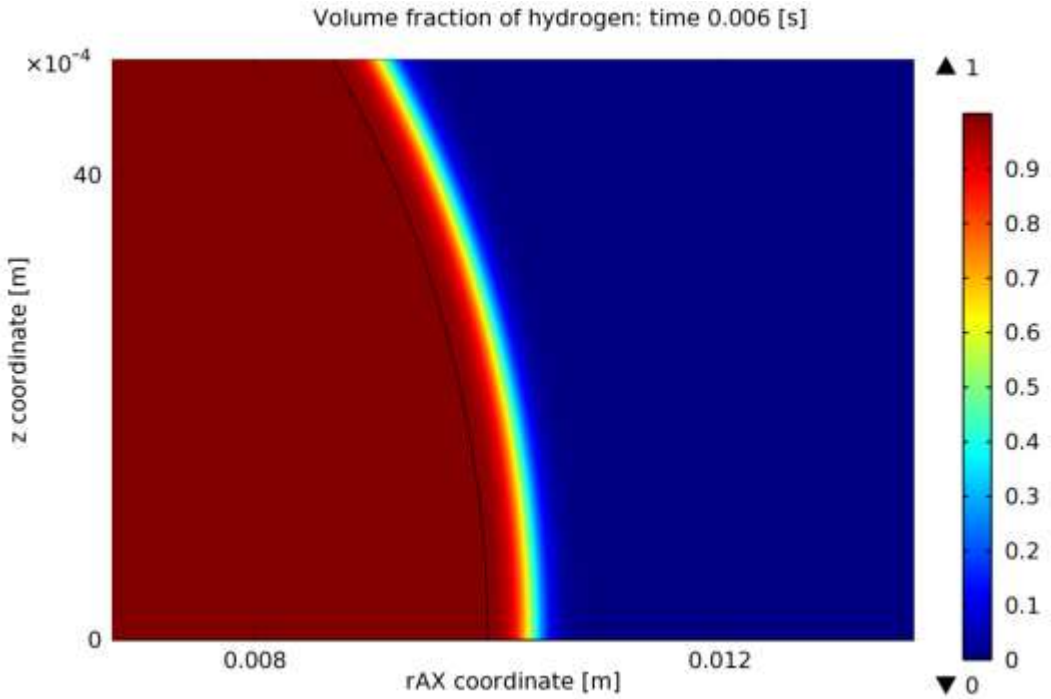
$$\rho_G(t) = \frac{\rho_{G,0}}{\left\{1 + \frac{1}{4\eta_L}\left[p_{G,0} - (p_{EXT,0} + \frac{2\sigma}{R_0})\right] t\right\}^3}$$

during the expansion at time t [5]

η_L, dynamic viscosity of the liquid

Bubble expansion: simulation

$$p_{G,0} = 190.1\,\text{Pa},\quad \rho_L = 2.4x10^{3}\ \text{kg/m}^{3},\quad \mu_L = 4.5x10^{-3}\ \text{Pa}\cdot\text{s}$$



$$\nu = \frac{\mu}{\rho} \cong 1.9x10^{-6}\ \text{m}^2/\text{s}$$

$$\text{Re} \cong 293$$

Expanding a metal foam: model

A 2D solid region of precursor partially filling a circular mold placed horizontally inside a furnace.

Complex phenomena as bubble nucleation, their location, growth, etc. simplified. Air of the cavity substituted for H_2 (only 2 fluids).

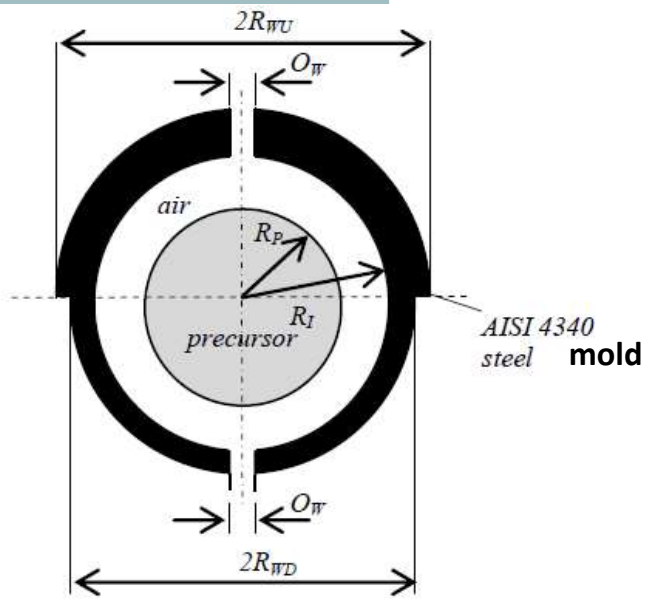
A simplified model [6] may be used for metal foaming, by assuming that:

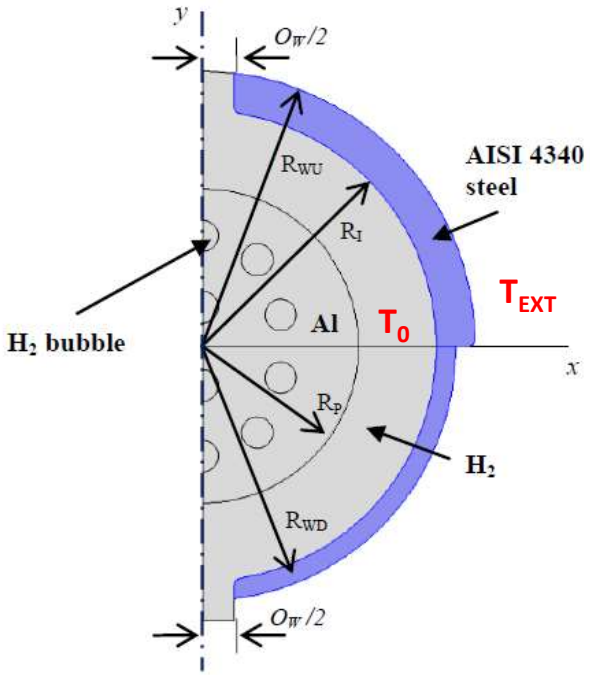
- <u>Step 1:</u>

  heat is transferred from the furnace wall to the solid precursor ;
- <u>Step 2:</u>

  H_2 starts to be released, then N H_2 bubbles are evenly generated inside the solid Al.
- <u>Step 3:</u>

  The N bubbles start expanding and moving after that Al is melted.





Expanding a metal foam: model

Equations (coupled)

(Heat transfer module [7] and level set method of the CFD module [4]):

continuity

gas expansion rate: $\rho_G(t) = \rho_{G,0}\exp(-t)$

momentum transfer

interface movement (level set)

+

heat transfer

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u}\nabla T = \nabla \cdot (k\nabla T) + Q$$

Free triangular mesh

on the mold wall: 2.6 x 10 $^{-3}$ m

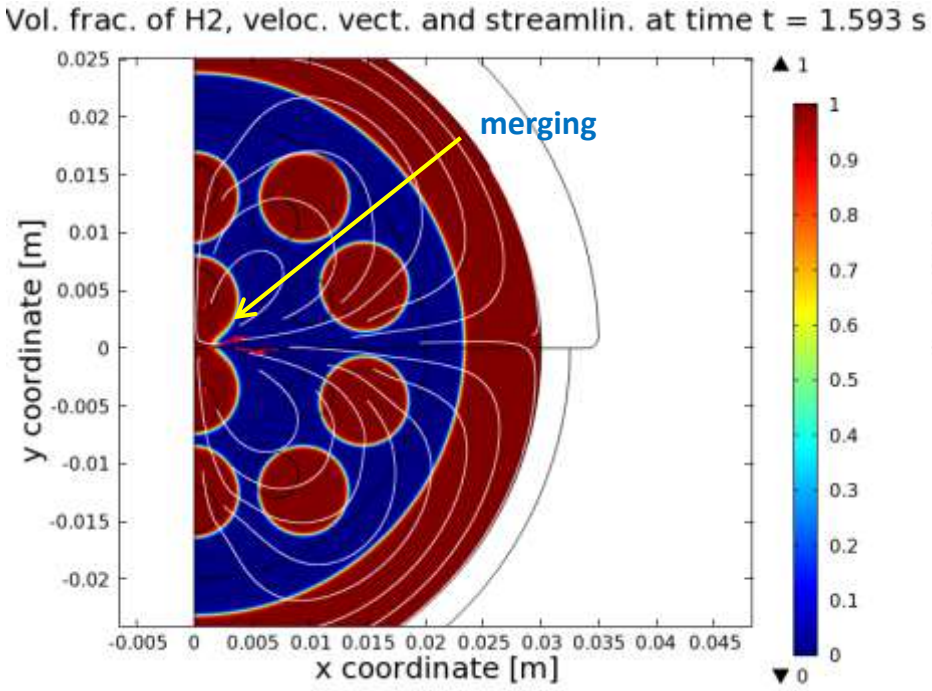
Magnitude	Symbol	Value
Max element size of the mesh	-	1.3×10^{-4} m
Time stepping	-	set by the solver
Relative tolerance	-	10^{-3}
Absolute tolerance	-	10^{-4}
Interface thickness	ε	1×10^{-4} m
Reinitialization	γ	0.1 m/s

DOF:
Step 1 and 2: 3.4 x 10^5
Step 3: 1.83 x 10^6

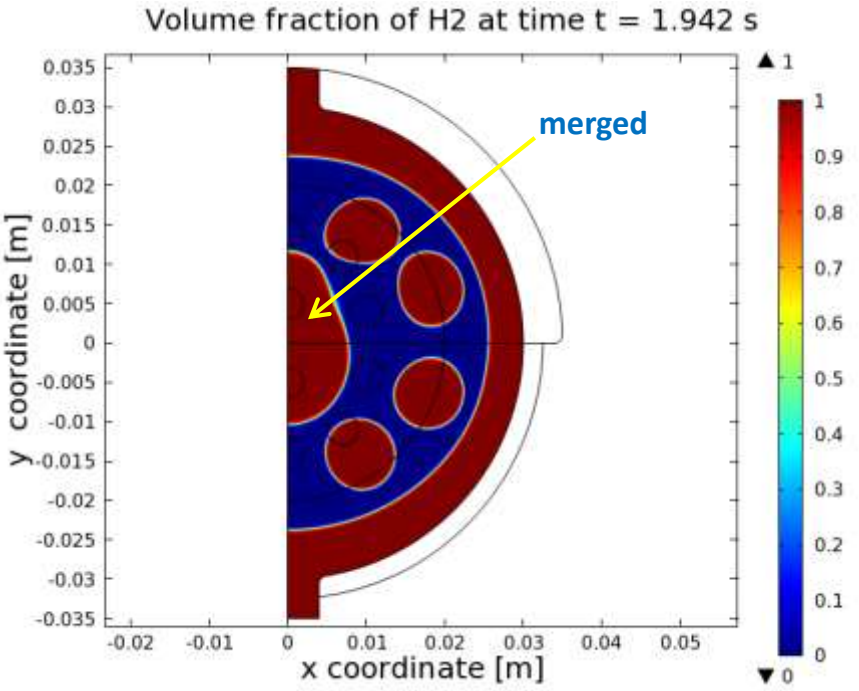
Segregated steps for the nonlinear solver
First: flow and level set variables
Second: heat transfer variables

TIME STEP (direct solver PARDISO):
Step 1: initial 10^{-6} s, final 31 s
Step 2: initial 10^{-2} s, final 58 s
Step 3: 10^{-2} s (**10^{-5} s when bubbles are merging**)

Expanding a metal foam: simulation of step 3



merging of two central bubbles with fluid acceleration, after 1.593 s the expansion is started



four central bubbles have merged after 1.942 s the expansion is started

Modeling the disjoining pressure

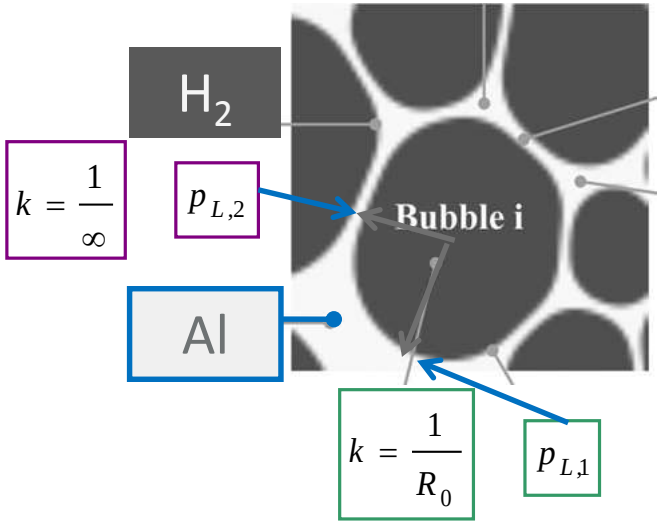
The liquid metal is suctioned from the capillary films to the borders of the foam (Plateau borders) causing the interfaces to thin and bubbles **to merge.**

The drainage of the thin films is slowed and prevented when interactions between the film surfaces come into play (***disjoining pressure*** $\Pi(h)$, [8]).

In the model, once ***the film h between the bubbles became sufficiently small***, we take into account the disjoining pressure $\Pi(h)$ (representing a stabilization effect reducing the driving force for film thinning):

$$p_{G,0} = p_L + \sigma k$$

$p_{G,0}$ is the same $\Rightarrow \tilde{p}_{L,2} > p_{L,1}$



$$p_{G,0} = p_L + \sigma k + \Pi(h)$$ ← disjoining pressure

σ = surface tension coefficient

Modeling by the phase field method

Equations (coupled) (CDF and Chemical Reaction Engineering modules):

continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

momentum transfer

1. gas compressibility considered
2. flow is laminar

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \eta(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - (\frac{2\eta}{3} - \kappa_{DV})(\nabla \cdot \mathbf{u})\mathbf{I}] + \mathbf{F} + \rho \mathbf{g} + \mathbf{F}_{ST}$$

gas expansion rate: $\rho_G(t) = \rho_{G,0} \exp(-t)$

interface movement (phase field ϕ)

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

$$\psi = -\nabla \cdot \varepsilon^2 \nabla \phi + (\phi^2 - 1)\phi + \left(\frac{\varepsilon^2}{\lambda}\right)\frac{\partial f_{ext}}{\partial \phi}$$

help variable ψ

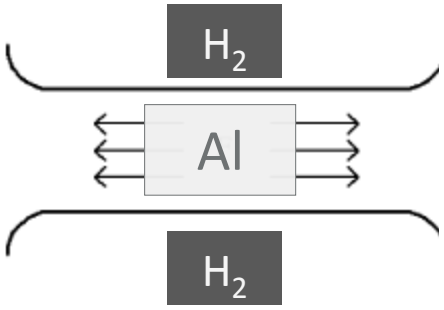
$$\mathbf{F}_{st} = \left(G - \frac{\partial f}{\partial \phi}\right)\nabla \phi$$

Surface tension force

$\phi = 1$ **hydrogen phase**

$\phi = 0$ **aluminium phase**

$\phi_{int} = 0.5$ the middle of the interface



But when two bubbles are approaching ➡ External force [9] (due to the disjoining pressure)

in Comsol:

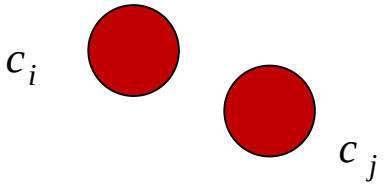
$$\mathbf{F}_{ext} = \left(\frac{\partial f}{\partial \phi}\right)\nabla \phi$$

Modeling by the phase field method

in Comsol

$$\mathbf{F}_{\text{ext}} = \left(\frac{\partial f}{\partial \phi}\right)\nabla \phi$$

External force (due to the disjoining pressure) is a defined source of free energy



to track each interface (if N=number of bubble is $\neq$ 1):
assigning a **marker c_i** to each **bubble *i*** and moving the marker like a species in the system, with the same velocity field of the corresponding bubble [10]

transport of diluted species (Fick's eq. and convection term), [11]

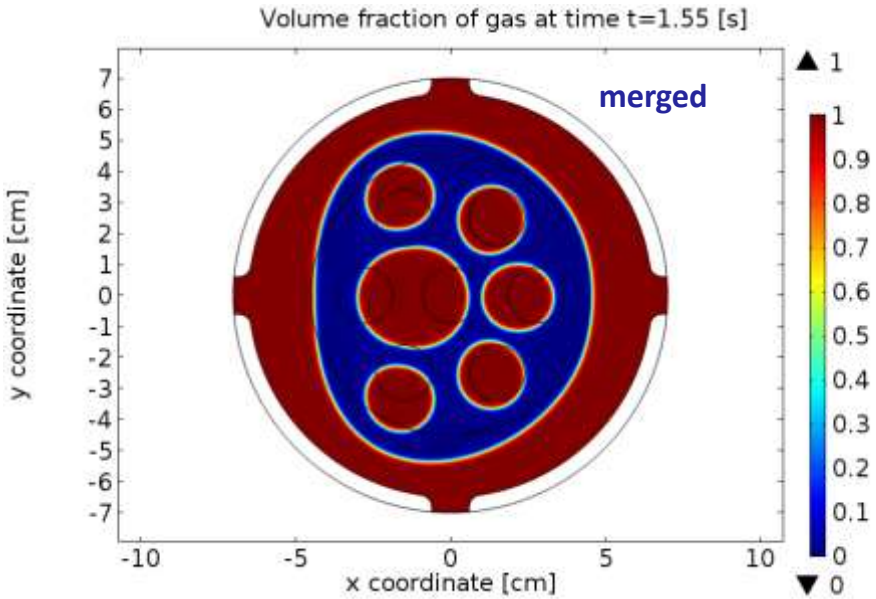
$$\frac{\partial c_i}{\partial t} + \nabla \cdot \left(-D_i \nabla c_i\right) + \mathbf{u} \cdot \nabla c_i = R_i \qquad R_i = 0$$

$D_i \approx 10^{-30}\, m^2/s$ **the marker is only convected**

then, if $c_i \; x \; c_j > set \;\; value$

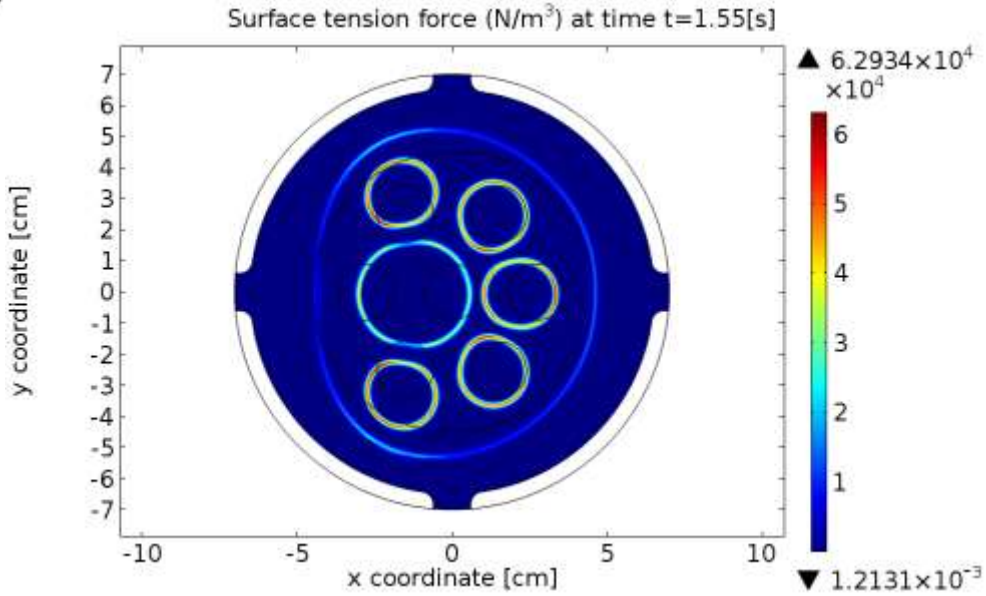
disjoining pressure is switched on

Simulations: without disjoining pressure

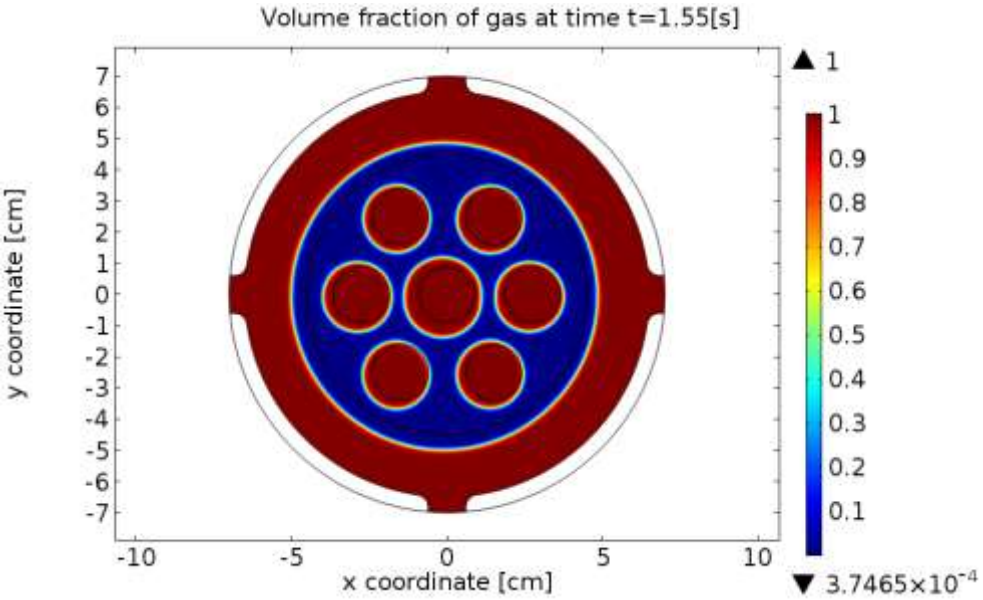


without repulsive effects

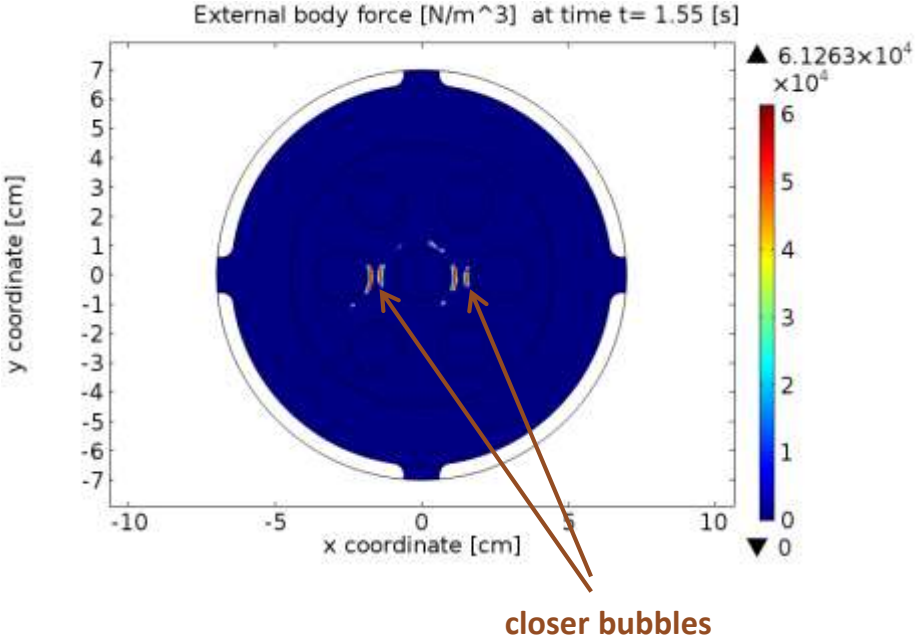
two central bubbles have already merged
after 1.55 s the expansion is started



Simulations: with disjoining pressure, stabilization effect



with repulsive effects due to the disjoining pressure



volume fraction of H_2 a the same time, with the disjoining pressure setting a **repulsive stabilization** effect between the bubbles interfaces

closer bubbles

Conclusions

•A modeling work by using Comsol Multiphysics has been developed for simulating a metal foam manufactured by an indirect foaming process via precursor.

• Bubble expansion, heat transfer and movement of H_2 gas bubbles in liquid Al has been modeled for a metal foam expanding in a 2D mold, driving the expansion by a specific expansion rate.

•Then, an expanding foam in a mold has been simulated with repulsive forces modeling the disjoining pressure by diffuse interface methods.

• Numerical findings verify that the computational model, based on level set or phase field techniques, can be effective for modeling the foaming process of a metal.

•Finally, for more comprehensive foaming models, computational requirements should be also considered.

References

[1] J. Banhart, Manufacture, characterization and application of cellular metals and metal foams, *Progress in Materials Science*, **46**, 559-632 (2001).
[2] J. Banhart, Light-metal foams-History of innovation and technological challenges, *Advanced Engineering Materials,* **15**, 82-111. doi: 10.1002/adem.201200217 (2012).
[3] D. Weaire D. and S. Hutzler S., *The physics of foams*, Oxford University Press, Oxford (1999).
[4] Comsol AB, Comsol Multiphysics-CFD Module, *User's Guide*, **Version 4.3b,** (2013).
[5] S.V. Gniloskurenko, A.I. Raichenko, T. Nakamura, A.V. Byakova and A.A. Raichenko, Theory of initial microcavity growth in a liquid metal around a gas-releasing particle. II. Bubble initiation conditions and growth kinetics, *Powder Metall. And Metal Ceramics,* **41**, N.1-2, 90-96 (2002).
[6] B. Chinè and M. Monno, Multiphysics modeling of a metal foam, *Proceedings of 2012 European Comsol Conference*, Milan, (2012).
[7] Comsol AB, Comsol Multiphysics-Heat Transer Module, *User's Guide*, **Version 4.3b,** (2013).
[8] C. Körner, *Integral Foam Molding of Light Metals,* 124. Springer-Verlag, Berlin Heidelberg (2008).
[9] P. Yue, J.J. Feng, C. Liu and J. Shen, Diffuse-interface simulations of drop coalescence and retraction in viscoelastic fluids, *Journal of Non-Newtonian Fluid Mechanics,* **129**, 163-176 (2005).
[10] B. Chinè , M. Monno, E. Repossi and M. Verani, Diffuse interface models for metal foam, *Proceedings of 2013 Comsol Conference*, Rotterdam, (2012).
[11] Comsol AB, Comsol Multiphysics-Chemical Reaction Engineering Module, *User's Guide*, **Version 4.3b,** (2013).

Many thanks for your attention.

We would like to also acknowledge:

TEC Tecnológico de Costa Rica **Vicerrectoría de Investigación y Extensión**

POLITECNICO MILANO

MUSP
Macchine Utensili e Sistemi di Produzione

… and to the organizers of the

COMSOL CONFERENCE
2014 CAMBRIDGE