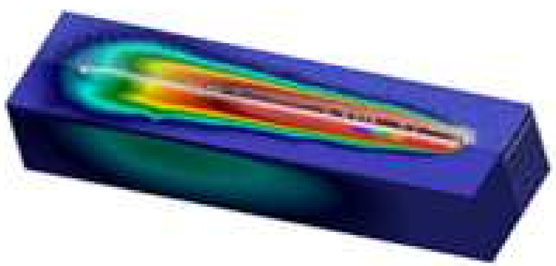
Thermo-mechanical modeling of additive manufacturing: continuum or particles with level set formulation applied to track and part scale simulations



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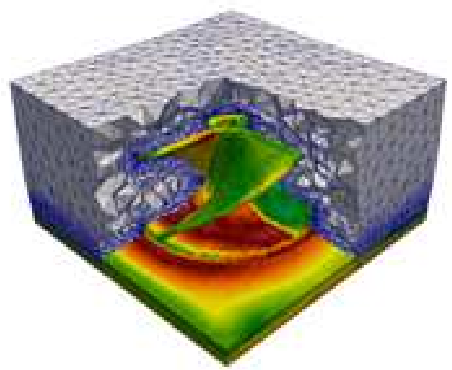
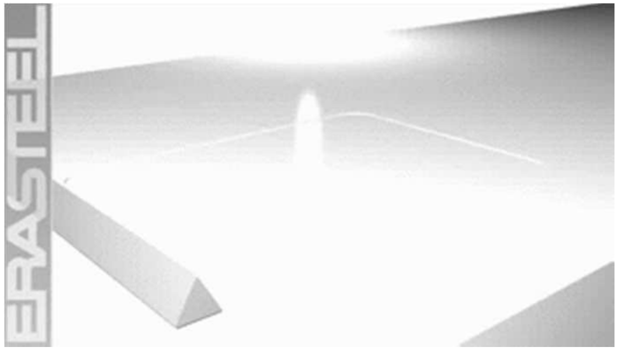


Forum Teratec, 2019

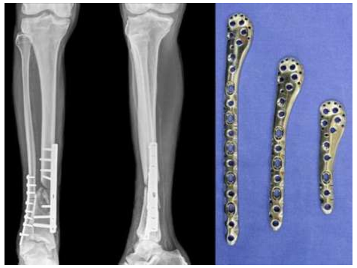
Introduction: additive manufacturing selective laser melting (SLM)



Advantages:
- Complex part geometry
- Variety of products and materials
- No time gap between design and prototyping
- Less waste than processes by subtraction

  …

Jet engine
(site
[Scienceinpublic])



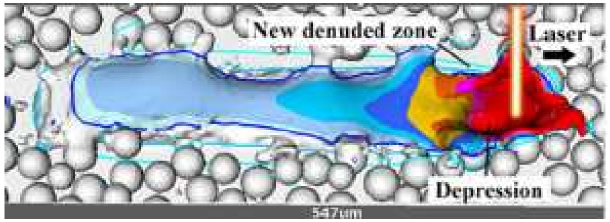
Implant
(Titanium, site
[Farinia])

Resistojet heat
exchanger
(316L, [Romei2017])

Challenges:
- Difficult to control
- Time consuming
- Defects (cracks, deformation, poor surface quality …)

I. Introduction: 3 scales for SLM numerical modeling

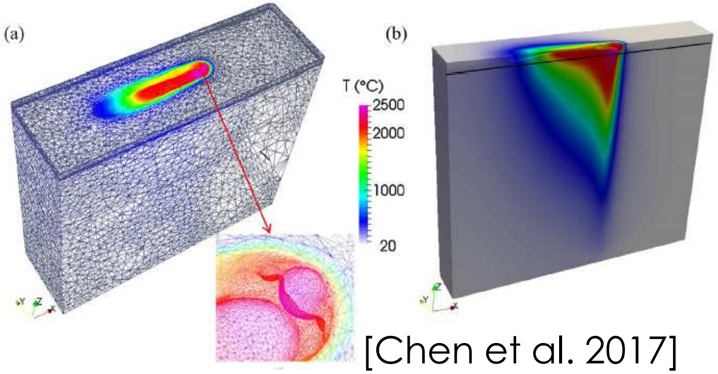
Powder particles « microscopic »



[Khairallah et al. 2016]

- ***Interaction laser*** – powder particles
- ***Denudation phenomenon***
- ***Formation of melted zone, porosities***
- ***Influence of powder granulometry distribution***
- ***Very high computing time***

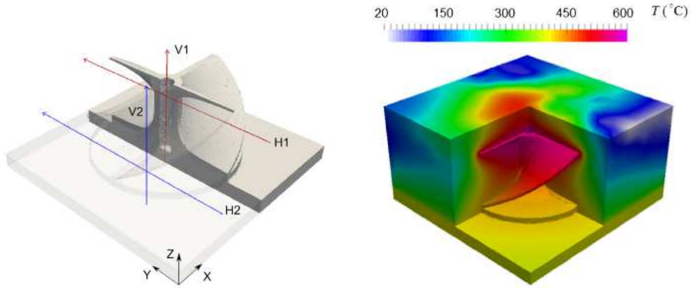
Track scale – Continuous powder bed « mesoscopic »



[Chen et al. 2017]

- ***Interaction laser*** – powder bed
- ***Shape of elementary deposits*** (tracks)
- Formation of ***microstructure in extremely fast solidification and cooling***
- Formation of ***stress*** in wake of the melted zone
- Occurrence of defects: ***balling, hot tearing***

Part scale « macroscopic »



[Zhang et al. 2017]

- Energy and material inputs: simplified
- ***Temperature*** distribution
- Distributions of ***distortions and stress***, during and after processing
- Thermal and mechanical role of ***support*** structures
- Occurrence of defects: ***cold*** cracking

Objective

Numerical strategy developed in CEMEF to simulate the SLM process with **powder bed** at the **meso-** and **macro-scale** by **level set** and **finite element** methods

Khairallah, Anderson, Rubenchik, King, Laser powder-bed fusion additive manufacturing: physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones, **Acta Materialia (2016)**

Chen, **Guillemot**, **Gandin**, **Bellet**, Three-dimensional finite element thermomechanical modeling of additive manufacturing by selective laser melting for ceramic materials, **Additive Manufacturing (2017)**

Zhang, **Guillemot**, **Bernacki**, **Bellet**, Macroscopic thermal finite element modeling of additive metal manufacturing by selective laser melting process, **Comp. Meth. Appl. Mech. Eng. (2018)**

Presentation plan

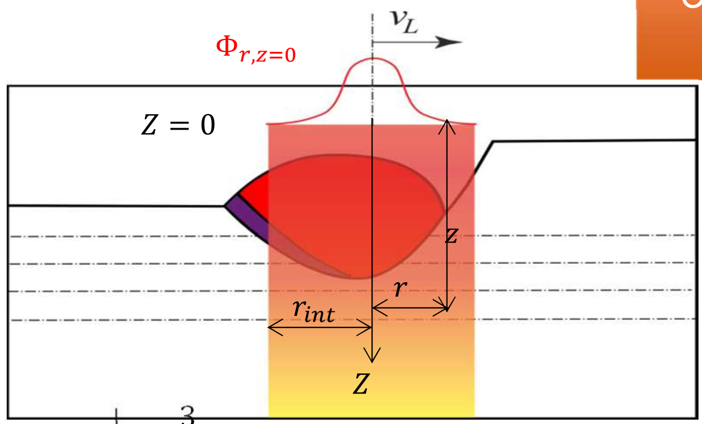
- Introduction
- Thermal and mechanical solvers in developed meso- and macro-scale models
- Meso-scale model at the track level
  - Interaction of laser-material
  - Hydrodynamics
  - Balling effect
  - Thermomechanical analysis
- Macro-scale model at part level
  - Strategy of fraction of layer
  - Thermomechanical analysis
  - Inherent strain rate method
- Conclusions
- Perspectives

Thermal solver: meso-scale model

- **Heat transfer:**

$$\frac{\partial\{\rho h\}}{\partial t} + \nabla\cdot(\{\rho h\}\boldsymbol{u}) - \nabla\cdot(\{\lambda\}\nabla T) = \dot{q}_L - \dot{q}_r$$

Heat loss



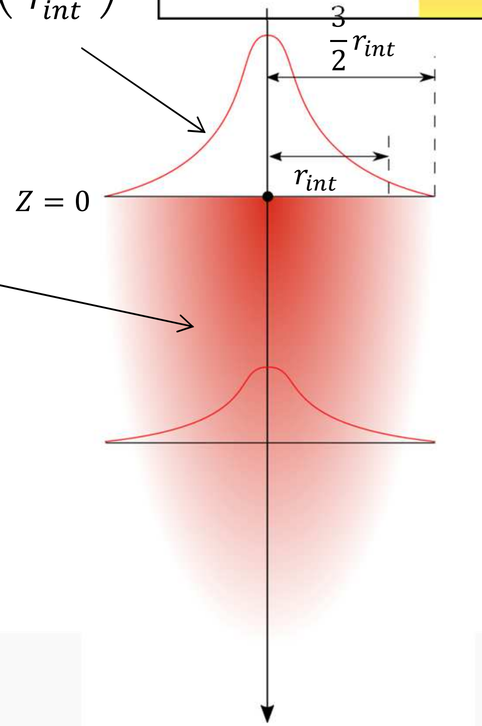
- **Laser heat source : $\dot{q}_L$**

$$\phi_{r,z=0} = (1-R)\frac{2P_L}{\pi r_{int}^2}\exp\left(\frac{-2r^2}{r_{int}^2}\right)$$

  - Gaussian surface distribution $\phi_{r,z=0}$
  - Volume heat source based on Beer-Lambert law

$$\frac{d\phi}{dz} = -\alpha\phi \quad \Rightarrow \quad \phi(r,z) = \phi_{r,z=0}\exp\left(-\int_0^z \alpha dz\right)$$

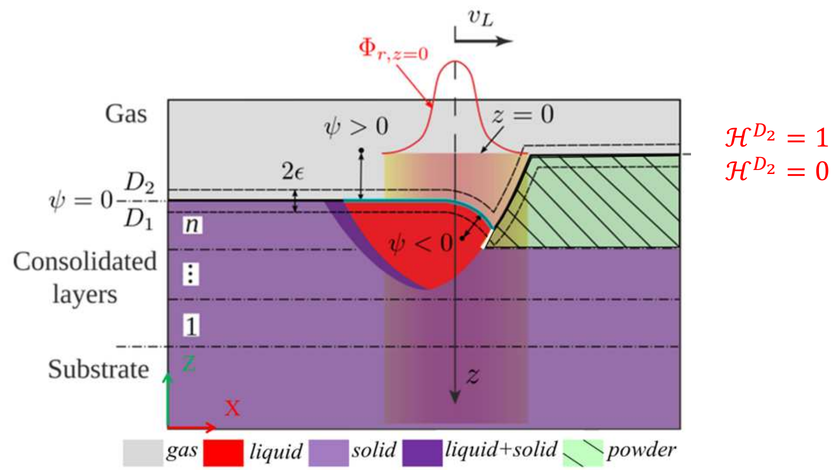
$$\dot{q}_L = -\frac{d\phi}{dz} = \phi_{r,z=0}\cdot\alpha\cdot\exp\left(-\int_0^z \alpha dz\right)$$

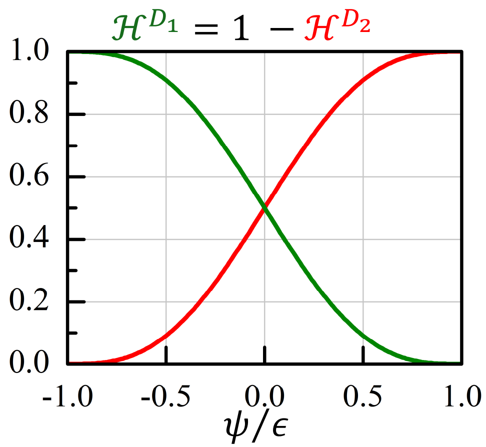


Meso-scale modeling – track scale: approach

Multidomain multiphase level set representation [Hagedorn et al., 2010 and Chen et al., 2017]

- **Multidomain system: $\mathbf{D_i},\ \mathbf{i} = \{\mathbf{1}, \mathbf{2}\}$**
  - ❑ Single phase domain D_2: phase gas
  - ❑ Multiphase domain D_1: phase α_l
  - ❑ Powder is considered as continuous
- **Interdomain boundary $\mathbf{D_1/D_2}$**
  - ❑ Level set function ψ, i.e. signed distance from boundary D_1/D_2 with $\psi = 0$
  - ❑ Heaviside function with half-interface thickness ϵ
- **Volume averaging**
  - ❑ Within the system: $\chi = \sum_{D_i} \mathcal{H}^{D_i} \langle\chi\rangle^{D_i}$
  - ❑ Within each domain D_i: $\langle\chi\rangle^{D_i} = \sum_{\alpha_l} g_{D_i}^{\alpha_l} \chi_{D_i}^{\alpha_l}$





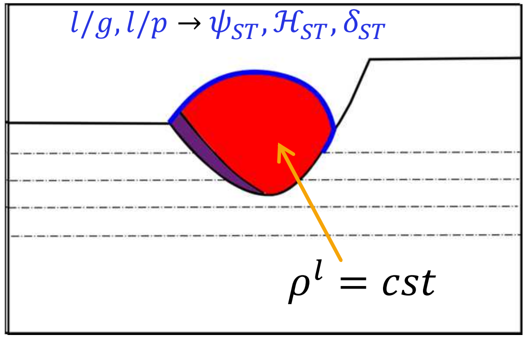
Hagedorn, Wilkes, Meiners, Wissenbach, and R. Poprawe, *Phys. Procedia*, 5: 587–594, Jan. 2010.
Chen, Guillemot, Gandin and Bellet, Add. Manu, 2017

Meso-scale modeling: hydrodynamics

- **Momentum equation:**

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)-\nabla\cdot\underline{\underline{\boldsymbol{\sigma}}}=\rho\boldsymbol{g}+\boldsymbol{f}$$
$$\nabla\cdot\boldsymbol{u}=\dot{\theta}$$

Buoyancy force & recoil pressure not studied



- **Compressible Newtonian behavior**

$$\underline{\underline{\boldsymbol{\sigma}}}=2\mu\left(\underline{\underline{\dot{\boldsymbol{\epsilon}}}}-\frac{1}{3}tr\left(\underline{\underline{\dot{\boldsymbol{\epsilon}}}}\right)\underline{\underline{\boldsymbol{I}}}\right)-p\underline{\underline{\boldsymbol{I}}} \quad \textbf{and } tr\left(\underline{\underline{\dot{\boldsymbol{\epsilon}}}}\right)=\nabla\cdot\boldsymbol{u}=\dot{\theta}$$

- **Surface tension $\boldsymbol{f}_s$** [Hysing, 2005, Khalloufi et la., 2016] **and Marangoni force $\boldsymbol{f}_m$**

$$\boldsymbol{f}=\boldsymbol{f}_s+\boldsymbol{f}_m$$

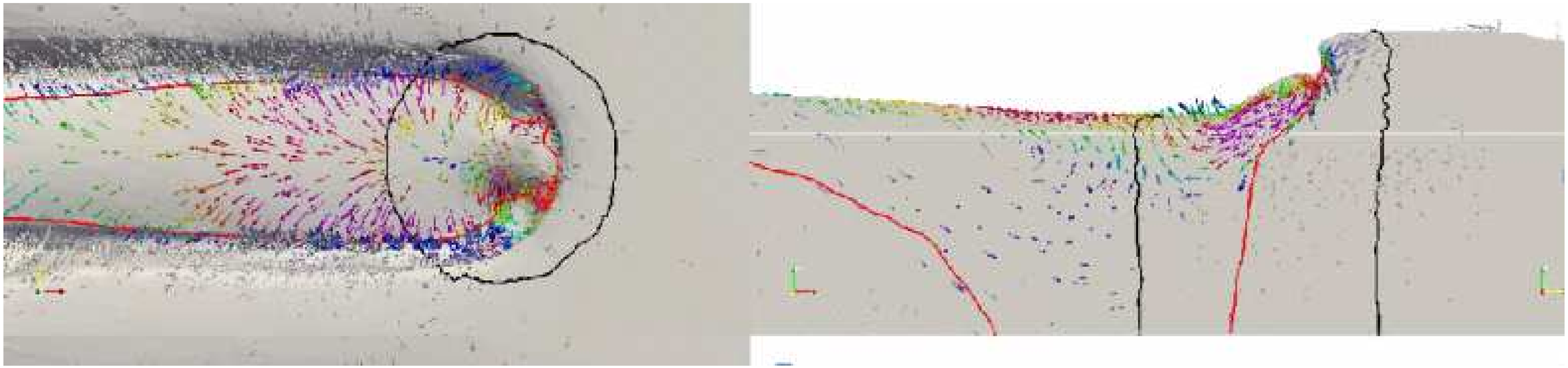
$$\boldsymbol{f}_s=\delta_{ST}\gamma\kappa\boldsymbol{n} \qquad\qquad \boldsymbol{f}_m=\delta_{ST}\frac{\partial\gamma}{\partial T}\nabla_s \mathrm{T}$$

CSF method [Brackbil et al., 1992] is applied with $\delta_{ST}=\partial\mathcal{H}_{ST}/\partial\psi_{ST}$

Hysing, International Journal for Numerical Methods in Fluids, 51:659-672, 2005.
Khalloufi, Mesri, Valette, Massoni, Hachem, Computer Methods in Applied Mechanics and Engineering, 307: 44-67, 2016.
Brackbill, Kothe, Zemach, Journal of Computational Physics 100 (1992) 335–354

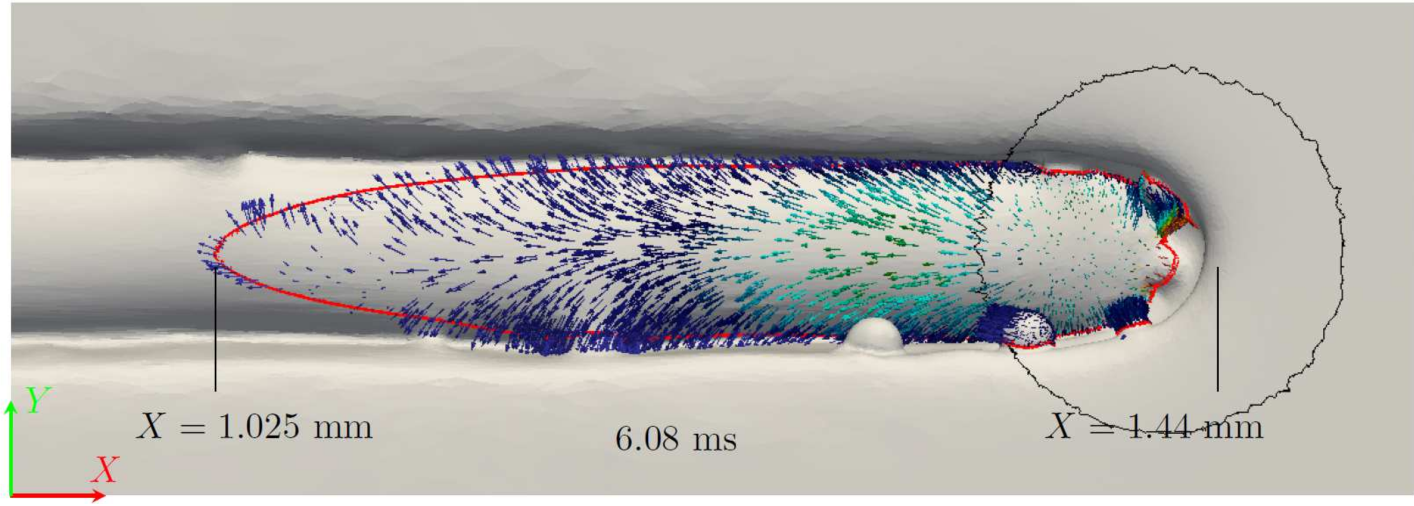
Meso-scale: fluid flow

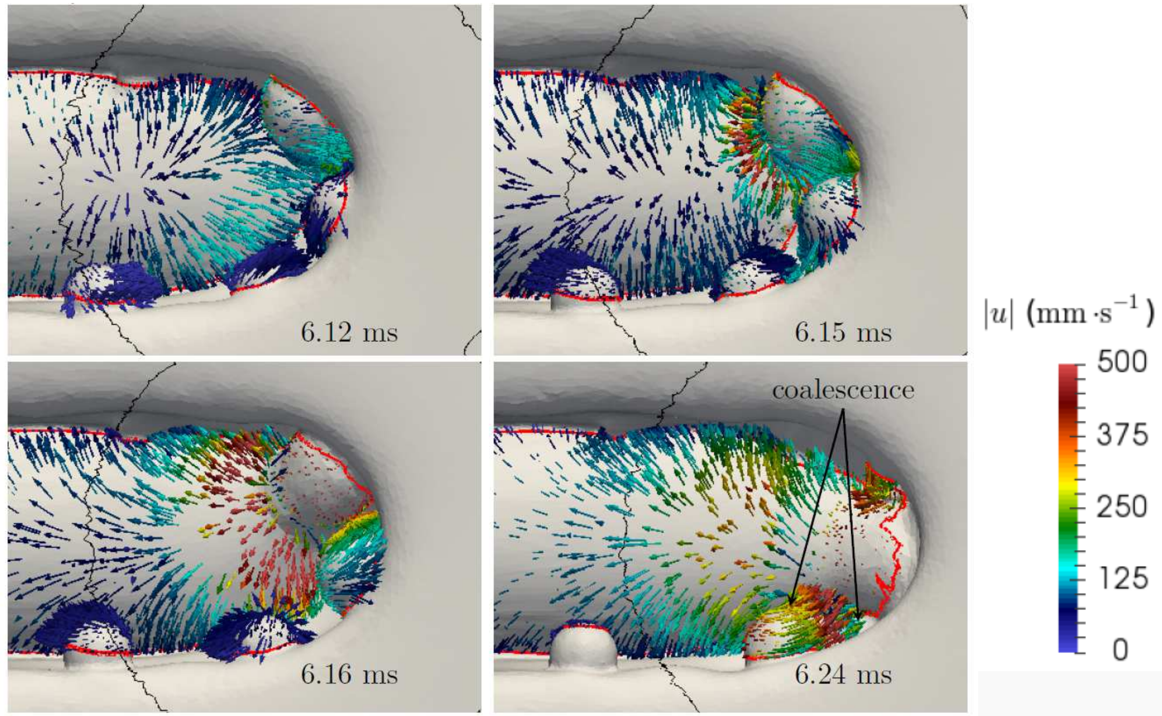
- **Heat transfer solver:** fusion, solidification, non-linear (latent heat)…
- **Navier-Stokes solver:** stabilized, surface tension, Marangoni…
- **Coupling of both:** convection effects

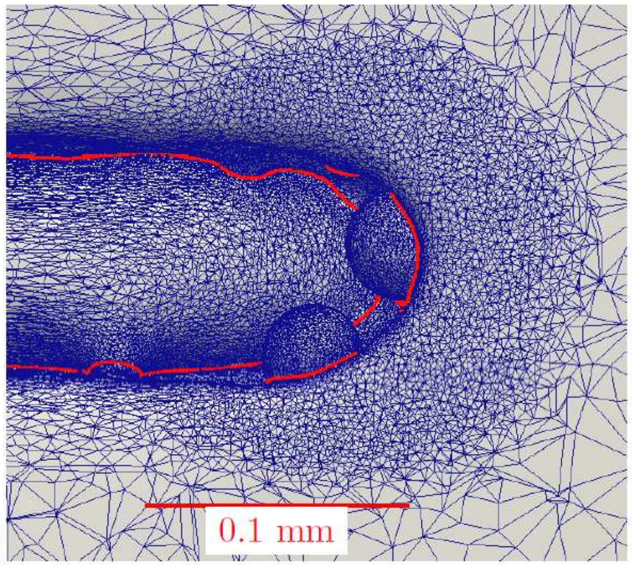


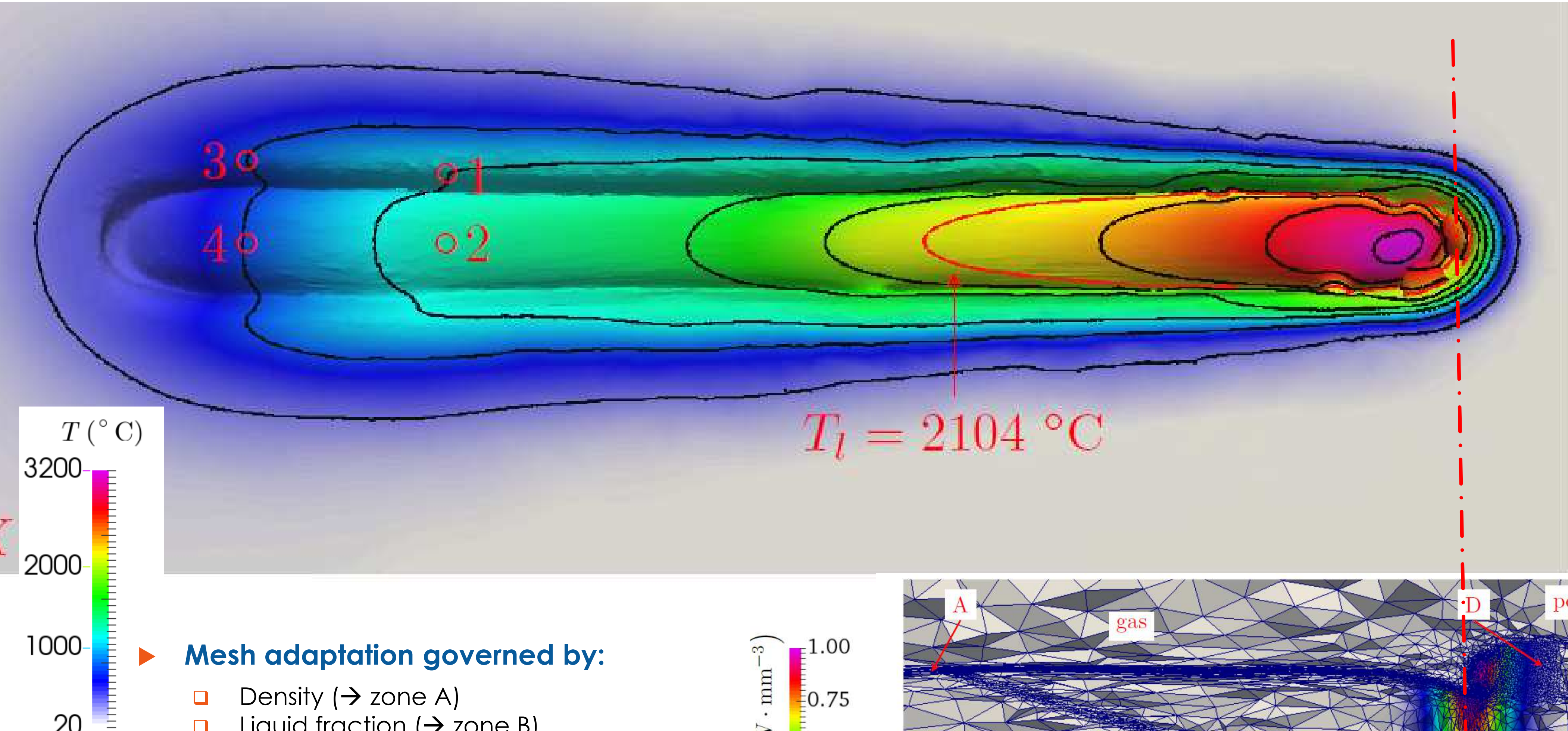
Fluid flow

- **Heat transfer solver:**
  fusion, solidification, non-linear (latent heat)…
- **Navier-Stokes solver:**
  stabilized, surface tension, Marangoni…
- **Coupling of both:**
  convection effects

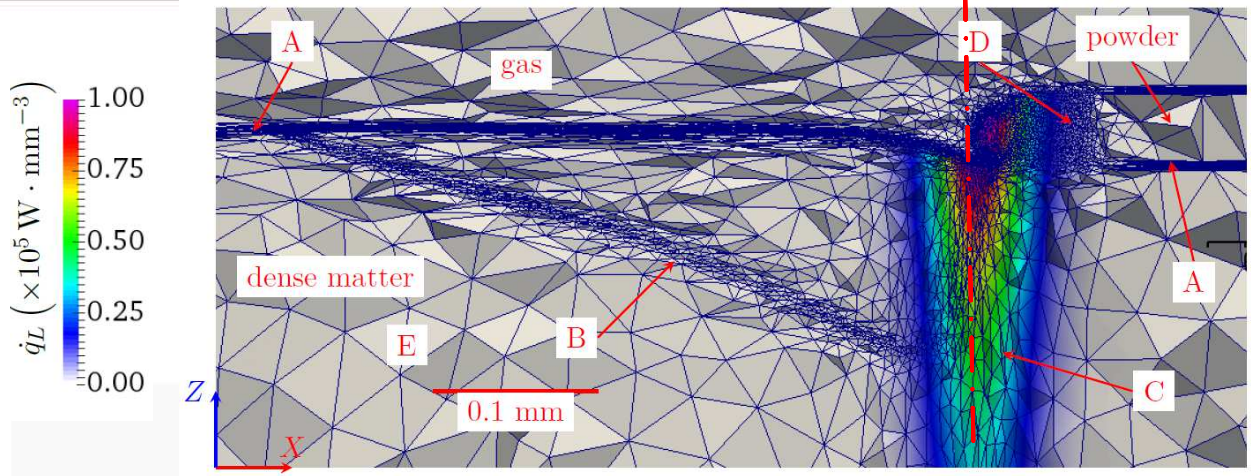








- **Mesh adaptation governed by:**
  - Density (→ zone A)
  - Liquid fraction (→ zone B)
  - Heat source (→ zone C)
  - Background mesh size : 50 µm



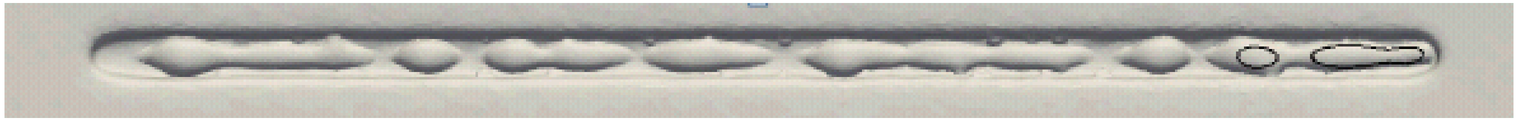
Thermal analysis and mesh

Meso-scale: balling effect

- **Destabilization of the liquid bead by increasing the speed of the laser**

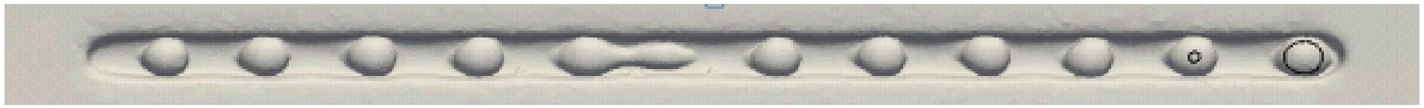
$P_L = 84\ \mathrm{W}$

V550

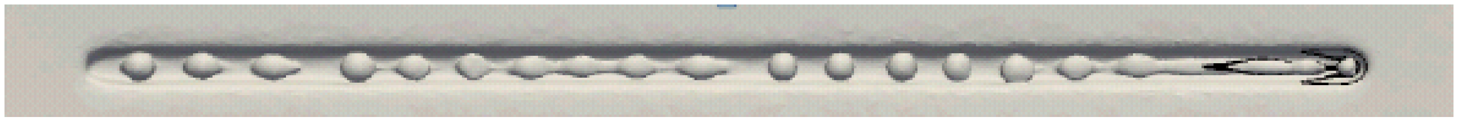


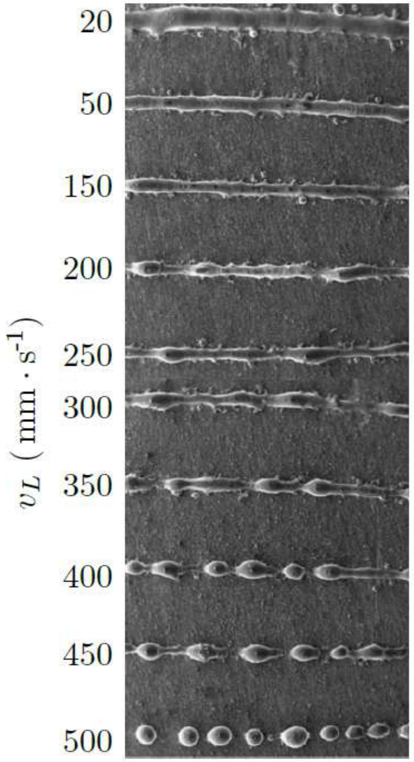
Black contour=
temperature at the end
of solidification
($T = 2004\ °\mathrm{C}$)

V600



V800





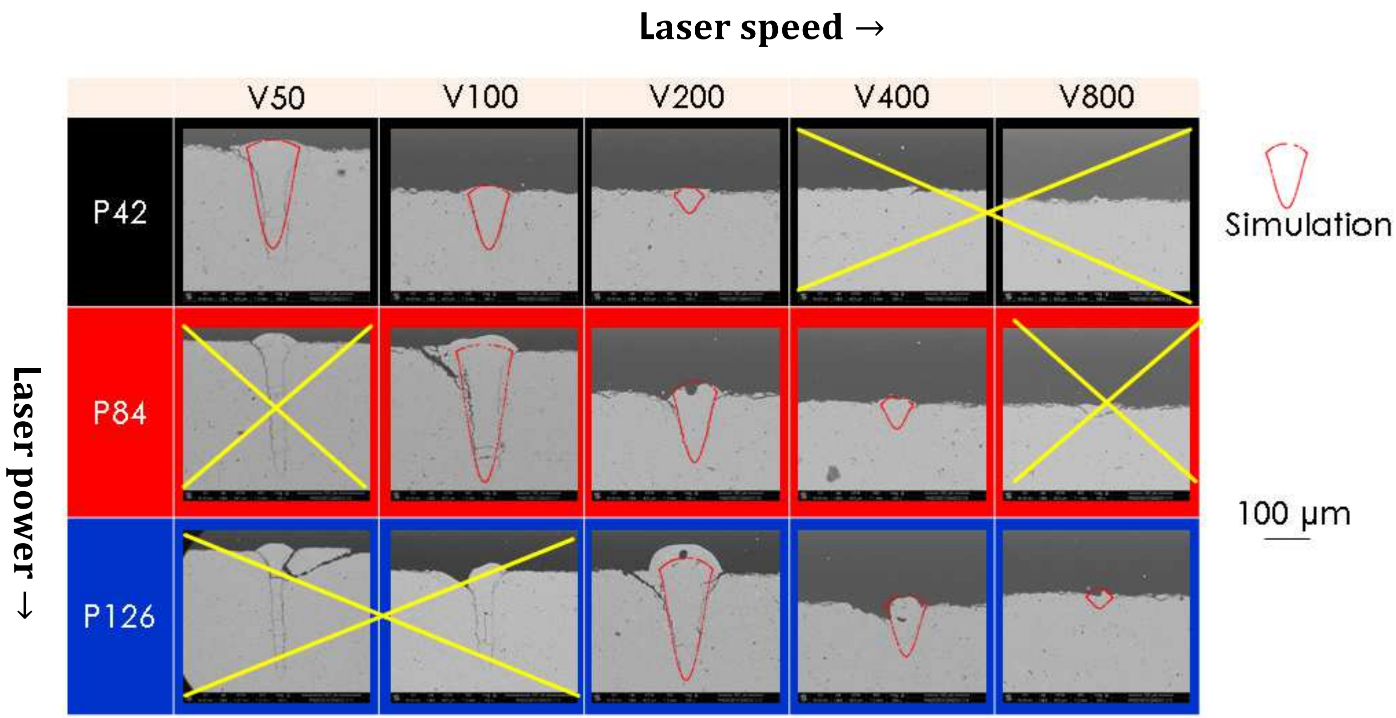
Balling effect (316L stainless steel)

Li et al., Balling behavior of stainless steel and nickel powder during SLM, Int J Adv Manuf Tech 59 (2012)

Meso-scale: track shape

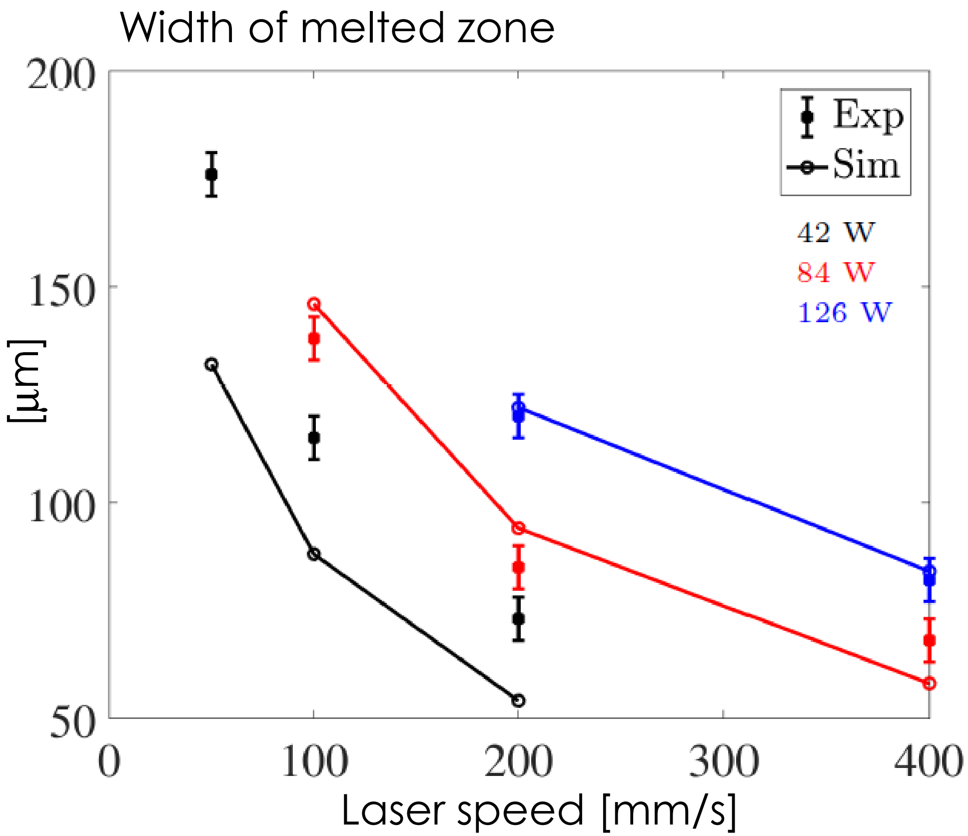
- **Simulation vs Experimental**
- **PhD of Liliana Moniz, Centre des Matériaux, MINES ParisTech, Evry**

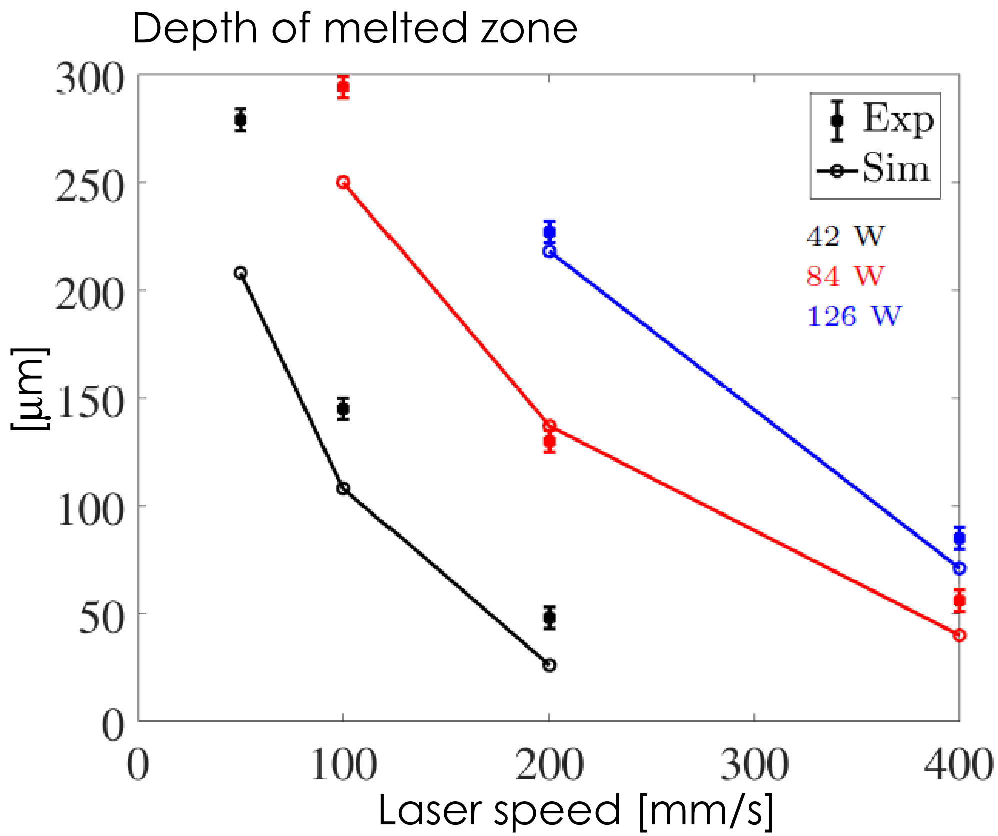
- Alumina powder $D_V(50) = 14.9$ µm doped with 1% carbon (in mass)
- Undoped quasi-dense alumina substrate
- Layer thickness: 50 µm
- Porosity of powder bed: 60%
- Laser Yb:YAG, $\lambda_L = 1070$ nm, $P_L = 168$ W max



Validation - form of melted zone: simulation vs experiment

- **Calibration of 3 parameters: R_{int}, α_s et α_l and applied simulations**



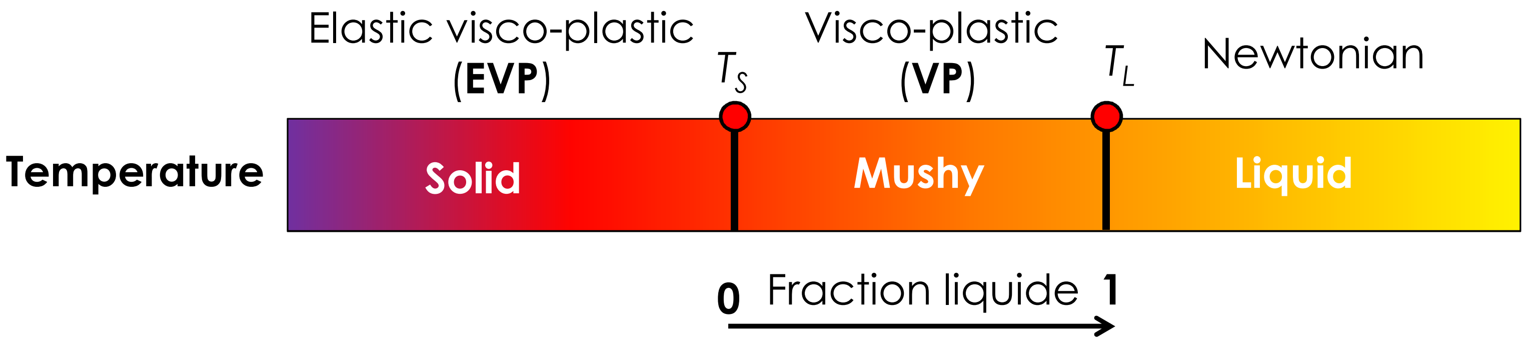


Mechanical solver: meso- and macro-scale models

- **Equilibrium equation:**

$$\nabla \cdot \underline{\underline{\boldsymbol{\sigma}}} + \rho \boldsymbol{g} = \boldsymbol{0}$$

- **State and constitutive model:**
  - **Constructed part:**



- **EVP**

$$\dot{\underline{\underline{\boldsymbol{\epsilon}}}} = \dot{\underline{\underline{\boldsymbol{\epsilon}}}}^{el} + \dot{\underline{\underline{\boldsymbol{\epsilon}}}}^{vp} + \dot{\underline{\underline{\boldsymbol{\epsilon}}}}^{th}$$

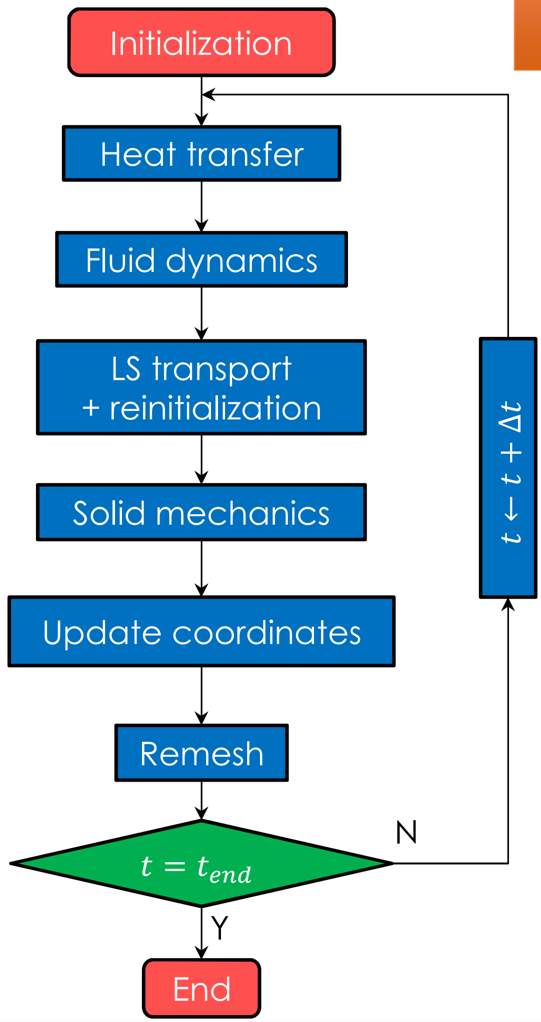
$$\bar{\sigma} = \sigma_Y + K\left(\sqrt{3}\right)^{m+1} \bar{\epsilon}^{n} \dot{\bar{\epsilon}}^{m}$$

- **VP**

$$\dot{\underline{\underline{\boldsymbol{\epsilon}}}} = \dot{\underline{\underline{\boldsymbol{\epsilon}}}}^{vp} + \dot{\underline{\underline{\boldsymbol{\epsilon}}}}^{th}$$

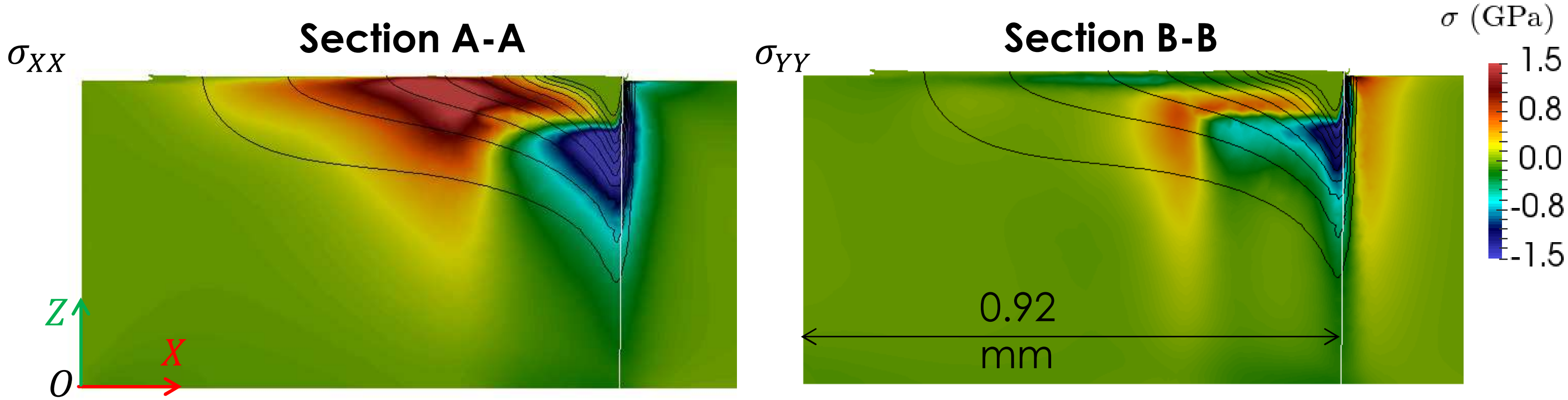
$$\bar{\sigma} = K\left(\sqrt{3}\right)^{m+1} \dot{\bar{\epsilon}}^{m}$$

  - **Non-melted powder and gas**: Newtonian



Meso-scale: hot stress during the process

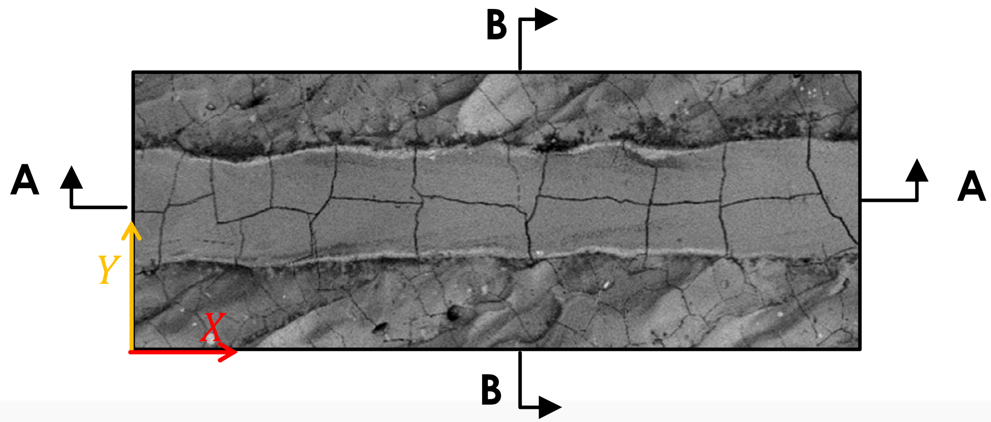
$P_L = 84\ \mathrm{W}$ $\quad v_L = 200\ \mathrm{mm \cdot s^{-1}}$



$t = 3.6\ \mathrm{ms}$

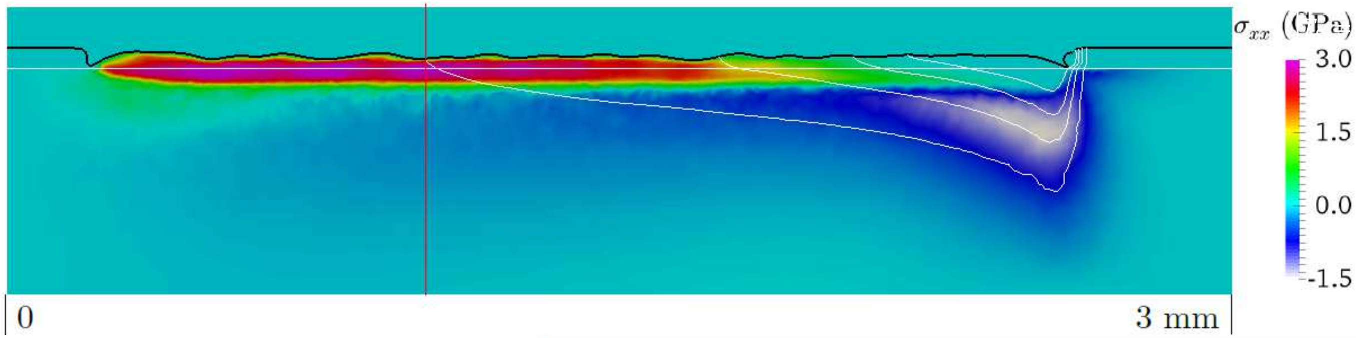
Iso-contours: $T = 300{\sim}2100\ °\mathrm{C}$ with $\Delta T = 200\ °\mathrm{C}$

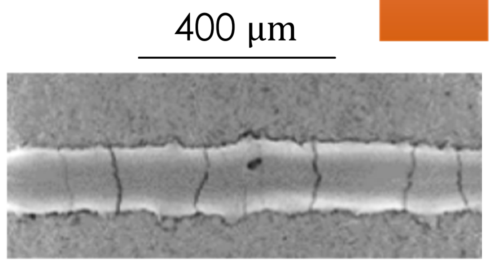
Experimental observation (top view)



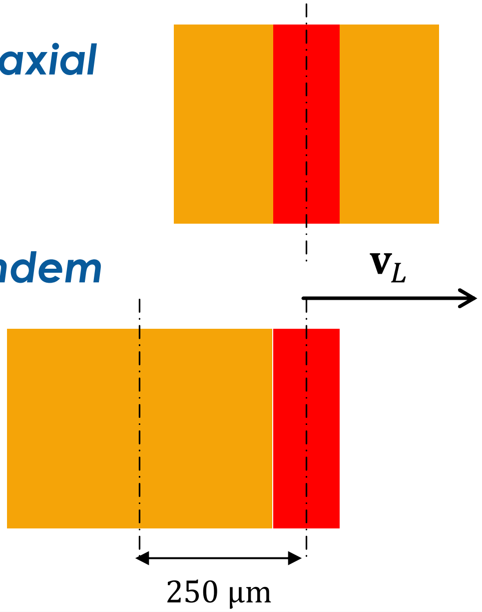
Effect of auxiliary heating

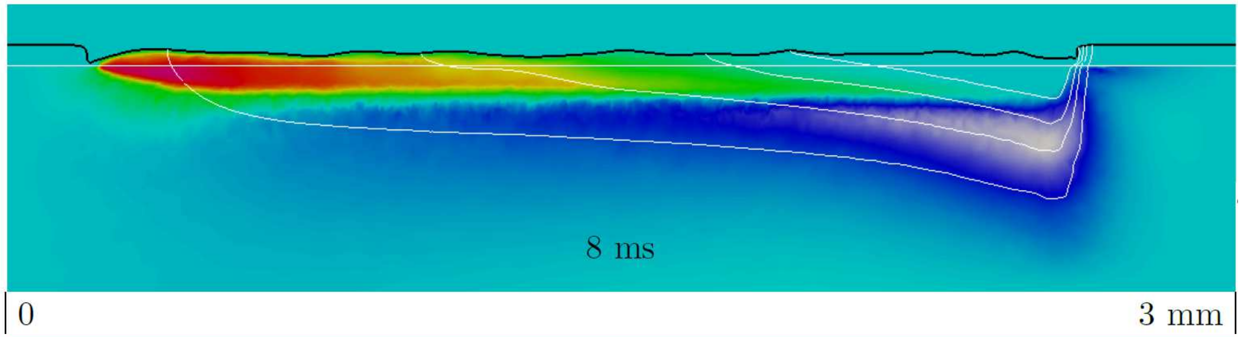
- *Single laser*

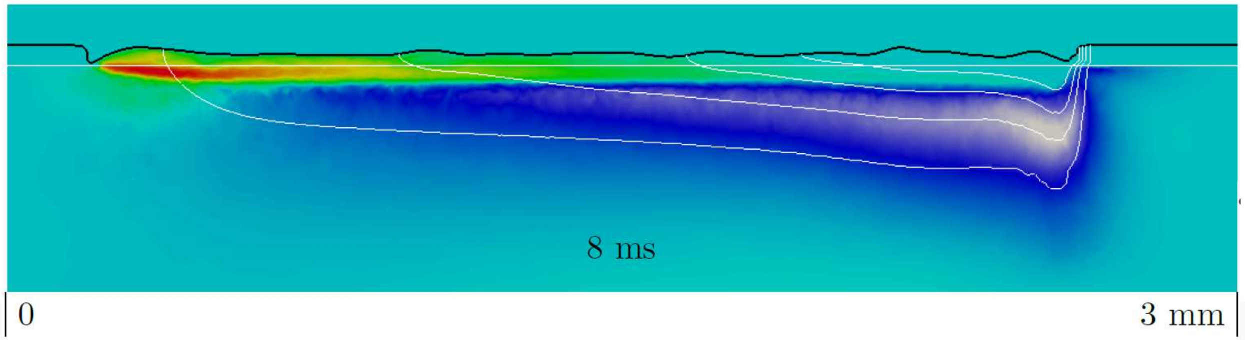




- *2 lasers, coaxial*
- *2 lasers, tandem*







Axial stress $\boldsymbol{\sigma}_{xx}$

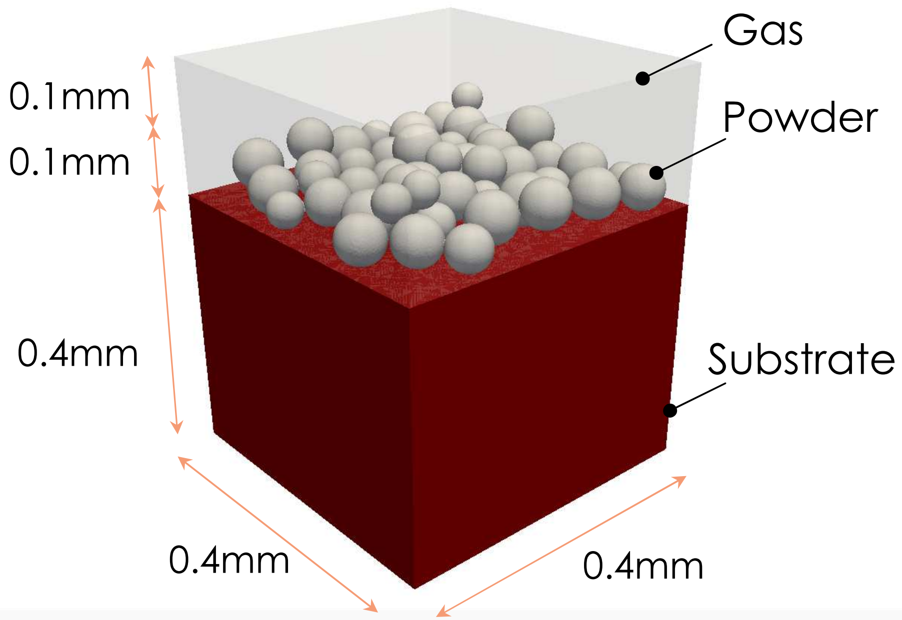
Micro-scale model: explicit particles of powder

- **Master thesis: Yuwei SHAN (co-supersion), SPEIT, Shanghai Jiaotong University.**

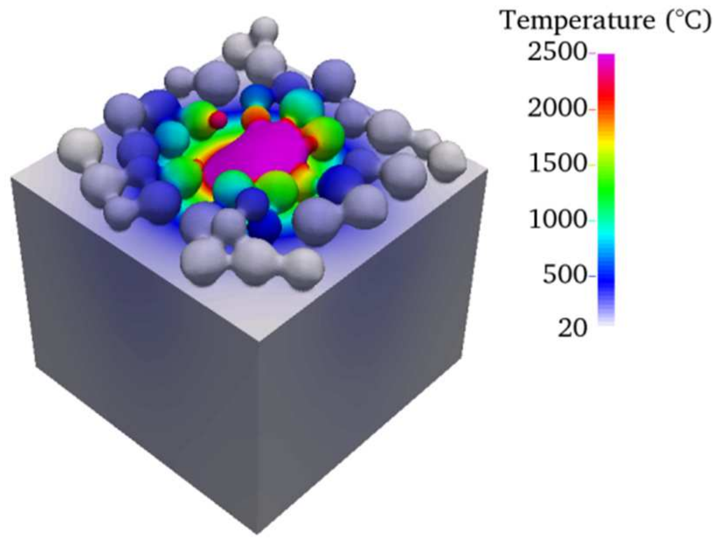
Supervisors: CEMEF: Yancheng ZHANG and Michel BELLET
SPEIT: Jin YU and lingxuan SHAO

The aim is to study the melting and coalesce of the particles by both experimental and simulation aspects:

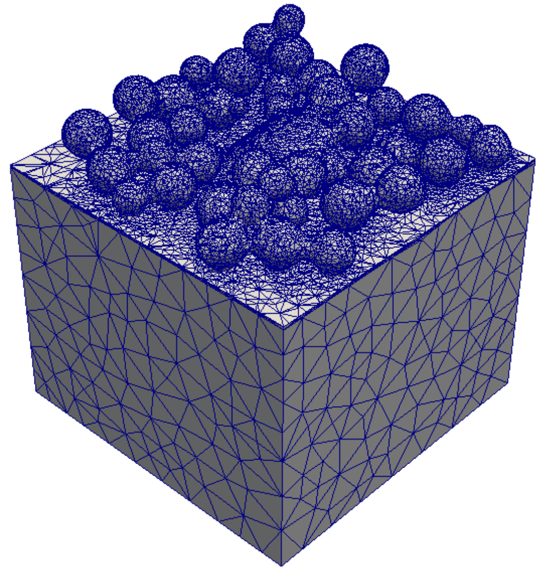
- Predict the porosity of the constructed part due to ineffcient laser power
- Validate the selected the model of heat source (**Beer-Lambert law** at the first step).



Simulation system



Preliminary simulation results
(Fixed heat source)

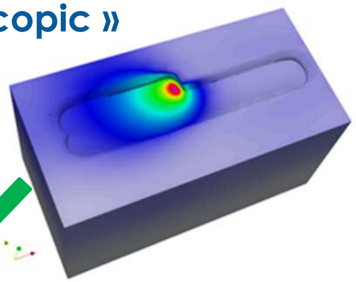


Mesh adaptation

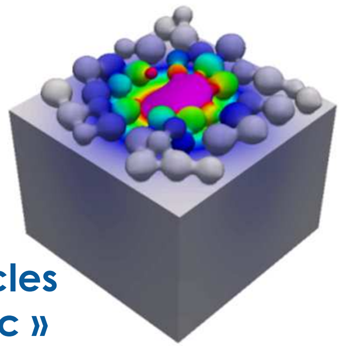
Modelling strategy for scale selection

- **Calculation in 28 cores with cluster**

Track scale – Continuous powder bed « mesoscopic »



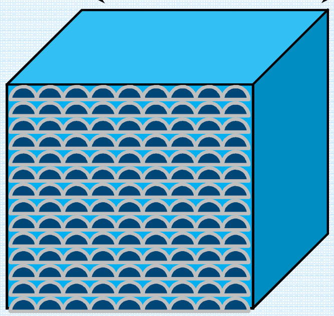
Comp. time:
1300 day/m
(~**30** h / mm)



Comp. time:
15000 day/m
(~**15** day / mm)

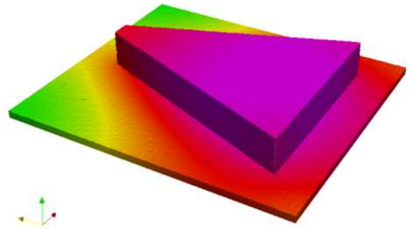
Powder particles « microscopic »

Cube:
3 cm



Laser diameter: 100 µm
Hatch distance: 100 µm
Layer thickness: 100 µm
Laser length: **2.7 km**

Part scale « macroscopic »



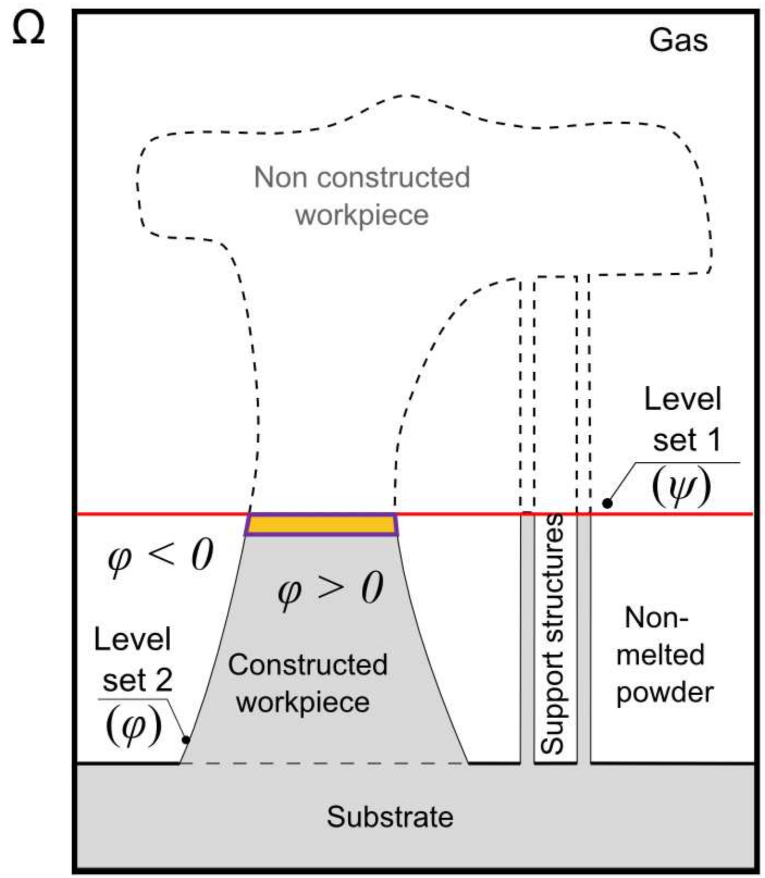
Comp. time:
Fraction of layer: **0.05** day/m
Layer by layer: $0.05/n_f$ day/m
Super layer: $0.05/n_f/n_l$ day/m

n_f: number of fraction
n_l: number of layer

Mesoscopic : [Che18] Q. Chen, G. Guillemot, Ch.A. Gandin, M. Bellet, Numerical modelling of the impact of energy distribution and Marangoni surface tension on track shape in SLM of ceramic material, Add. Manuf. 21 (2018), 713-723 **Macroscopic :** [**Zha18**] Y. Zhang, G. Guillemot, M. Bernacki, M. Bellet, Macroscopic thermal finite element modeling of AM manufacturing by SLM process, Comp. Met. App. Mech. Eng. 331 (2018) 514-535

Macro-scale modeling: in part level

- **Works of Yancheng Zhang**
- **Principles of the construction**
  - Starting point: **CAD** of **the part** to be built, completed by **the substrate** and the possible **supports**.
  - Mesh of this **CAD.**
  - Take a **background mesh** Ω and immerse the previous **CAD** mesh into it.
  - Construct the conforme mesh at interfaces:
    - material / gas
    - constructed part/ non-exposed powder
  - Over time, the **level set** ψ is updated progressively through the mesh to simulate the material deposition **layer by layer** or **fraction of layer**
  - Resolve the **thermal** and **mechanical** problems in each time steps:
    - in the part under construction…
    - … but also in the non-exposed powder



Schematic of Level Set

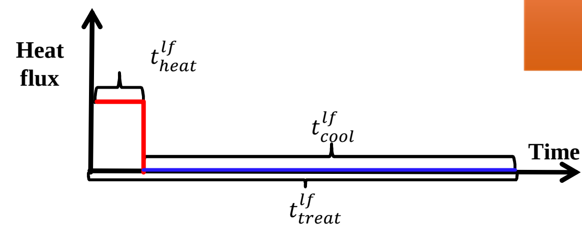
Zhang, **Guillemot**, **Bernacki**, **Bellet**, Macroscopic thermal finite element modeling of additive metal manufacturing by selective laser melting process, **Comp. Meth. Appl. Mech. Eng. (2018)**

Thermal solver: macro-scale model

- **Heat transfer:**

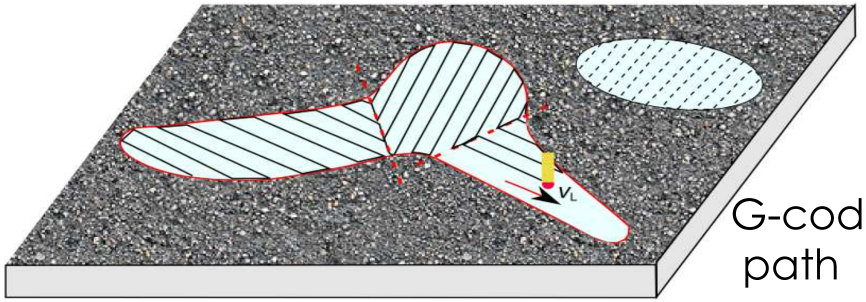
$$\frac{\partial\{\rho C\}}{\partial t} - \nabla\cdot(\lambda\nabla T) = \dot{q}_L$$

ρC and λ are element-wise mixed properties

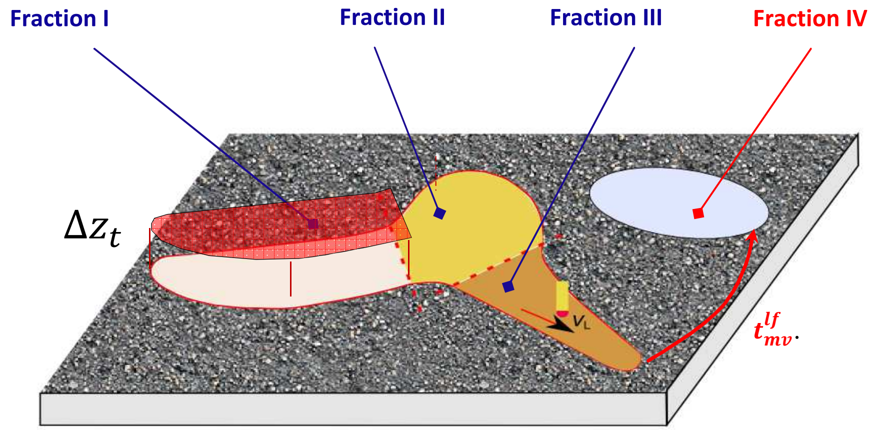


Decomposition of the time interval

- **Heat flux approximation for the fractions: $\dot{q}_L$**



G-code path

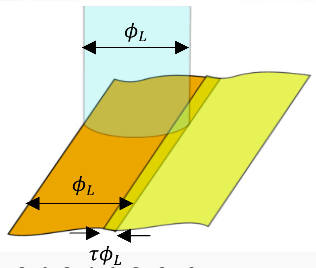


- Energy balance: surface heat source

$$(1-R)P_L t^{lf}_{scan} = S^{lf}\ \dot{q}^s_L t^{lf}_{heat}$$

- Homogeneous volume heat source

$$\dot{q}_L = \frac{\dot{q}^s_L}{\Delta z_t} = \frac{P_L(1-R)}{S^{lf}\Delta z_t}\frac{t^{lf}_{scan}}{t^{lf}_{heat}}$$



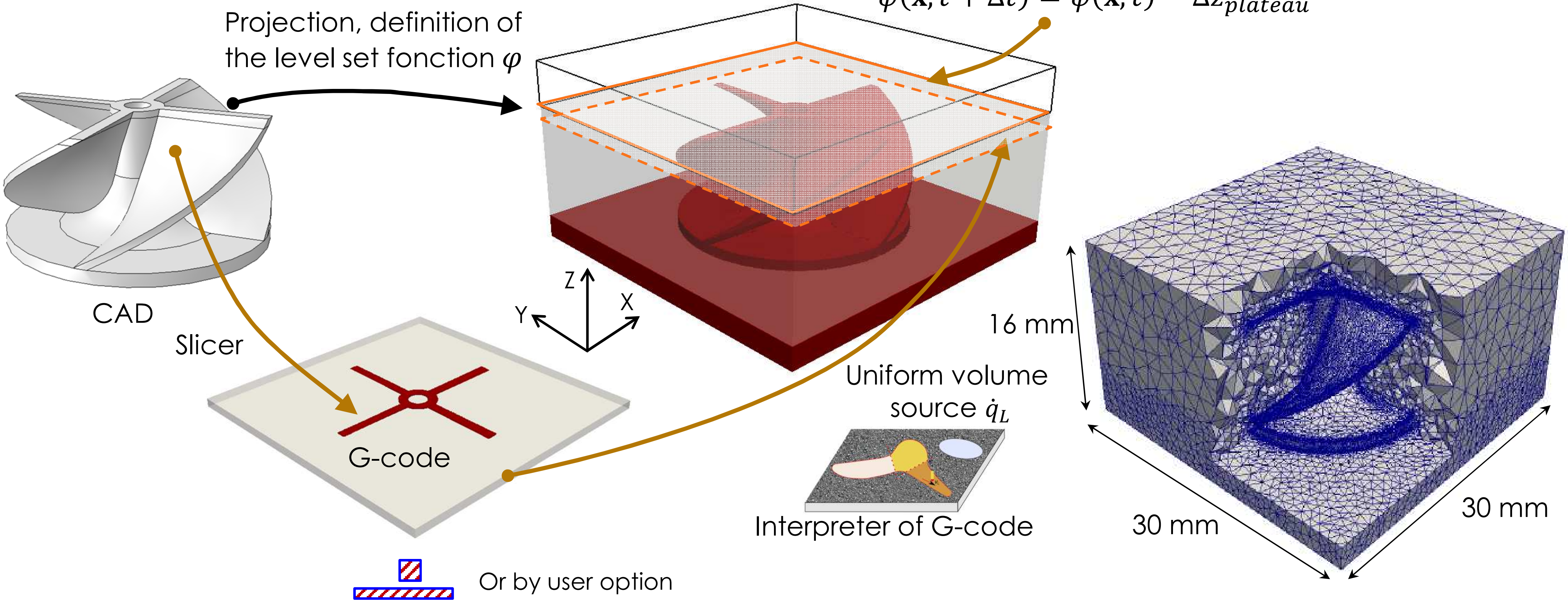
Laser scan intersection

Macro-scale modeling: application sample

- **In718 part**

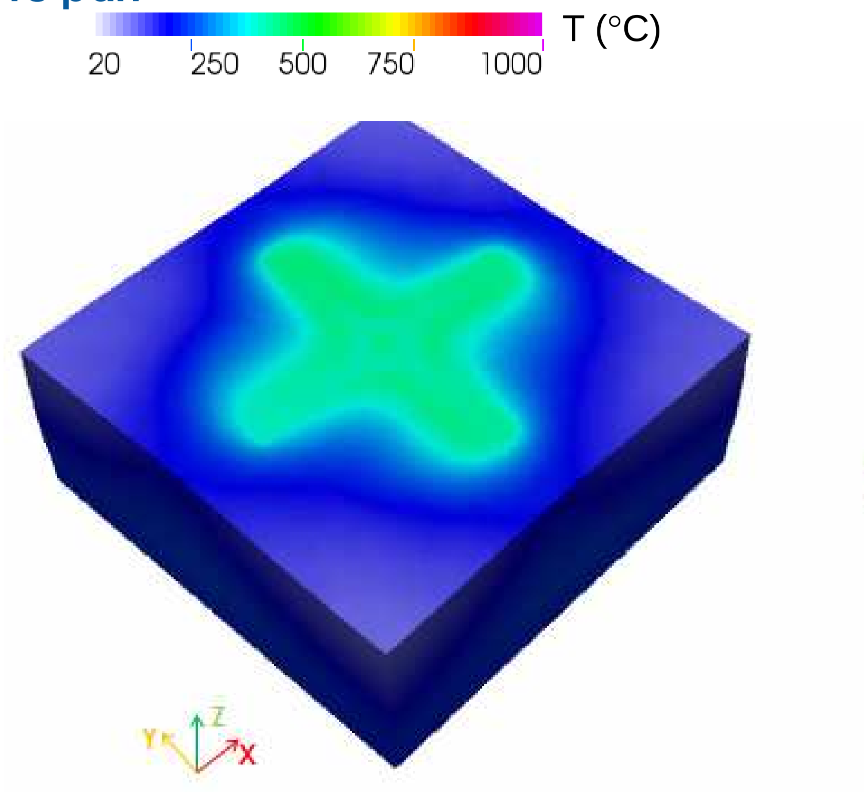
Update the construction level set fonction:

$$\psi(\mathbf{x}, t + \Delta t) = \psi(\mathbf{x}, t) - \Delta z_{plateau}$$

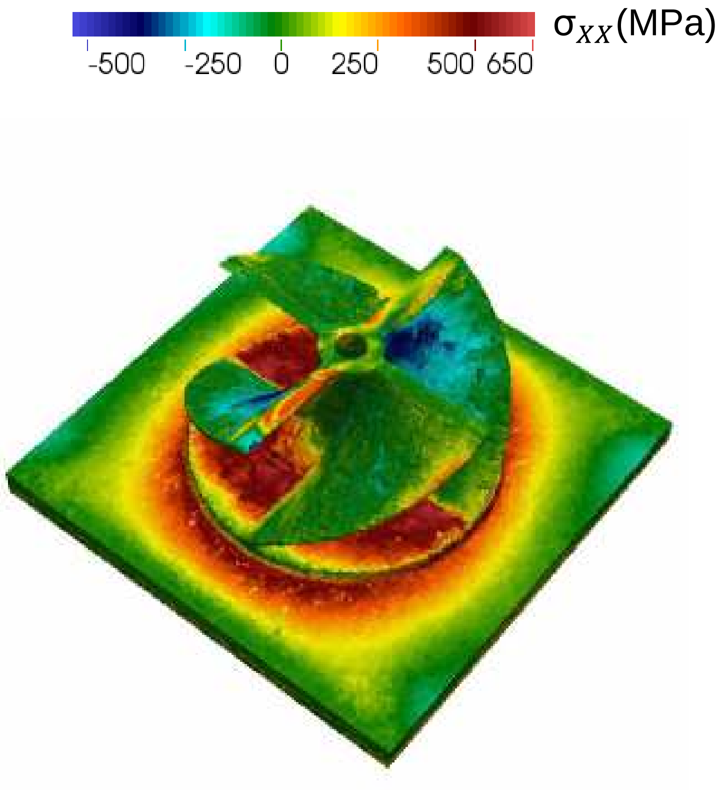


Macro-scale modeling: simulation results

- **In718 part**



Temperature: with non-exposed powder

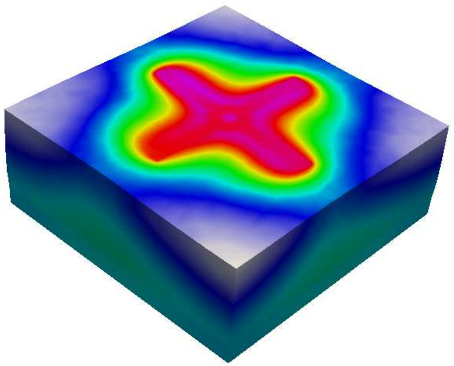


Stress: without non-exposed powder

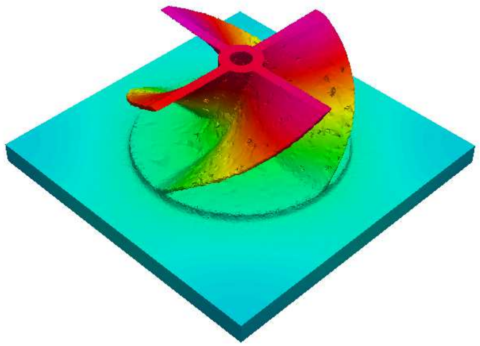
Temperature and stress distribution during the construction process (50 layers)

Macro-scale modeling: simulation results

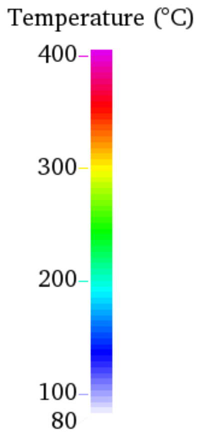
Final construction: temperature



Part + non-exposed powder



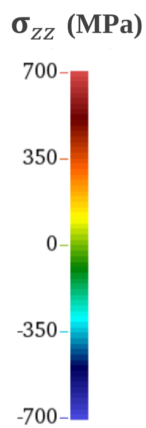
Part



Final construction + 2h: residual stress

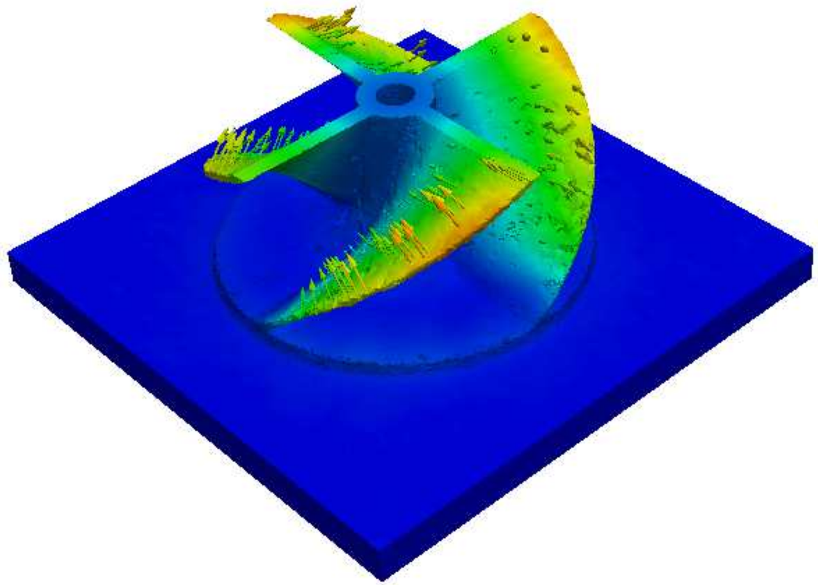
Cool down to room temperature

After removing from the substrate

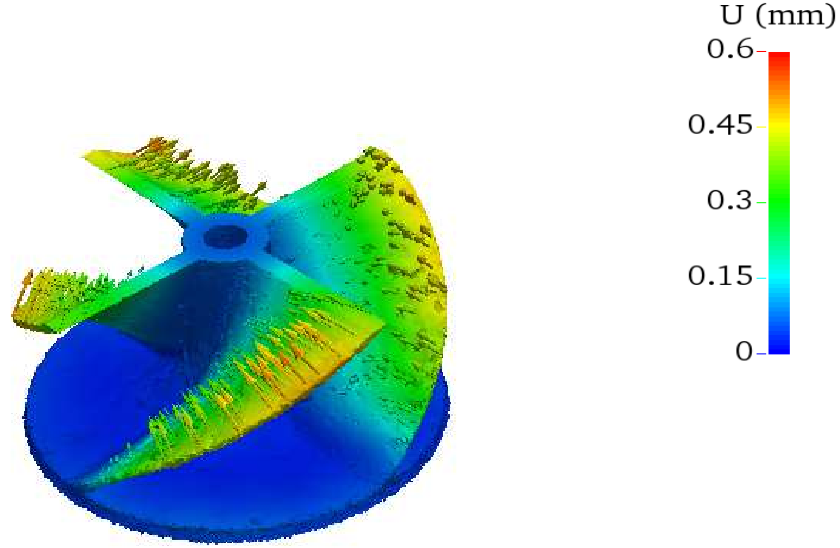


Macro-scale modeling: simulation results

Final construction



$||u||$ in part and substrate



$||u||$ after removing the substrate

SPEIT collab.: bachelor thesis - Jian YANG

- **Macro-scale numerical modeling of SLM process by the super-layer approach**

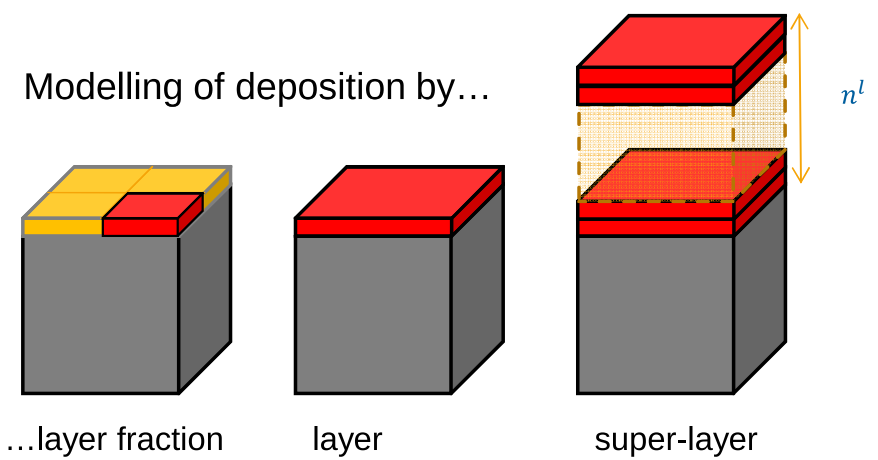
  3-month internship at CEMEF, April - June 2018

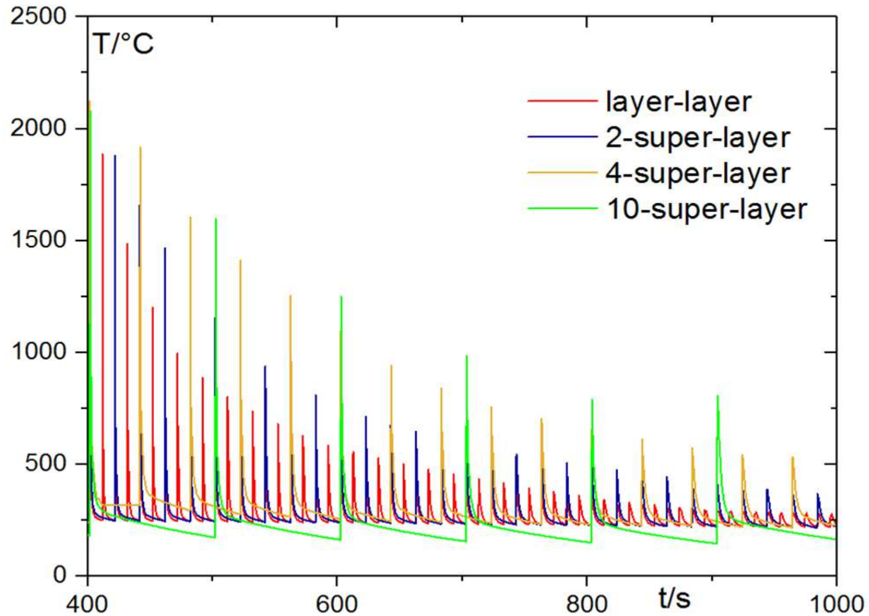
  Supervisors: Yancheng ZHANG and Michel BELLET (**CEMEF**), Shengyi ZHONG (**SPEIT**)

  Experiments in SJTU, Modeling in CEMEF

  - Reduce the calculation time of macroscale calculations
  - Explore the validation domain of super-layer formulation

Second prize for the thesis poster.





SPEIT collab.: bachelor thesis – Constant Prassette

- **Inherent strain rate method for Direct Energy Depostion (DED)**

  3-month internship at CEMEF, April - June 2019

  Supervisors: Yancheng ZHANG and Michel BELLET (**CEMEF**), Guanghua WEI(**SPEIT**)
  - Implementation of Inherent strain rate in **CIMLIB®**
  - Application to the process of DED

Implementation of inherent strain rate

Definition of inherent strain rate:

$$\dot{\boldsymbol{\epsilon}} = \dot{\boldsymbol{\epsilon}}^{\mathbf{el}} + \dot{\boldsymbol{\epsilon}}^{\mathbf{vp}} + \dot{\boldsymbol{\epsilon}}^{\mathbf{th}}$$

$$\dot{\boldsymbol{\epsilon}}^{*} = \dot{\boldsymbol{\epsilon}}^{\mathbf{vp}} = \dot{\boldsymbol{\epsilon}} - \dot{\boldsymbol{\epsilon}}^{\mathbf{el}} - \dot{\boldsymbol{\epsilon}}^{\mathbf{th}}$$

Equations of equilibrium and mass conservation:

$$\begin{cases} \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g} = 0 \\ \nabla . u = tr\dot{\boldsymbol{\epsilon}}^{\mathbf{el}} + tr\,\dot{\boldsymbol{\epsilon}}^{*} + tr\,\dot{\boldsymbol{\epsilon}}^{\mathbf{th}} = -\frac{\dot{p}}{x} - 3\alpha(T)\dot{T} = 0 \end{cases}$$

$$tr\,\dot{\boldsymbol{\epsilon}}^{*} = 0$$

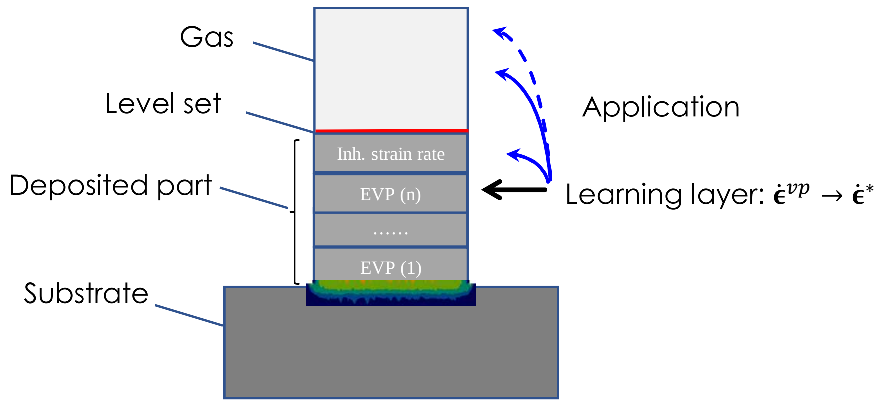
Adaptation to the process of DED

Problems:

- EVP calculation
- $\dot{\boldsymbol{\epsilon}}^{vp}(\dot{\boldsymbol{\epsilon}}^{*})$ on substrate

Resolutions:

- Full calculations in first few layers
- Extraction ($\dot{\boldsymbol{\epsilon}}^{*} = \dot{\boldsymbol{\epsilon}}^{vp}$) and application after learning layer

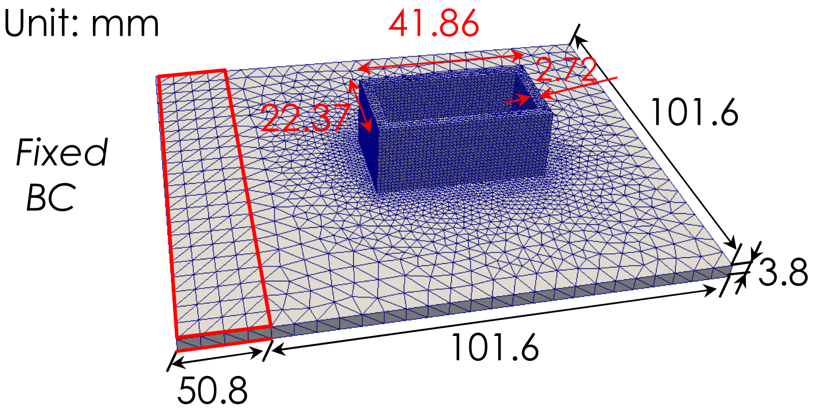


Inherent strain rate model

SPEIT collab.: bachelor thesis – Constant Prassette

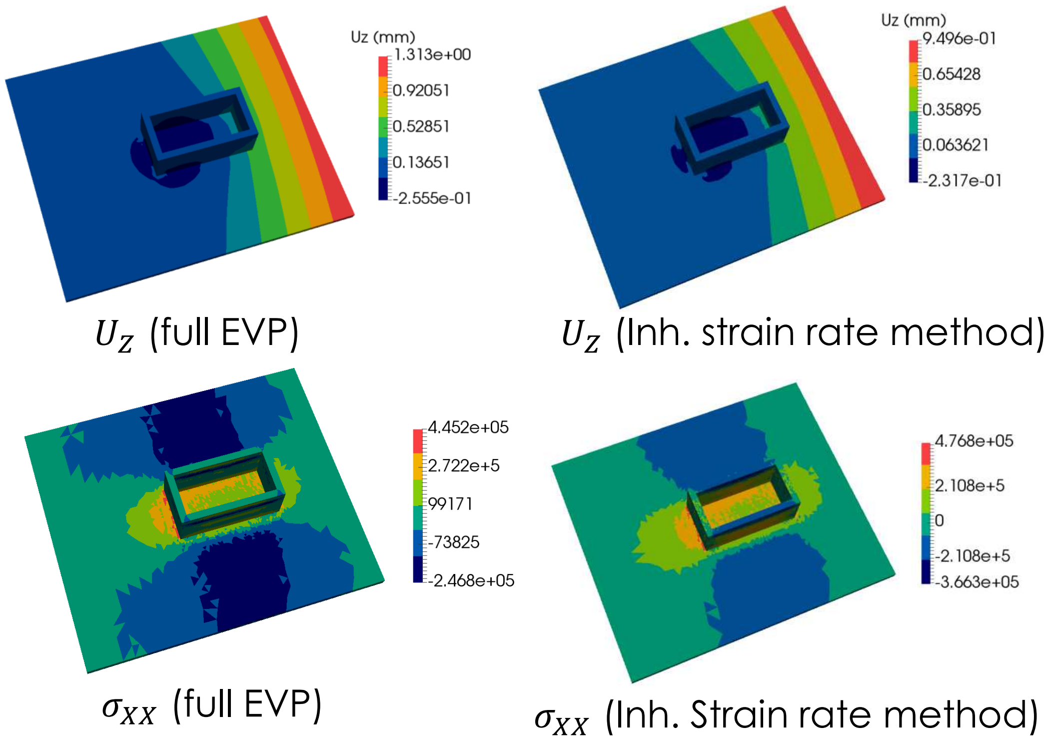
- Application to the process of DED

Simulation system: 20 layers
-Number of element 108801
-Number of node 23829



Simulation strategy:
10 EVP→ Inh. strain rate → 10 Inh. strain rate

Simulation time:
-Complete calculation: 1h48
-Inherent strain : 1h25



Comparison of final distortion and residual stress for 20 layers deposition

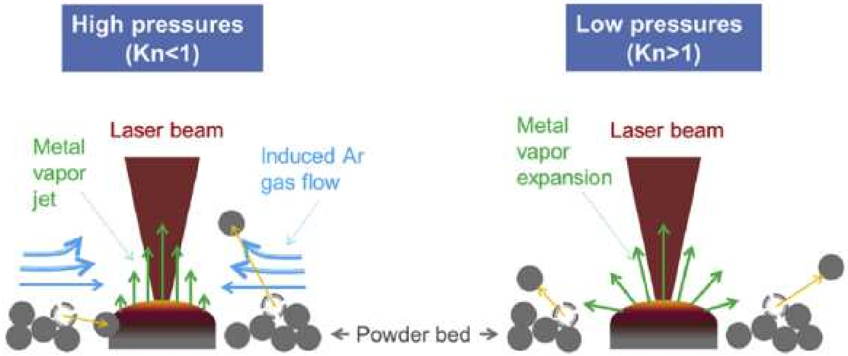
Final conclusions:

The thermo-mechanical analysis is performed for the **micro**-, **meso**- and **macro**-scale models under the **level-set** framework with **finite element** method:

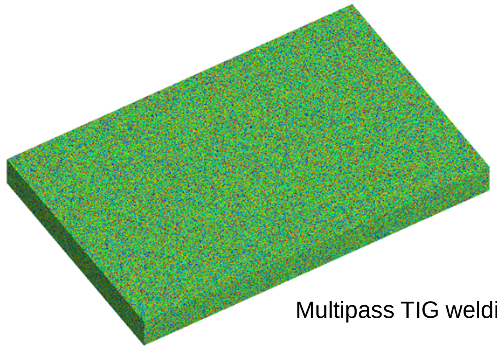
	Micro-scale	**Meso-scale**	**Macro-scale**
Temperature	Melt pool, or track	Melt pool and Track	Whole part
Non-melted powder	Yes	Yes	Yes
Melt pool dynamics+shape	Yes		-
Mesh adaptation	Error estimation	Error estimation – total element number control	User defined – size control
Stress	Hot stress	Hot stress	Hot stress+ Residual stress
Distorsion	-	-	Yes
Complex geometry	-	-	Yes

Small scale approaches: ongoing and future work

- **Hot tearing prediction**
- **Vaporization phenomena**
  - Impact on the shape of the fusion zone : recoil pressure, keyhole effect
  - Denudation process
- **Multitrack deposition**
  - Application to lattice structure details
- **Microstructure formation**
  - Modelling grain growth using CA-FE formulation (C.-A. Gandin and G. Guillemot at CEMEF)
- **Particle scale modelling**



Matthews et al., Acta Materialia (2016)

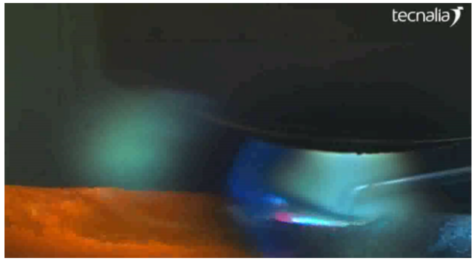


Multipass TIG welding (GTAW)

Chen, Guillemot, Gandin, Three-dimensional cellular automaton-finite element modeling of solidification grain structures for arc-welding processes, **Acta Materialia (2016)**

Macro-scale: ongoing and future work

- **Interactions between the different scales**
- **Meso or particle scale → macroscale**
  - Inherent strain method, to make faster macroscale calculations
  - Superlayer formulation: design, validity
  - Model reduction
- **Macroscale → meso or particle scales**
  - Initialization of small scale calculations

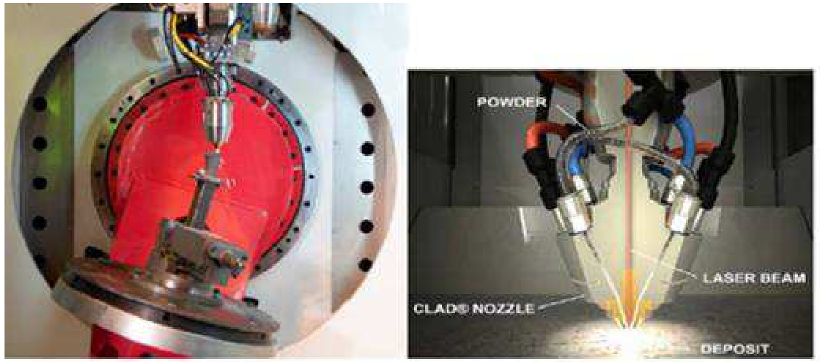


WAAM

… and also, all scales:

- **Extension to other additive manufacturing processes**
  - Wire arc metal additive manufacturing (WAAM)
  - Direct metal deposition (DMD)
  - Electron beam melting
  - …

DMD

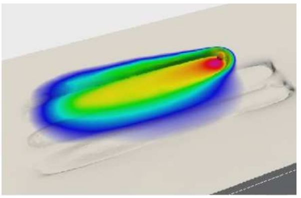


ongoing: Wire Arc Additive Manufacturing

PhD Thesis MACCADAM: L. Ravix (2018 – 2021)

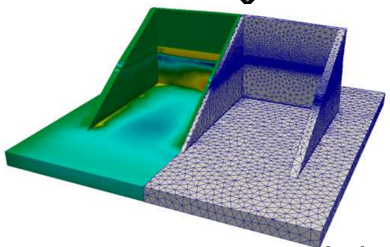
(co-supervised with: G. Guillemot, M. Bellet, Ch.-A. Gandin)

- **Controlled characteristics materials produced by WAAM (316L)**
  - Optimization of process parameters and building strategy
  - Coupling between and meso- and **macro-scale** approaches

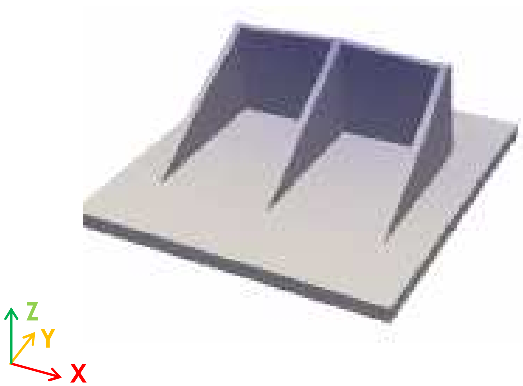


Meso – scale (T)

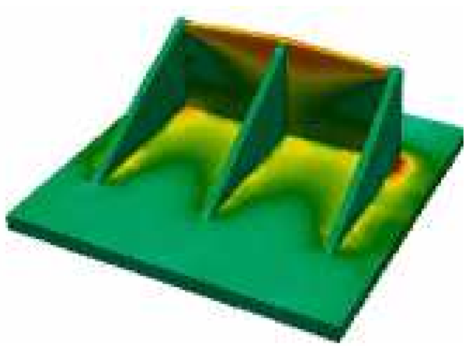
Coupling



Macro – scale (σ)



- Temperature evolution:



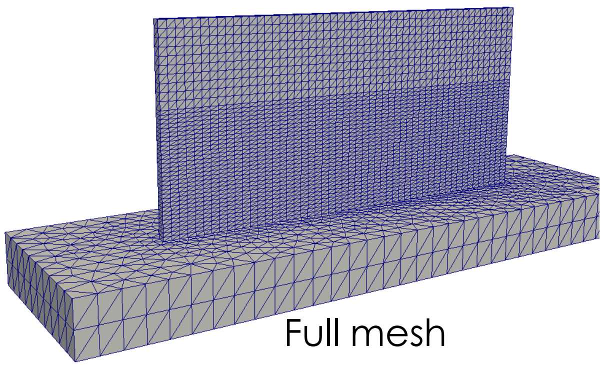
- Stress evolution:

[LMGC]

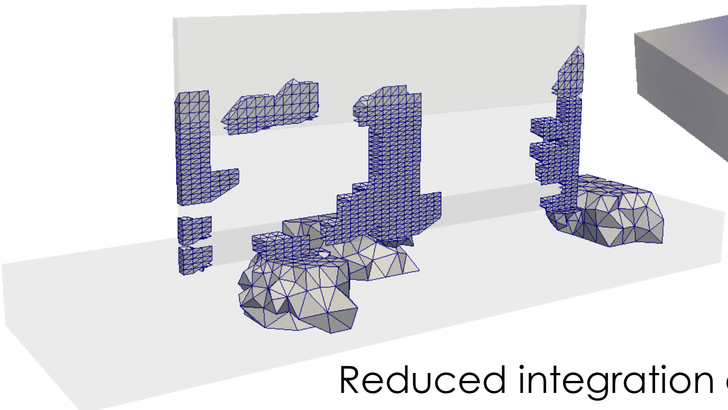
ongoing: model reduction of direct energy deposition

Thesis «Contrats Doctoraux Ecole»: J. Keumo Timatio (2018-2021)

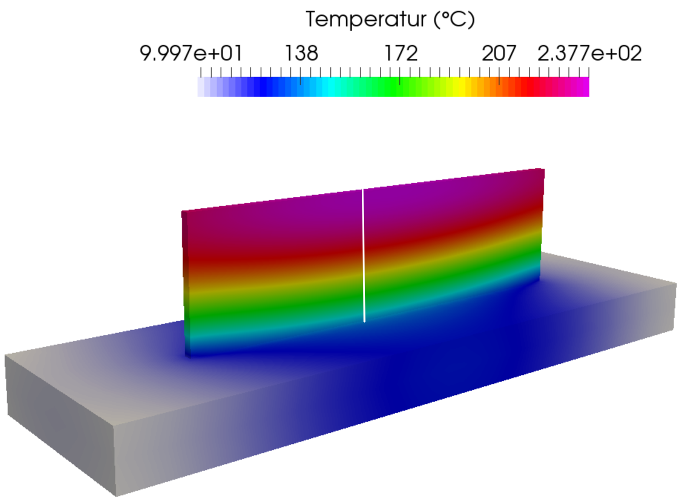
(co-supervisors: M. Bellet and D. Rycklynck)

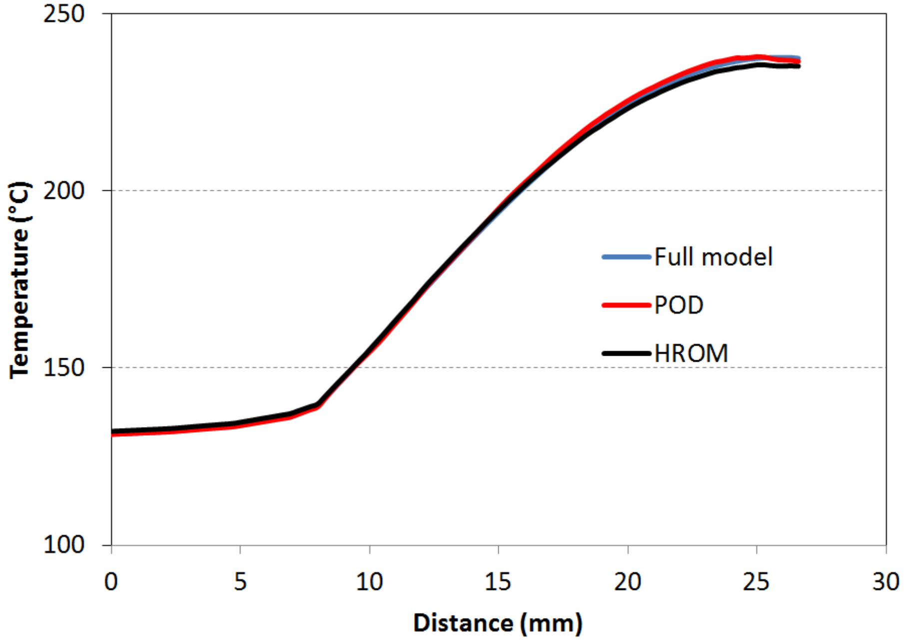


Full mesh



Reduced integration domain (RID)





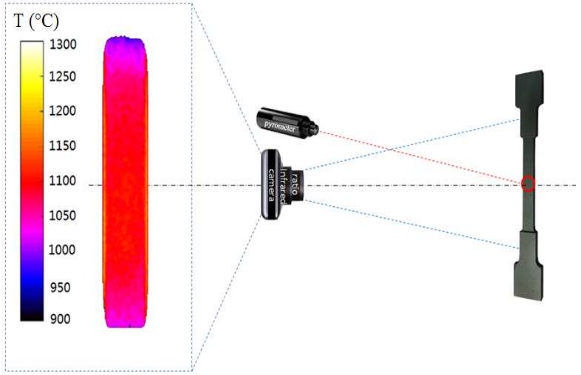
Hyper reduced-order model (316L)

Ongoing: characterization of mechanical behavior in FA condition

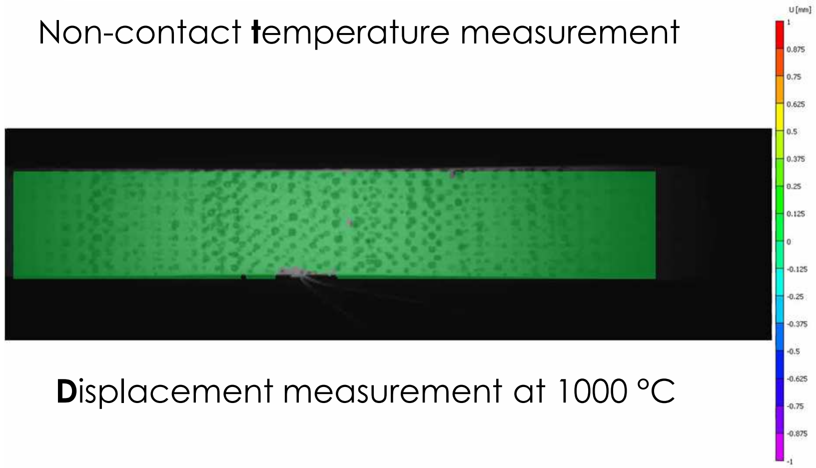
PhD Thesis SAFRAN and CSC: F. Gao (2017-2021)

(co-supervisors: M. Bellet)

- **Determine the material behavior at very high temperature (near fusion)**
- **Machine « Dedimet » developed at CEMEF**
  - Traction /relaxation tests with resistive heating (**Joule effect**), under **vacuum or controlled atmosphere**.
  - Infrared imaging **temperature field** (+ thermocouples, + pyrometers)
  - **Displacement field** by correlation image (laser speckle interferometry)
  - **Coupled electrical/thermal/mechanical modelling**, implemented in CIMLIB®
  - **Identification** by **inverse method**
  - **Characterization** of **anisotropic elasto-viscoplasticity**
  - **Ti-6Al-4V** and **In718** alloys



Non-contact **t**emperature measurement



Displacement measurement at 1000 °C

Dedimet machine

Questions ?

MINES
ParisTech

Cemef
CENTRE DE MISE EN FORME
DES MATERIAUX