Modeling of Expanding Metal Foam

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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.)
Bubble expansion: model

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

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

continuity

\[ \rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p \mathbf{I} + \eta (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \right] \]

\[ - \left( \frac{2\eta}{3} - \kappa_{ DV} \right) (\nabla \cdot \mathbf{u}) \mathbf{I} ] + \mathbf{F} + \rho \mathbf{g} + \mathbf{F}_{ ST} \]  
momentum

\[ \frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \gamma \nabla \cdot \left[ \phi (1-\phi) \nabla \phi \right] \]  
level set

\[ \rho_G (t) = \frac{\rho_{G,0}}{\left[ 1 + \frac{1}{4\eta_L} \left[ \rho_{G,0} - (p_{\text{EXT},0} + \frac{2\sigma}{R_0}) \right] t \right]^3} \]  
during the expansion at time t [5]

\[ \eta_L, \text{dynamic viscosity of the liquid} \]
Bubble expansion: simulation

\[ p_{G,0} = 190.1 \text{ Pa}, \quad \rho_L = 2.4 \times 10^3 \text{ kg/m}^3, \quad \mu_L = 4.5 \times 10^{-3} \text{ Pa \cdot s} \]

\[ \nu = \frac{\mu}{\rho} \approx 1.9 \times 10^{-6} \text{ m}^2/\text{s} \]

\[ \text{Re} \approx 293 \]
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:

- **Step 1:**
  heat is transferred from the furnace wall to the solid precursor ;

- **Step 2:**
  H$_2$ starts to be released, then N H$_2$ bubbles are evenly generated inside the solid Al.

- **Step 3:**
  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**

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

**on the mold wall:** \( 2.6 \times 10^{-3} \) m

**DOF:**

**Step 1 and 2:** \( 3.4 \times 10^5 \)

**Step 3:** \( 1.83 \times 10^6 \)

**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)

**Table:**

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max element size of the mesh</td>
<td>-</td>
<td>( 1.3 \times 10^{-4} ) m</td>
</tr>
<tr>
<td>Time stepping</td>
<td>-</td>
<td>set by the solver</td>
</tr>
<tr>
<td>Relative tolerance</td>
<td>-</td>
<td>( 10^3 )</td>
</tr>
<tr>
<td>Absolute tolerance</td>
<td>-</td>
<td>( 10^4 )</td>
</tr>
<tr>
<td>Interface thickness</td>
<td>( \varepsilon )</td>
<td>( 1 \times 10^{-4} ) m</td>
</tr>
<tr>
<td>Reinitialization</td>
<td>( \gamma )</td>
<td>0.1 m/s</td>
</tr>
</tbody>
</table>
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):

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

$\sigma$ = surface tension coefficient

\[ k = \frac{1}{\infty} \]

$\Pi(h)$

$\sigma$

$\sigma = \text{surface tension coefficient}$

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

$p_{G,0} = p_L + \sigma k$
Modeling by the phase field method

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

1. gas compressibility considered
2. flow is laminar

continuity

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

momentum transfer

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

gas expansion rate:

\[
\rho_c(t) = \rho_{c,0} \exp(-t)
\]

interface movement (phase field \( \phi \))

\[
\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \left( \frac{\gamma \lambda}{\varepsilon^2} \nabla \psi \right)
\]

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

help variable \( \psi \)

Surface tension force

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

\( \phi = 1 \) hydrogen phase \( \phi = 0 \) aluminium phase

In 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

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

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

in Comsol

to track each interface (if \( N=\text{number of bubble is} \neq 1 \)):
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]

\[ \frac{\partial c_i}{\partial t} + \nabla \cdot (- D_i \nabla c_i) + \mathbf{u} \cdot \nabla c_i = R_i \]

\[ R_i = 0 \]

\[ D_i \approx 10^{-30} \text{ m}^2 / \text{s} \]

the marker is only convected

then, if \( c_i \times c_j > \text{set value} \)

disjoining pressure is switched on
Simulations: without disjoining pressure

two central bubbles have already merged after 1.55 s the expansion is started
Simulations: with disjoining pressure, stabilization effect

Volume fraction of gas at time $t = 1.55 \text{[s]}$

with repulsive effects due to the disjoining pressure

Volume fraction of $\text{H}_2$ a the same time, with the disjoining pressure setting a repulsive stabilization effect between the bubbles interfaces
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 H₂ 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


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