

Some aspects of Numerical Modelling for Additive Manufacturing

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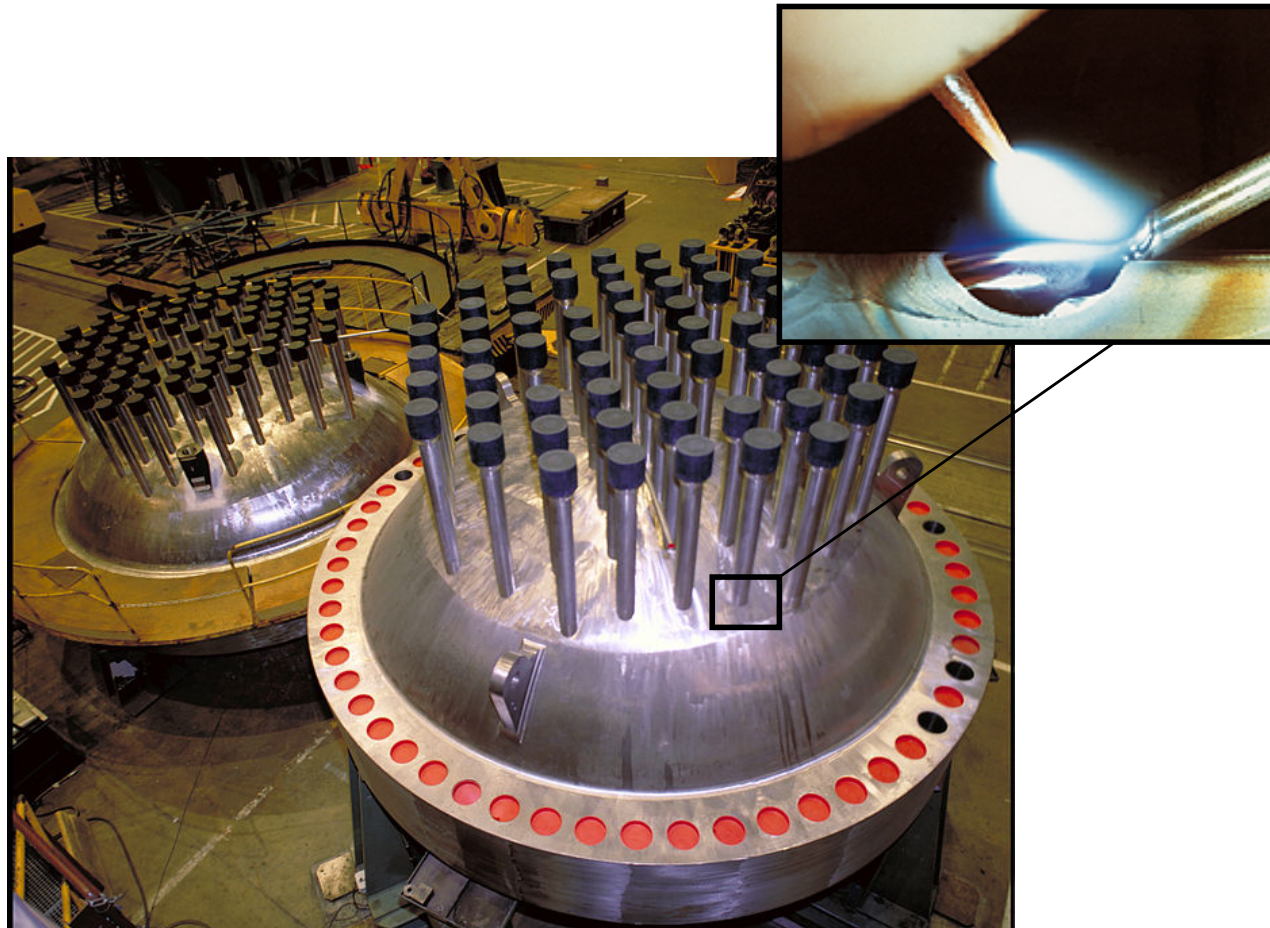
Summary

- 1 Context
- 2 Example I: melt pool
- 3 Example II: thermal + grain structure
- 4 Example III: thermomechanical
- 5 Conclusion – Bibliography

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Context



Pressurized Water Reactor Vessel Head ©NRC

WHY SIMULATE THE WELDING PROCESS ? OUR MAIN GOALS

Requirements

- safety: reliability (quality of welds) and maintainability (mitigation, repair, control, ...);
- manufacturability: welding procedure and process development.

Simulation to improve the control of

- welding processes (understanding the limitations, control, limit defects ...);
- effects of the welding operation on the manufacturability and their consequences on the behaviour:
 - residual stresses => structural integrity, e.g. fatigue, stress corrosion
 - microstructure, metallurgy => mechanical strength, joint coefficient

Process

**Metallurgy
Microstructure**

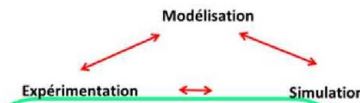
Effects

**Distorsions
Stresses**

Effects

Mechanical strength

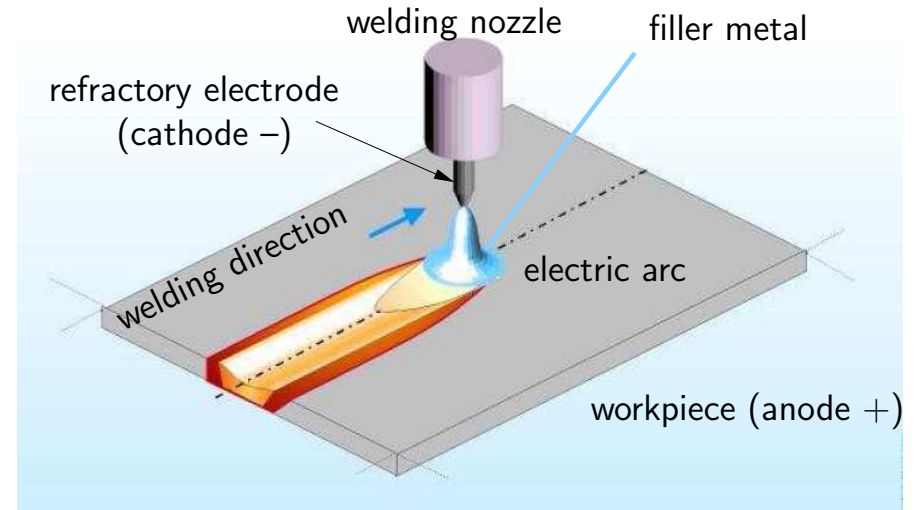
Consequences



TIG welding process



Tungsten Inert Gas (TIG) Process



[EWM AG, 2022; Nguyen, 2015]

TIG welding

- refractory electrode;
- input parameters: tension, intensity, welding speed, arc height, electrode geometry, shielding gas;
- output parameters: weldpool shape, velocity field, temperature field;
- TIG welding video: (local, web).

Observables in TIG welding

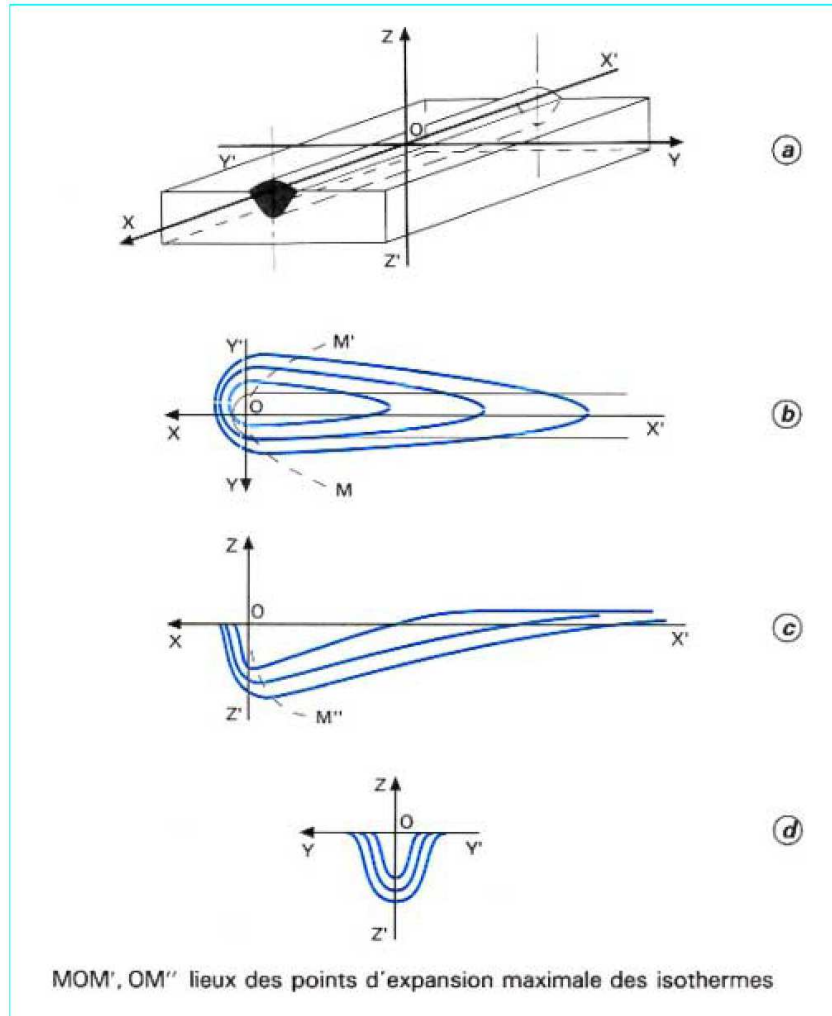


Figure 2 - Schémas de différentes coupes du solide thermique [Murry, 1994]

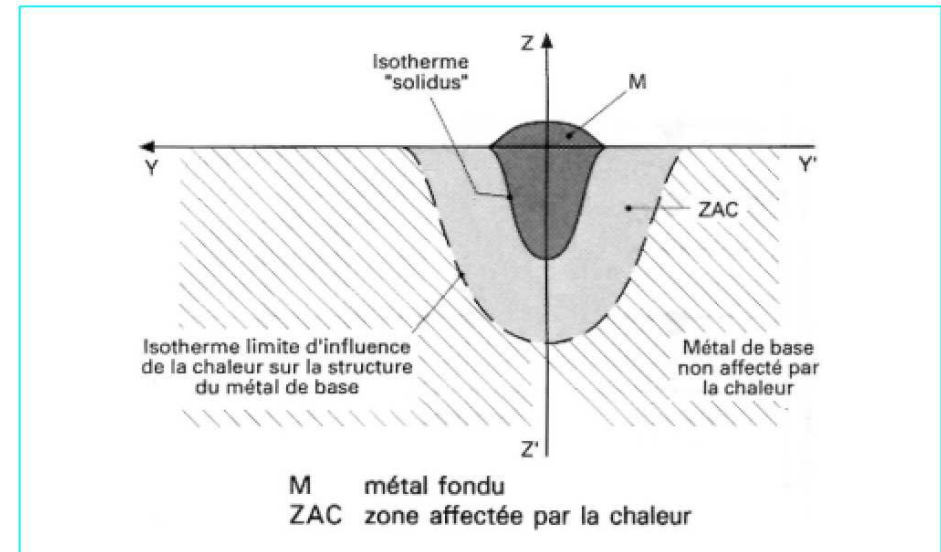


Figure 4 - Définition des différentes zones d'un joint soudé

Comparison with Additive Manufacturing

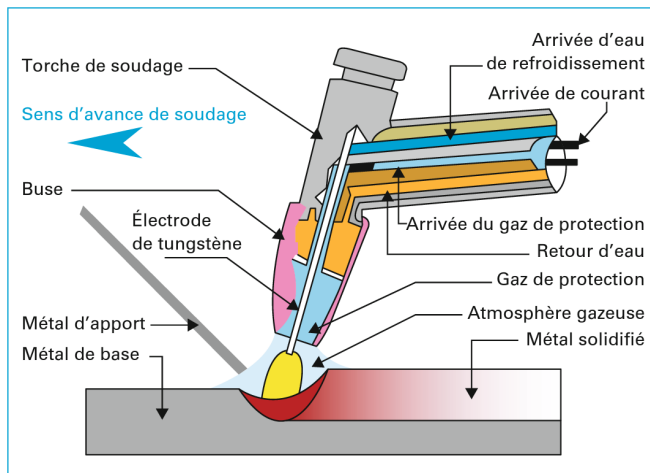
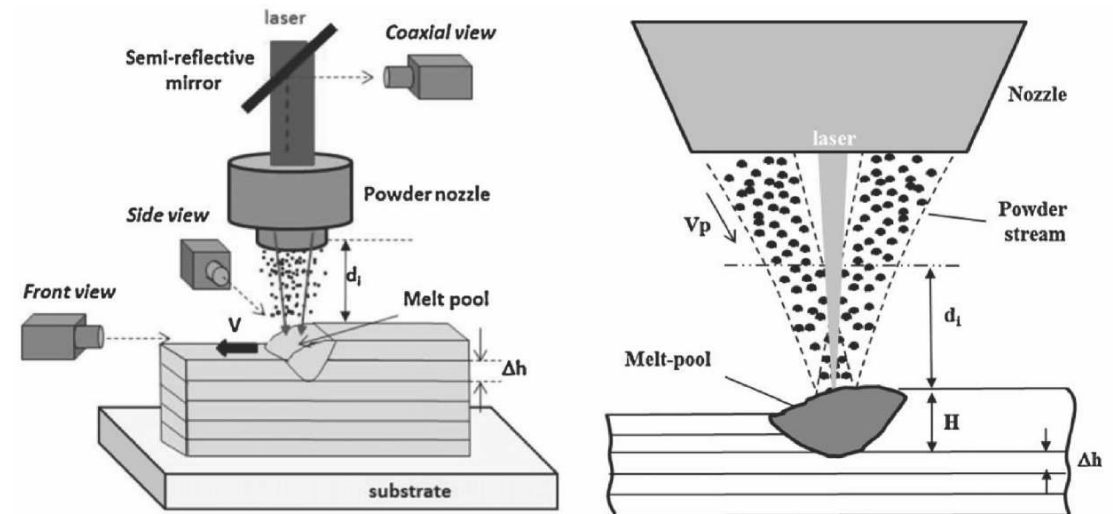


Figure 3 - Présentation en coupe d'une torche de soudage TIG manuel à refroidissement eau

TIG welding [Paillard, 2017]

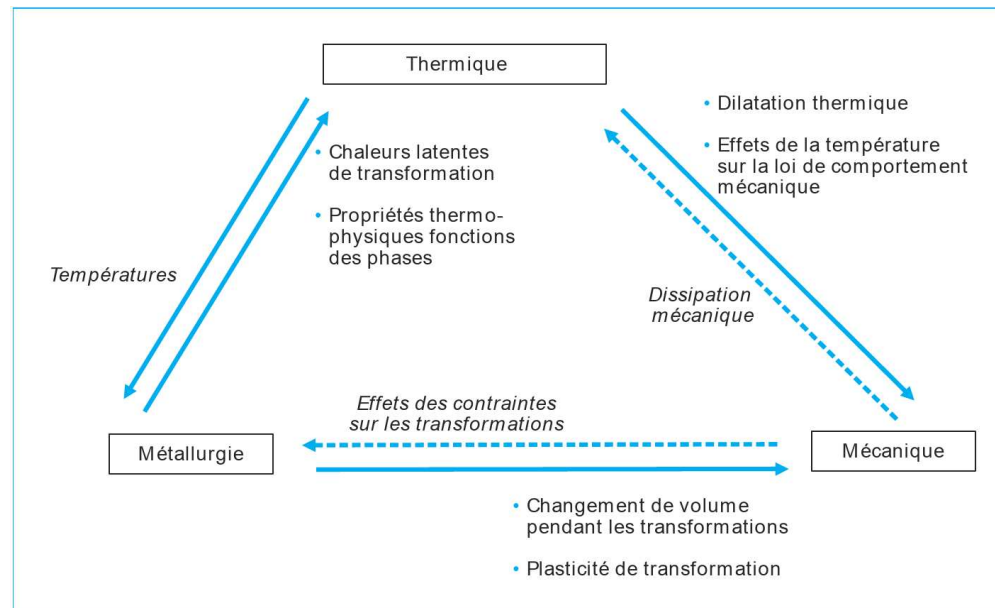


Direct Metal Deposition Laser process [Morville, 2012b]

Additive manufacturing

- S. Morville. **Multiphysics modelling of the Direct Laser Metal Deposition process with a focus on surface finish issues (in french)**. PhD thesis, Université de Bretagne-Sud, décembre 2012b. <https://tel.archives-ouvertes.fr/tel-00806691>, PDF file;
- same physics but different process parameters (heat source velocity, filler metal).

Macroscopic modelling of welding



[Bergheau, 2004]

Thermo-mechanico-metallurgical modelling

1. **Heat source** definition Q ;
2. **Thermal** (T nodal), **metallurgical** (phase content p_k Gauss points);
3. **Mechanical** (nodal displacement, stress at Gauss points);
4. **Analysis:** residual stresses and deformations.

Macroscopic modelling: analysis

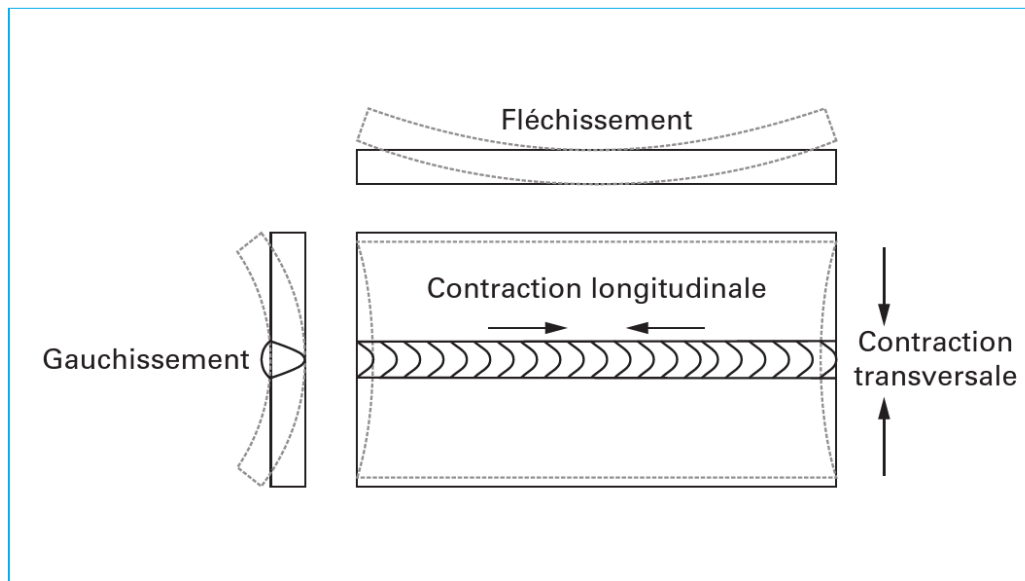


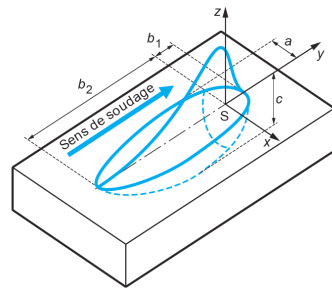
Figure 32 – Distorsions typiquement rencontrées lors du soudage en V de deux tôles minces assemblées en « bout à bout »

[Feulvarch, 2016]

Analysis

- deformation: alignment defect;
- fatigue: residual stresses are superimposed to other applied stresses.

Macroscopic modelling: heat source



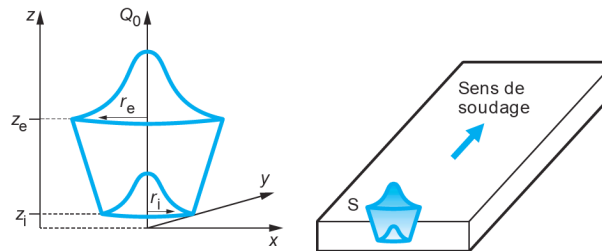
Devant la source

$$Q(x, y, z) = Q_1 \exp\left(-\left(\frac{(x-x_S)^2}{a^2} + \frac{(y-y_S)^2}{b_1^2} + \frac{(z-z_S)^2}{c^2}\right)\right)$$

Derrière la source

$$Q(x, y, z) = Q_2 \exp\left(-\left(\frac{(x-x_S)^2}{a^2} + \frac{(y-y_S)^2}{b_2^2} + \frac{(z-z_S)^2}{c^2}\right)\right)$$

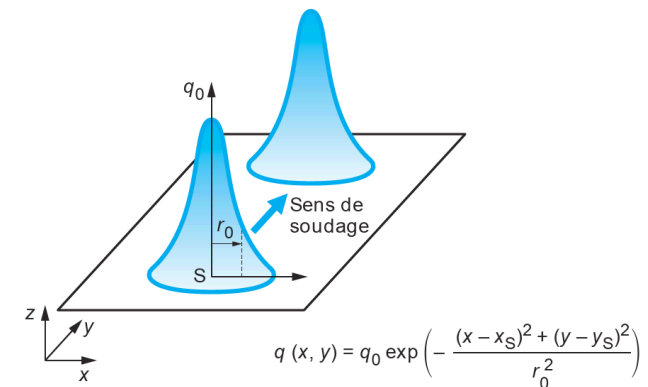
(a) source interne en deux demi-ellipsoïdes



$$Q(x, y, z) = Q_0 \exp\left(-\frac{(x-x_S)^2 + (y-y_S)^2}{r_0^2(z)}\right)$$

$$r_0(z) = r_e + \frac{r_i - r_e}{z_1 - z_e}(z - z_e)$$

(b) source gaussienne à décroissance linéaire dans l'épaisseur



$$q(x, y) = q_0 \exp\left(-\frac{(x-x_S)^2 + (y-y_S)^2}{r_0^2}\right)$$

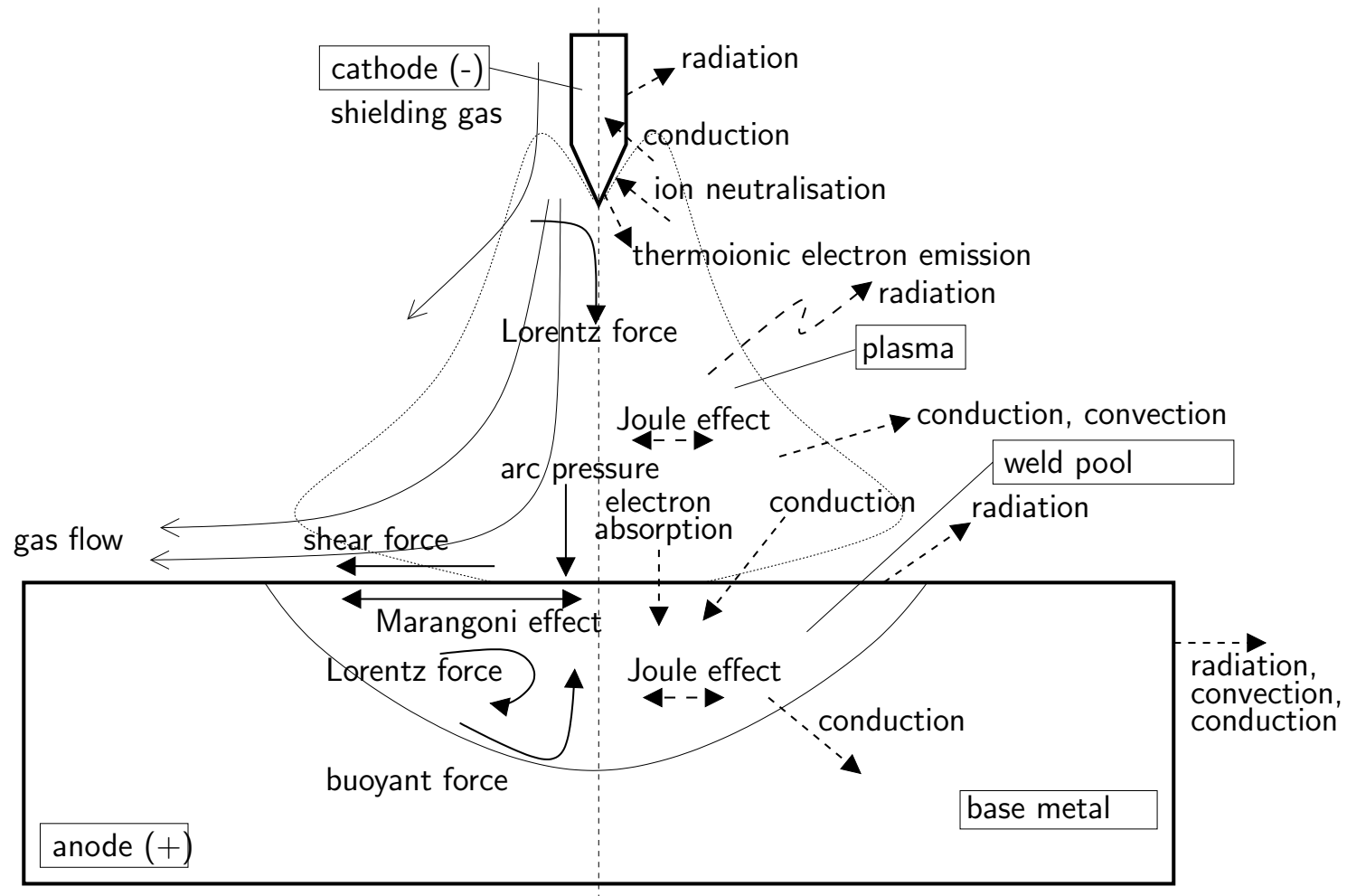
(c) source gaussienne surfacique

[Bergheau, 2004]

Heat source

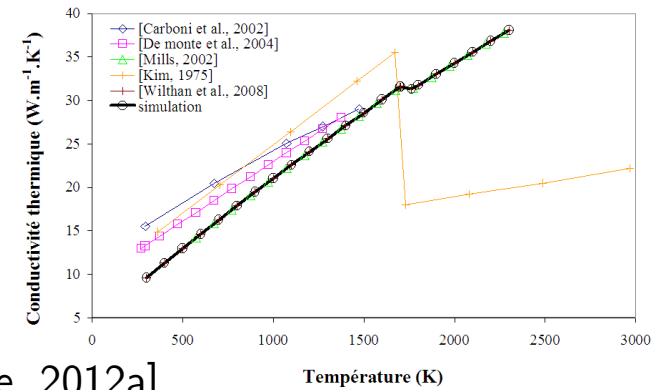
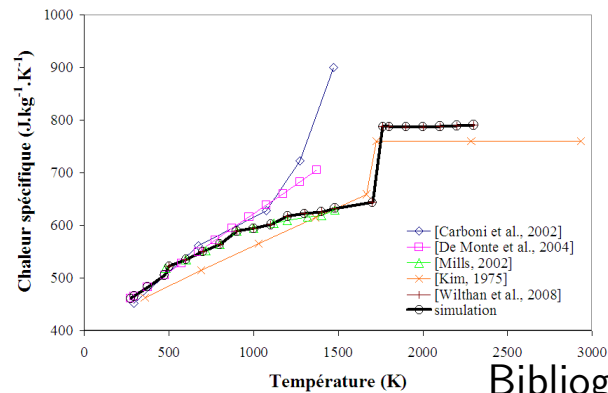
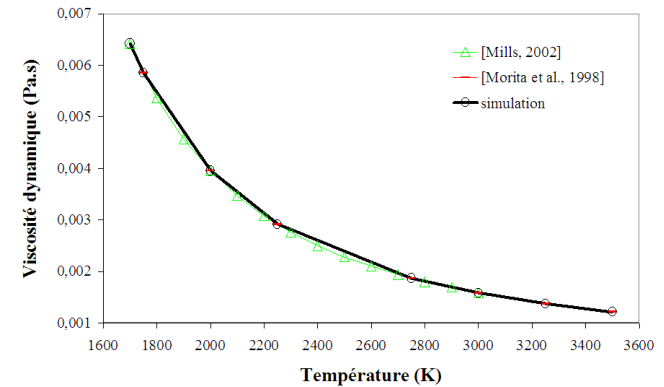
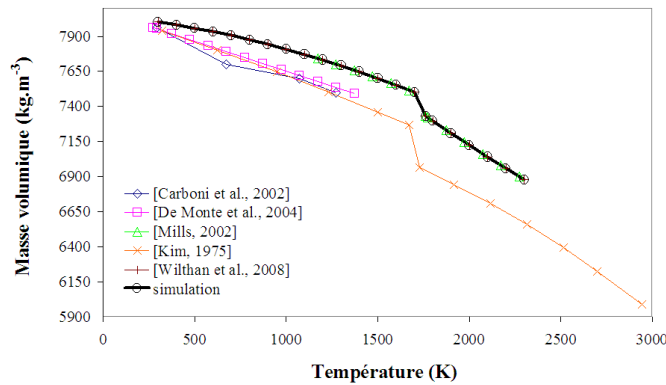
- Goldak (filler material), Gaussian linear attenuation (high energy process), Surface Gaussian;
- problem 1: Heat source calibration depends on material, process and process parameters => costly experiments;
- problem 2: No physical modelling above the melting temperature (higher artificial conductivity).

Mesososcopic modelling: heat source



Physical phenomena in TIG process [Brochard, 2009] + free surface + filler metal

Context : Mesoscopic modelling: material properties (I)



Bibliographical study [Morville, 2012a]

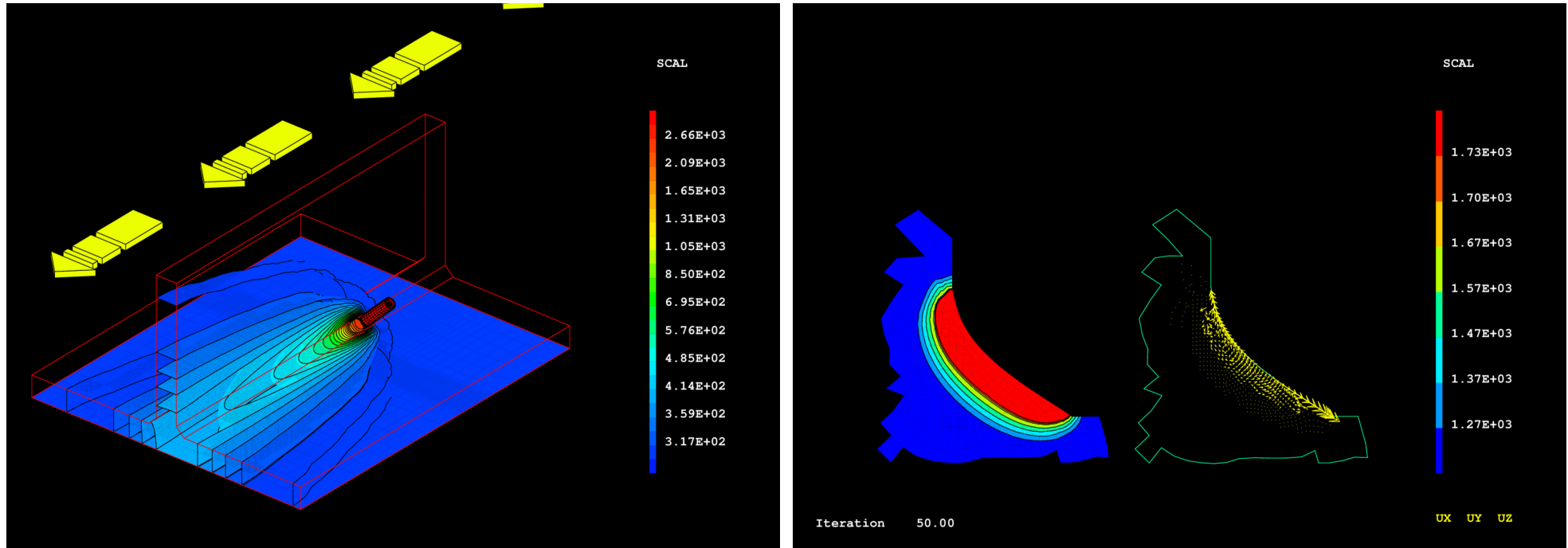
Complexity

High temperature material properties difficult to measure (316L steel)

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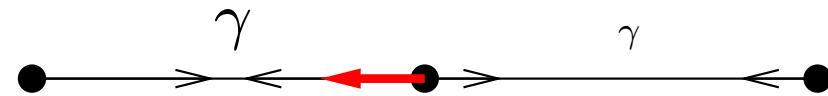
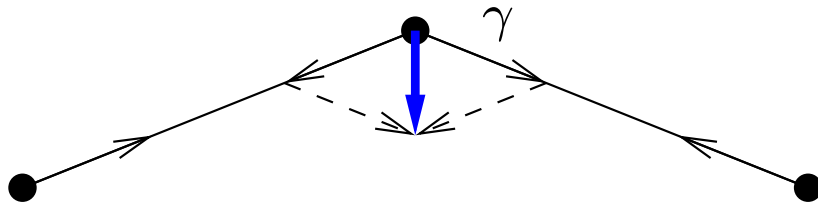
Melt pool computation



Example (S. Gounand)

Tee-like geometry TIG welding, WProcess-Cast3m  : (local, web).

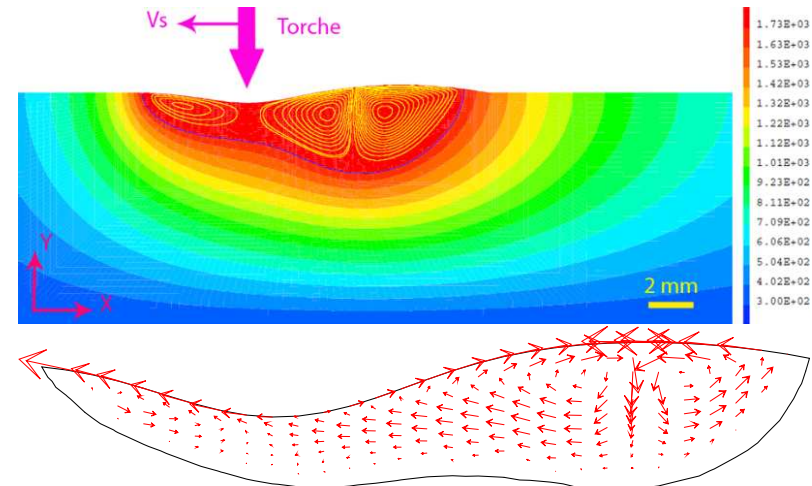
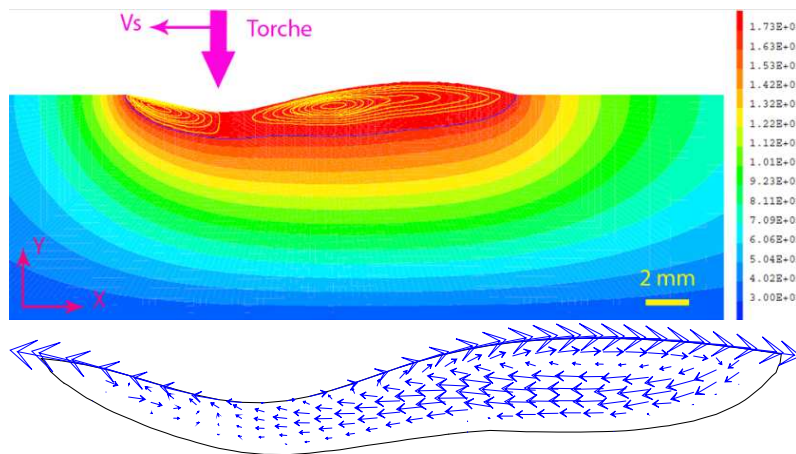
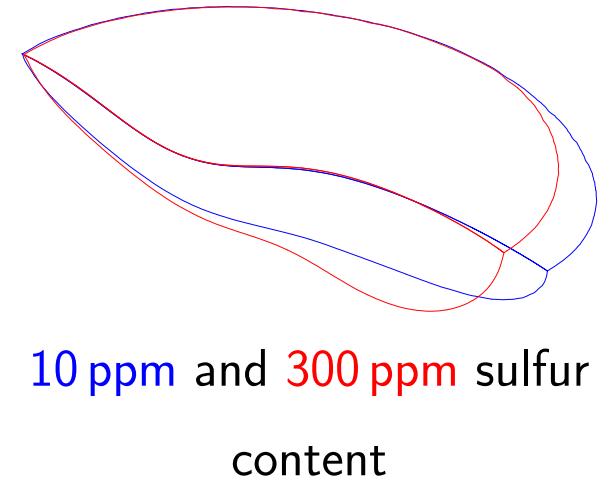
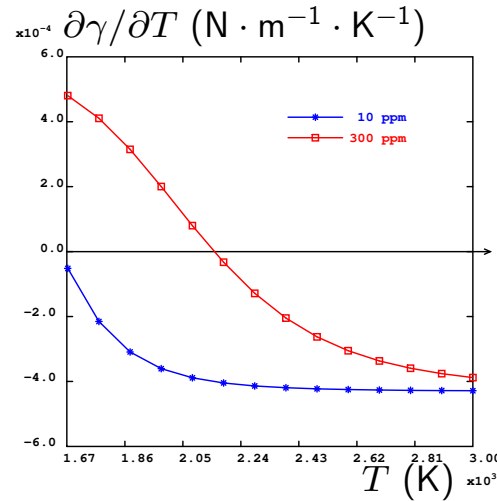
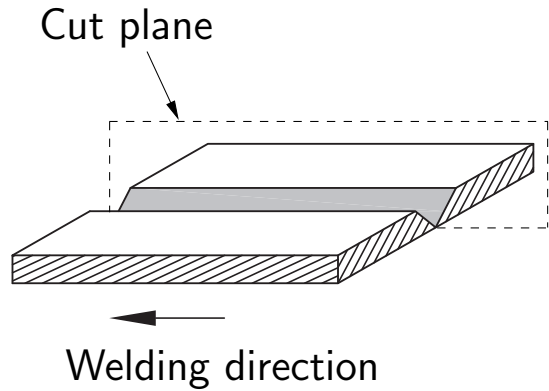
Surface tension in 2D



Normal and tangential force

$$f_{\text{Tension}} = \underbrace{\frac{\gamma}{R} \mathbf{n}}_{\text{Surface tension}} + \underbrace{\nabla_s \gamma}_{\gamma \text{ surface gradient (Marangoni effect)}}$$

Liquid metal weld pool, Marangoni effect



Melt pool shape [Nguyen, 2015]

Summary

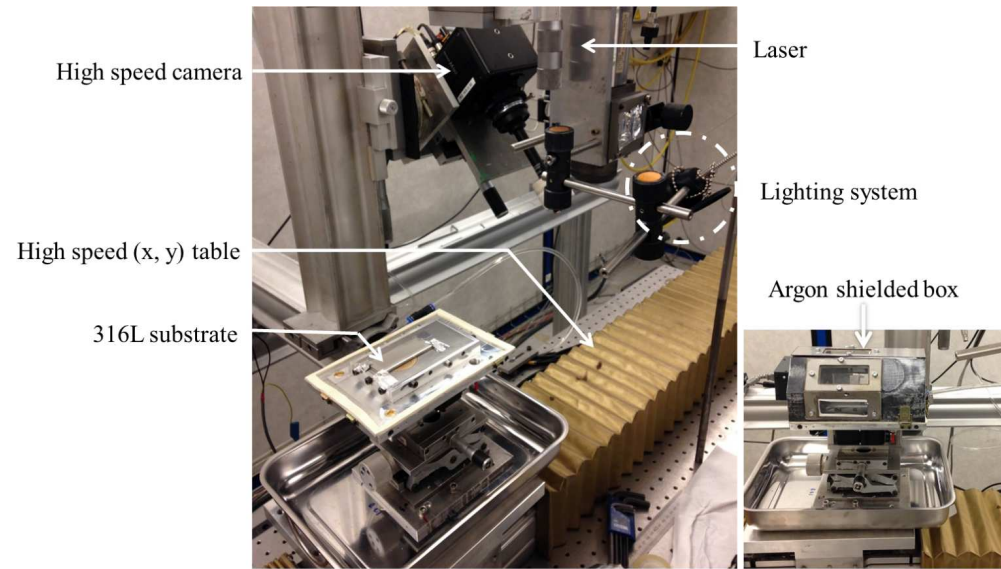
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CAFE : context (I)

Anisotropic grain structure (A. Baumard)

- A. Baumard, D. Ayrault, O. Fandeur, C. Bordreuil, and F. Deschaux-Beaume. Numerical prediction of grain structure formation during laser powder bed fusion of 316l stainless steel. **Materials & Design**, 199:109434, 2021. URL <https://www.sciencedirect.com/science/article/pii/S0264127520309709>;
- Experimental-numerical comparison;
- Macroscopic modelling: Finite Element thermal analysis;
- Mesoscopic modelling: Cellular Automata grain growth model (phenomenological, driven by surfusion);
- [Gandin and Rappaz, 1994].

CAFE : experimental setup (II)

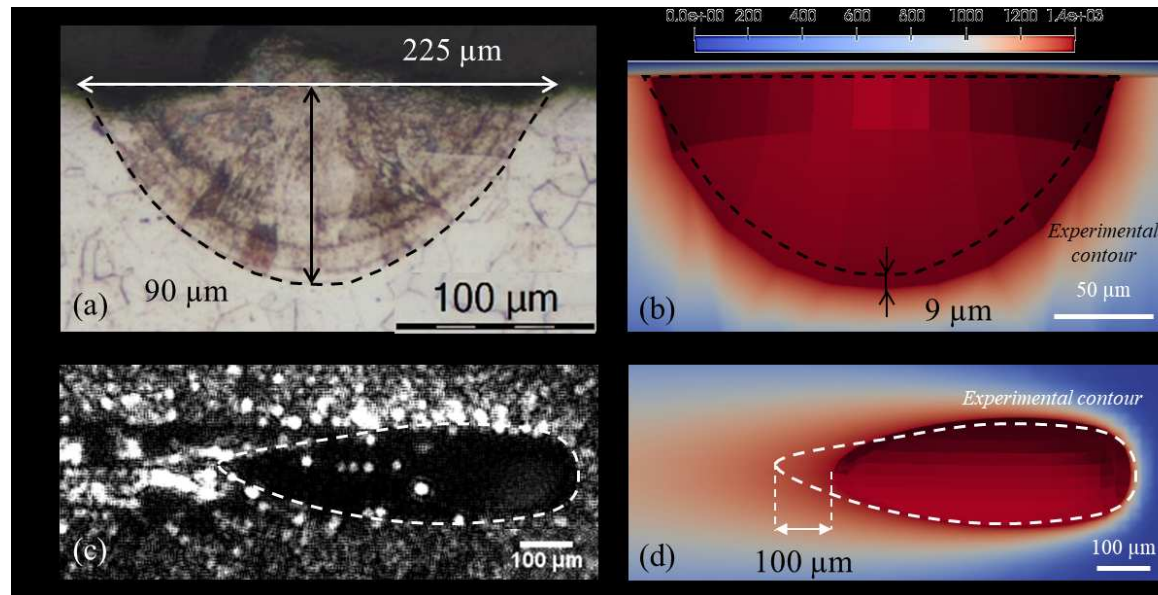


Powder bed laser fusion installation (PIMM – ENSAM, France)

Process parameters

- $P = 400 \text{ W}$, $d = 150 \mu\text{m}$, $\lambda = 1030 \text{ nm}$, $v = 400 \text{ mm} \cdot \text{s}^{-1}$

CAFE : thermal analysis (III)

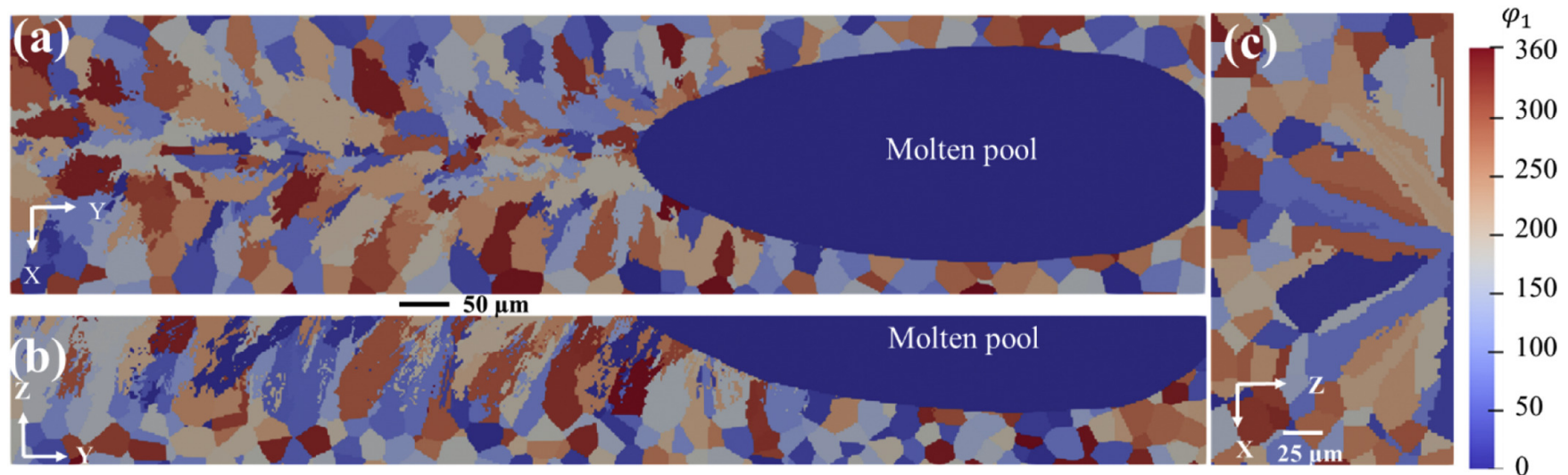


Finite Element Analysis


- 4 geometric parameters Goldak heat source q ;
- $\rho c_p \frac{\partial T}{\partial t} = \Delta T + q$ Finite element solver: Cast3m
- Molten pool videos: raw, powder bed



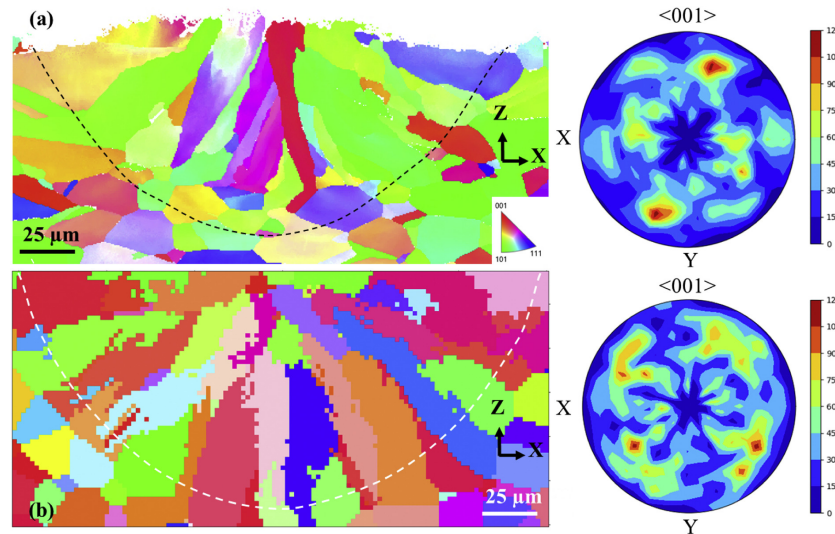
CAFE : grain structure (IV)



Cellular Automata

- Fine Cartesian Grid;
- In-house Fortran 2008 code chained with Cast3m ;
- Grain structure videos: longitudinal view (local, web) and top view (local, web).

CAFE : experimental–numerical comparison (V)



Grain structure


		Avg cross-sectional area (μm^2)	Avg diameter (μm)	Aspect ratio
Substrate	Experimental	509	25.5	1.5
	Numerical	390	22.3	1.8
Fusion line	Experimental	380	22.0	3.4
	Numerical	546	26.4	3.0

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Thermomechanics : context (I)

316L WAAM Mock-up for residual stresses (S. Pascal)


- C. Cambon, S. Rouquette, I. Bendaoud, C. Bordreuil, R. Wimpory, and F. Soulie. Thermo-mechanical simulation of overlaid layers made with wire + arc additive manufacturing and GMAW-cold metal transfer. **Welding in the World**, 64(8):1427–1435, 2020. URL <https://doi.org/10.1007/s40194-020-00951-x>;
- Experimental-numerical comparison;
- Macroscopic modelling: Finite Element transient non-linear thermal analysis;
- Macroscopic modelling: Finite Element static non-linear mechanical analysis (small and large displacements; 3 behavior laws: perfect plasticity, linear isotropic hardening, linear kinematic hardening);
- Cast3m .

Thermomechanics : experimental setup (II)

$I_\varepsilon(\varphi) = \int \dots \lim \dots W(\cdot, F) = \infty$

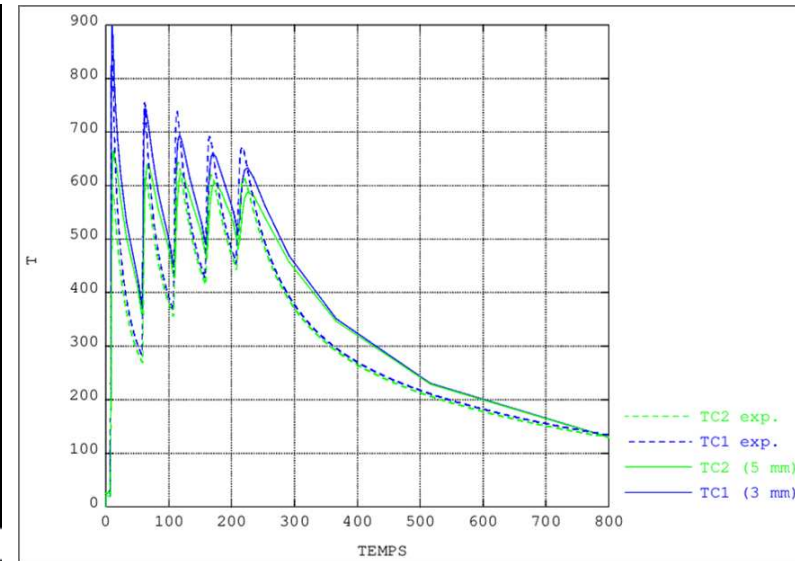
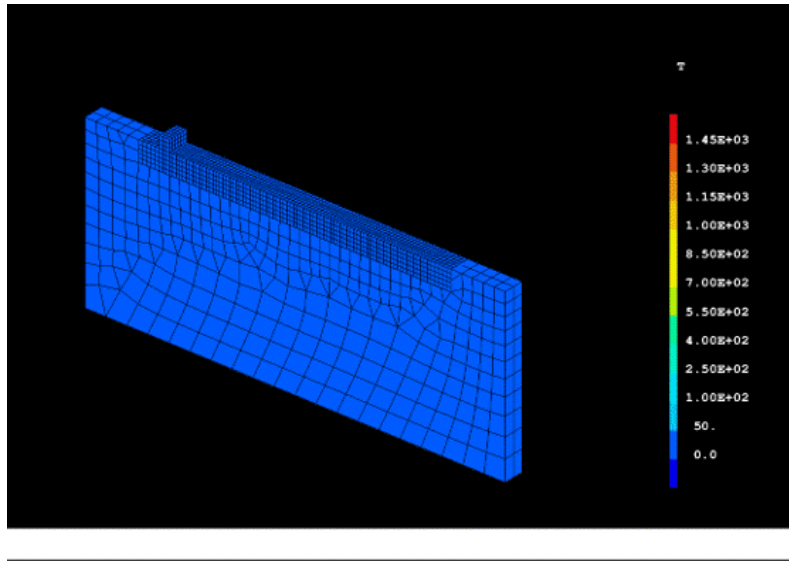
LMGC experimental bench

- *T-base plate 316 L*
- *Laser scan*
- *5 thermocouples*
- *Camera CCD*
- *LEM (current & tension)*



6

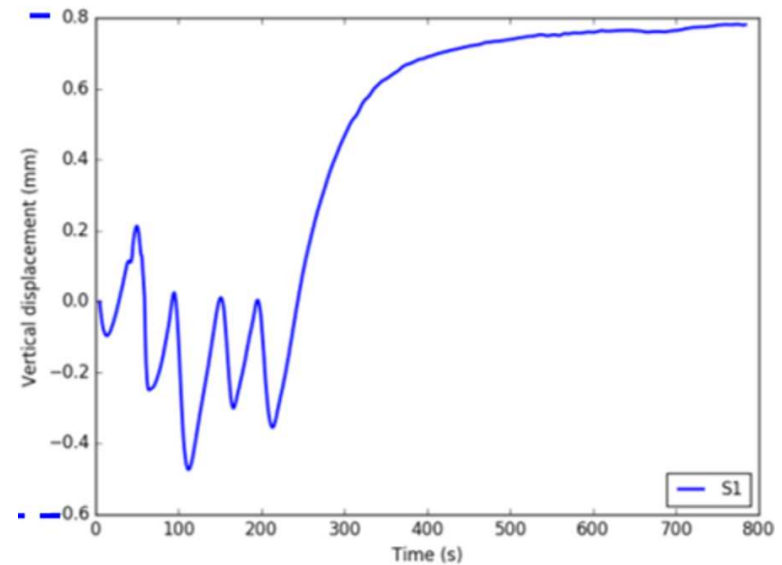
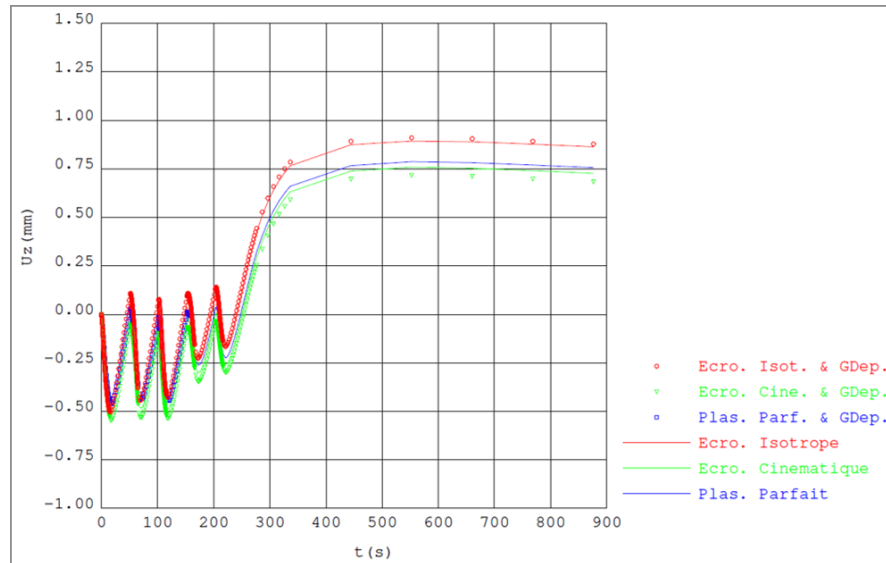
Thermomechanics : thermal analysis (III)



Finite Element thermal Analysis

- Spherical Gaussian heat source;
- $P = 2600 \text{ W}$ (first pass) 2000 W , $d = 37 \text{ s}$, $v = 0,36 \text{ m} \cdot \text{min}^{-1}$;
- Video: temperature

Thermomechanics : mechanical analysis (IV)



Finite element mechanical analysis

- Linear isotropic hardening, large displacements;
- Video: Von Mises stress

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Conclusions (I)

Conclusions

- welding, additive manufacturing: major role of surface tension on the melt pool shape and fluid flow;
- multiphysics \Rightarrow more material properties, numerically harder, better physical insights and predictions;
- usefulness of multimodel coupling or chaining;
- multiscale necessity depends on the simulation goals.


Conclusions (II)

Outlook

- better characterization of material properties especially for liquid metals (ex: 50% error for $\partial\gamma/\partial T$ Eustathopoulos and Drevet [2017]);
- measurement techniques in the melt pool: velocity, temperature;
- multiphysics: uncertainty quantification ? (error bars for numerical results);
- more physics: metal evaporation, turbulence...;
- more coupling or chaining: arc-melt pool, grain structure-behavior laws;
- numerics: efficient linear solvers for badly-conditioned linear systems, automatic, adaptive meshing...


Conclusions (III)

Training sessions (S. Pascal)

Thermomechanical modeling of Additive Manufacturing in Cast3m  scheduled October, 21 2022, just after a beginners' course.

See <http://www-cast3m.cea.fr/>, Training Sessions tab.

Doctoral course (in french)

Metallic Additive Manufacturing (50 hours spread over 2 years) at Paris-Saclay University  scheduled March, 2023.

See <https://www.adum.fr/psaclay/formations.pl?mat=289085>.

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- [Brochard, 2009]** M. Brochard. *Modèle couplé cathode-plasma-pièce en vue de la simulation du procédé de soudage à l'arc TIG*. PhD thesis, Université de Provence (Aix-Marseille I), janvier 2009. <http://www-cast3m.cea.fr/index.php?page=these>, PDF file.
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Book

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