Numerical Simulation of the Friction Stir Welding Process using Lagrangian, Eulerian & ALE Approaches

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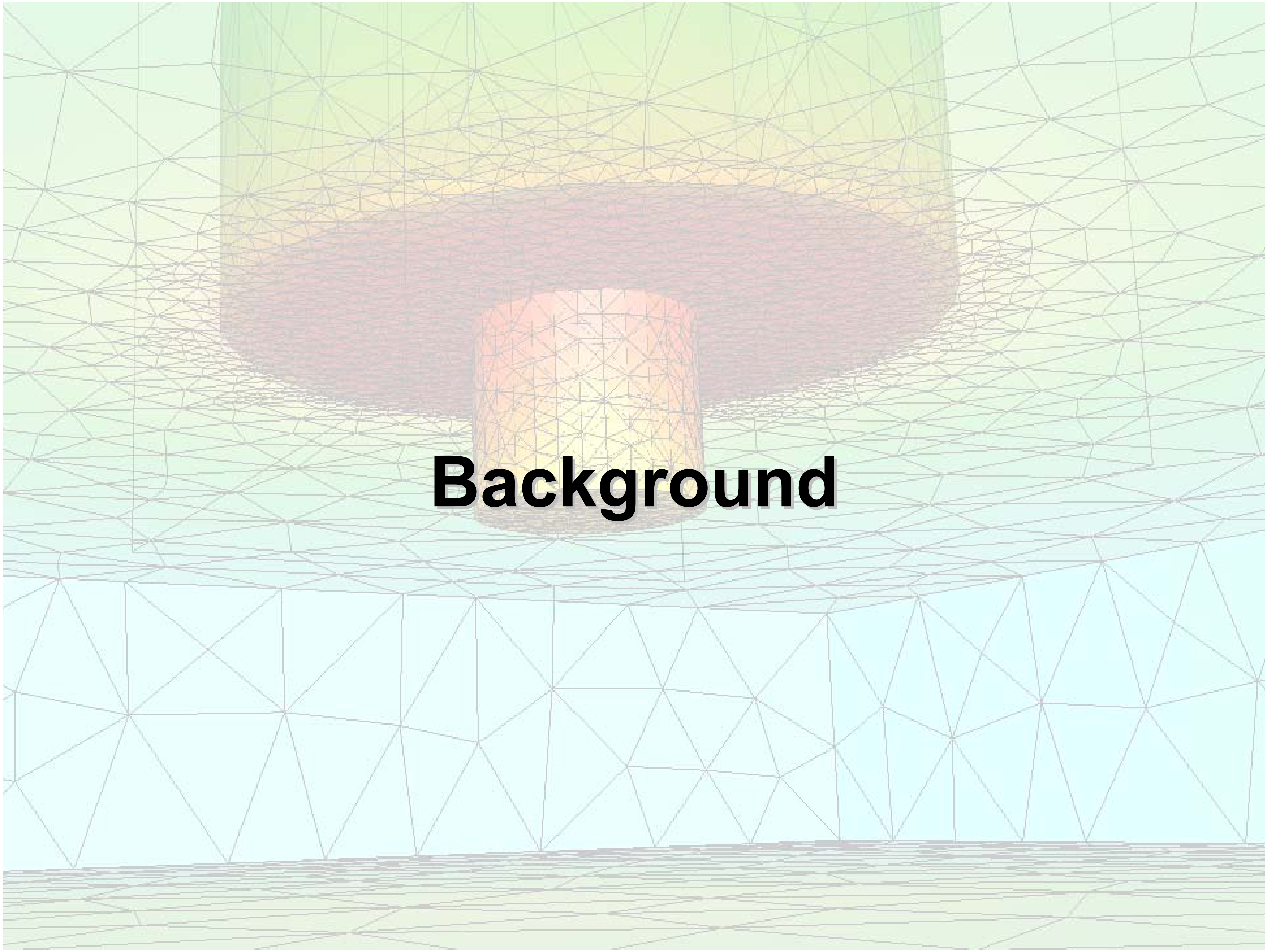
Overview

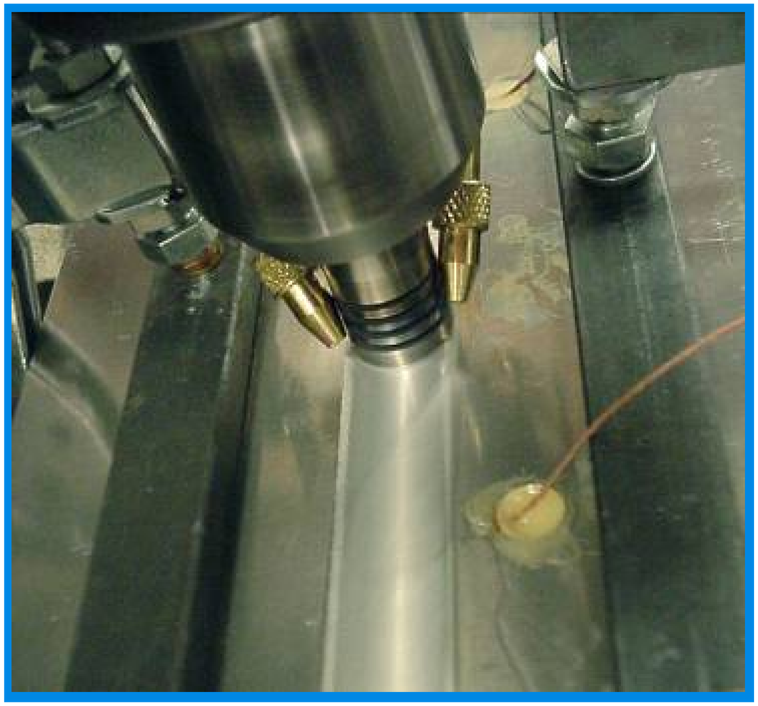
- Background
  - The Friction Stir Welding Process
  - Modeling of FSW
- Numerical models : FORGE3® & THERCAST®
- Modeling and experimental results
  - Plunging phase : comparison between experimental and numerical result
  - Welding phase :
Lagrangian / Eulerian simulations capabilities
  - ALE formulation and first results
- Future work



Background

The Process

- Friction Stir Welding Process
  - Patented in 1991 by TWI
  - A solid-state joining process
  - Potential commercial and military users
    - aerospace
    - automotive
    - marine
  - Capable of joining aluminum,steel, stainless steel



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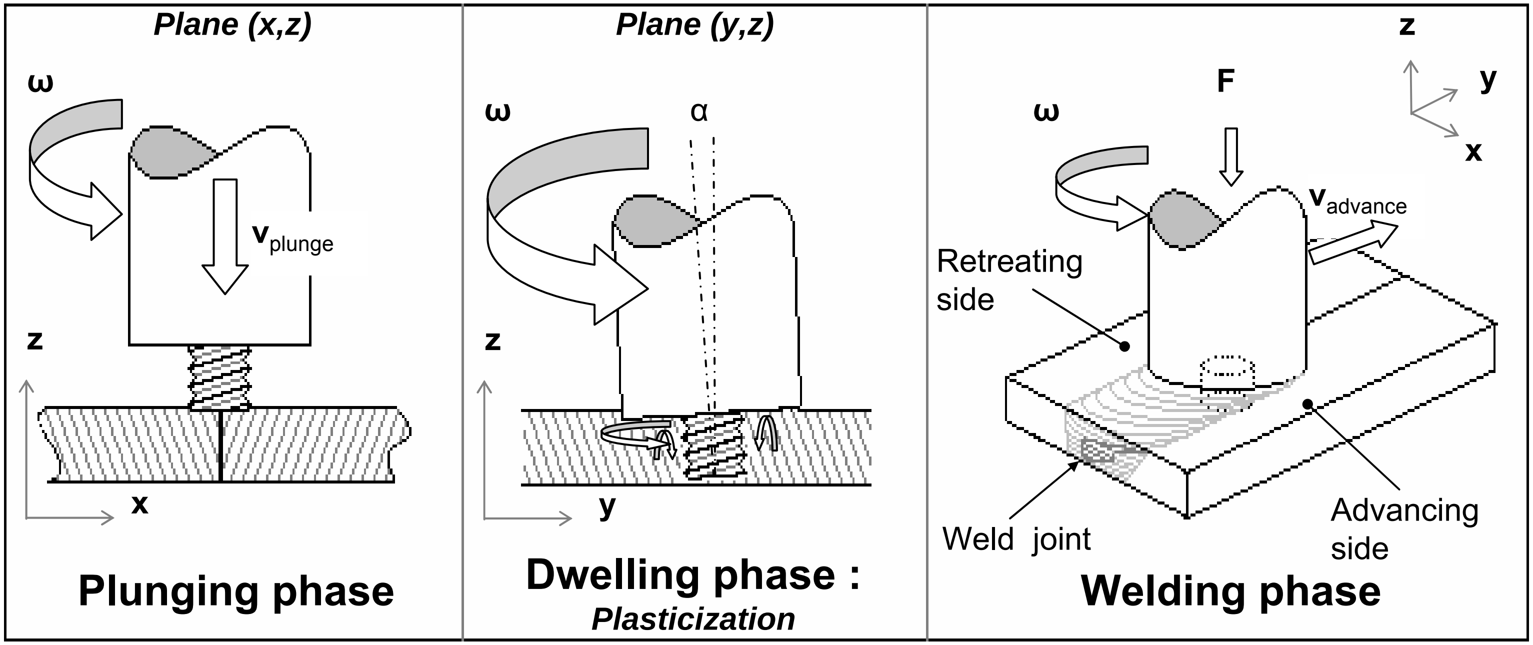
Dwelling phase

Future Work

Different main phases of FSWP



Plunging phase

Dwelling phase : *Plasticization*

Welding phase

Modeling of FSW

➢ Motivation:

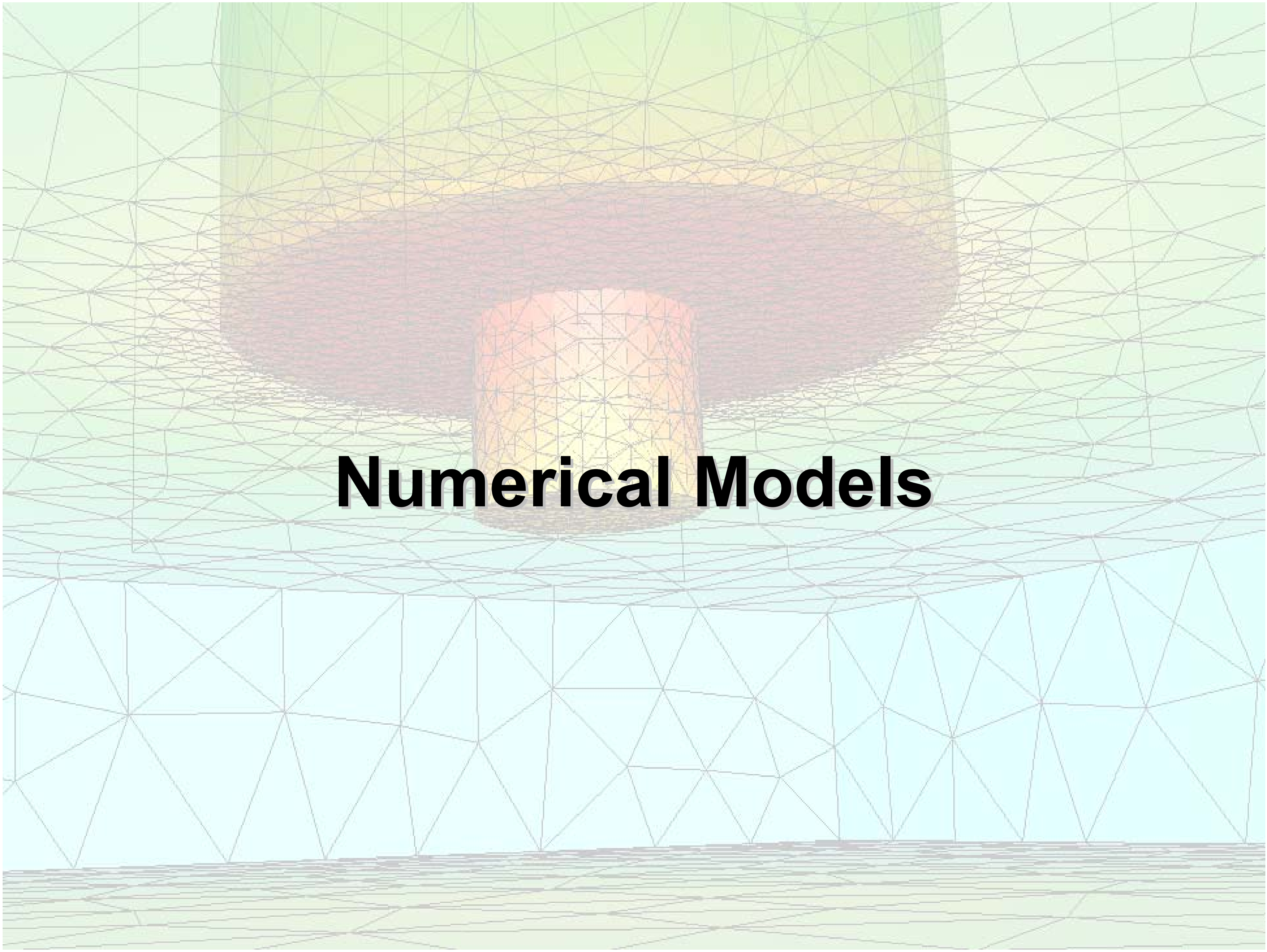
- Predict material flow: try to minimize heat input, and eliminate defects
- Use to develop better tooling designs
- Predict mechanical properties of weld:

  flow & thermal history

  => mechanical properties and eventually microstructure

Approaches in literature

- CFD approach: obtain information on material flow, but neglect free surface deformation and effect of deformation history
- Lagrangian FE:
  - use analytical heat source and apply a compressive stress along the weld line; calculate residual stresses
  - simulate material flow, including heat from friction and material deformation; requires complex remeshing
- Arbitrary Lagrangian Eulerian (ALE) FE: can simulate flow and include heat from friction and deformation; avoids degeneration of mesh; allows for deformation of free surface



Numerical Models

FORGE3® & THERCAST®

- Hot, warm, and cold forging (FORGE3®)
  Filling and cooling of foundry parts (THERCAST®)
- 3D thermo-mécanical computation
- Lagrangian (FORGE3®) and /or ALE (THERCAST®) Finite Element Formulation
- Automatic Remeshing

- Strong form of the mechanical problem :

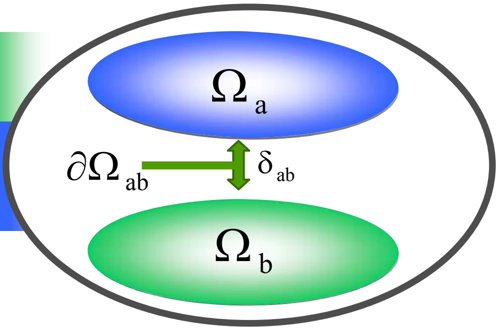
Pure viscoplastic behaviour (firstly) with thermal coupling

$$\begin{cases} \dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}_{\mathrm{vp}} + \dot{\boldsymbol{\varepsilon}}_{\mathrm{th}} \\ \mathbf{s} = \boldsymbol{\sigma} + p\mathbf{I} = 2K_{(T,\bar{\varepsilon})}\left(\sqrt{3}\dot{\bar{\varepsilon}}\right)^{m_{(T,\bar{\varepsilon})}-1}\dot{\boldsymbol{\varepsilon}}_{\mathrm{vp}} \\ \dot{\boldsymbol{\varepsilon}}_{\mathrm{th}} = \alpha\dot{T}\mathbf{I} \end{cases}$$

Incompressibility and equilibrium

$$\begin{cases} \mathrm{tr}(\dot{\boldsymbol{\varepsilon}}_{\mathrm{vp}}) = \mathrm{div}\,\mathbf{v} - 3\alpha\dot{T} = 0 \\ \nabla.\boldsymbol{\sigma} + \rho\mathbf{g} - \rho\boldsymbol{\gamma} = \nabla.\mathbf{s} - \nabla p + \rho\mathbf{g} - \rho\boldsymbol{\gamma} = 0 \end{cases}$$

+ B.C.



Contact equation :

$$\begin{cases} 0 \le \delta_{ab}^{t+\Delta t} \\ \delta_{ab}^{t+\Delta t} \approx \delta_{ab}^{t} - (\mathbf{v}_a^t - \mathbf{v}_b^t).\mathbf{n}_{ab}^t \, \Delta t \end{cases}$$

$$\Rightarrow \quad (\mathbf{v}_a^t - \mathbf{v}_b^t).\mathbf{n}_{ab}^t - \frac{\delta_{ab}^t}{\Delta t} \le 0$$

Norton friction equation :

$$\begin{cases} \text{si } \sigma_n < 0 \text{ alors } \boldsymbol{\tau} = -\alpha_f K_{(\bar{\varepsilon},T)} \left\|\Delta \mathbf{v}_g\right\|^{p_f-1} \Delta \mathbf{v}_g \\ \text{avec } \Delta \mathbf{v}_g = (\mathbf{v}_a - \mathbf{v}_b) - \left((\mathbf{v}_a - \mathbf{v}_b).\mathbf{n}_{ab}\right)\mathbf{n}_{ab} \end{cases}$$

- Strong form of the thermical problem :

Heat Equation

$$\rho c \frac{dT}{dt} - div(k\nabla T) = \boxed{\dot{W}} \qquad \text{dans } \Omega \quad ; \quad \text{avec } \dot{W} = \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}$$

+ B.C.

» Heat transfert by convection/radiation :

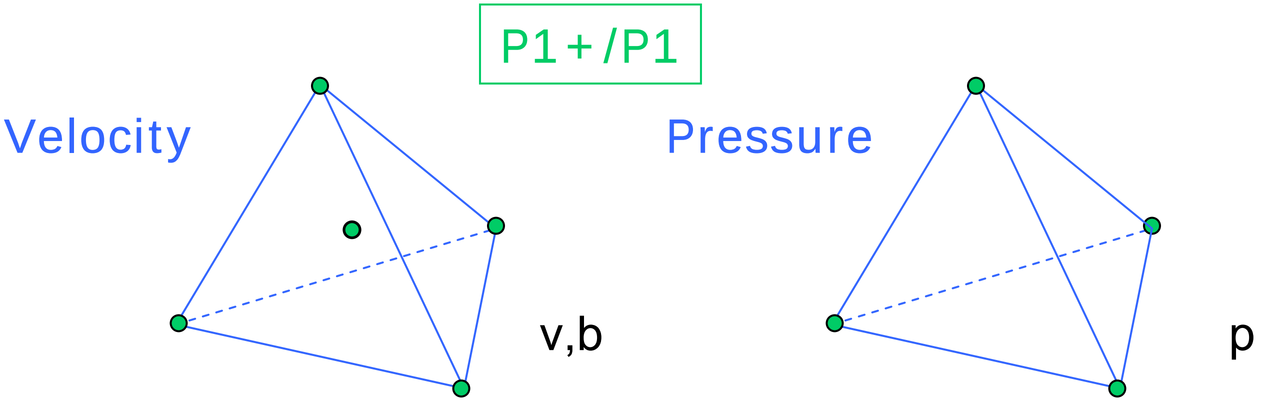
$$-k\nabla T \cdot \mathbf{n} = h_{cr}\left(T + T_{ext}\right)$$

» Conduction with tools and heat due to friction :

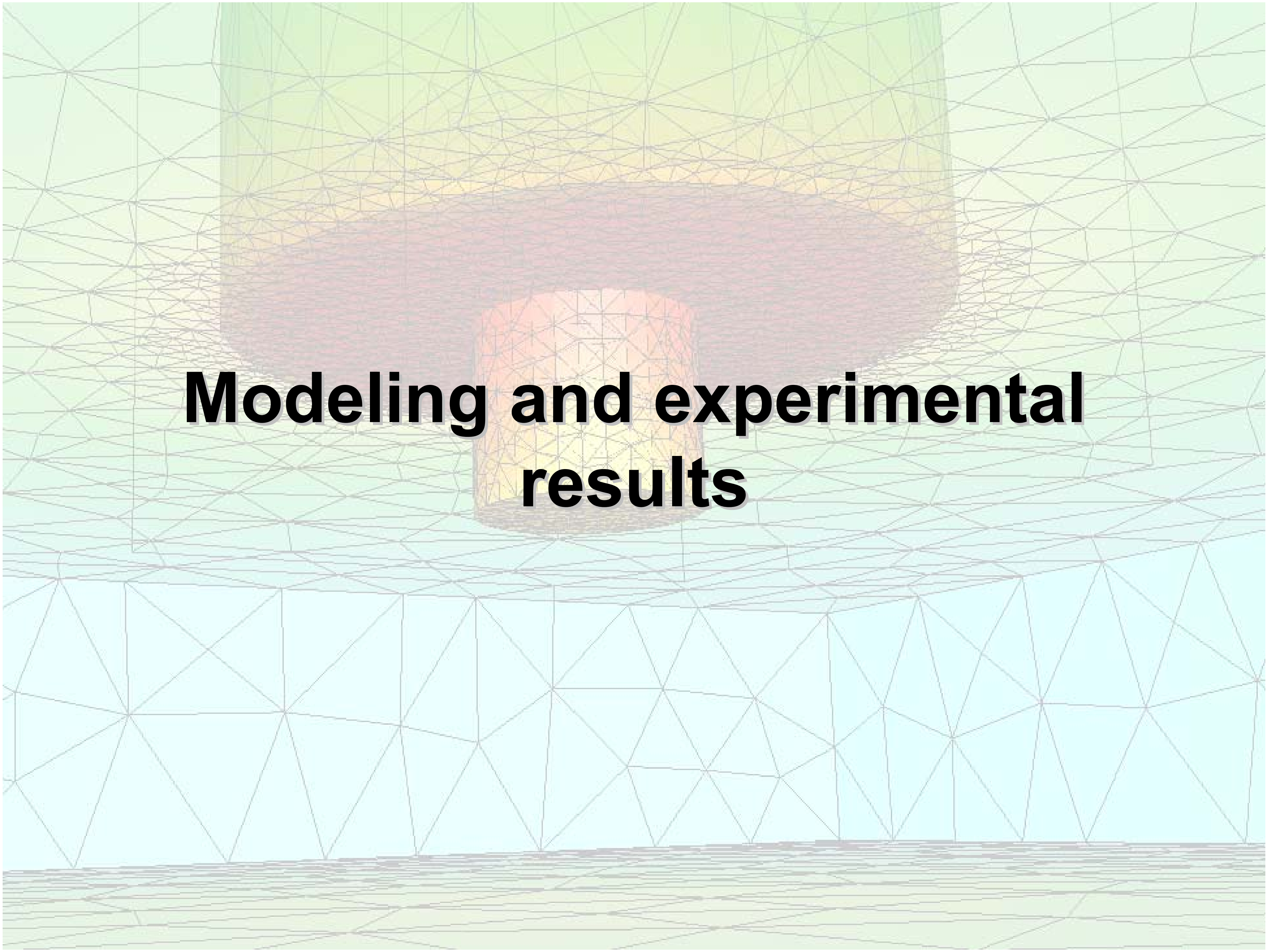
$$-k\nabla T \cdot \mathbf{n} = -h_{cd}\left(T + T_{tool}\right) + \boxed{\frac{b}{b + b_{tool}} \tau.v_g}$$

Heat Sources

Finite Element discretisation & FORGE3® solveur



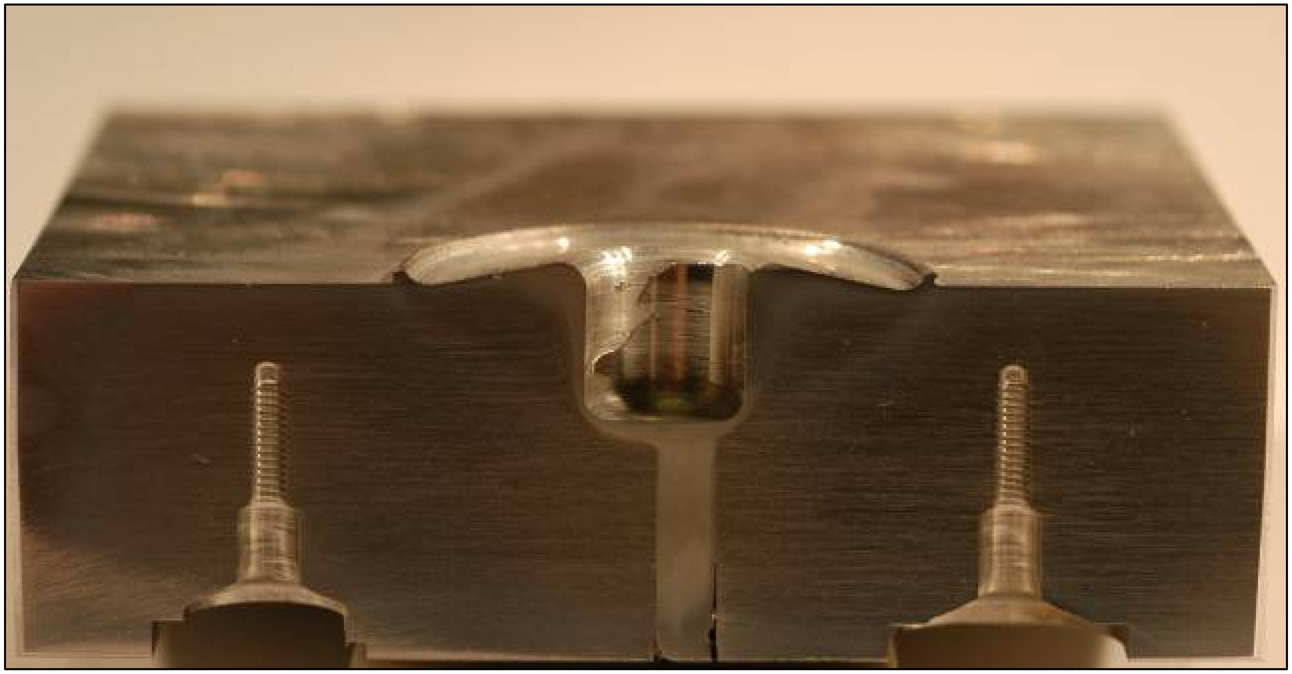
- Time discretisation $X^{t+\Delta t} = X^t + V^t \Delta t$
- Newton-Raphson algorithm $\rightarrow \boxed{R^t\left(V^t, P^t\right) = 0}$
- Preconditioned Conjugate Gradient solver
- Parallel resolution by mesh partitioning
- Updated Lagrangian formulation
  with automatic remeshing (topological, MTC)



Modeling and experimental results

Plunging phase

- Plunge experiment
  - Thermocouples
    - Weld Material—12.7 mm to 20.6 mm radius, at a depth of 1.6 mm
    - FSW Tool—1.2 mm of depth



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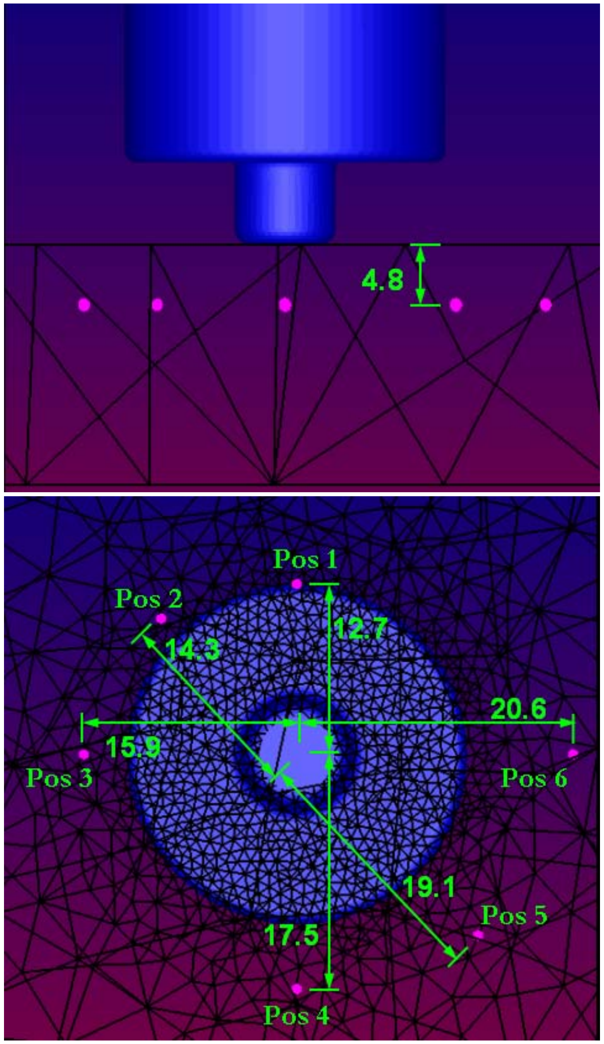
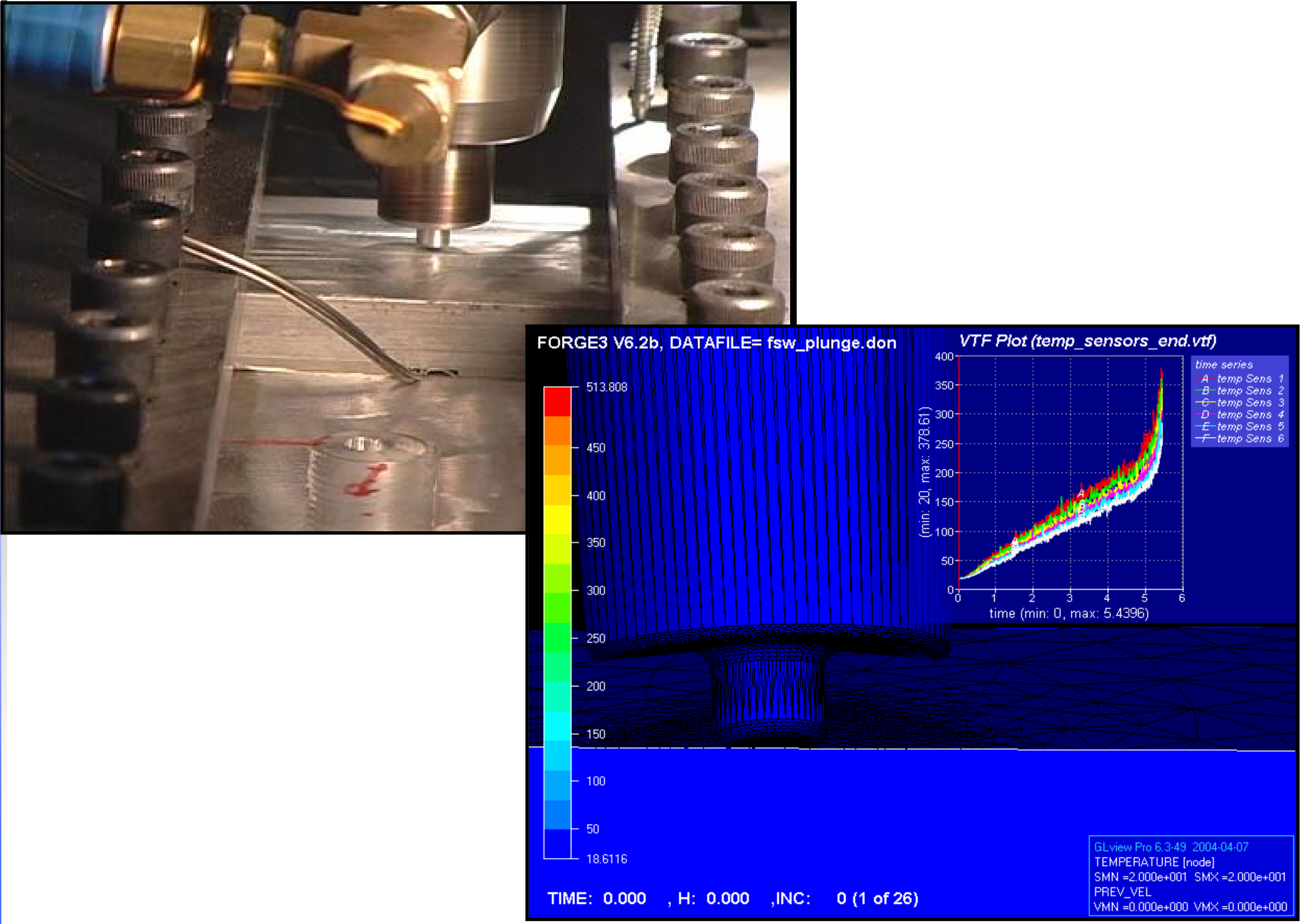
Future Work

➢ FORGE3® simulation

- 6 Second Plunge
  1.19 mm/s plunge speed, 600 RPM
- Lagrangian sensors were placed in the FSW weld material (1.6 mm)
- Remesh every 4 time steps
- Adiabatic contact heat transfer condition, Convective cooling on free surfaces



Comparison : experimental / numerical results



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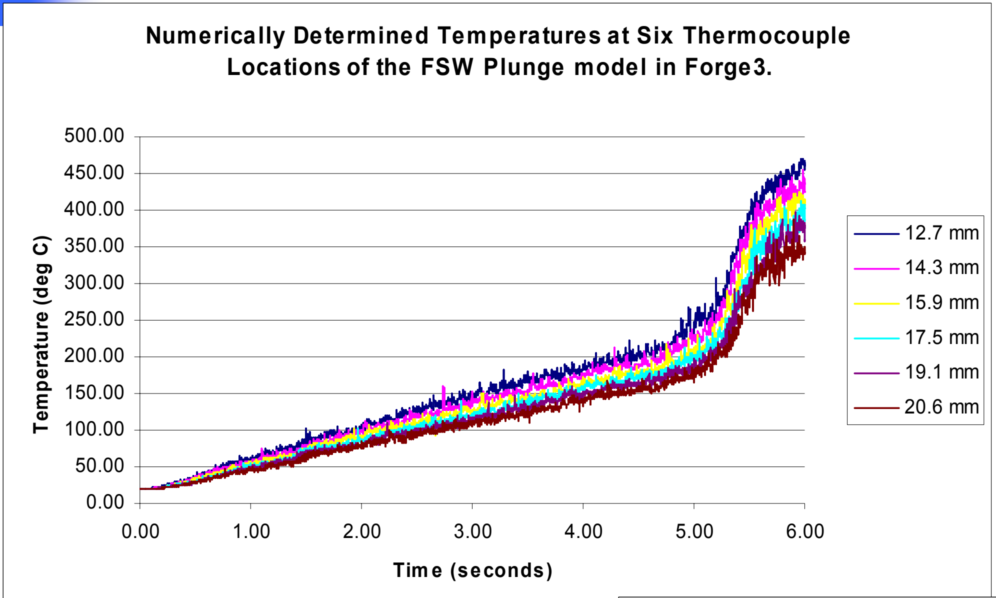
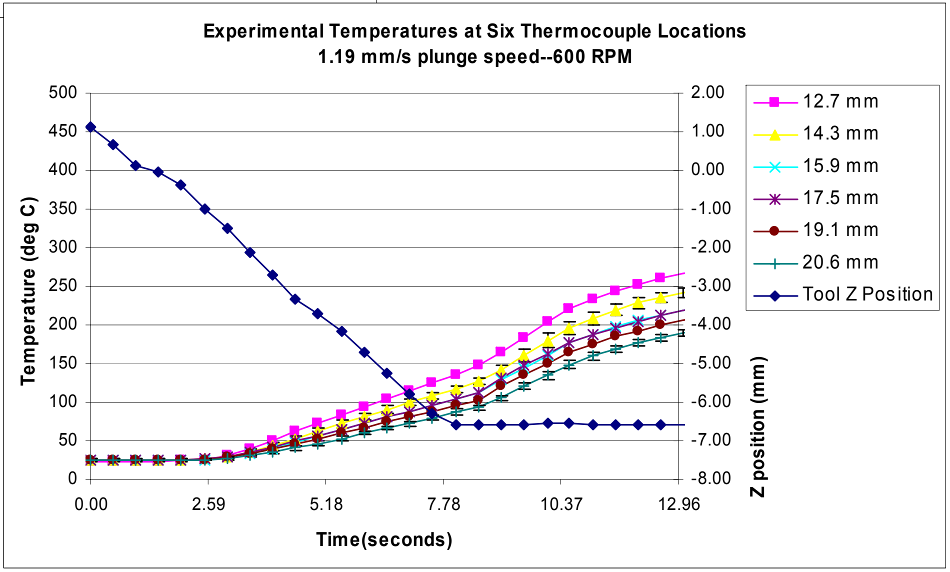
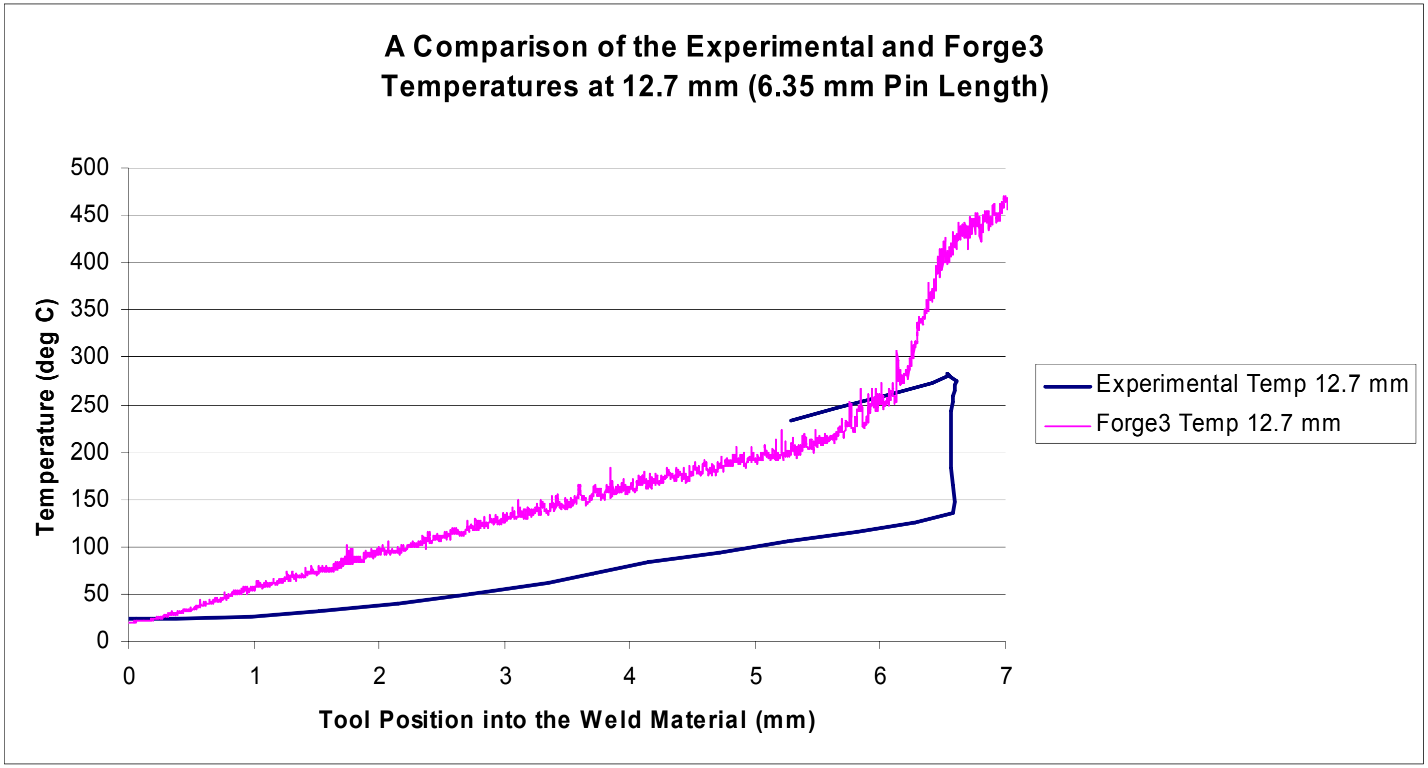
Future Work

Workpiece Temperature Rise





- Workpiece Temperature Rise
  - Weld Material Temperature Profiles



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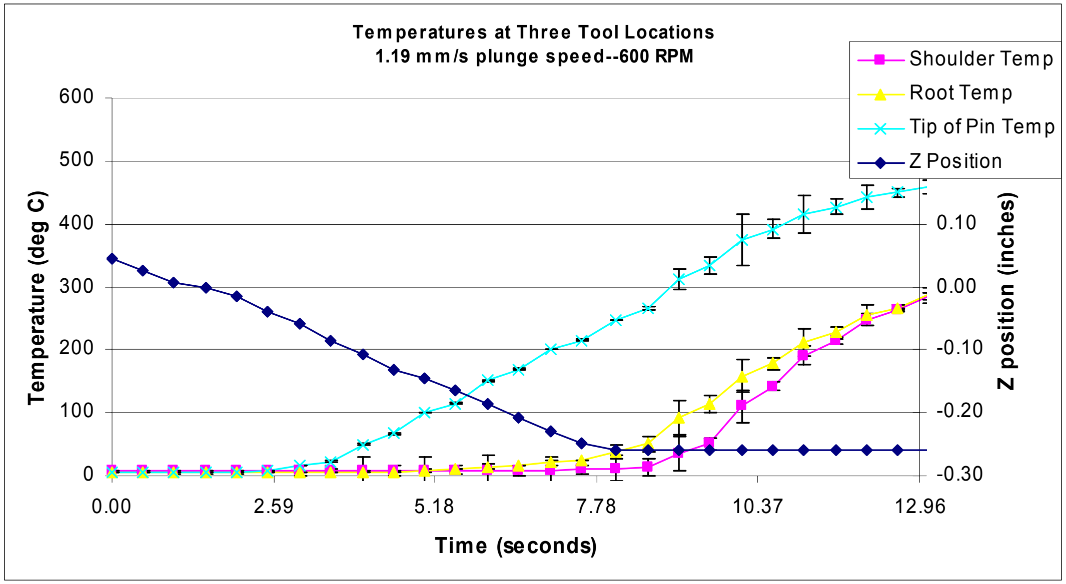
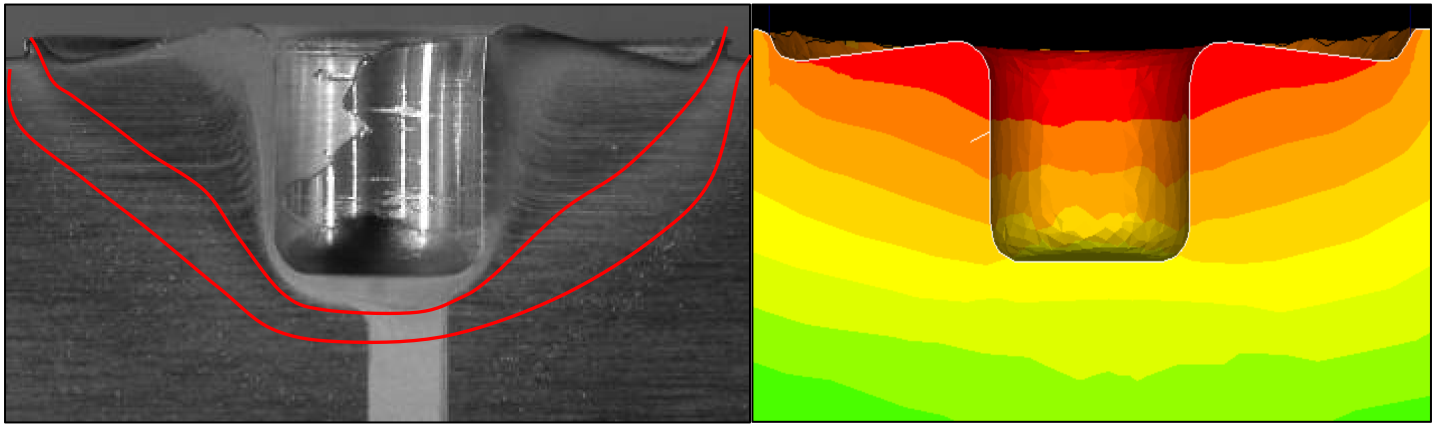
Tool Temperature and Workpiece Isotherms

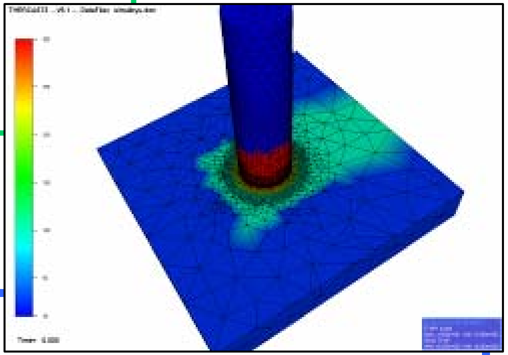




Welding phase

Geometric data :

- part : 127mm x 127mm x 19mm
- experimental welding tool (concave shoulder, 3° tilted) :
  - pin : ∅=8mm , h= 7mm
  - shoulder : ∅=25.4mm, h=90mm
    (cooling ➔ *10°C forced on 60mm from the top surface)*
  - rotational speed : 15 rotation/second
  - advance speed : 5 mm/second



Thermal and mechanical data :

- Convective exchange with air on all surfaces (h_{cr}=30 W/m²)
- Same standard behavior law for aluminum
- Norton viscoplastic law : coefficient α_f from 0.6 at 0°C to 1.1 at 650°C (linear evolution)
  q from 1 at 0°C to 0.5 at 650°C (linear evolution)
- Density, conductivity, and heat capacity in paper

Pure Eulerian Simulation : neglect of free surfaces movement / no remeshing

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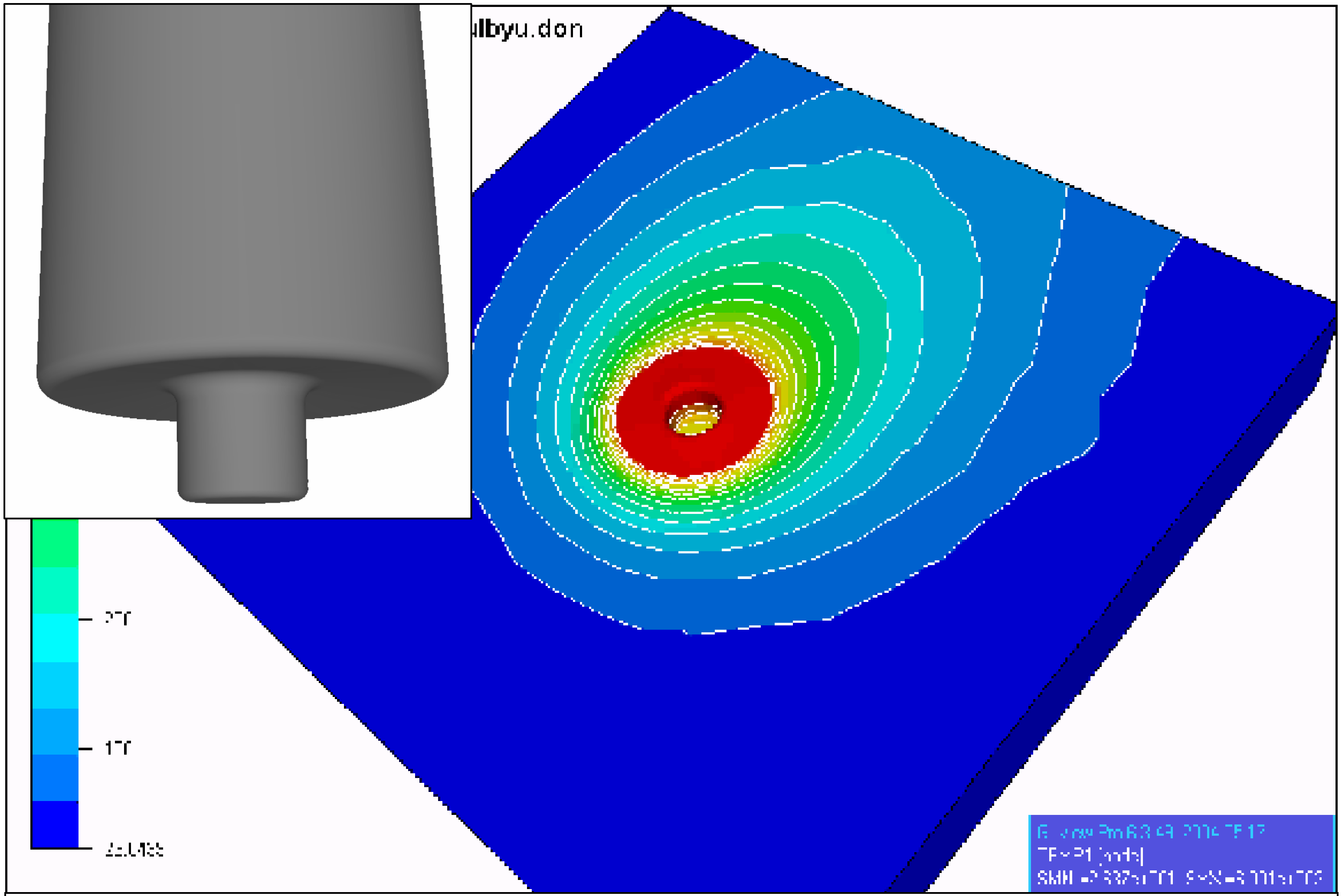

6s simulation with an arbitrary initial temperature

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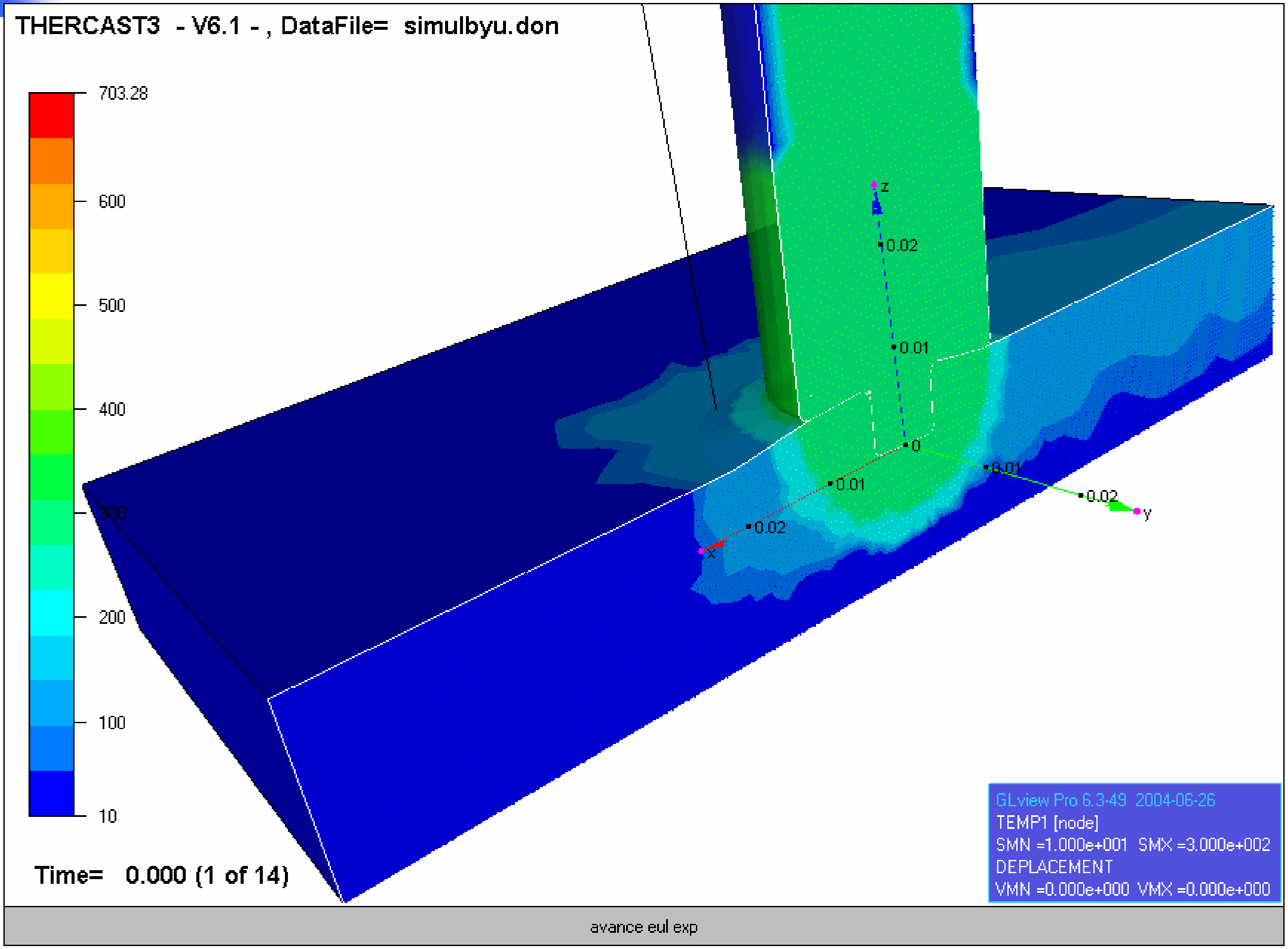
- 6s simulation with an arbitrary initial temperature field



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DEPLACEMENT
VMN =0.000e+000 VMX =0.000e+000

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Lagrangian capabilities : simulation of a defect during “cold welding”

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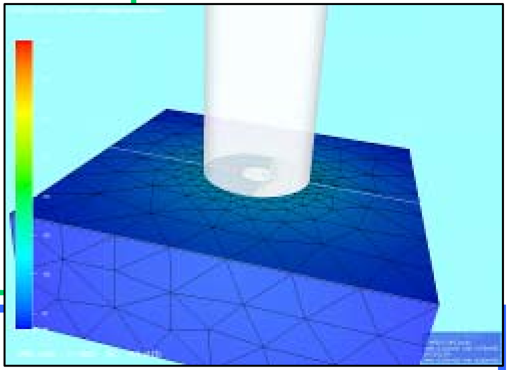
Geometric data :

- part : 60mm x 60mm x 20mm
- simplified welding tool (no concave shoulder, 3° tilted) :
  - pin : ∅=6mm , h= 6mm
  - shoulder : ∅=20mm, h=60mm
  - rotational speed : 15 rotation/second
  - advance speed : 1 mm/second



Thermal and mechanical data :

- Adiabatic rigid tool ➔ heat due to friction and plastic deformation only
- Standard behavior law for aluminum in hot forming process (Hansel Spitel law) :

$$\sigma_f = Ae^{-0.0479T}\bar{\varepsilon}^{-0.01383}\dot{\bar{\varepsilon}}^{0.09964}e^{\frac{-0.0011}{\bar{\varepsilon}}}$$

- “Strong” friction (Coulomb law) :

$$\begin{cases} \tau = 0.3\sigma_n \dfrac{\Delta v}{\|\Delta v\|} & if \quad 0.3\sigma_n < K_{(T,\varepsilon)} \\ \tau = 0.6K_{(T,\varepsilon)} \dfrac{\Delta v}{\|\Delta v\|} & if \quad 0.3\sigma_n > 0.6K_{(T,\varepsilon)} \end{cases}$$

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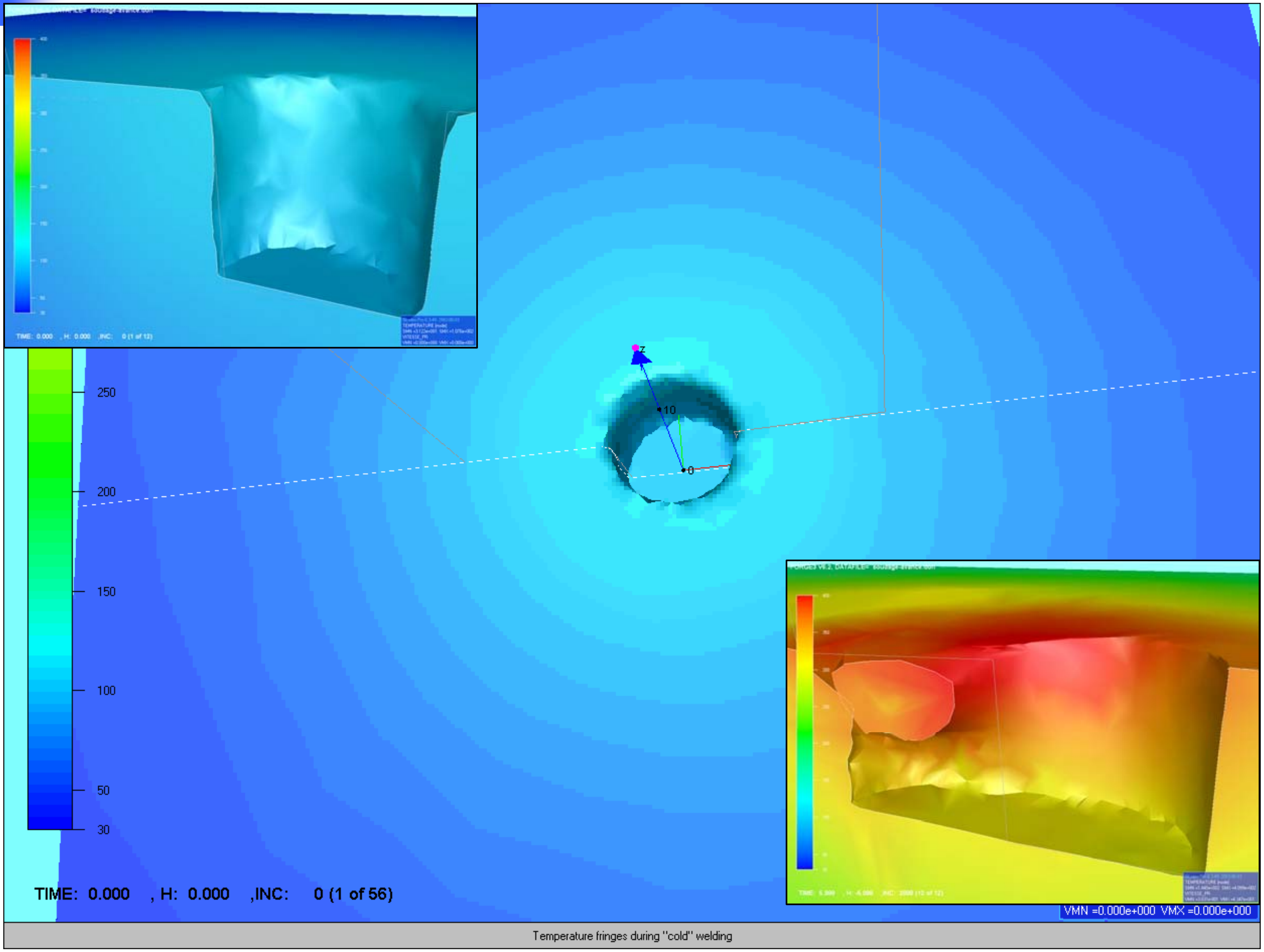
- 6s simulation with a low low initial temperature



Temperature fringes during "cold" welding

ALE formulation

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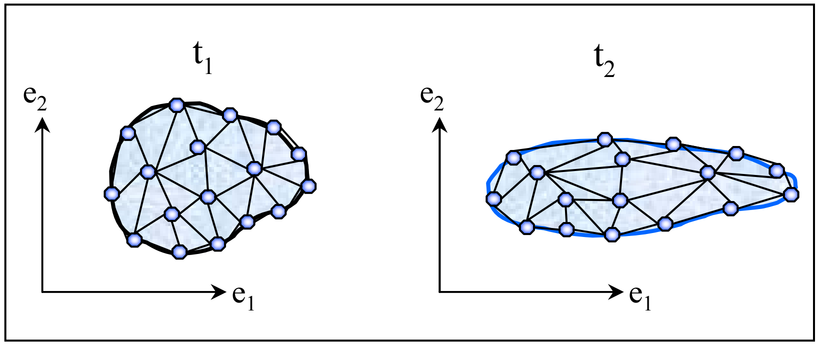
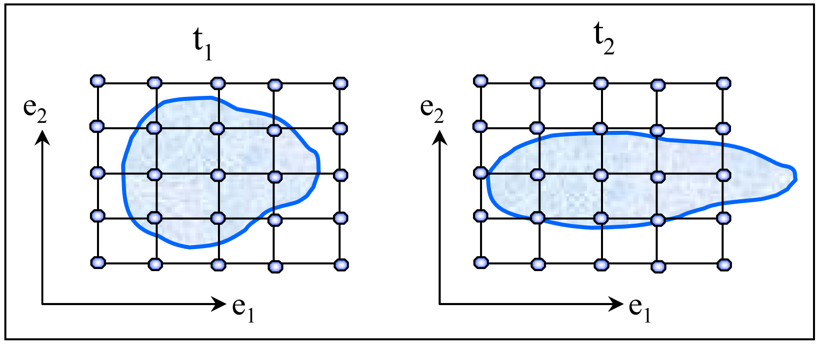
Different Descriptions :

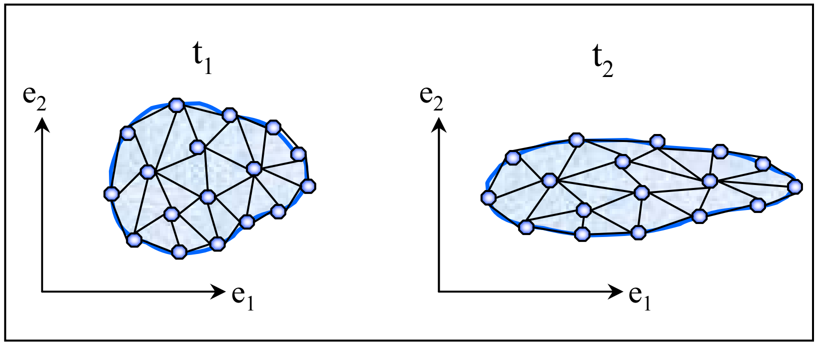
Lagrangian mesh



Eulerian mesh



ALE mesh



The two main steps of the ALE description implemented in Thercast :

- Convective terms treatment

$$\begin{cases} \dfrac{\mathrm{d}\varphi}{\mathrm{dt}} = \dfrac{\mathrm{d}_g\varphi}{\mathrm{dt}} + \mathbf{c}.\nabla\varphi \\ \mathbf{c} = \mathbf{v} - \mathbf{w} \end{cases}$$

v : material velocity
w : mesh velocity

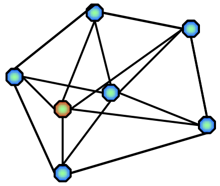
Splitting Method (used firstly)
= lagrangian iteration + transport on the new mesh

Convective Approach (upwind aspect) → **No Updated Lagrangian Mesh construction**

$$\varphi_{\mathrm{ALE}}^{\mathrm{t+\Delta t}} = \varphi_{\mathrm{ref}}^{\mathrm{t}} + \int_{\Delta t} \frac{\mathrm{d}_g\varphi}{\mathrm{dt}}$$

→ Mesh velocity computation : w

Velocity Centering Method →



ALE

ALE simulation of the dwelling phase

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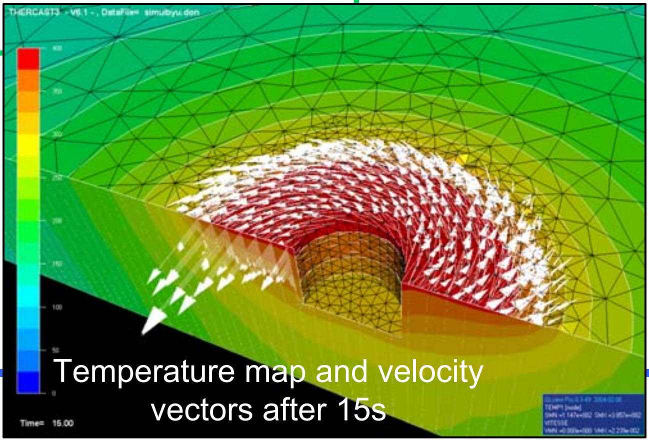
Geometric data :

- part : 127mm x 127mm x 19mm
- simplified tool (no concave shoulder, not tilted) :
  - pin : ∅=8mm , h= 7mm
  - shoulder : ∅=25.4mm, h=90mm (cooling ➔ *10°C forced on 60mm from the top surface)*
  - rotational speed : 15 rotation/second
  - no advance speed



Temperature map and velocity vectors after 15s

Thermal and mechanical data :

- Exange with bottom plate model by a coefficient h_{cr}=300 W/m² and exchange with air on other surfaces (h_{cr}=30 W/m²)
- Same standard behavior law for aluminum
- Norton viscoplastic law
- Density, conductivity, and heat capacity depend on temperature

- 15s simulation without any remeshing
  ➔ stability of ALE formulation
  (Initial temperature obtained after plunging phase)

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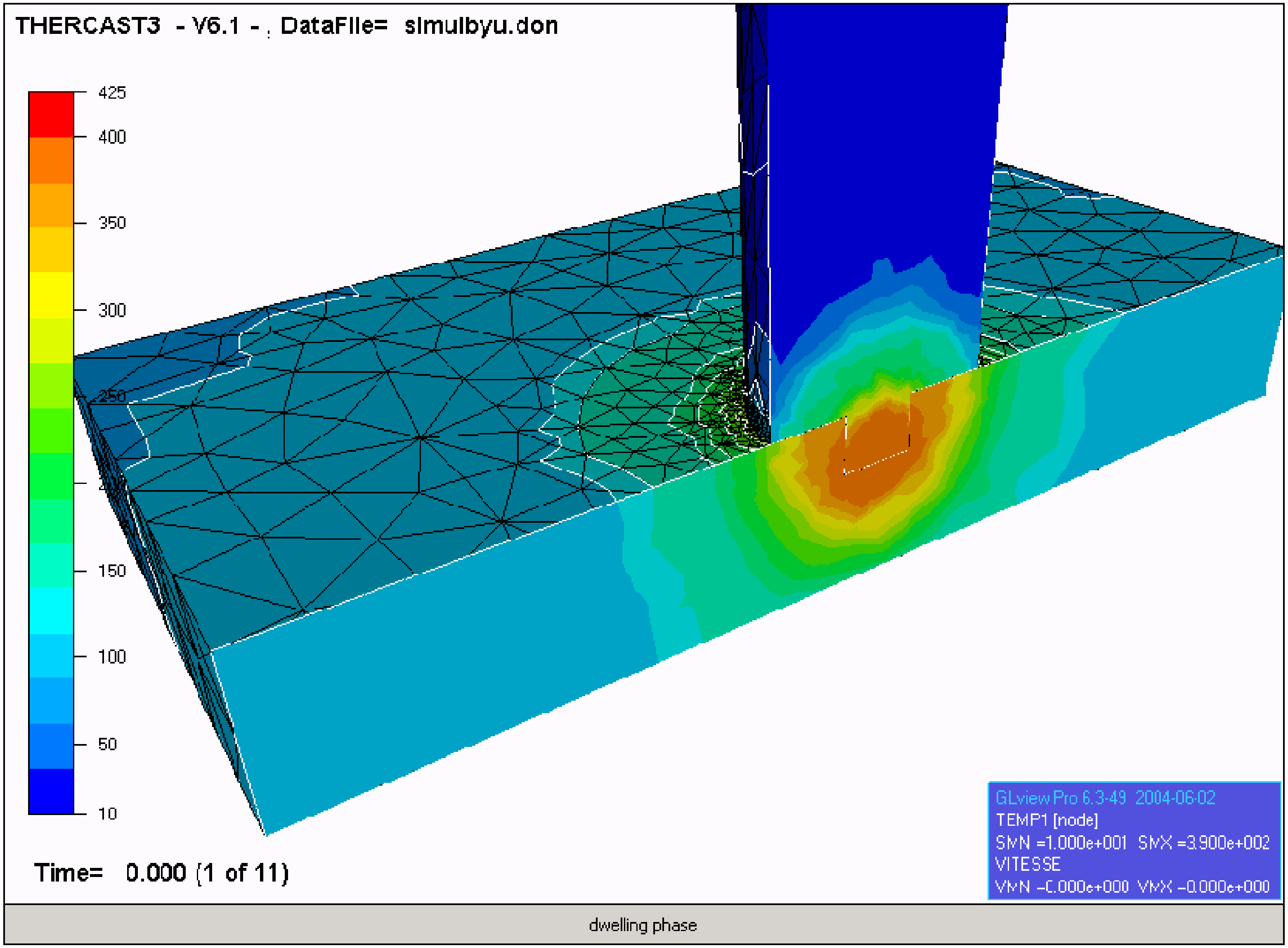
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VMN =0.000e+000  VMX =0.000e+000
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dwelling phase

Comparison with experimental results

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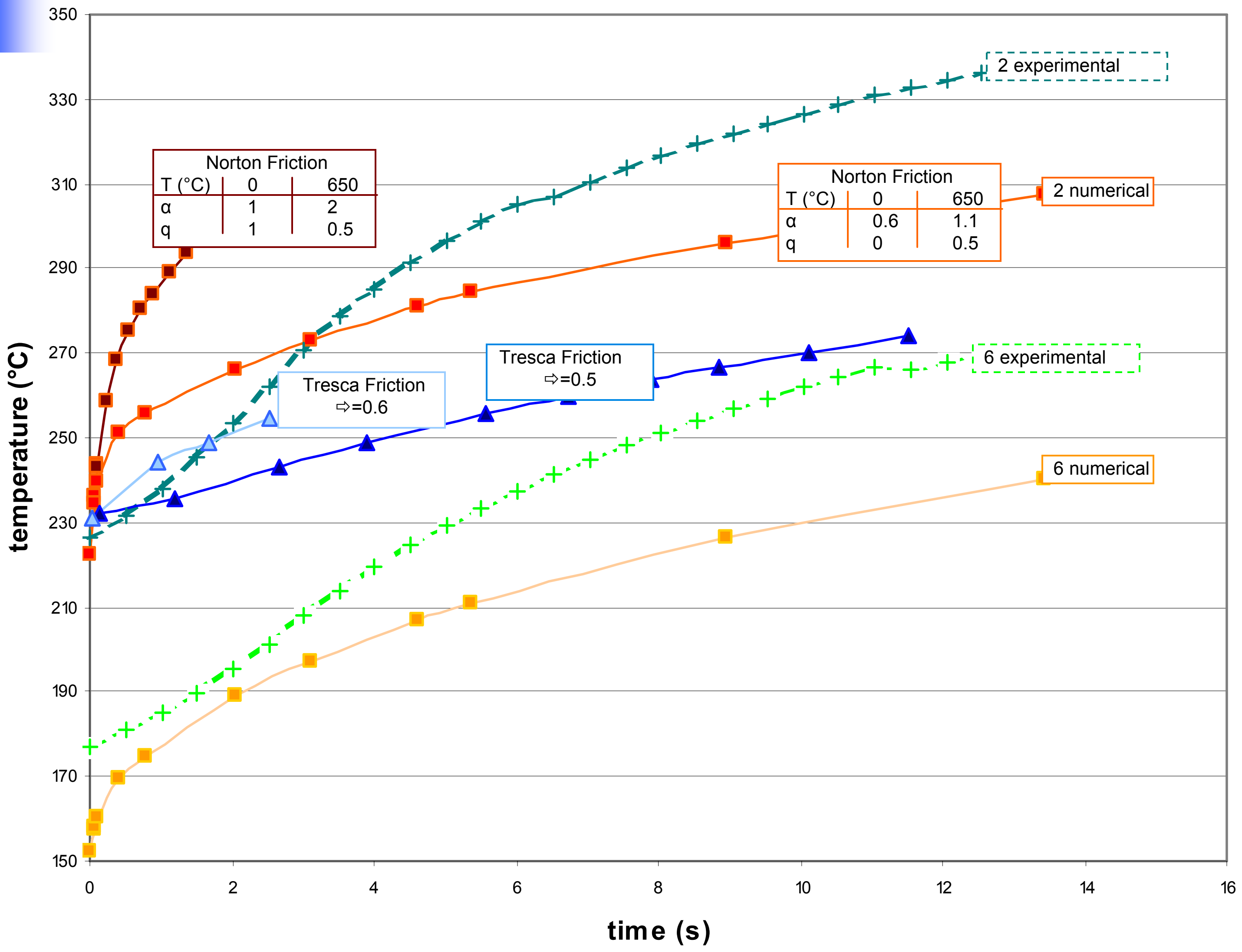

Summary

- Lagrangian, Eulerian, and ALE approaches have been used to simulate FSW, using Forge3® and Thercast®
- The ALE approach is best adapted for modeling this process, because it takes into account changes in the free surface while avoiding element degeneration in high deformation zones

Future Work

- Implementation of a <u>complete ALE formulation</u> in Forge3® code
- Test of <u>different transport techniques</u> :
  - nodal upwind
  - SUPG
  - MLS / RBF

  with use of <u>adaptive remeshing</u> to minimize transport diffusion
- Further comparison between experiment and simulation
- Experimental work to study friction, material behavior, and heat transfer coefficients