Centre de Mise en Forme des Matériaux

Numerical simulation of additive manufacturing processes by Laser Beam Melting : Thermomechanical features

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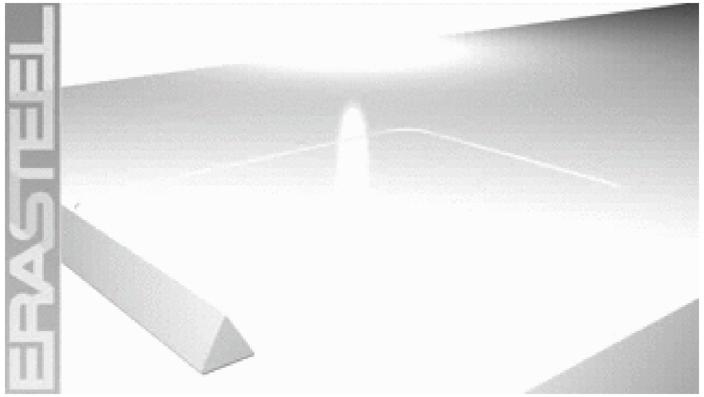
JOURNEE SNS – CFV,
Synergies de Simulation entre Fabrication Additive et Soudage
EDF Laboratoire Paris-Saclay, 26 Juin 2018

Introduction

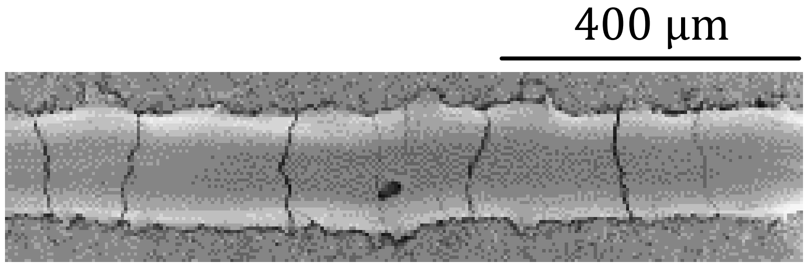
▶ *Laser Beam Melting (LBM)*



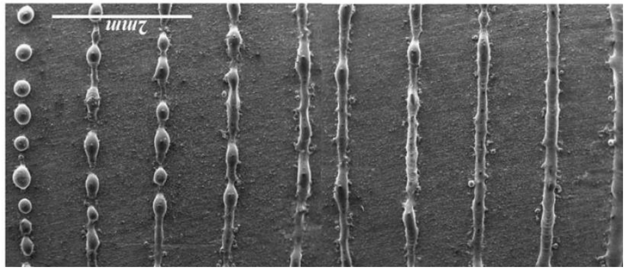
Advantages

- Direct manufacturing of complex shape geometries based on CAO-models pieces
- Decrease of the duration time required in the design to manufacturing cycle
- Limitation of the final stages processes
- Wide range of material for application
  - metallic (Aluminium, Titanium, Nickel, Steel …)
  - ceramic (Alumina / Zirconia)

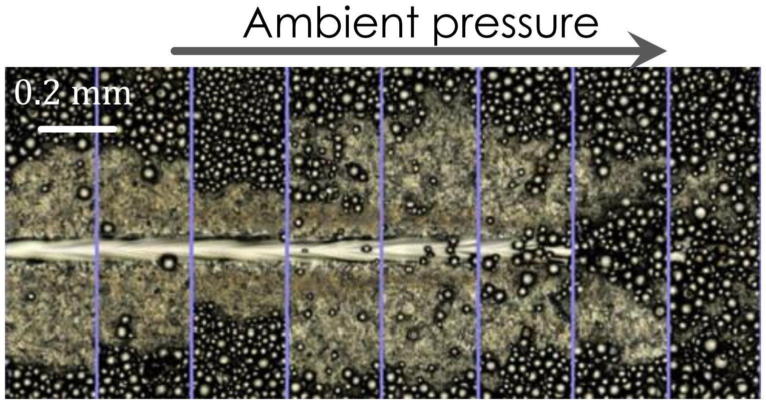
▶ *… with some defects*



Cracks on alumina Al_2O_3
[L. Moniz Da Silva Sancho, CdM, CEFALE Project]

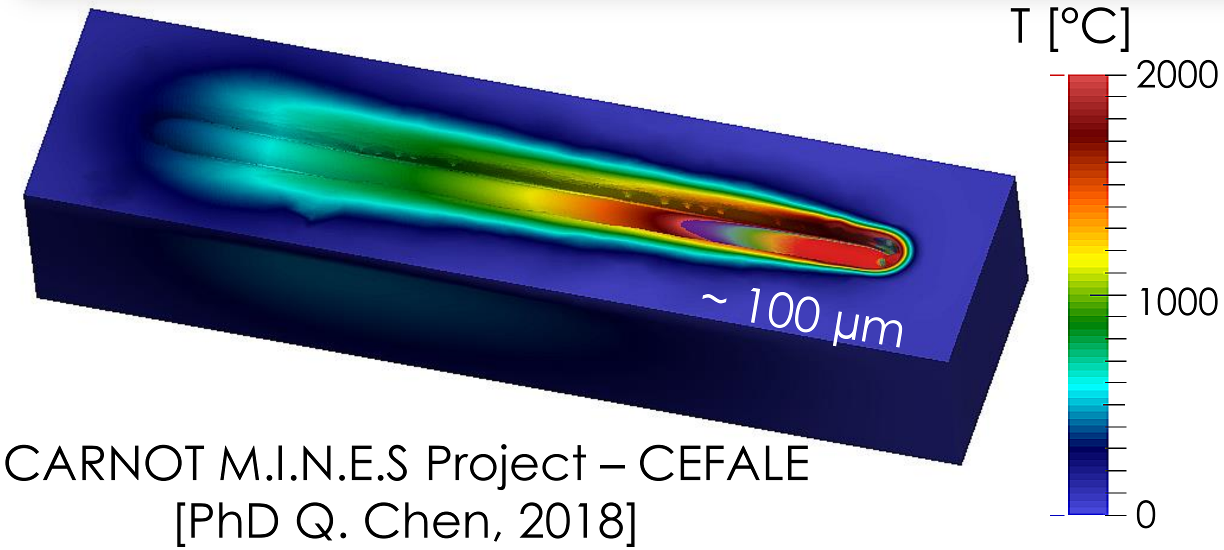


Melt pool instabilities - 316L
Balling effects [Li, 2012]



Denudation, Ti-6Al-4V
[Matthews, 2016]

Simulations – Level Set approaches [CEMEF]



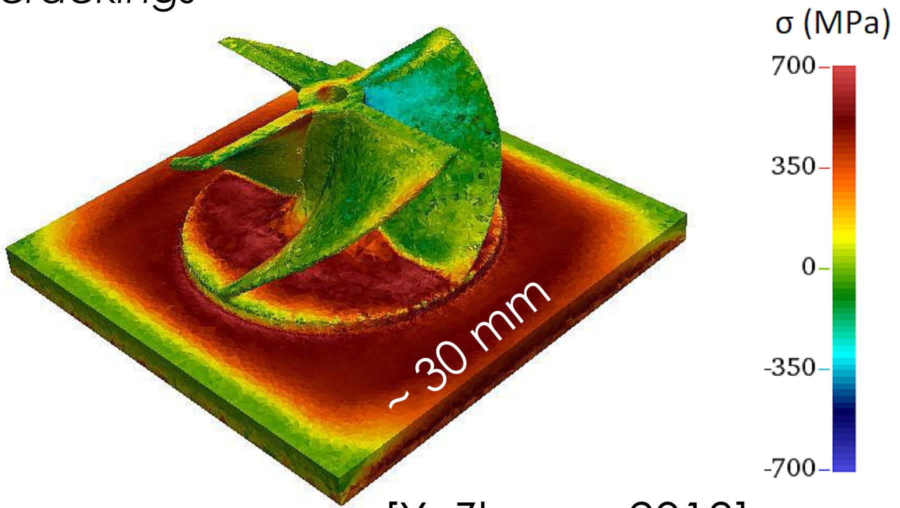
CARNOT M.I.N.E.S Project – CEFALE
[PhD Q. Chen, 2018]

Scale of the track development : Meso-

- Objectives : ***To master LBM process***
  - ***Laser / powder bed interaction*** – Heat source definition
  - ***Track geometry*** after melting / solidification
  - ***Microstructure*** evolution (phase transformation and associated segregation in rapid solidification)
  - ***Stress*** induced in the back part of the melt pool
  - ***Defects*** at micro-scale as *track irregularities, porosities and hot crackings*

Scale of the piece geometry : Macro-

- Objectives : ***To optimize the building strategy***
  - ***Temperature field*** on the whole piece
  - ***Strain and stress field***, developed during process and after cooling (residual stress)
  - Thermal and mechanical effects of the ***supports***
  - Development of the ***macrostructure*** (size and grain texture)
  - ***Defects*** formed at macro-scale as cracks developments in solid state (cooling)



[Y. Zhang, 2018]

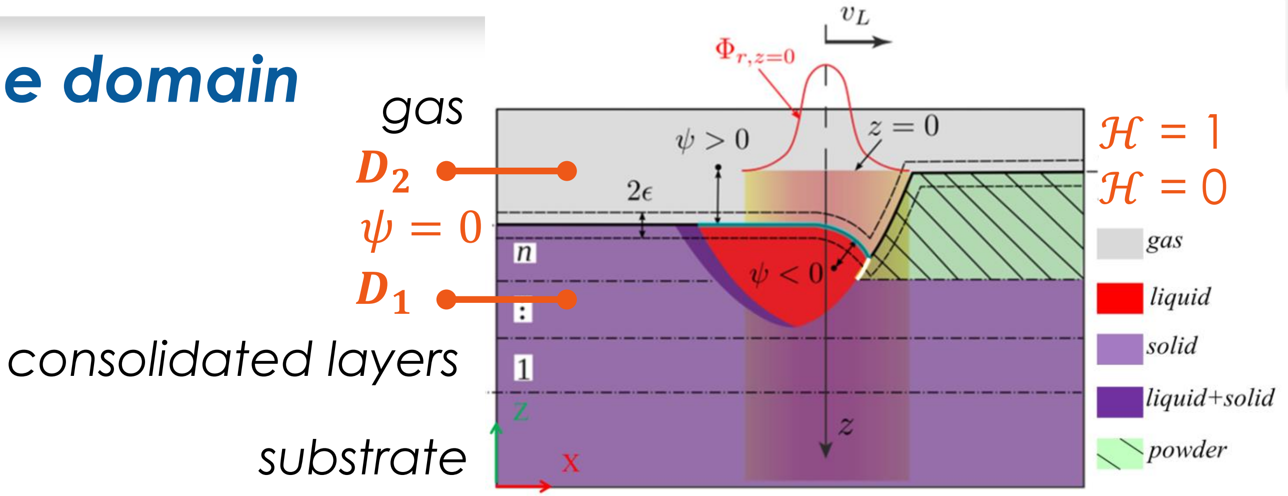
Y. Zhang, Q. Chen, G. Guillemot, Ch.-A. Gandin, M. Bellet, Numerical modelling of fluid and solid thermomechanics in additive manufacturing by powder bed fusion: continuum and level set formulation applied to track and part scale simulations, CRAS, Computational Methods in Welding and Additive Manufacturing, *Accepted, To be published*

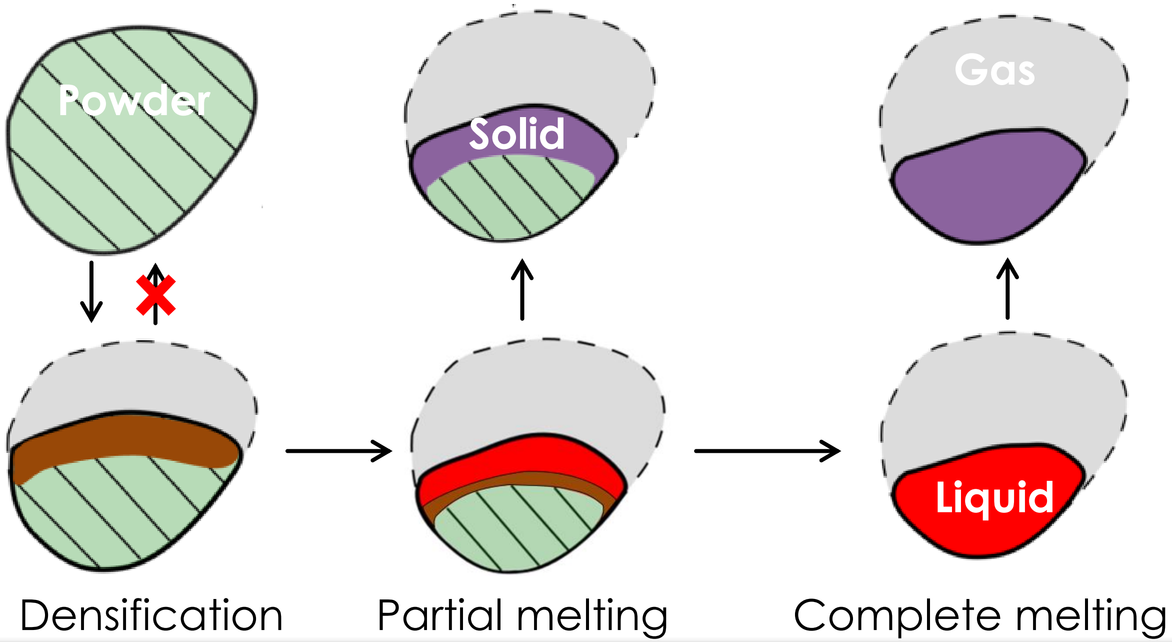
CNRS ARMINES Cemef MINES ParisTech

LBM process modelling – Meso-scale

▶ *Level set approach – Multiphase domain*

- System definition
  - Multi-domain, $D_i, i \in \{1,2\}$
    - Single-phase domain $\boldsymbol{D_2}$: *gas*
    - Multi-phase domain $\boldsymbol{D_1}$: α_j
  - Interdomain boundary D_1/D_2
    - Level set signed distance function ψ, depending from the position of the D_1/D_2 interface where $\psi = 0$
    - Heaviside function $\mathcal{H}$ with the half-thickness transition domain ϵ and associated Dirac function $\delta = \partial\mathcal{H}/\partial\psi$
  - Averaged approach
    - System scale : $\{\chi\} = \sum_i \mathcal{H}^{D_i} \langle\chi\rangle^{D_i}$
    - Domain scale : $\langle\chi\rangle^{D_i} = \sum_j g_{D_i}^{\alpha_j} \chi^{\alpha_j}$





Q. Chen, Thermomechanical numerical modeling of additive manufacturing by selective laser melting of powder bed – Application to ceramic materials,
Doctorat Université Paris Sciences et Lettres, PSL Research University, 2018

Heat transfer

▶ Heat conservation equation

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

Heat loss (radiation)

$$\dot{q}_r = \delta\sigma_r\epsilon_r(T^4 - T_{ext}^4)$$

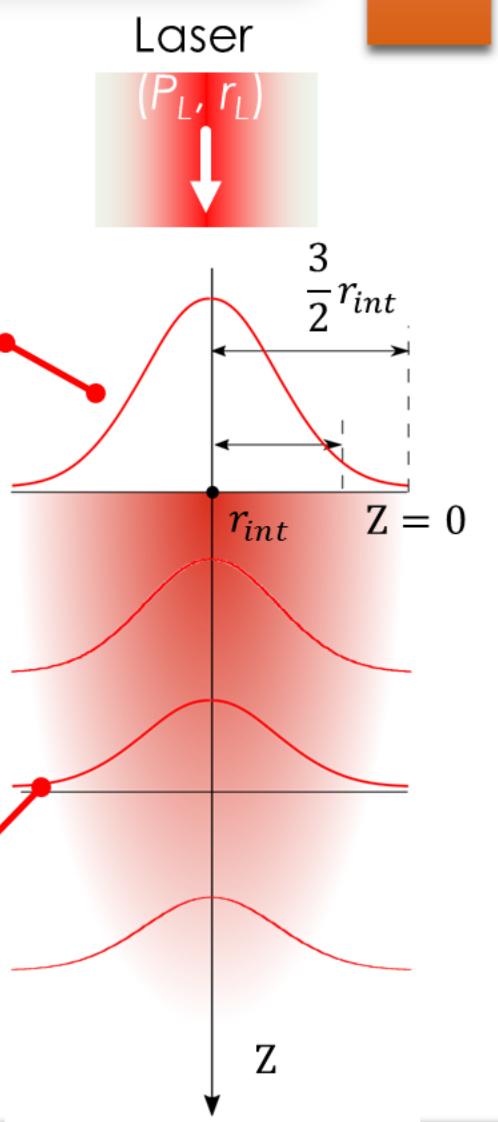
▶ Heat source / Laser

- Laser source $\dot{q}_L$
  - Gaussian surface distribution $\phi_{r,z=0}$
  - Volume heat source / Beer-Lambert model

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

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

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



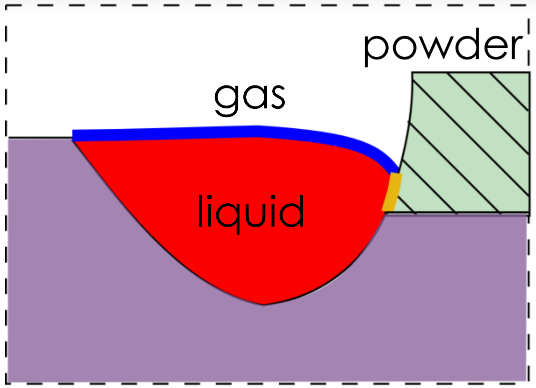
Q. Chen, G. Guillemot, Ch.-A. Gandin, M. Bellet, Three-dimensional finite element thermomechanical modeling of additive manufacturing by selective laser melting for ceramic materials,
Additive Manufacturing 16 (2017) 124 – 137

Fluid dynamics

▶ *Navier – Stokes equation*

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

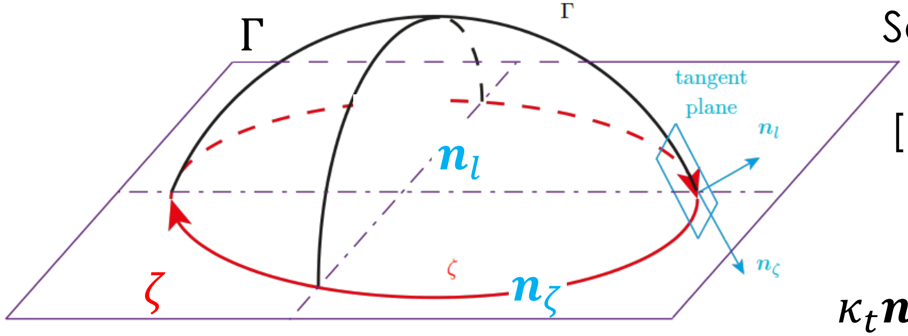
$$\nabla\cdot\boldsymbol{u}=\dot{\theta}=-\frac{1}{\rho}\frac{d\rho}{dt}$$



Surface tension & Marangoni force imposed on both the **liquid/gas** interface & the **liquid/powder** boundary

- Compressible Newtonian behaviour :

$$\begin{cases}\underline{\underline{\boldsymbol{\sigma}}}=2\,\eta\left(\underline{\underline{\dot{\boldsymbol{\epsilon}}}}-\frac{1}{3}\mathrm{tr}\left(\underline{\underline{\dot{\boldsymbol{\epsilon}}}}\right)\underline{\underline{\boldsymbol{I}}}\right)-p\,\underline{\underline{\boldsymbol{I}}}\\ \mathrm{tr}\left(\underline{\underline{\dot{\boldsymbol{\epsilon}}}}\right)=\nabla\cdot\boldsymbol{u}=\dot{\theta}\end{cases}$$



Semi-implicit implementation of **surface tension** [Hysing, 2005, Hamide, 2008, Khalloufi, 2016]

$$\kappa_t\boldsymbol{n}_l=(\kappa_t\boldsymbol{n}_l)^-+\nabla_s\cdot(\nabla_s\boldsymbol{u})\,\Delta t$$

Explicit   Stabilization

- Volumetric force $\boldsymbol{f}_V$:
  - Gravity : $\{\rho\}\,\boldsymbol{g}$
  - Surface tension : $\boldsymbol{f}_s=\gamma\kappa_t\boldsymbol{n}_l$
  - Marangoni force : $\boldsymbol{f}_M=\frac{\partial\gamma}{\partial T}\nabla_s T$ with $\nabla_s T=\nabla T-(\nabla T\cdot\boldsymbol{n}_l)\boldsymbol{n}_l$ $(\times\,\delta)$ [Brackbill1992]
- Transport and reinitialization of level set field : $\frac{d\psi}{dt}=\frac{\partial\psi}{\partial t}+\boldsymbol{u}\cdot\nabla\psi=0$

Geometrical reinitialization with respect to $\psi = 0$ [Shakoor, 2015]

Solid mechanics

Equilibrium

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

- Behavior law
  - Dense medium
    - Elasto-Viscoplastic (EVP), if $T < T_s$

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

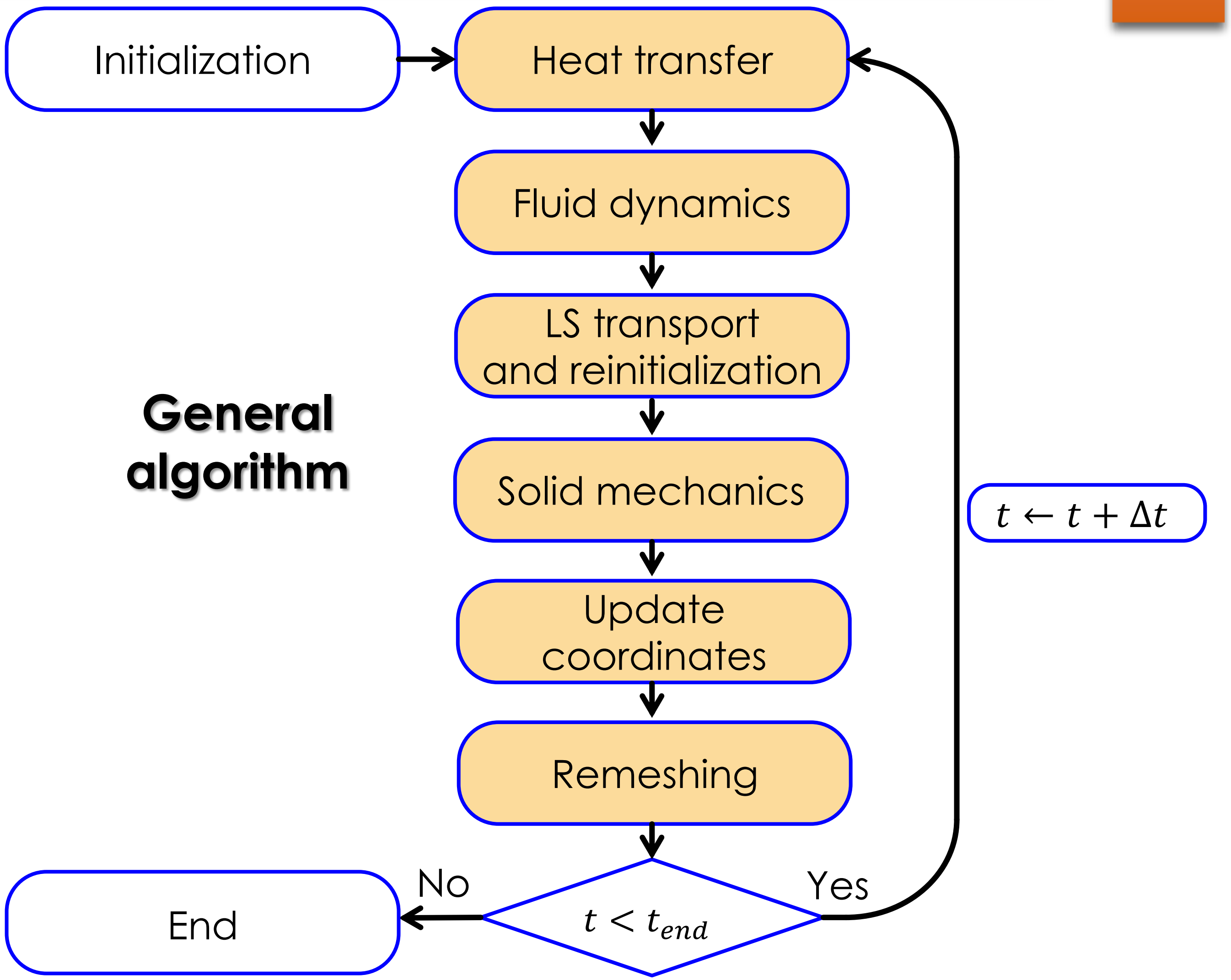
$$\bar{\sigma} = \sigma_Y + K\left(\sqrt{3}\right)^{m+1} \bar{\epsilon}^n \ \dot{\bar{\epsilon}}^m$$

    - Visco-Plastic (VP), if $T_s \leq T \leq T_l$

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

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

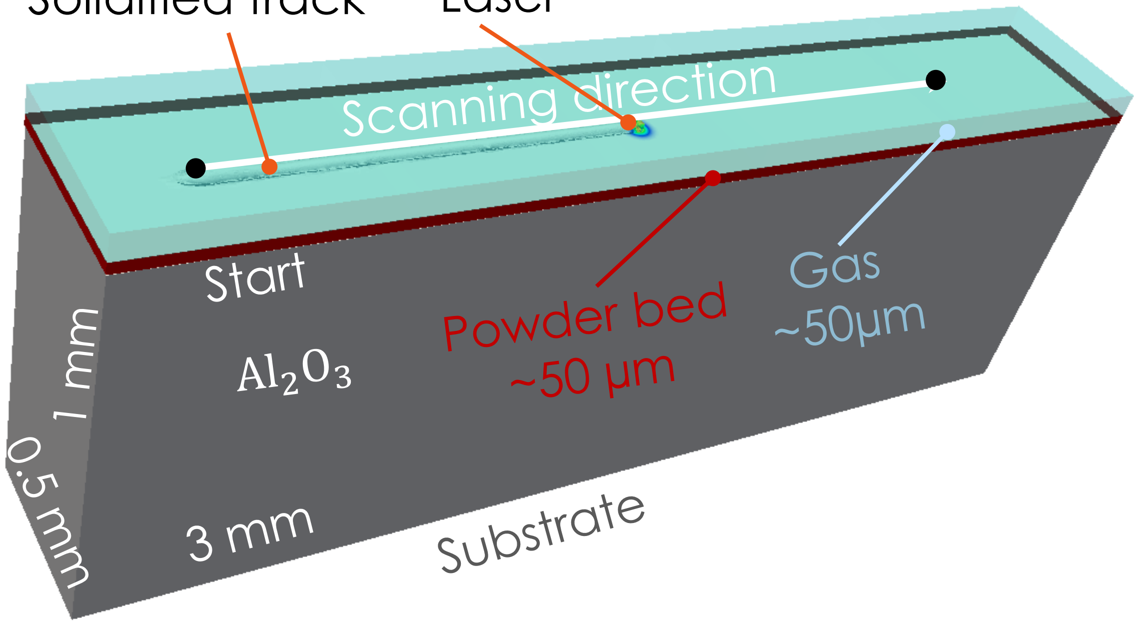
    - Newtonian (N), if $T > T_l$
  - Gas and powder
    - Newtonian (N)

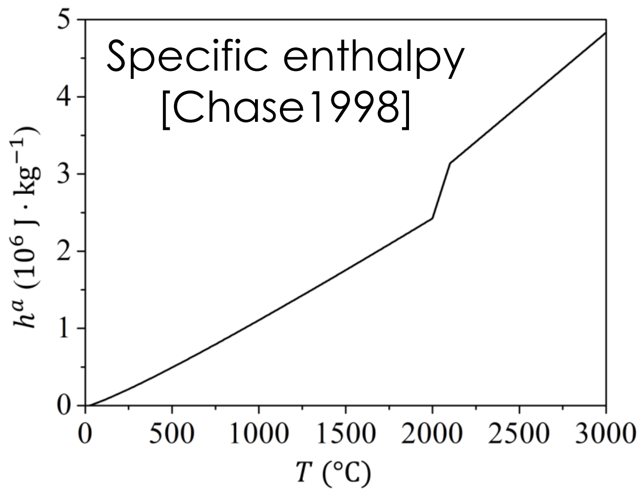


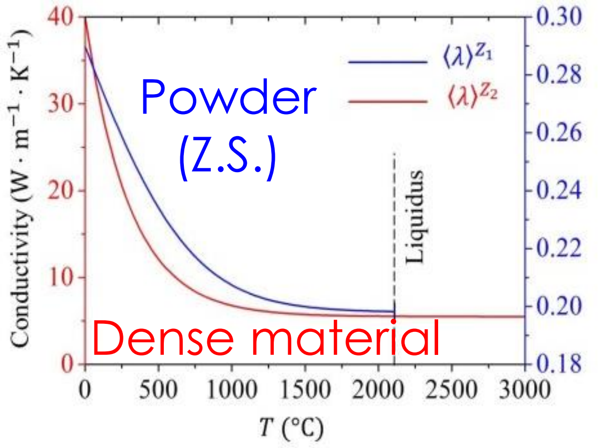
Application – Track development

▶ *Configuration*

- Absorption
  - Solid and powder α_s
  - Liquid α_l
- Emissivity $\epsilon_r = 0.4$ (radiation on gas/material boundary)
- Initial and ambient temperature : $T_0 = 20\ °\mathrm{C}$







[Zehner, 1970]

Face	Thermal	Fluid	Solid
Bottom	$h_T = 40\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$	$\boldsymbol{u} = 0$	$\boldsymbol{u} = 0$
Lateral		$\boldsymbol{u} \cdot \boldsymbol{n} = 0$	Free
Top	Adiabatic	Free	

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 selective laser melting of ceramic material, Additive Manufacturing 21 (2018) 713 – 723

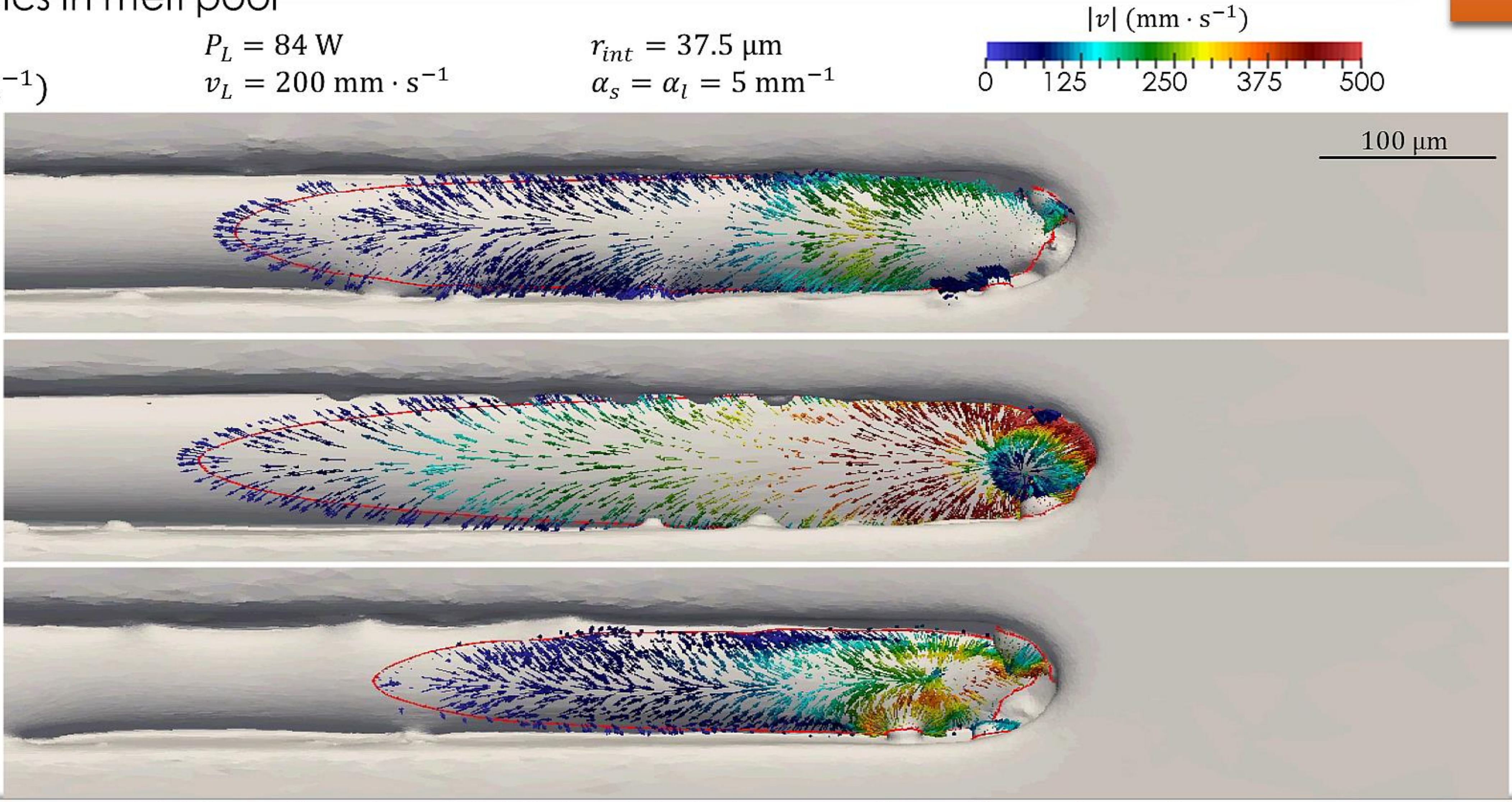
Application – Fluid flow evolution

- Fluid dynamics in melt pool

$\partial\gamma/\partial T$ $(\times 10^{-5} N \cdot m^{-1} \cdot K^{-1})$

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

$r_{int} = 37.5\ \mu m$
$\alpha_s = \alpha_l = 5\ mm^{-1}$



– 8.2 (Nominal value)

– 48

+ 48

Fluid flow directions highlighted / Higher centrifugal (centripetal) convection flow caused by higher negative (positive) $\partial\gamma/\partial T$

Application – Balling effect

- Irregularity on liquid interface

$P_L = 84$ W

$r_{int} = 37.5$ µm
$\alpha_s = \alpha_l = 5$ mm^{-1}

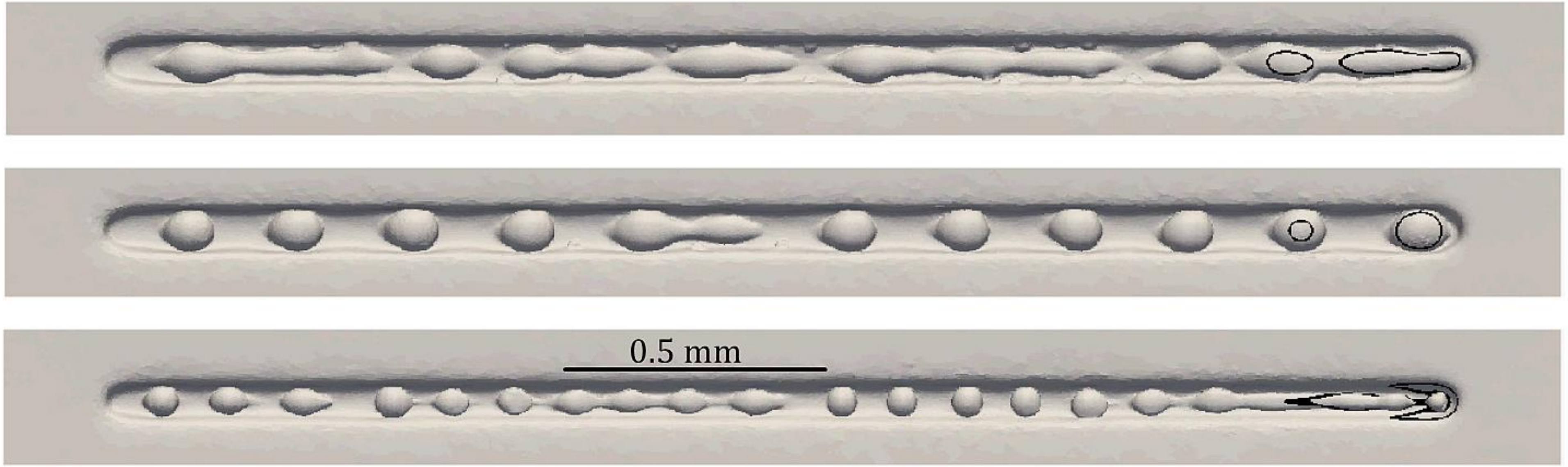
Black contour (solidus, $T_s = 2004$ °C)

v_L (mm·s^{-1})

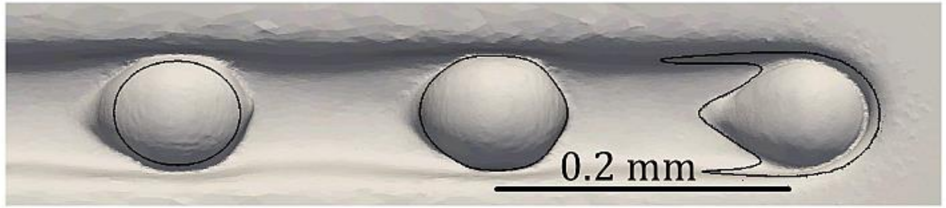
550

600

800

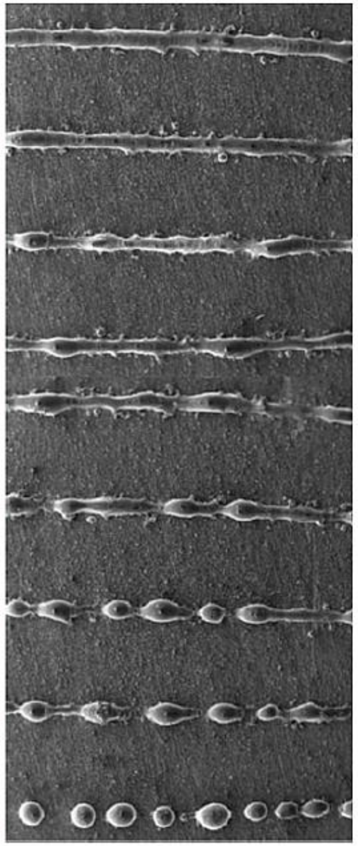


600



v_L (mm·s^{-1})
316L stainless steel

50
150
200
250
300
350
400
450
500



[Li, 2012]

Transition from continuous to interrupted track with increasing v_L, leading to balling

Application – Irregularities

- Track height variation

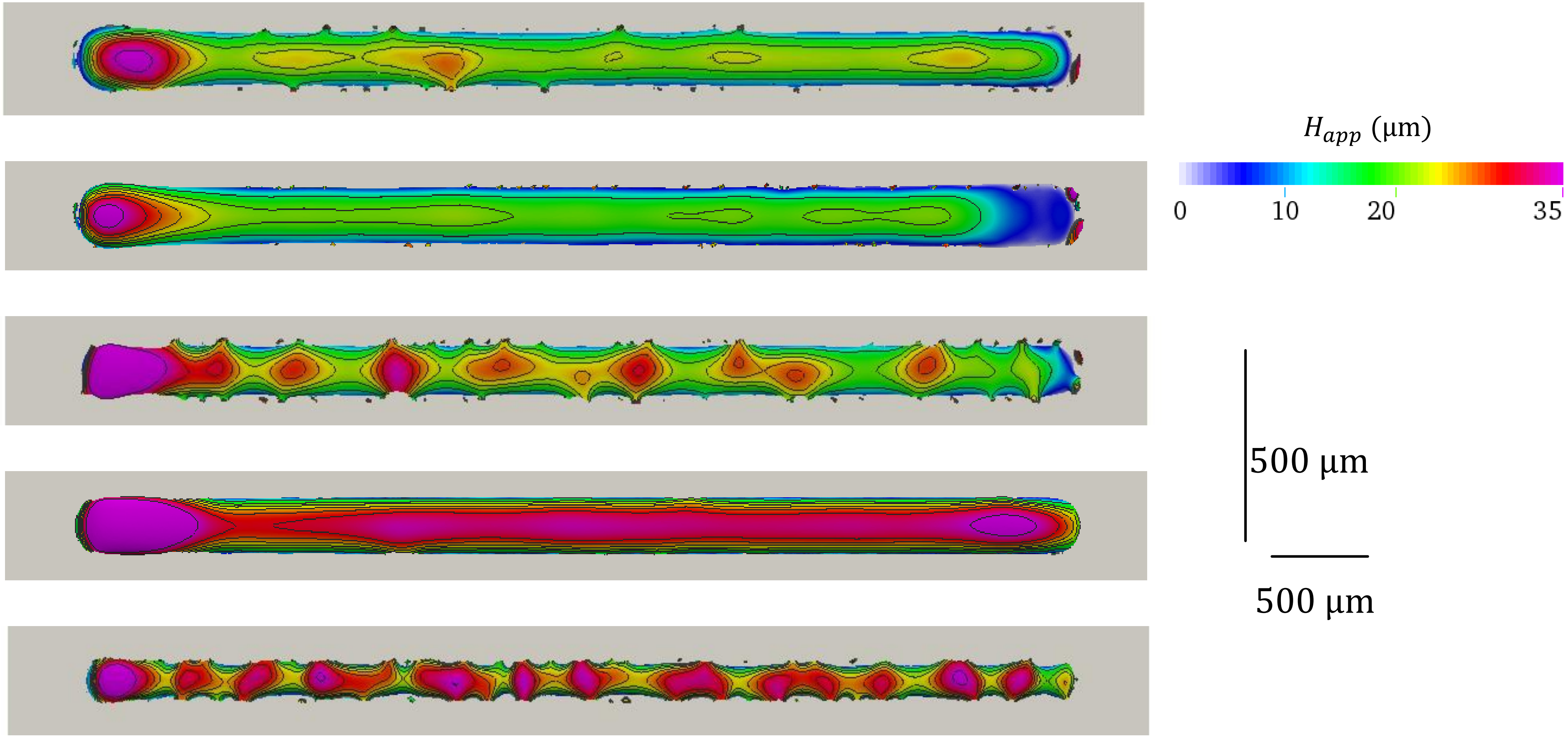
$\partial\gamma/\partial T = -\,8.2 \times 10^{-5}$ $\mathrm{N \cdot m^{-1} \cdot K^{-1}}$

$\partial\gamma/\partial T = -\,48 \times 10^{-5}$ $\mathrm{N \cdot m^{-1} \cdot K^{-1}}$

$\partial\gamma/\partial T = +\,48 \times 10^{-5}$ $\mathrm{N \cdot m^{-1} \cdot K^{-1}}$

Higher liquid viscosity $0.2\ \mathrm{Pa \cdot s}$

Double scanning speed $400\ \mathrm{mm \cdot s^{-1}}$



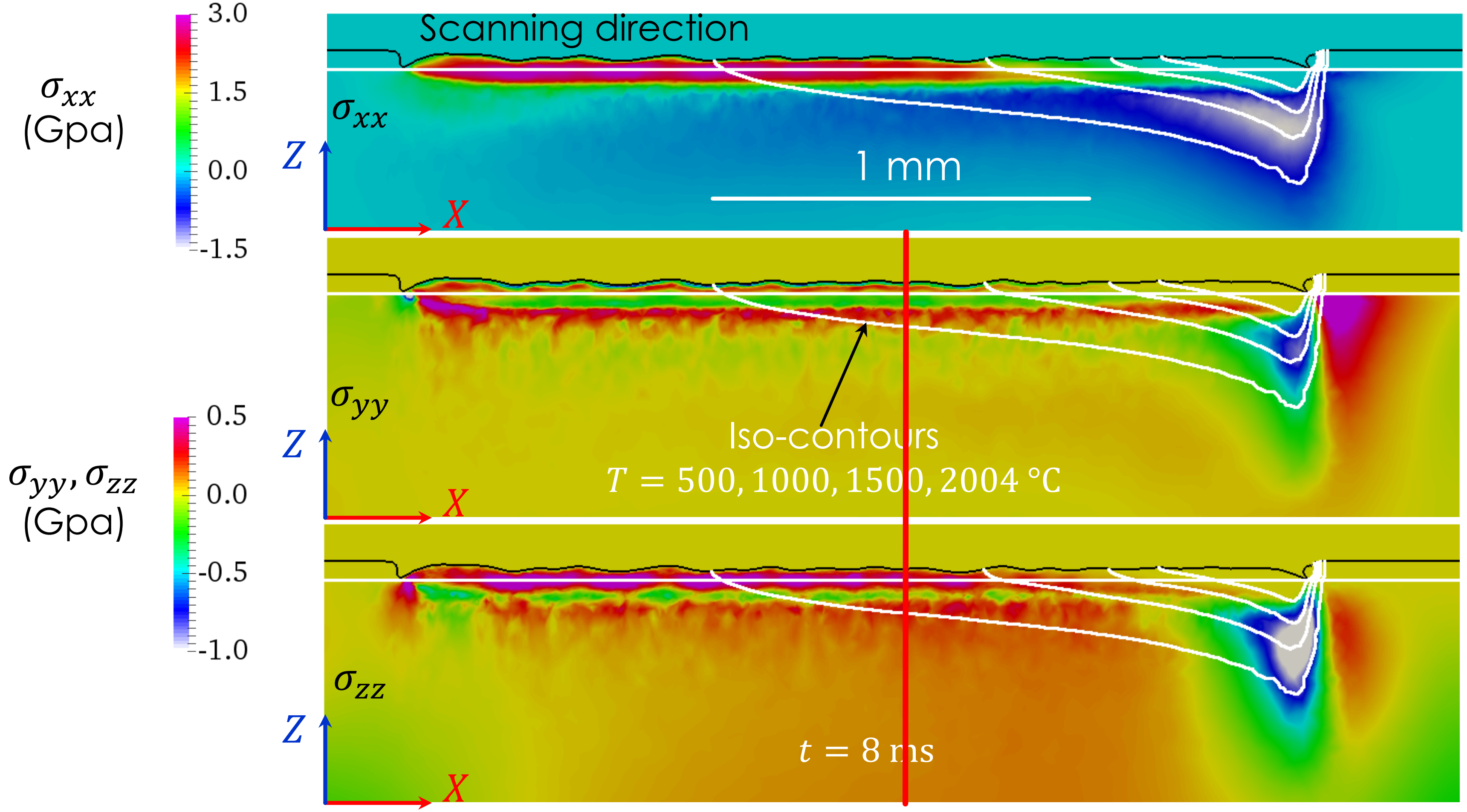
Higher negative $\partial\gamma/\partial T$ or viscosity → less surface height variation
Higher positive $\partial\gamma/\partial T$ or scanning speed → more surface height variation

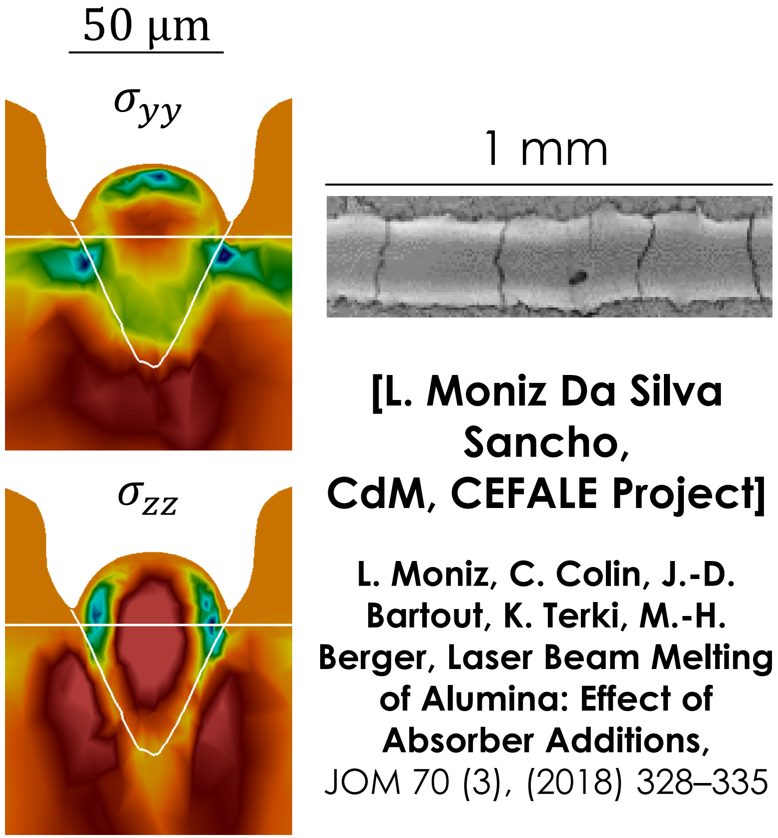
Application – Stress distribution

- Stress distribution

$P_L = 84$ W $\quad r_{int} = 50$ µm

$v_L = 300$ mm · s^{-1} $\quad \alpha_s = \alpha_l = 5$ mm^{-1}





[L. Moniz Da Silva Sancho, CdM, CEFALE Project]

L. Moniz, C. Colin, J.-D. Bartout, K. Terki, M.-H. Berger, Laser Beam Melting of Alumina: Effect of Absorber Additions, JOM 70 (3), (2018) 328–335

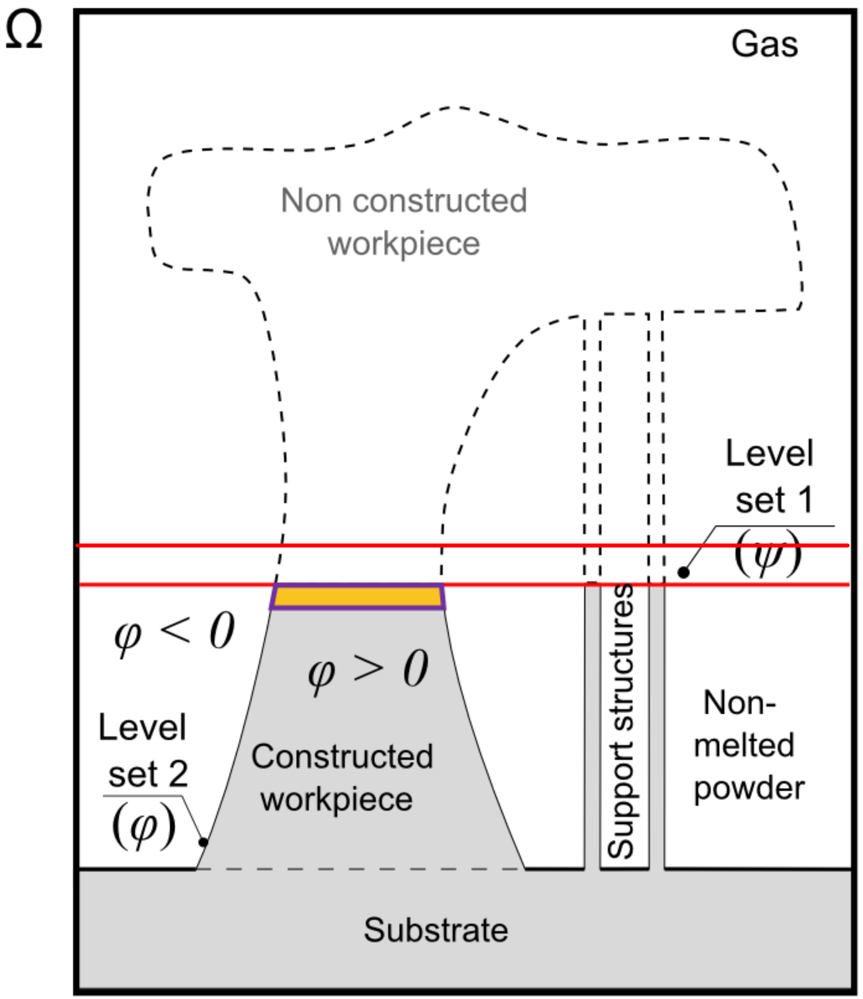
Higher σ_{xx} and σ_{zz} → more risk of cracks ⊥ scanning direction and delamination

LBM process modelling – Macro-scale

Principles

- Starting point: **CAD** of **the part** to be built, completed by **the substrate** and the possible **supports**
- Mesh of this **CAD** and immerse in a **background mesh Ω**
- Construct the conform mesh at interfaces:
  - material / gas
  - constructed part/ non-exposed powder
- Over time, the **level set** y is updated progressively through the mesh **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 Macro-Scale modelling

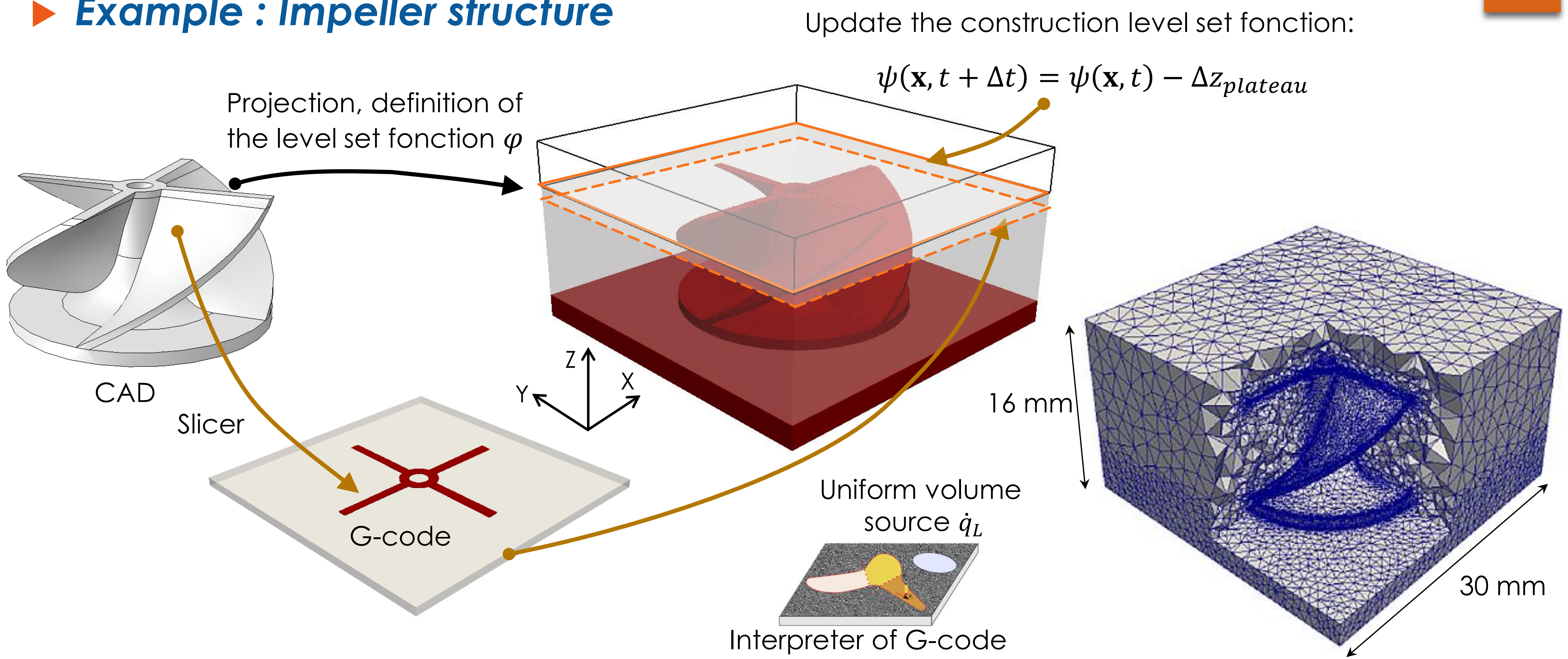


[Y. Zhang]

Y. Zhang, G. Guillemot, M. Bernacki, M. Bellet, Macroscopic thermal finite element modeling of additive metal manufacturing by selective laser melting process, Computer Methods in Applied Mechanics and Engineering 331 (2018) 514-535

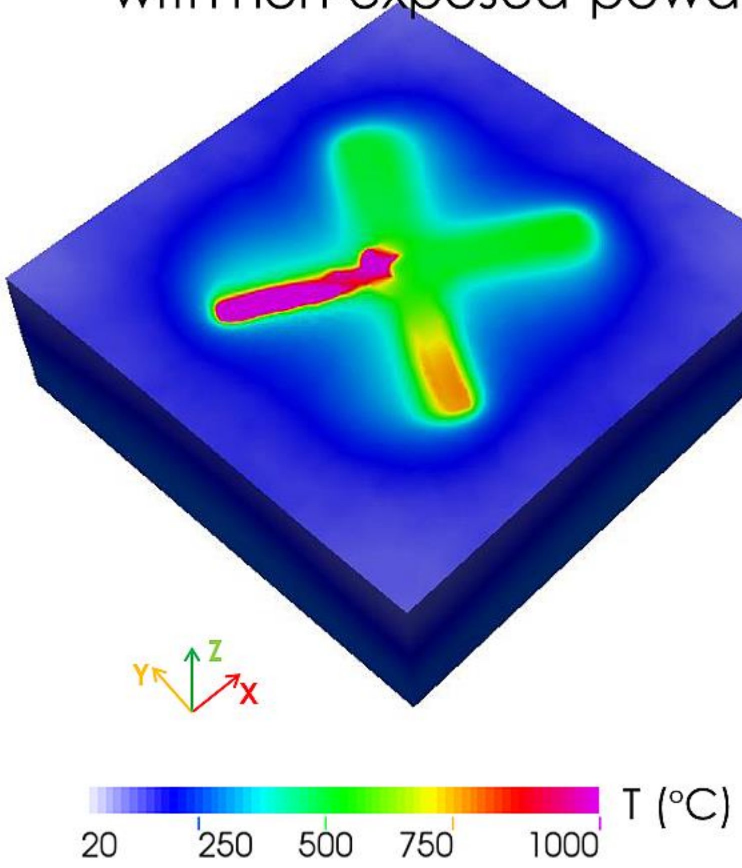
Strategy – Overview

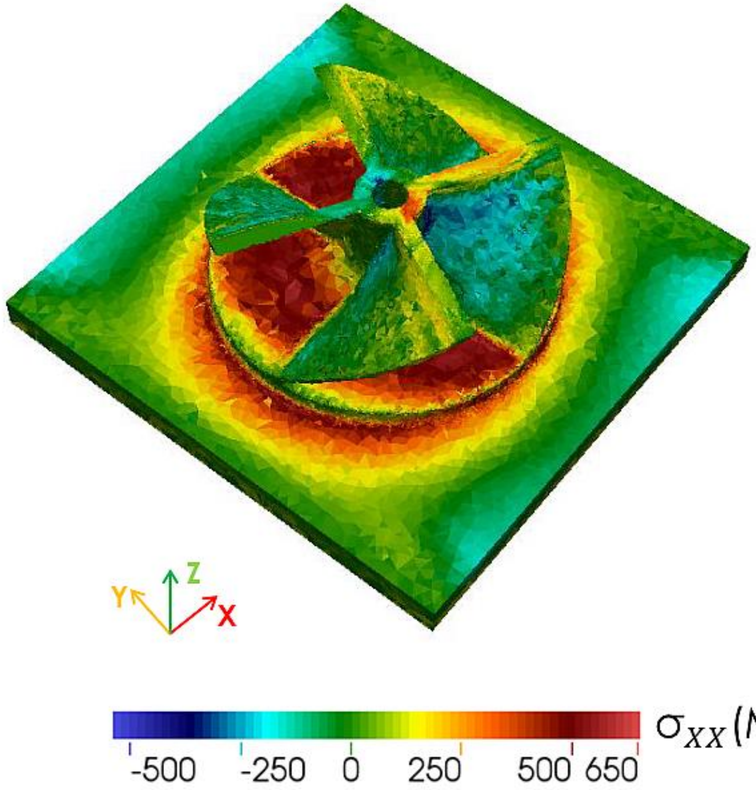
▶ *Example : Impeller structure*



Application – Temperature and Stress fields

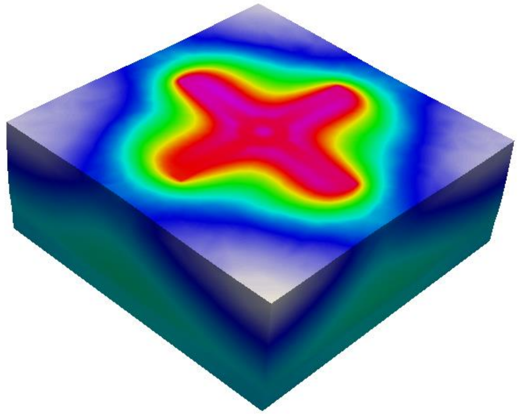
- ***In718 part :*** Temperature and stress distribution during the construction process (50 layers)
  - Temperature: with non-exposed powder
  - Stress: without non-exposed powder



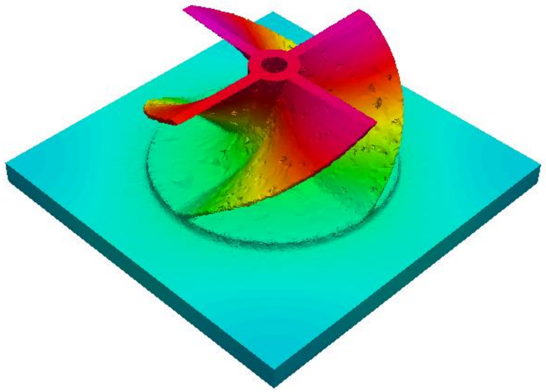


Application – Temperature and Stress fields

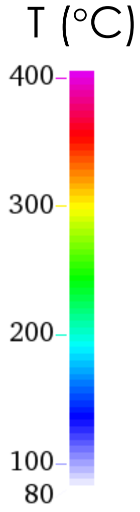
- ***Final construction:*** *temperature*



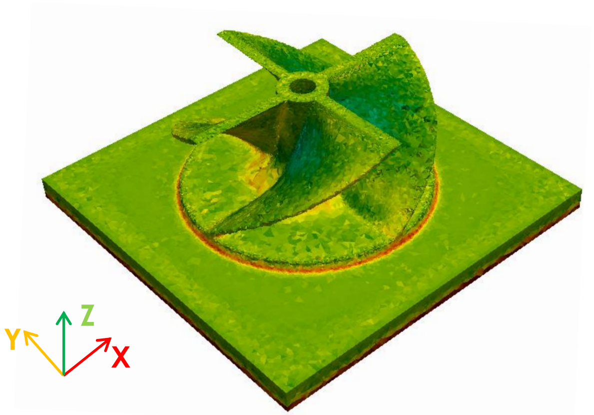
Part + non-exposed powder



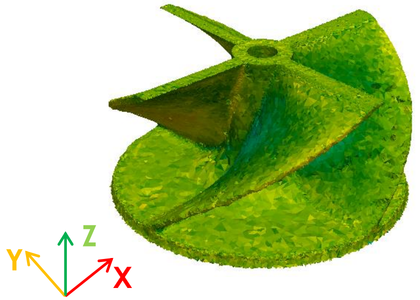
Part



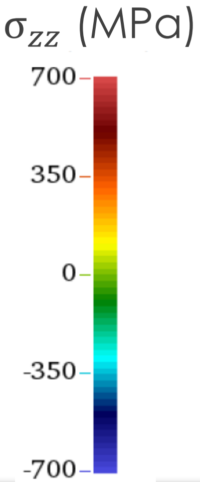
- ***Final construction + 2h:*** *residual stress*



Cool down
to room temperature

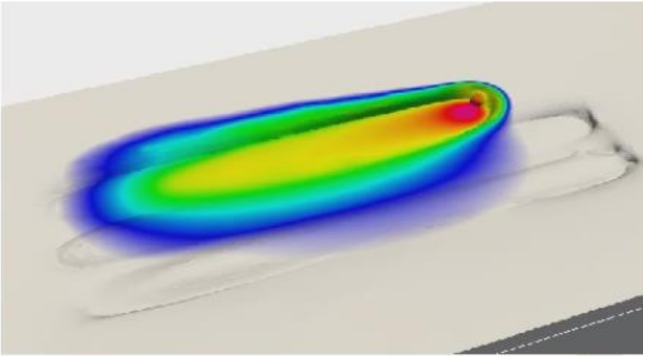


After removing
from the substrate



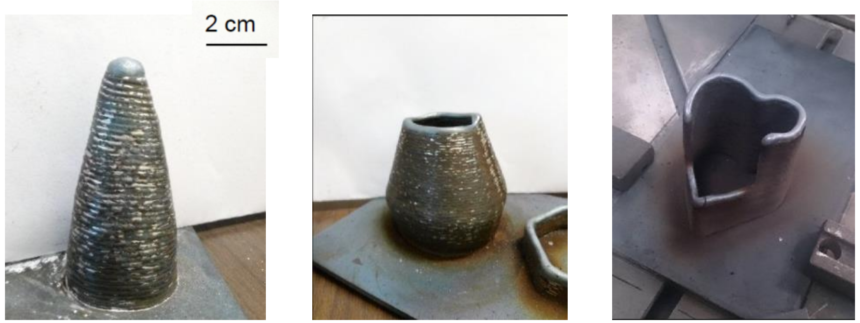
… Ongoing and Future Projects

- ***PhD CIFRE SAFRAN** (A. Queva) **(2017-2020)***
  (PIMM, I2M)



- **Laser Beam Melting process applied onto metallic materials**
  - Laser / metal interaction and associated effects at meso-scale
  - Energy absorption, fluid flow evolution and vaporisation

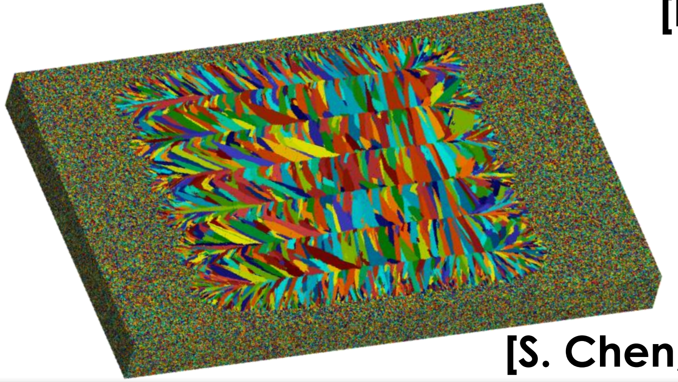
- ***PhD MACCADAM (ANR – 2018-2021)***
  (LMGC, ICA, LGP, Poly-Shape)



[LMGC]

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

- ***PhD NEMESIS (ANR – 2018-2021)***
  (LMGC, ICB, CEA List, Arcelor Mittal, EDF R&D, Transvalor)



[S. Chen, CEMEF]

- **Numerical metallurgy supporting arc welding processes**
  - Predictions of cracks and brittle phase developments
  - Application to NDT technologies in welding process

Conclusions

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

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