An approach to thermomechanical modelling of welding and additive manufacturing in Cast3M

S. Pascal, DES/ISAS/DRMP/SRMA/LTA, CEA Saclay, France

Introduction

- State of the art
  - Numerical welding simulation uses finite element codes for structural analysis
  - It takes benefit of decades of experience in thermomechanical modelling that have led to:
    - Robust and proven numerical methods
    - Performant nonlinear solvers
    - Numerous mechanical behavior laws
    - Accessible and validated material data
- However, modelling welding and additive manufacturing processes presents two specific characteristics:
  - Mobile heat input, also variable in time
  - Material deposition

Subject of today's talk!

Outlines

1. **Mobile heat input**

   Heat source models

   Spatiotemporal evolution

2. **Material deposition**

   Model geometry evolution

   Energy conservation

3. **Applications**

Mobile heat input

- Heat source models: why?
  - Heat input processes impose heat fluxes (electric arc, laser…)

  However:
  - Thermal modelling of these processes uses heat source models
    to account for hydrodynamic effects in the molten pool
  - Example: Goldak[1] heat source model
    Good representation of the molten pool but 8 parameters to identify (at least)
- Heat source models in Cast3M
  - Development of heat source models:
    `MOD1 = MODE GEO1 THERMIQUE SOURCE… ;`
  - Two gaussian heat source models:
    - `… SOURCE GAUSSIENNE ELLIPTIQUE ;`
    - `… SOURCE GAUSSIENNE ELARGIE ;`

Goldak[1] heat source model

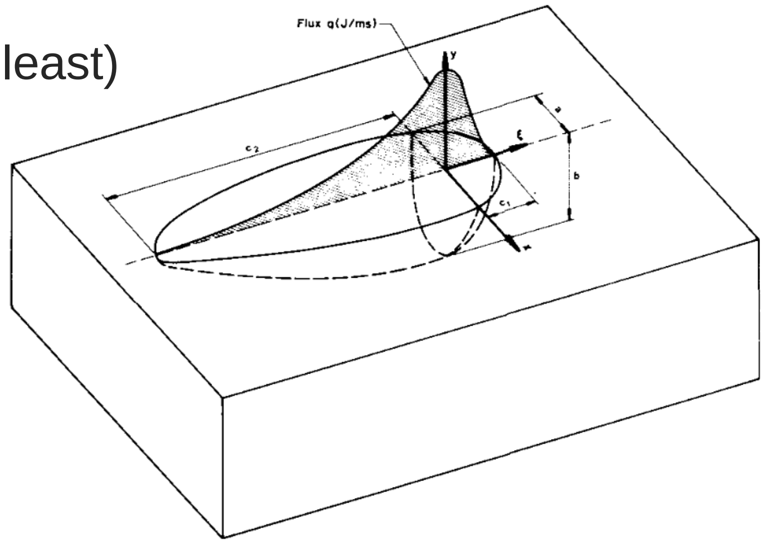
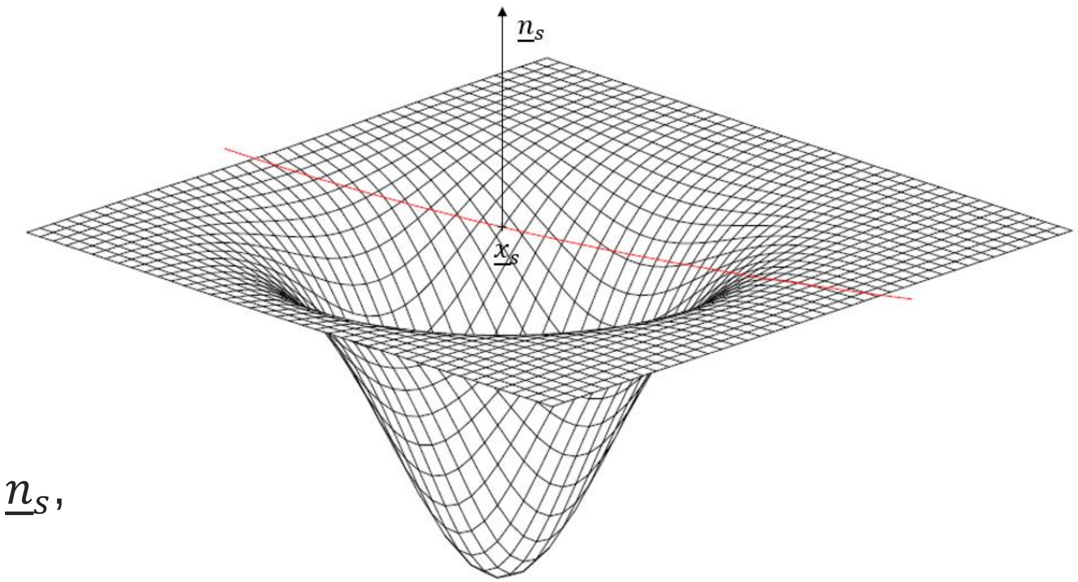


Fig. 3—Double ellipsoid heat source configuration together with the power distribution function along the ξ axis.

[1]J. Goldak, A. Chakravarti, M. Bibby. “A new finite element model for welding heat sources”, Metallurgical Transactions B, vol. 15, 299–305, 1984.

Mobile heat input

- “SOURCE GAUSSIENNE ELLIPTIQUE”
  - “Basic” gaussian heat source model



- Thermal power density distribution function:

$$s\left(\underline{x}\right) = s_0 e^{-2\left(\left(\tilde{r}/r_g\right)^2 + \left(\tilde{z}/z_g\right)^2\right)}$$

$(\tilde{r}, \tilde{z})$ space coordinates in local cylindrical frame of axis $\underline{n}_s$, and s_0 such that:

$$\iiint_{\tilde{z}<0} s(\underline{x})dV = Q_s$$

- 5 parameters:
  - $\underline{x}_s, \underline{n}_s$: location and orientation
  - r_g, z_g : shape
  - Q_s : power

Expression of s_0 for 3 calculation modes: plane, axisymmetric and tridimensional.

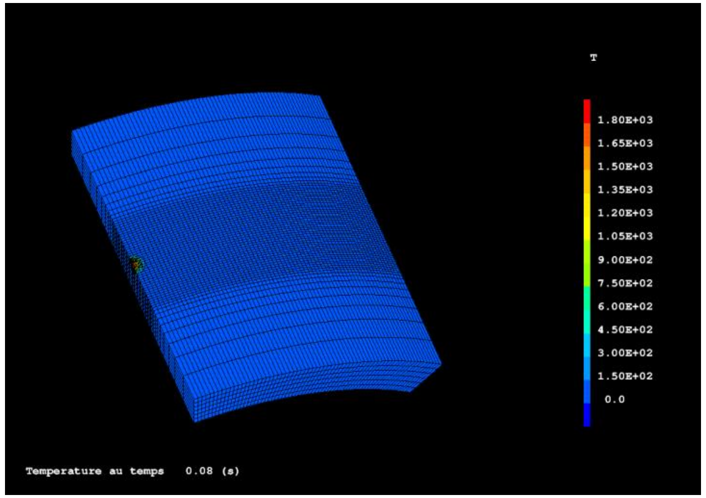
mode de calcul	2D plan	2D axisymétrique	tridimensionnel
expression de s_0	$\frac{4}{\pi}\frac{Q_s}{r_g z_g}$	$\sqrt{\frac{2}{\pi^3}}\frac{Q_s}{z_g(\kappa_1+\kappa_2+\kappa_3)}$	$\sqrt{\frac{2^5}{\pi^3}}\frac{Q_s}{r_g^2 z_g}$
avec, pour le mode axisymétrique : $\kappa_1 = \frac{r_g^2}{4}e^{-2(r_s/r_g)^2}$, $\kappa_2 = \sqrt{\frac{\pi}{8}}r_g r_s$, $\kappa_3 = \sqrt{\frac{\pi}{8}}r_g r_s erf(\sqrt{2}r_s/r_g)$, r_s étant la 1re coordonnée du centre de la source dans le mode axisymétrique.			

Mobile heat input

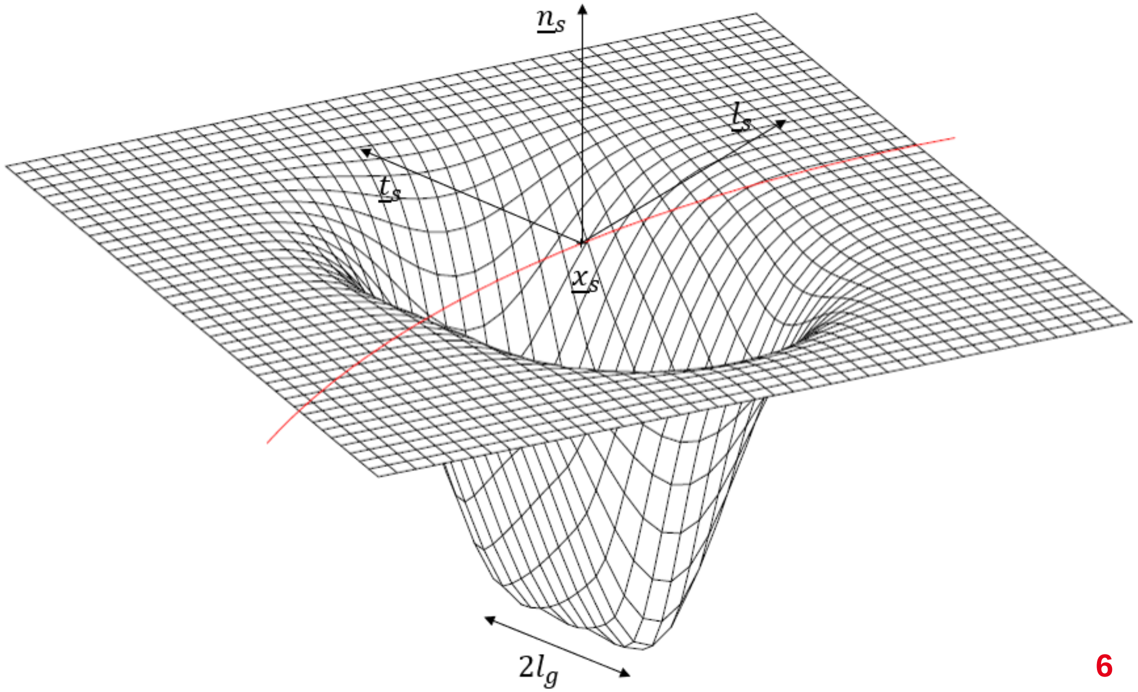
- “SOURCE GAUSSIENNE ELARGIE”
  - Simplified heat source model to represent sweep welding
  - Thermal power density distribution function (only in 3D mode):

$$s\,(\underline{x}) = \frac{Q_s}{(\sqrt{\pi^3/32})r_g^2 z_g + (\pi/2) r_g z_g l_g}\, e^{-2\left((u/r_g)^2 + (max(0,|v|-l_g)/l_g)^2 + (w/z_g)^2\right)}$$

(u, v, w) space coordinates in local frame $(\underline{l_s}, \underline{t_s}, \underline{n_s})$



  - 7 parameters:
    - $\underline{x_s}, \underline{t_s}, \underline{n_s}$: location and orientation
    - r_g, z_g, l_g : shape
    - Q_s : power



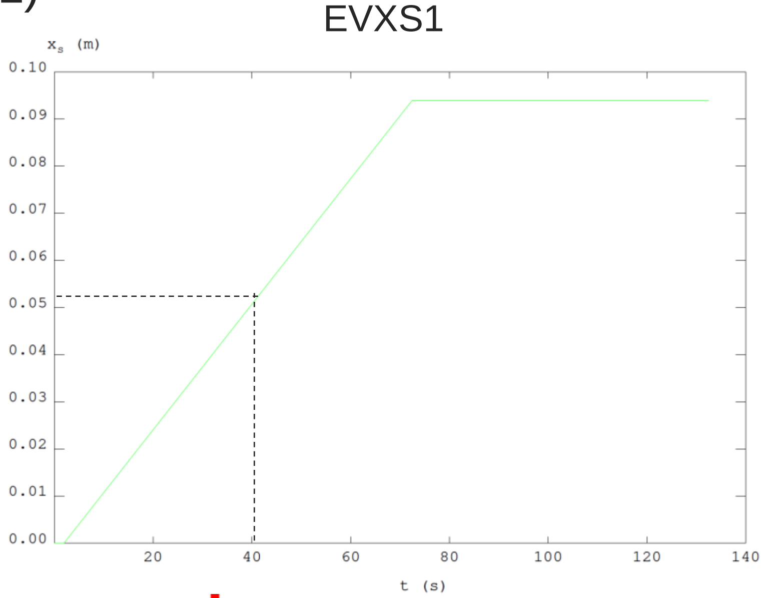
Mobile heat input

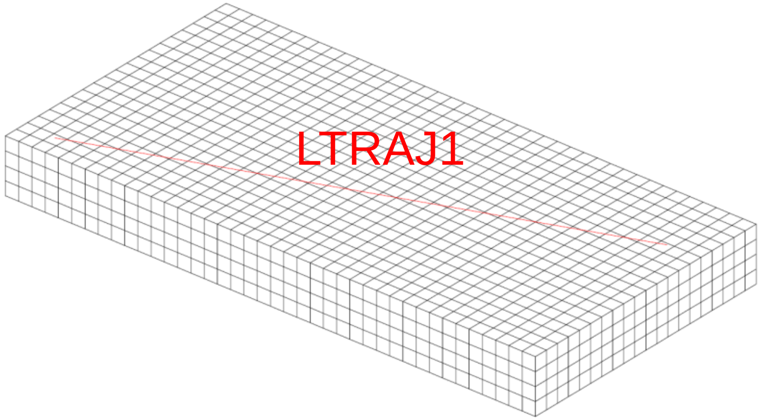
- Mobile heat source modelling
  - Based on:
    - Heat source trajectory, modelled as an oriented meshed line (LTRAJ1)
    - Time evolution of its displacement along this line (EVXS1)
  - In Cast3M, definition of a CHARGEMENT type object:

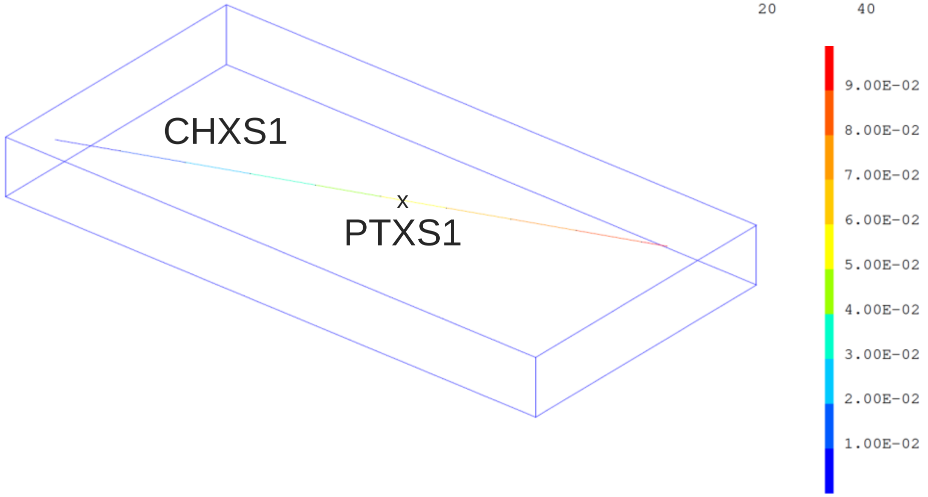
```
CHXS1   = LTRAJ1 COOR CURV ;
CGXS1   = CHAR TRAJ CHXS1 EVXS1 ;
```

  - Use for a given time TPS1:

```
PTXS1   = TIRE CGXS1 TRAJ TPS1 ;
```





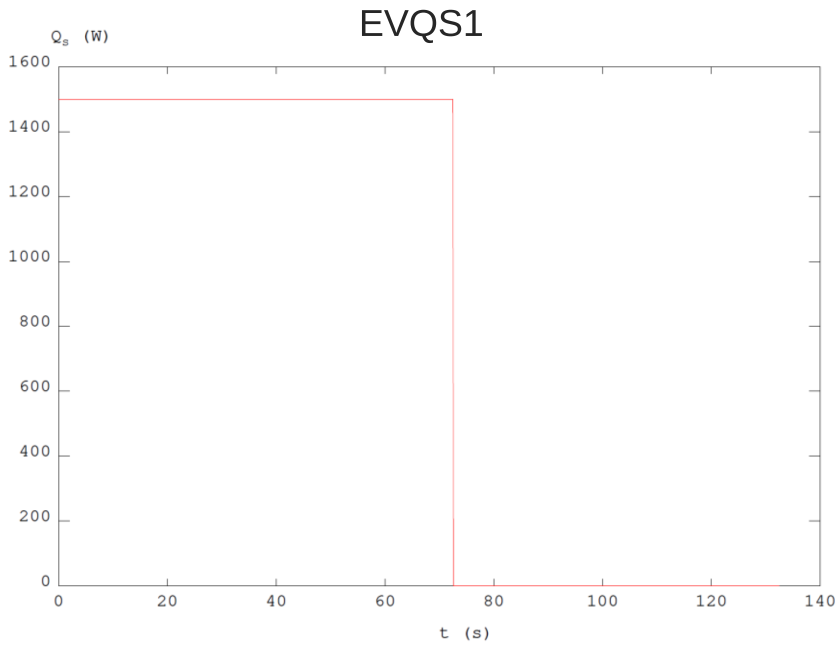


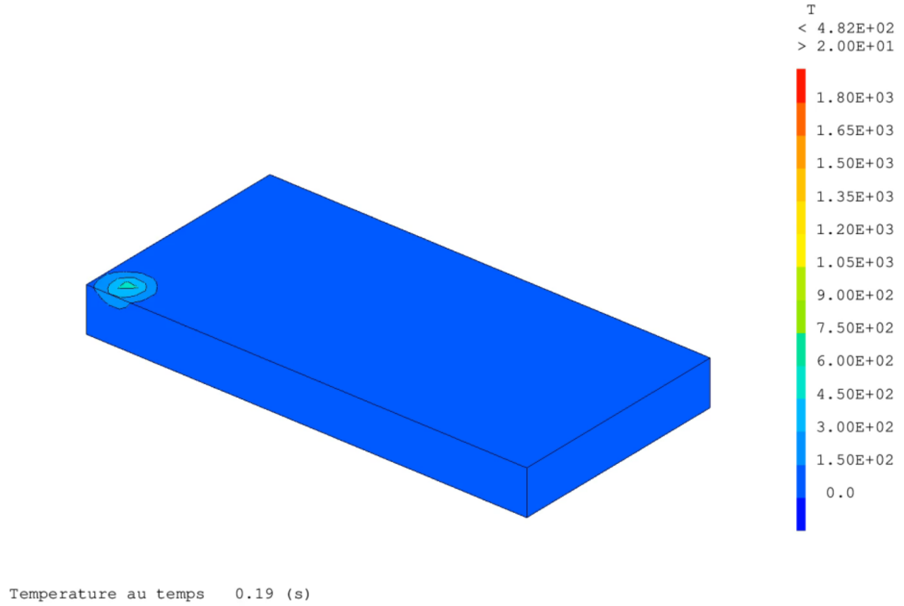
Mobile heat input

- Mobile heat source modelling
  - Connection to the heat source models in Cast3M:

```
MODQS1  = MODE GEO1 THERMIQUE SOURCE GAUSSIENNE… ;
MATQS1  = MATE MODQS1 ORIG CGXS1 QTOT EVQS1 RGAU RG1 ZGAU ZG1 DIRE NS1… ;
```

  - the location of the heat source can be updated at any time by giving `CGXS1`, as well as the heat source intensity by giving `EVQS1`





Outlines

1. **Mobile heat input**

   Heat source models

   Spatiotemporal evolution

2. **Material deposition**

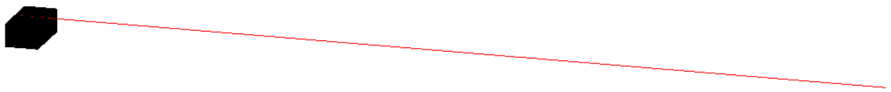
   Model geometry evolution

   Energy conservation

3. **Applications**

Material deposition

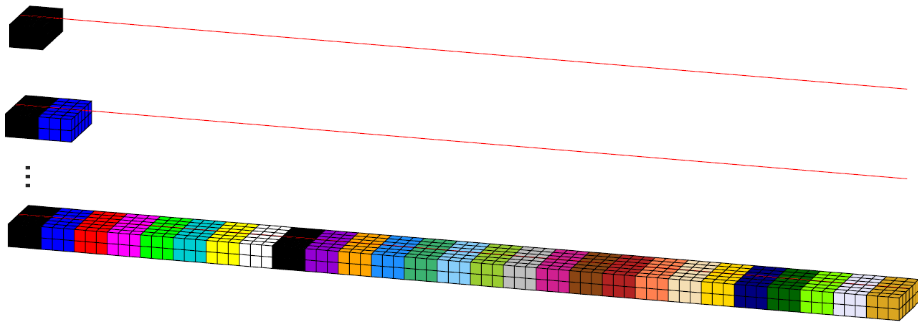
- Geometry evolution
  - Basic idea: add blocks of finite elements du simulate material deposition



  - In practice:

    Define as many mesh as there are geometries involved in the simulation

    At time t, update the geometry according to the following rule:



$t_0 \leq t < t_1$ geometry GEO1

$t_1 \leq t < t_2$ geometry GEO2

⋮

$t_{n-1} \leq t < t_n$ geometry GEOn

  - Data structure in Cast3M: create a list of meshes (LISTOBJE) and a timetable (LISTREEL):

```
LGEO1   = ENUM GEO1 GEO2 GEO3 … GEOn ;
LTPS1   = PROG t0 t1 t2 … tn ;
```

Material deposition

- Model evolution
  - Define as many models as there are meshes in LGEO1:

```
LMOD1   = ENUM ;
LMAT1   = ENUM ;
REPE B1 (DIME LGEO1) ;
  GEOI1   = LGEO1 EXTR &B1 ;
  MODI1   = MODE GEOI1 MECANIQUE ELASTIQUE … ;
  MATI1   = MATE MODI1 YOUN YM1 NU NU1 … ;
  LMOD1   = LMOD1 ET MODI1 ;
  LMAT1   = LMAT1 ET MATI1
FIN B1 ;
CGMOD1   = CHAR MODE LTPS1 LMOD1 ;
CGMAT1   = CHAR MATE LTPS1 LMAT1 ;
```

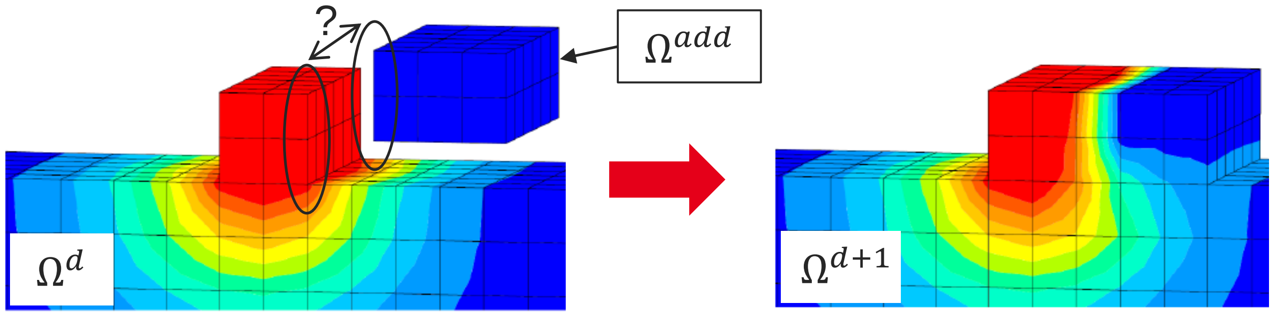
  - Use in PASAPAS input table:

```
TAB1.MODELE                  = CGMOD1 ;
TAB1.CARACTERISTIQUES        = CGMAT1 ;
```

During resolution, PASAPAS updates the model and its characteristics, which makes the geometry evolving.

Material deposition

- Thermal analysis: temperature initialization during model change



- Temperature at interface $\Omega^{d} \cap \Omega^{add}$? ➔ energy conservation

$$C^{d+1}\, T^{d+1} = C^{d}.T^{d} + C^{add}.T^{add},$$

where C^{x} are the heat capacity matrices and T^{x} the nodal temperatures.

- With:

$$C^{d+1} = C^{d} + C^{add},$$

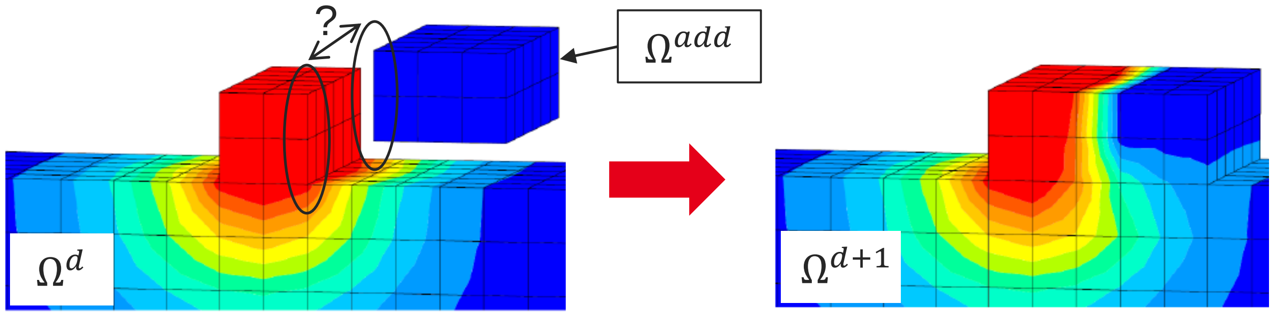
we get:

$$T^{d+1} = \left(C^{d} + C^{add}\right)^{-1}\left(C^{d}.T^{d} + C^{add}.T^{add}\right).$$

Important remark: T^{d+1} is temperature at the beginning of the next time step.

Material deposition

- Mechanical analysis: displacements and stresses initialization during model change



- Static analysis: no mechanical energy in Ω^{add}

- Displacement field at interface $\Omega^{d} \cap \Omega^{add}$:

$$u\left(\Omega^{d} \cap \Omega^{add}\right) = u^{d} \Rightarrow \varepsilon^{add} \neq 0 \Rightarrow E_{m}^{\varepsilon,add} \neq 0$$

- Moreover:

$$\varepsilon^{th,add} = \varepsilon^{th}\left(T^{d+1}\right) \neq 0 \Rightarrow E_{m}^{th,add} \neq 0$$

- Initial stress free strain ε^{L} applied to the added part to cancel this input of mechanical energy:

$$\varepsilon^{L} = \varepsilon^{add} - \varepsilon^{th}\left(T^{d+1}\right) \Rightarrow \sigma^{add} = L^{e}:\left(\varepsilon^{add} - \varepsilon^{th} - \varepsilon^{L}\right) = 0$$

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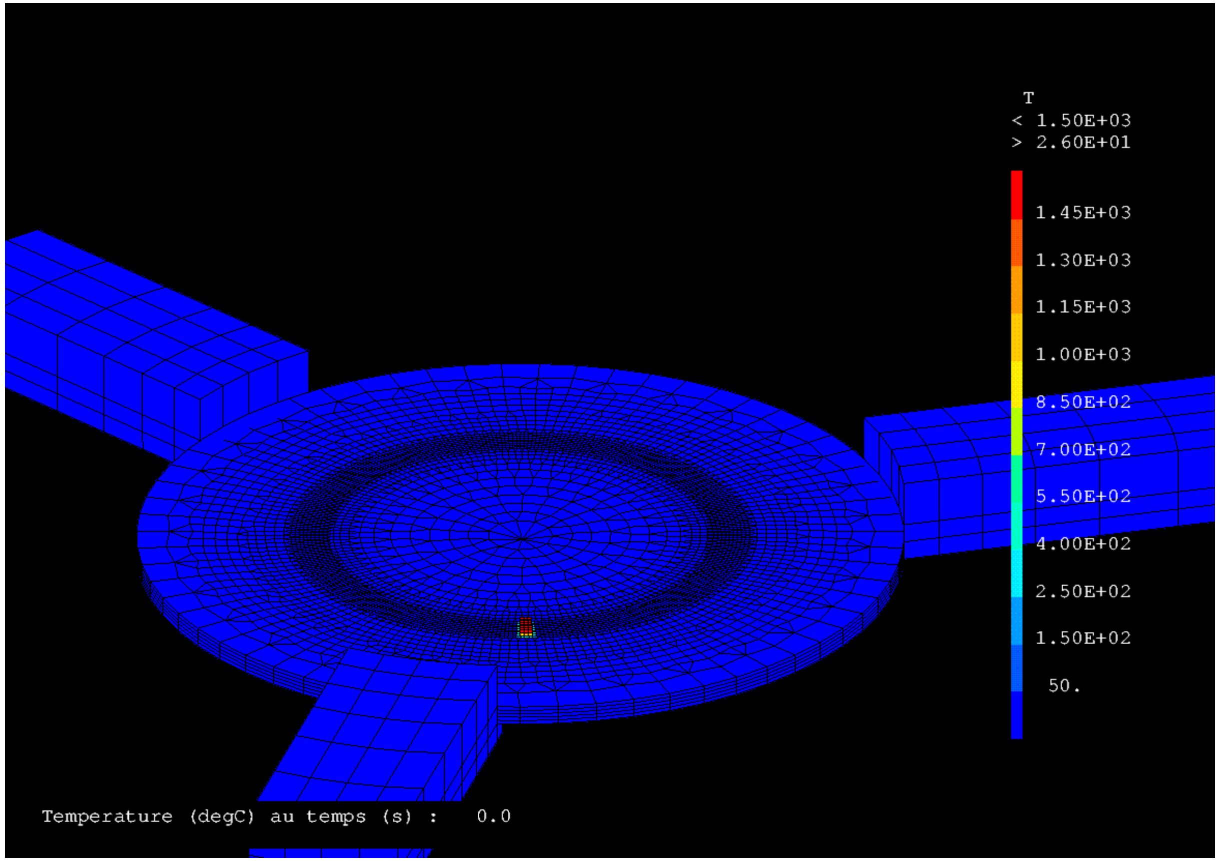
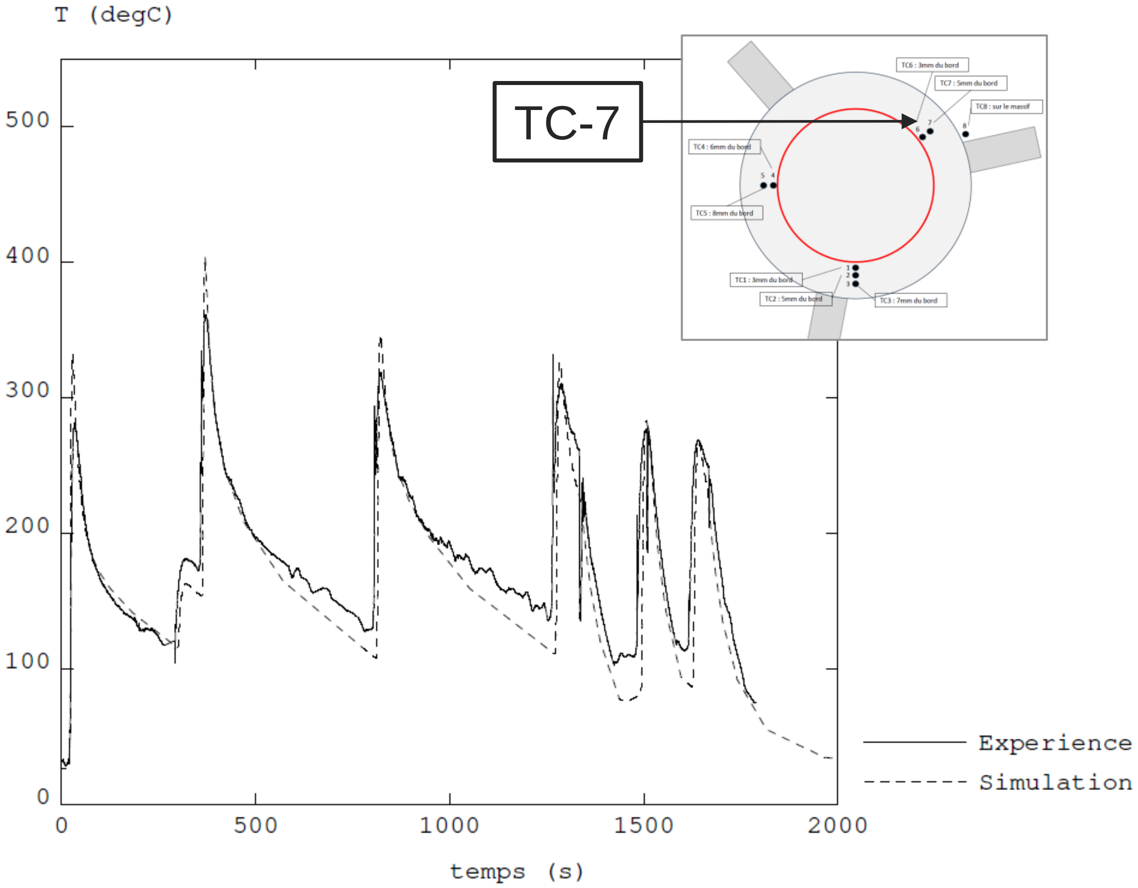
Applications

- Example of thermal analysis : tube manufacturing with WAAM process [1]

Time evolution of temperature node field (°C)



Time evolution of temperature (°C) at a thermocouple location

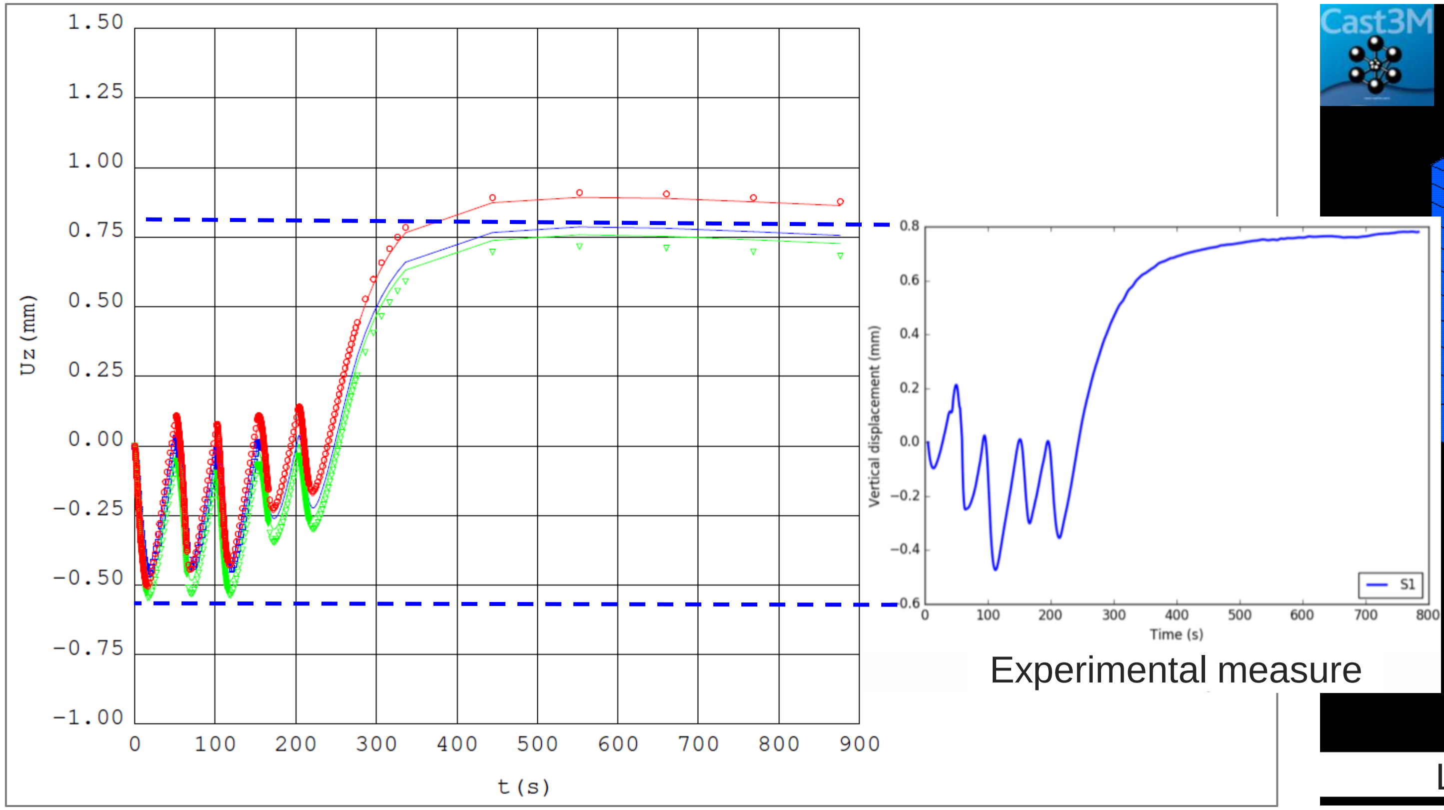


[1]S. Pascal, M. Garnier, M. Garric, J. Le Mercier. *Modélisation thermomécanique de la fabrication additive arc-fil d'un tube droit avec Cast3M*, 16ieme Colloque National en Calcul des Structures (CSMA 2024), CNRS, CSMA, ENS Paris-Saclay, CentraleSupélec, mai 2024, Hyères, France.

Applications

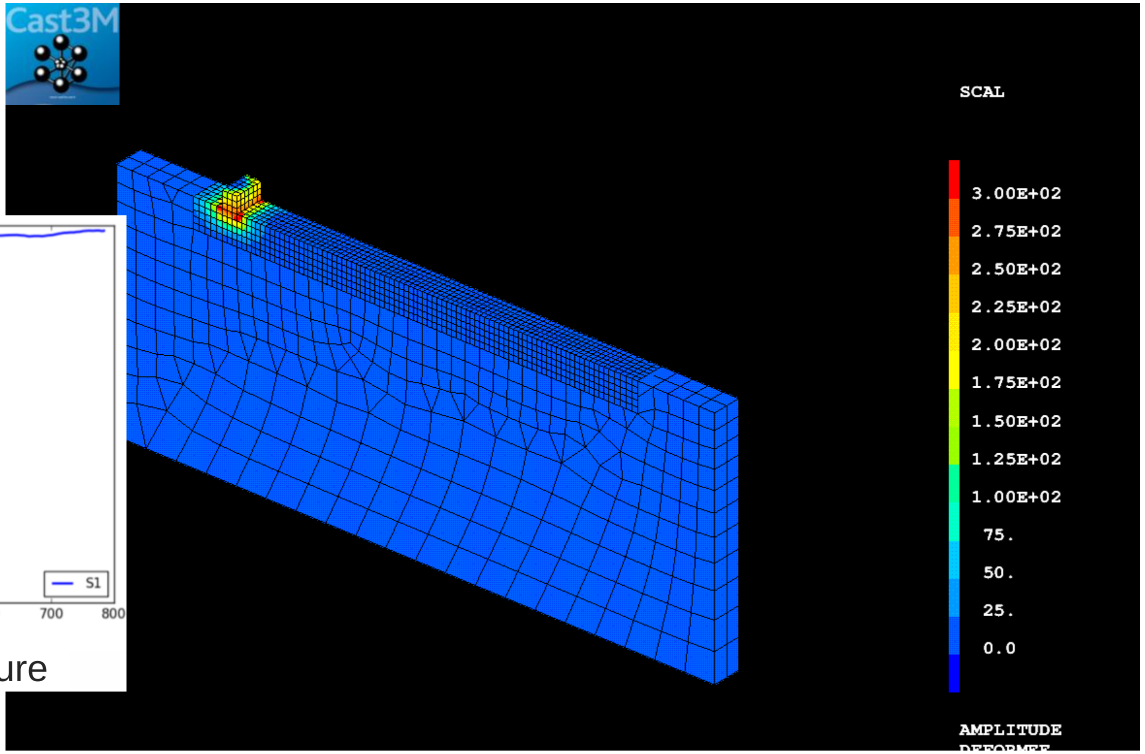
- Example of mechanical analysis : wall manufacturing with WAAM process[1,2]

Time evolution of U_z displacement (mm) at the plate end



Experimental measure

Time evolution of von Mises stress field (MPa)



Linear isotropic hardening, large displacement analysis

[1]C. Cambon, S. Rouquette, I. Bendaoud, C. Bordreuil, R. Wimpory, F. Soulié. *Thermo-mechanical simulation of overlaid layers made with Wire + Arc Additive Manufacturing and GMAW-Cold Metal Transfer*, Welding in the World, Vol. 64 No. 8, pp 1427-1435.

[2]S. Pascal, S. Gounand. *Modélisation thermomécanique d'un cas d'étude de fabrication additive arc-fil*,15ieme Colloque National en Calcul des Structures (CSMA 2022), Université Polytechnique Hauts-de-France, [UPHF], mai 2022, Hyères, France.

Applications

- Example of mechanical analysis : wall manufacturing with WAAM process[1]

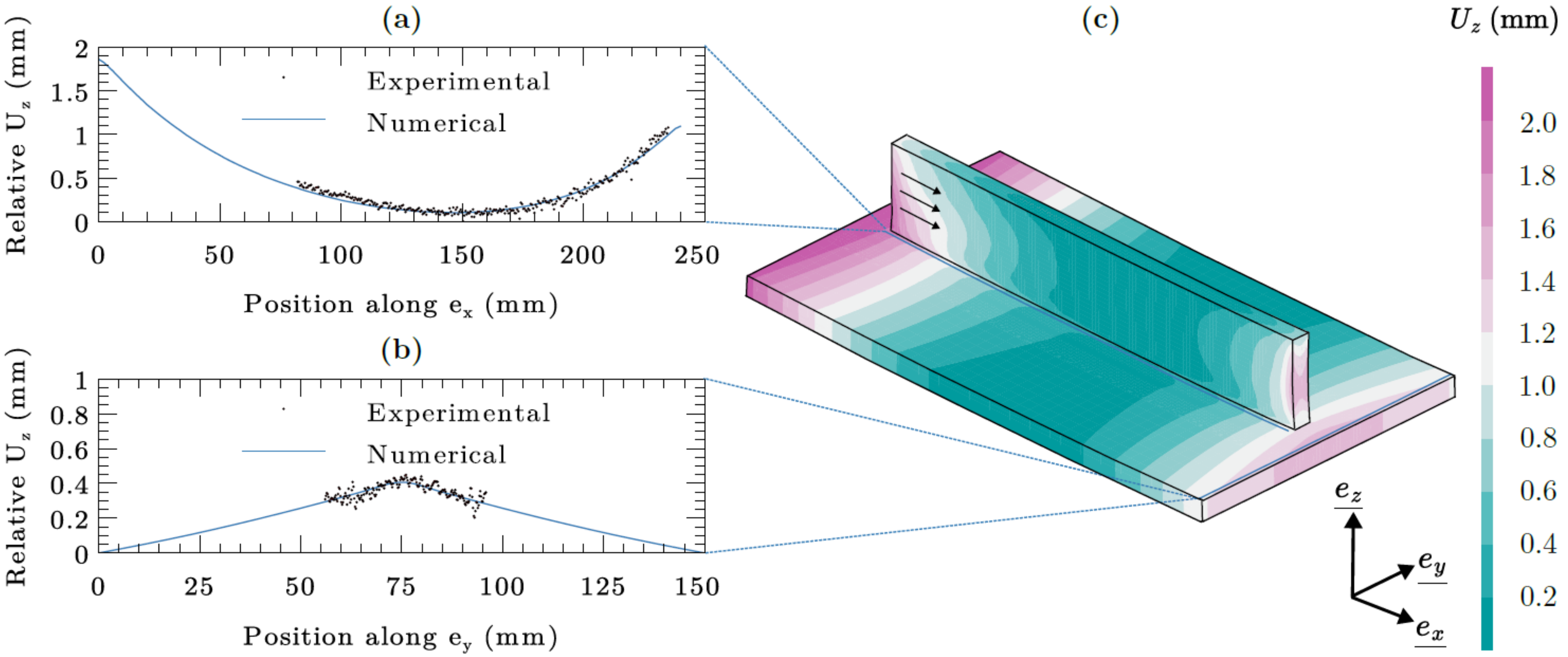


Figure 10. Comparison of the experimental and numerical displacements in the $\underline{e}_z$ direction at the end of the deposition after cooling and unclamping the WAAM specimen: (a) experimental laser profilometry and numerical $\underline{e}_z$-displacement evolution along the $\underline{e}_x$ axis near the manufacturing area; (b) experimental laser profilometry and numerical $\underline{e}_z$-displacements evolution along the $\underline{e}_y$ axis at the extremity of the substrate; (c) numerical estimation of the $\underline{e}_z$-displacements after complete cooling and unclamping of the component.

[1]D. Artieres. *Microstructure et propriétés de l'acier 316L élaboré par fabrication additive par dépôt de fil (WAAM & WLAM) : caractérisation expérimentale et modélisation*, thèse de doctorat, Université Paris sciences et lettres, 2025.

Merci de votre attention

CEA SACLAY
91191 Gif-sur-Yvette Cedex
France
serge.pascal@cea.fr
Standard. + 33 1 69 08 60 00