Simulation directe par couplage CAFE de la structure de solidification primaire en soudage multipasse

Gildas GUILLEMOT, Michel BELLET, Charles-André GANDIN

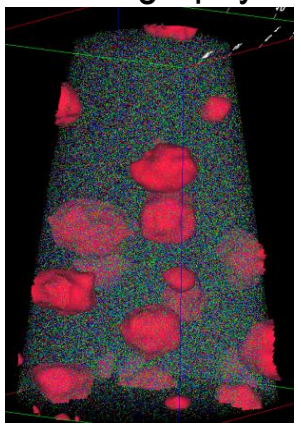
MINES ParisTech CEMEF, UMR CNRS 7635, Sophia Antipolis, FR

13EME COLLOQUE MODÉLISATION ET SIMULATION NUMÉRIQUE DU SOUDAGE
"Modélisation du soudage de grands composants“
26 mars 2015, Maison de la mécanique, Paris La Défense

INTRODUCTION

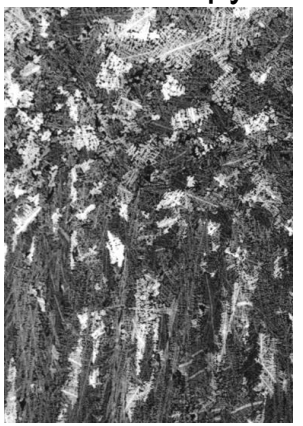
OBSERVATIONS

Atom Probe Tomography



Electron microscopy

Optical microscopy

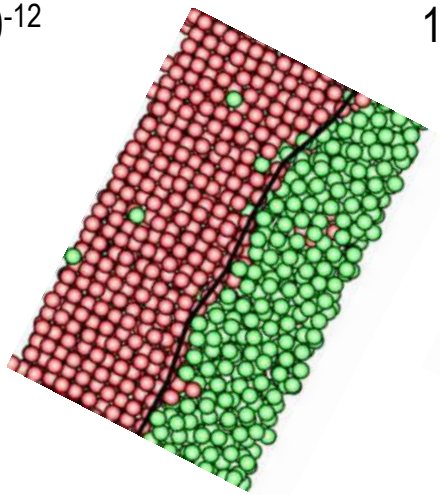


Naked eye

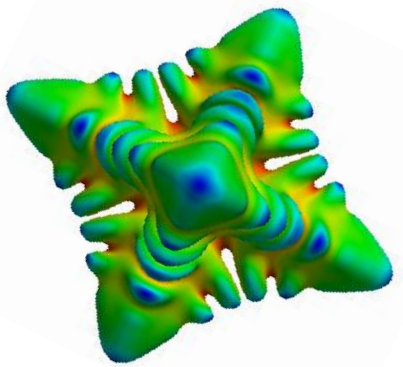
10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 [m]

10^{-12} 10^{-8} 10^{-4} 1 10^{4} [s]

SIMULATIONS

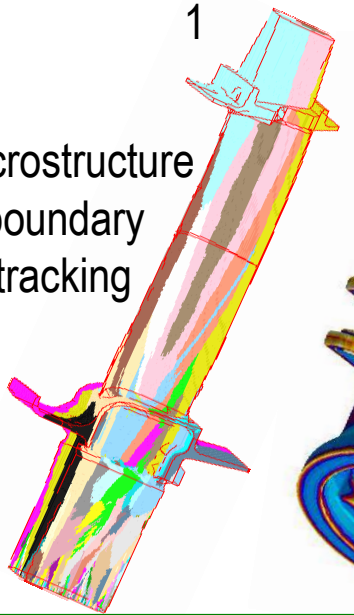


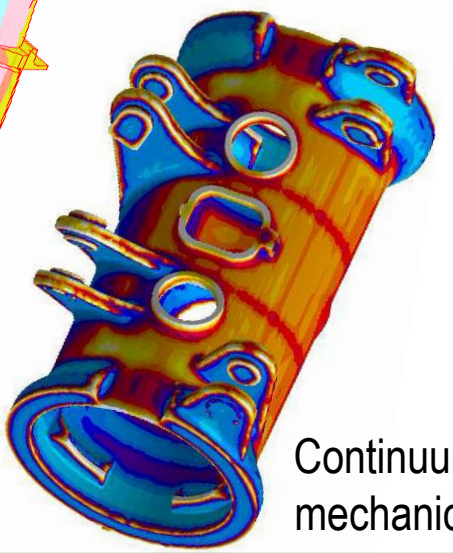
Ab initio molecular dynamics



Phase interface tracking

Macrostructure boundary tracking





Continuum mechanics

CONTENTS

Scales \ Tracking	Indirect	Direct
Macroscopic	Averaging over a multiphase domain	Macrostructure boundary tracking ➔ *Length scales* ➔ *Interface kinetics* *Transformation paths* ➔ Mush-liquid boundary Grain size and texture (cellular automaton method)
Microscopic	Averaging over each phase	Phase interface tracking

MODELING…

… AVERAGING OVER A MULTIPHASE DOMAIN (SATURATED TWO-PHASE MEDIUM, FIXED SOLID PHASE, CONSTANT AND EQUAL DENSITY OF THE PHASES): ***FINITE ELEMENT (FE)***

Momentum

Boussinesq

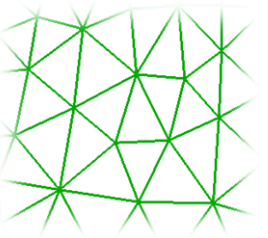
$$\rho_0 \frac{\partial \langle \mathbf{v}^l \rangle}{\partial t} + \frac{\rho_0}{g^l} \nabla \cdot \left(\langle \mathbf{v}^l \rangle \times \langle \mathbf{v}^l \rangle \right) = \nabla \cdot \left(\mu^l \left(\nabla \langle \mathbf{v}^l \rangle + \nabla \langle \mathbf{v}^l \rangle^T \right) \right) - g^l \nabla p^l + g^l \rho^l \mathbf{g} - \frac{\mu^l}{K} g^l \langle \mathbf{v}^l \rangle$$

Mass $\nabla \cdot \langle \mathbf{v}^l \rangle = 0$

Kozeny-Carman

Energy $\frac{\partial \langle \rho h \rangle}{\partial t} + \langle \mathbf{v}^l \rangle \cdot \nabla \langle \rho h \rangle^l = \nabla \cdot \left(\langle \kappa \rangle \nabla T \right)$

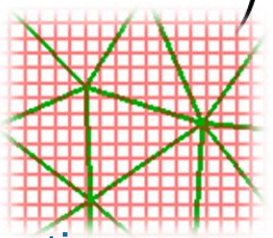
Solute $\frac{\partial \langle w_i \rangle}{\partial t} + \langle \mathbf{v}^l \rangle \cdot \nabla \langle w_i \rangle^l = \nabla \cdot \left(\langle D^l \rangle \nabla \langle w_i \rangle^l \right)$



… AVERAGING OVER EACH PHASE

Transformation path (thermod. tabulations) $\frac{\partial \langle \rho h \rangle}{\partial T} = \frac{\partial}{\partial T} \left(\sum_{\phi} g^{\phi}_{[T, \langle w_i \rangle]} \langle \rho h \rangle^{\phi}_{[T, \langle w_i \rangle^{\phi}]} \right)$

… MACROSTRUCTURE BOUNDARY TRACKING: ***CELLULAR AUTOMATON (CA)***



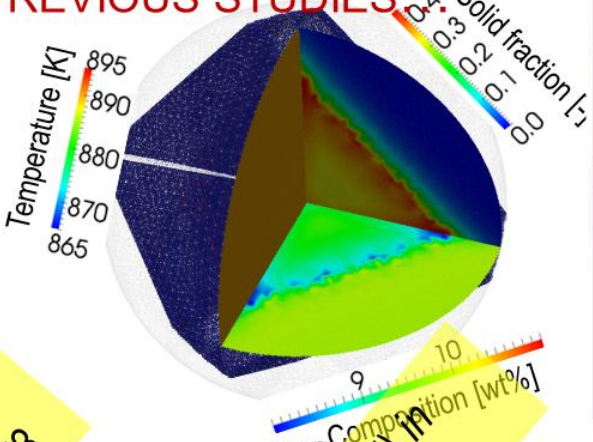
Nucleation and growth algorithms for the cellular automaton method

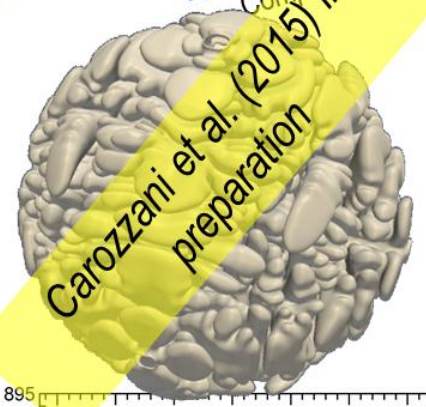
Microscopic models for the nucleation rate and the dendrite tip growth kinetics

MACROSTRUCTURE BOUNDARY TRACKING

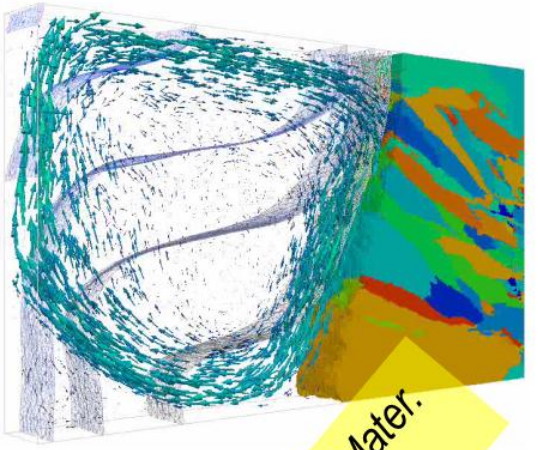
EXAMPLES OF PREVIOUS STUDIES

Carozzani et al., Modelling Simul. Mater. Sci. Eng 22 (2014) 015012 44 (2013) 873

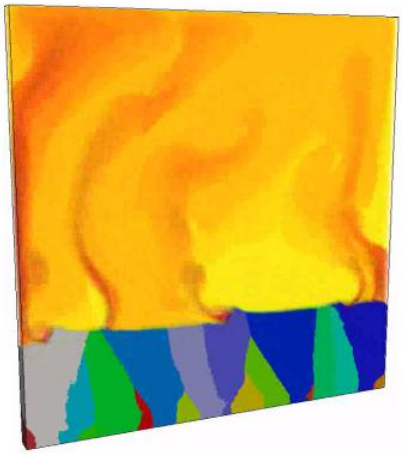


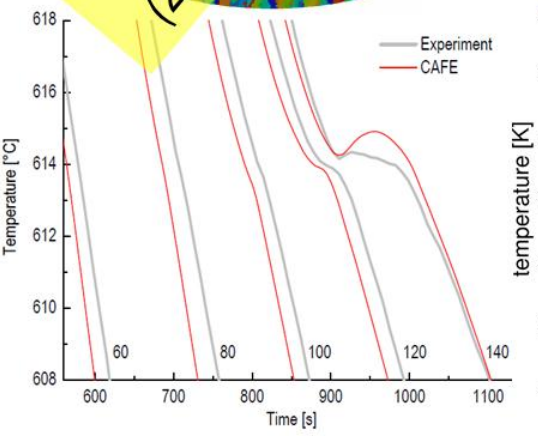


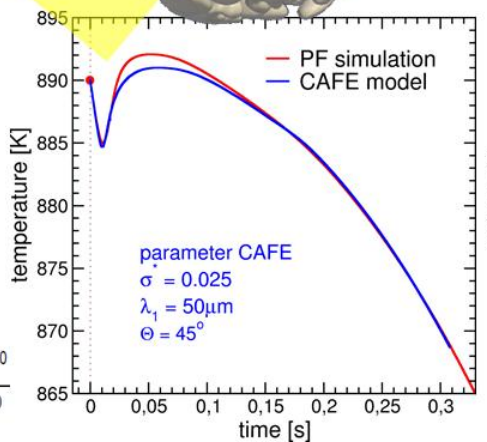
Carozzani et al. (2015) in preparation

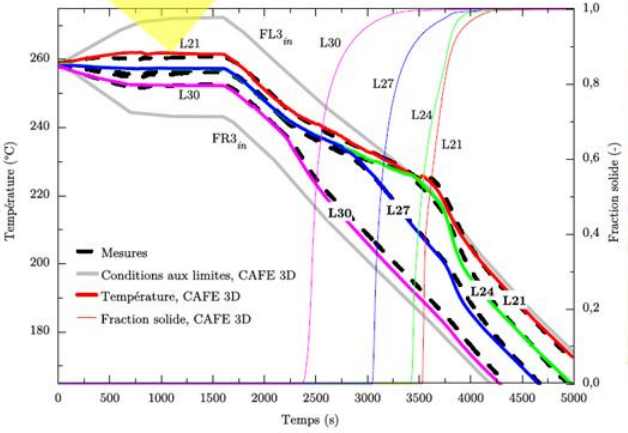


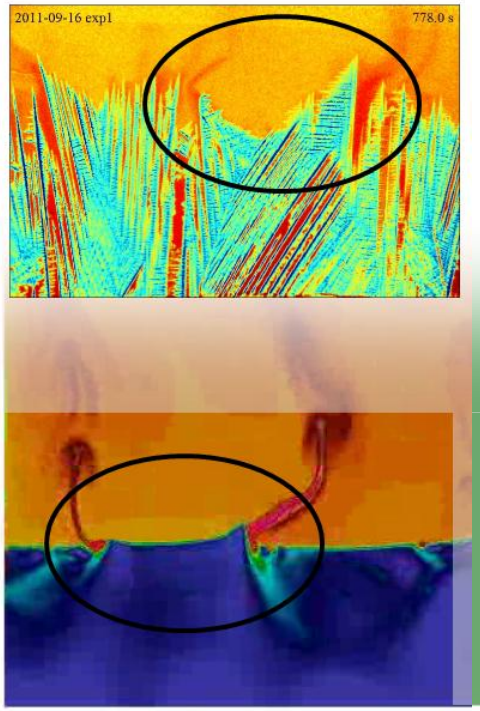
Carozzani et al., Metall. Mater. Trans. A 44 (2013) 873



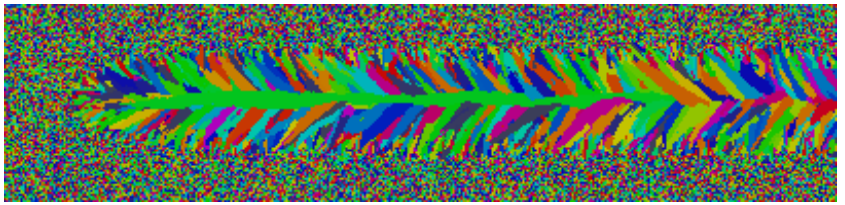
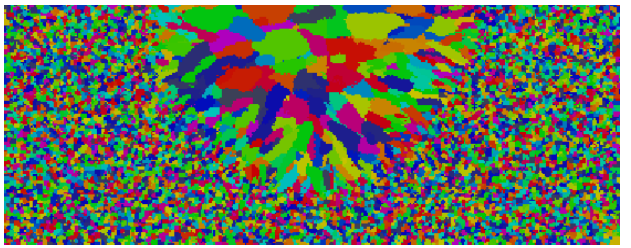
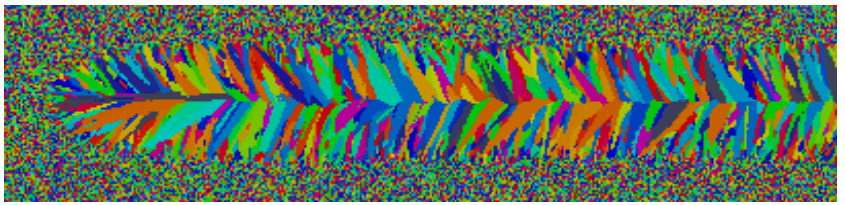
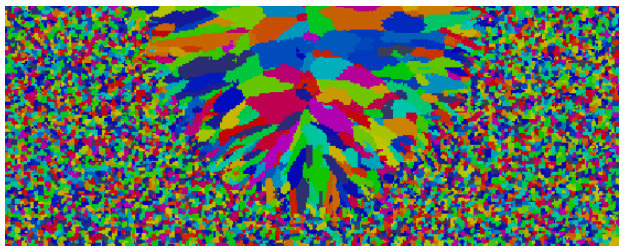
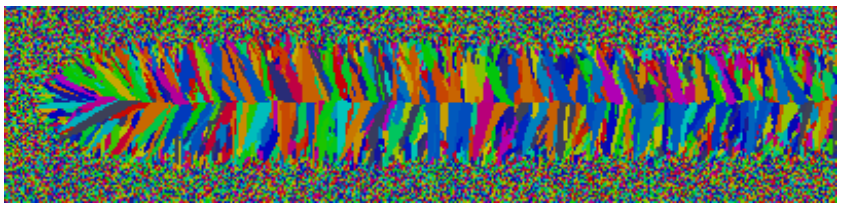
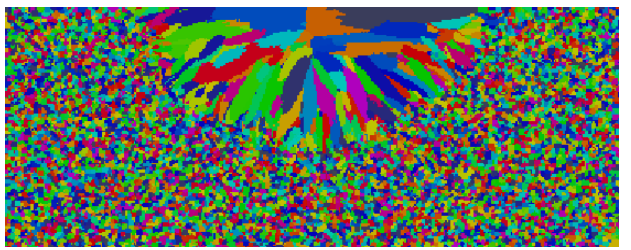
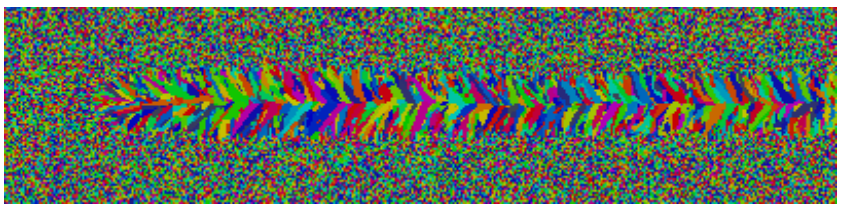
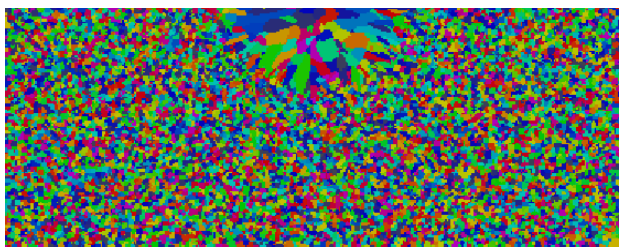








LINEAR SINGLE PASS

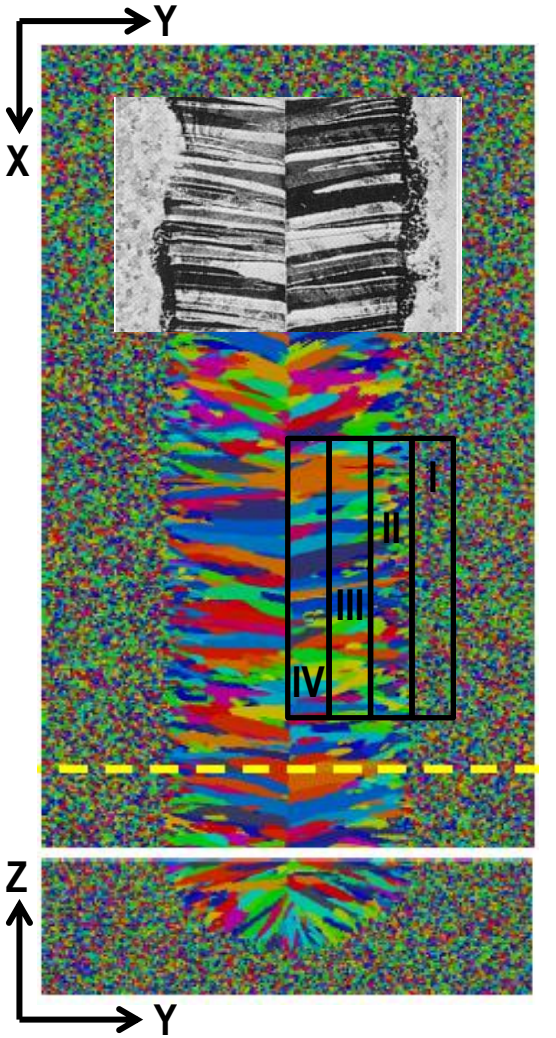
V [mm s^{-1}]	Q [W]	Computed longitudinal section	Computed transverse section
1	5000		
2	8000		
5	15000		
2	6000		

Shijia CHEN, PhD thesis, MINES ParisTech (2014)

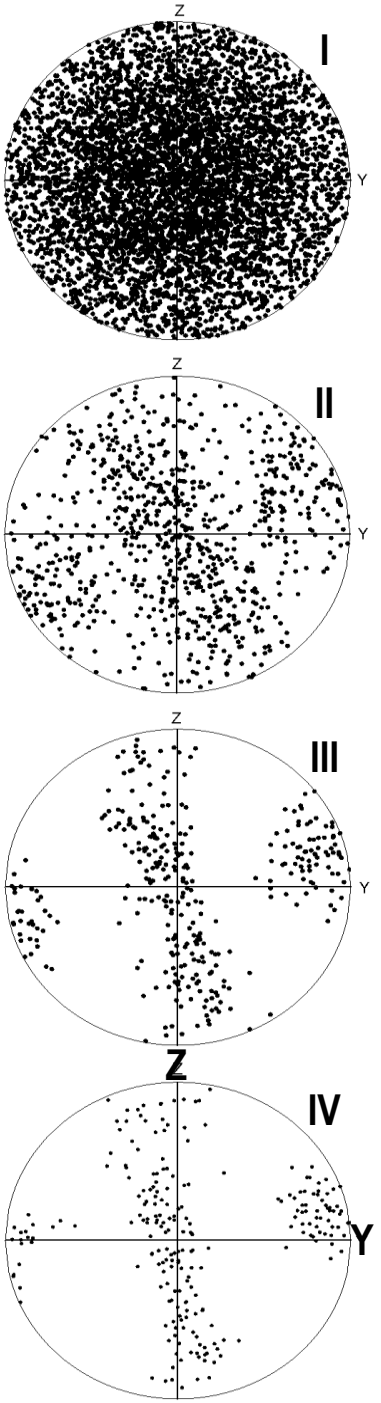
LINEAR SINGLE PASS

TEXTURE FORMATION UPON COLUMNAR DENDRITIC GROWTH

- GTAW process of a duplex steel
  - Linear single pass remelting
  - Welding coupon
    - 350 mm long
    - 150 mm width
    - 12 mm thick
  - Initial grain density: 10^{11} m^{-3}
  - **Velocity: 5 mm s^{-1}**
  - **Heat source power: 15000 W**
- Texture revealed by
  - <100> pole figures for grains observed at the top surface in windows I-IV distributed from weld periphery to center
  - Fiber texture mainly aligned with Y-axis



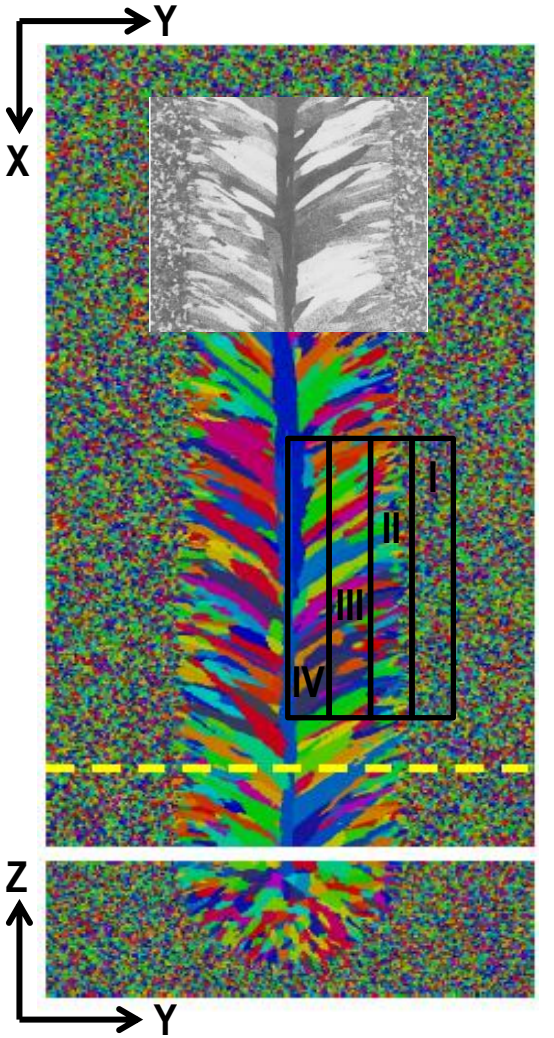
Welding coupon: 350 mm long, 150 mm width, 12 mm thick



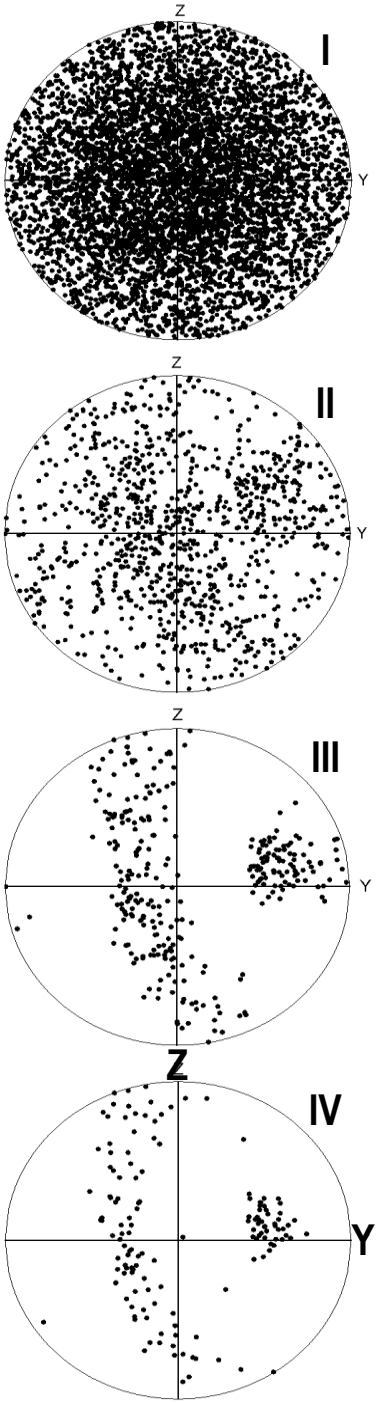
LINEAR SINGLE PASS

TEXTURE FORMATION UPON COLUMNAR DENDRITIC GROWTH

- GTAW process of a duplex steel
  - Linear single pass remelting
  - Welding coupon
    - 350 mm long
    - 150 mm width
    - 12 mm thick
  - Initial grain density: 10^{11} m^{-3}
  - **Velocity: 1 mm s^{-1}**
  - **Heat source power: 4500 W**
- at lower velocity…
  - Fiber texture off the Y-axis due to a more complicated heat flow, not aligned with the Y-direction
  - Demonstrate the need for systematic 3D analyses



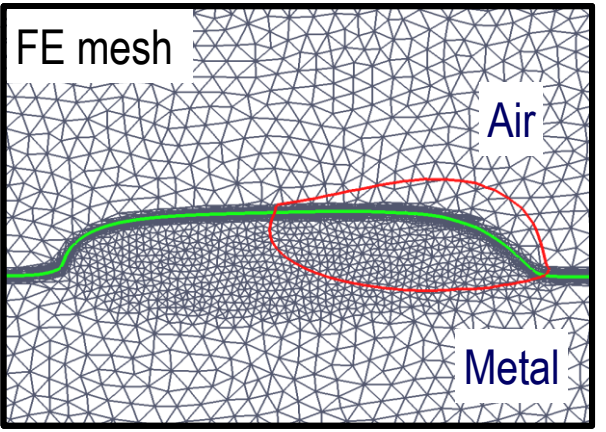
Welding coupon: 350 mm long, 150 mm width, 12 mm thick

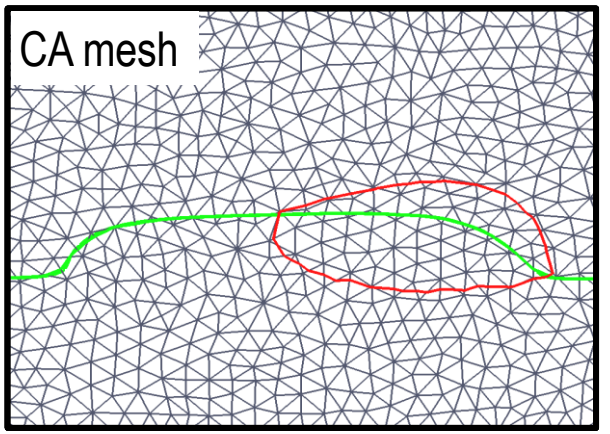


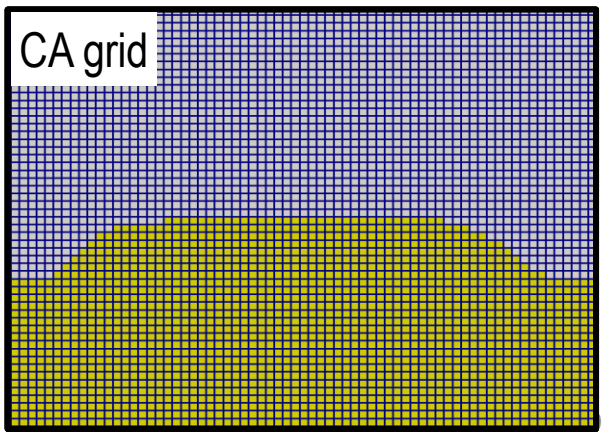
MODEL ADAPTATION FOR MASS ADDITION

METAL-AIR FREE BOUNDARY TRACKING USING A MULTIPLE MESH STRATEGY

- FE mesh
  - *adaptive* tracking of the metal-air boundary
  - computation of the heat and momentum solutions
- CA mesh
  - *fixed* over the CA simulation domain
  - inherits the projected fields computed on the FE mesh
  - Inherits the grain fraction from the CA grid
- CA grid
  - *fixed* lattice of cubic cells overlapping the CA mesh
  - inherit interpolated fields from the CA mesh
  - transition rules for air ↔ metal cell index transitions
  - computation of the grain structure
  - storage of the grain structure







DESMAISON et al., Comp. Mater. Sci. (2014)
Shijia CHEN, PhD thesis, MINES ParisTech (2014)

MODEL ADAPTATION FOR LARGE SYSTEMS

DYNAMIC ALLOCATION/STORAGE OF CELL DATA INFORMATION

- An initial structure is stored on ROM memory for each CA mesh element
  - activation criteria

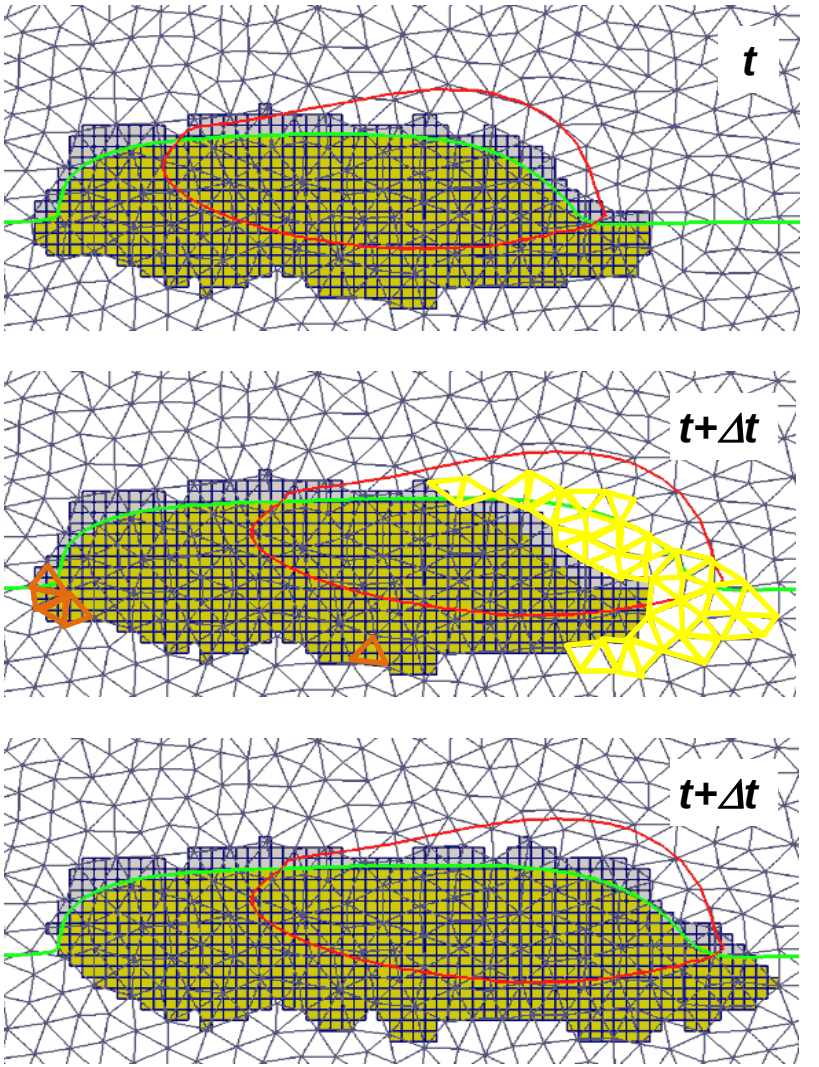
    yellow elements

    $T>T_L$ and cells are in the metal domain
    ➔ read and load data information on RAM memory, delete corresponding ROM memory
  - deactivation criteria

    orange elements

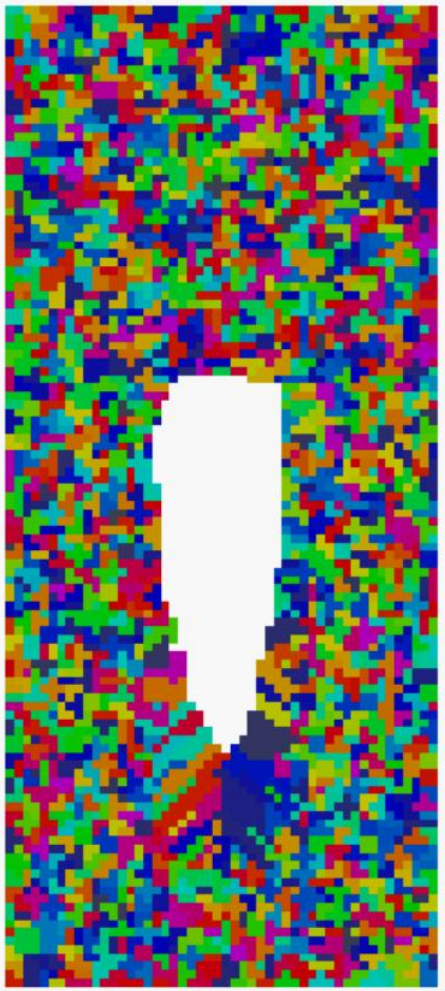
    $T<T_L$ and no mush remain in the element
    ➔ create and write data information on ROM memory, release RAM memory
- Advantages/drawbacks
  - restart and/or multiple passes can be handled from an initial structure
  - billions of cells can be manipulated, thus extending the domain dimensions
  - read/write on ROM memory is less effective
  - large number of files handled (1 for each element of the CA mesh)

CA mesh + CA grid

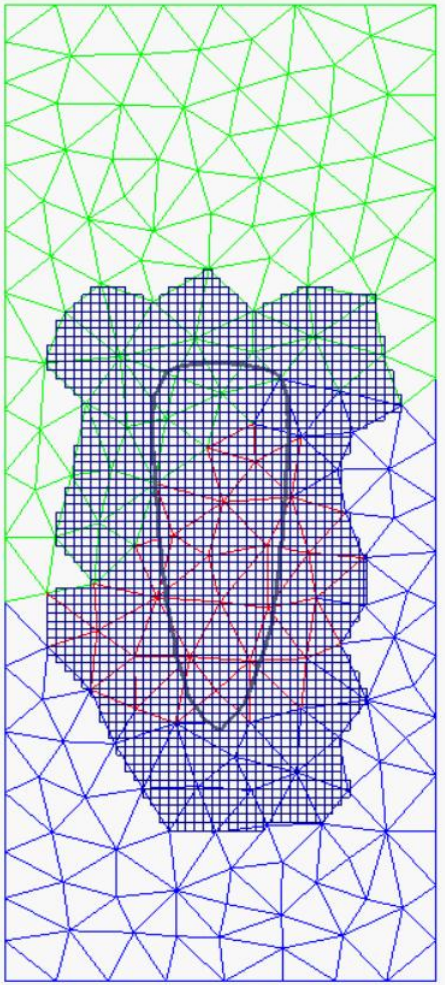


MODEL ADAPTATION FOR LARGE SYSTEMS

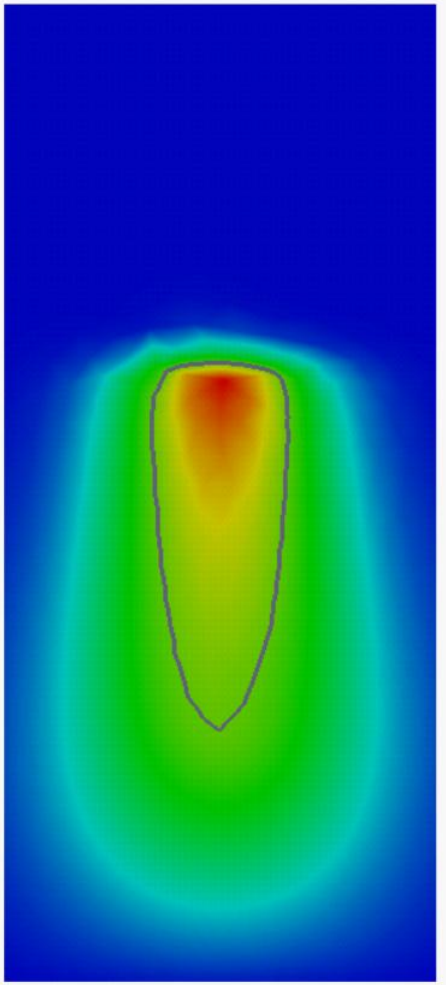
DYNAMIC ALLOCATION/STORAGE OF CELL DATA INFORMATION



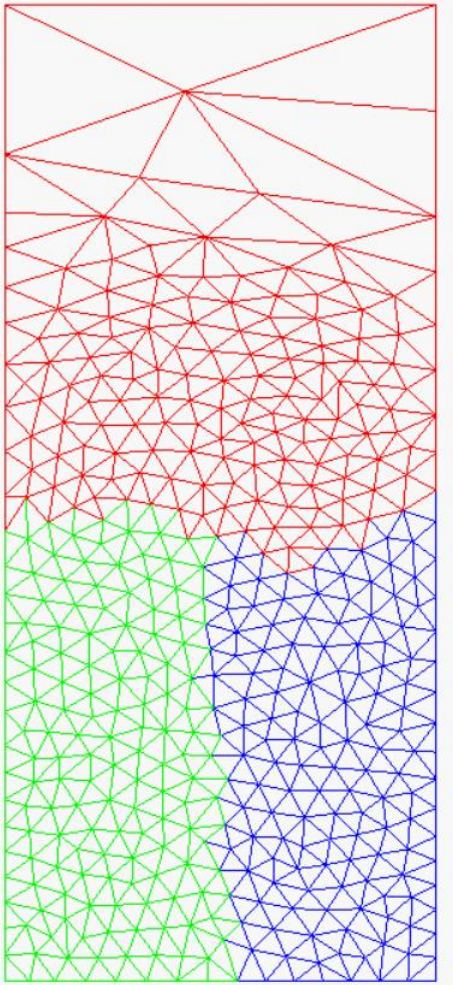
Grain structure



CA mesh & partitioning
Activate CA grid



Temperature field



FE mesh & partitioning

LINEAR MULTIPLE PASSES

COATING ON A DUPLEX STAINLESS STEEL

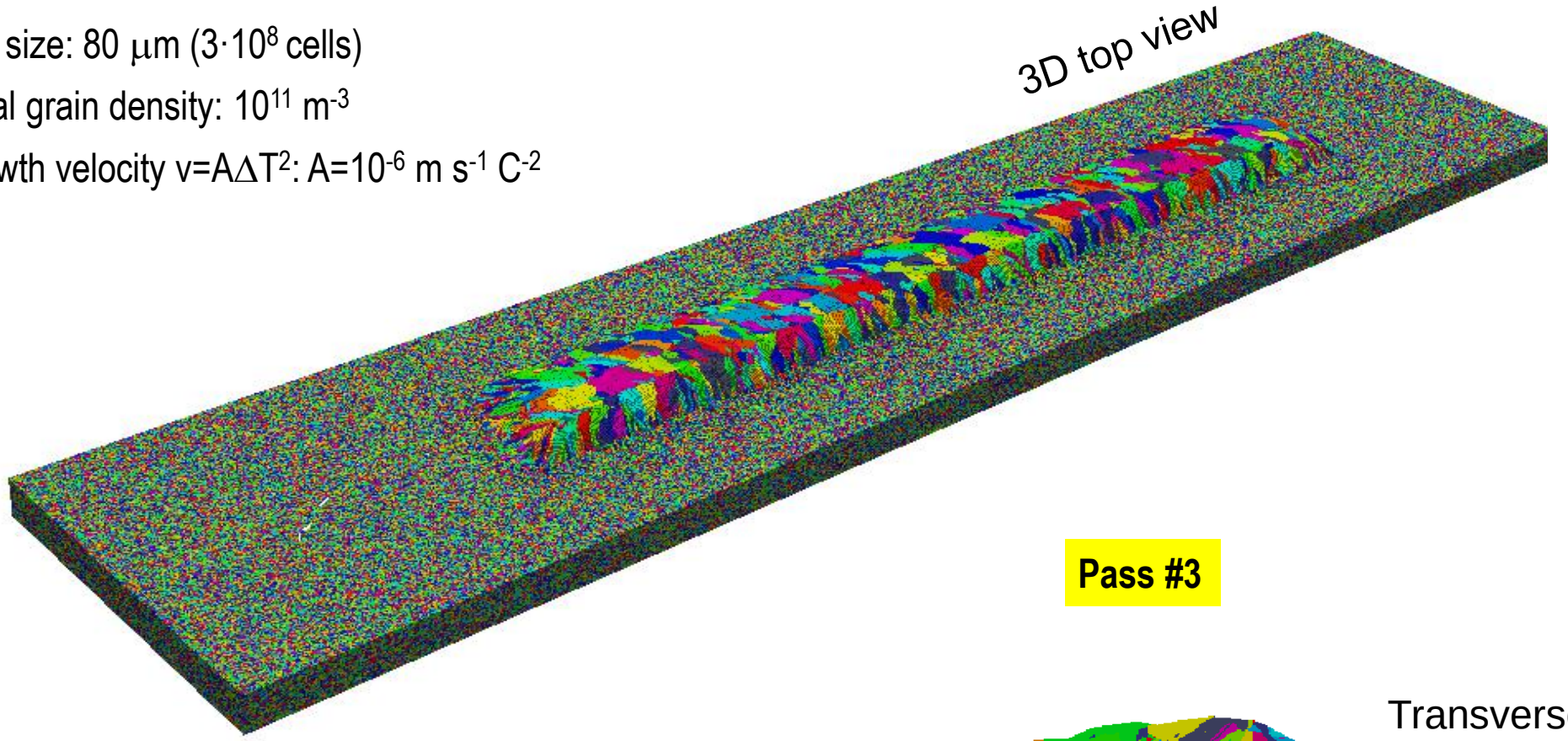
Domain size: $250 \times 50 \times 12$ mm^3

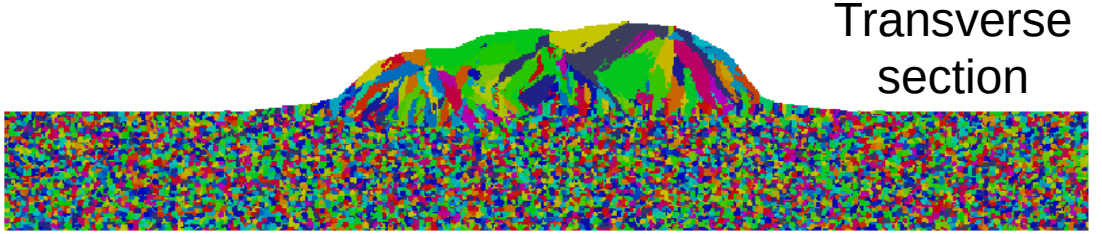
CA mesh size: 3 mm

Cell size: 80 μm ($3 \cdot 10^8$ cells)

Initial grain density: 10^{11} m^{-3}

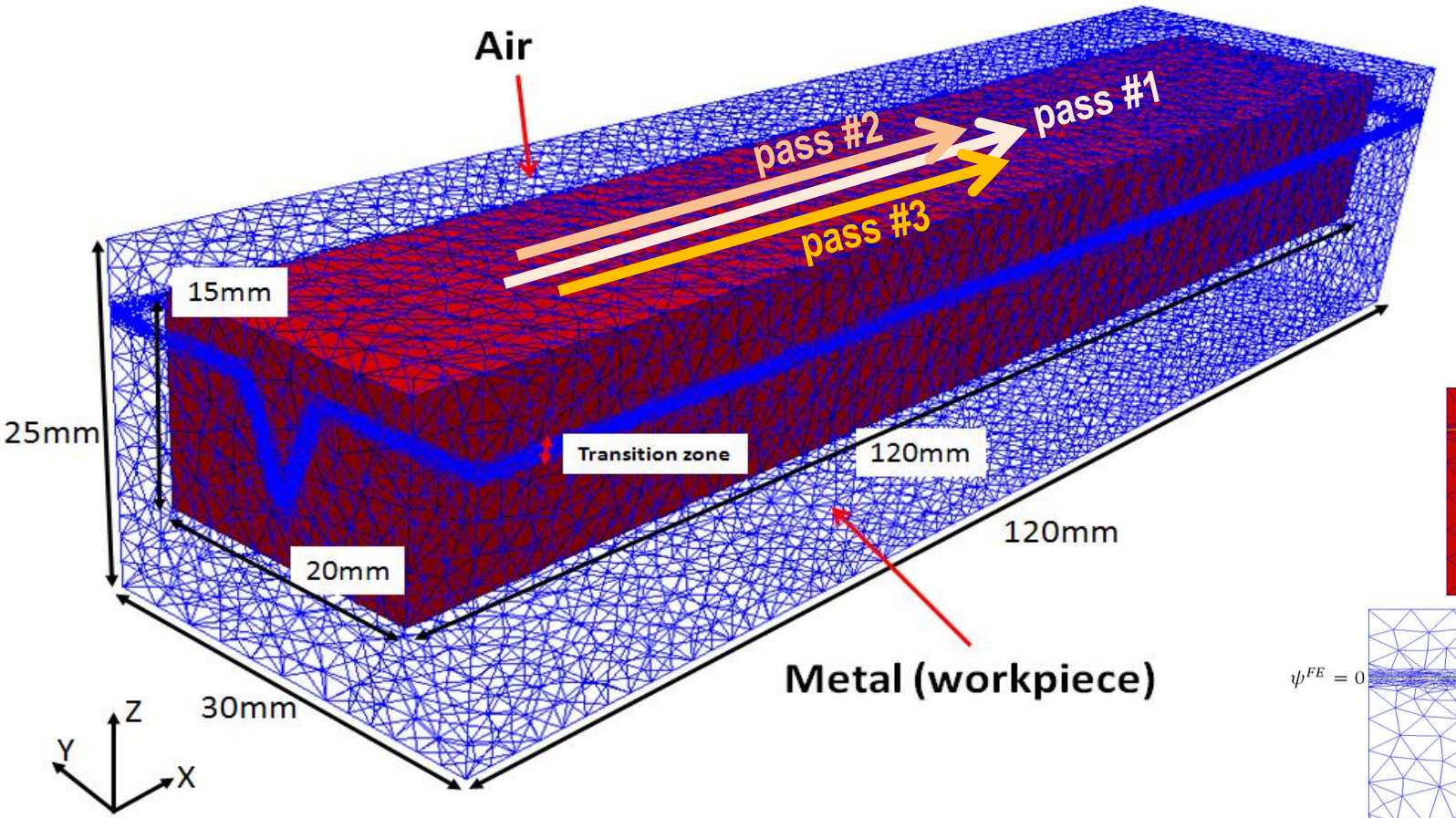
Growth velocity $v = A\Delta T^2$: $A = 10^{-6}$ m s^{-1} C^{-2}

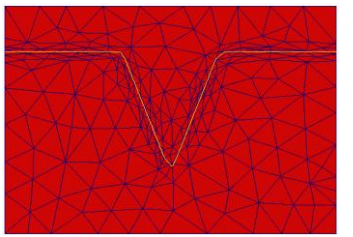


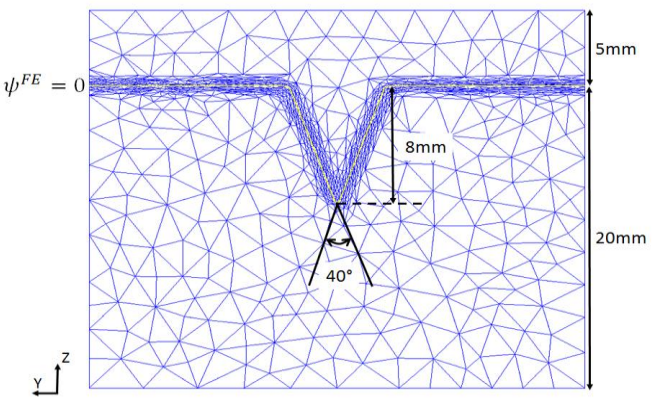


LINEAR MULTIPLE PASSES

GMAW WITH A V-SHAPED CHAMFER





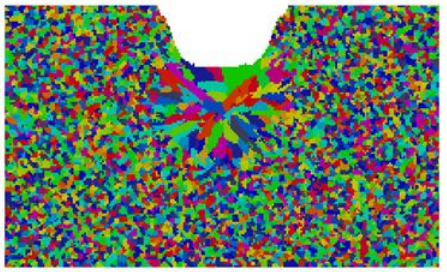


Olivier DESMAISON, PhD, MINES ParisTech, 2013
Shijia CHEN, PhD, MINES ParisTech, 2014

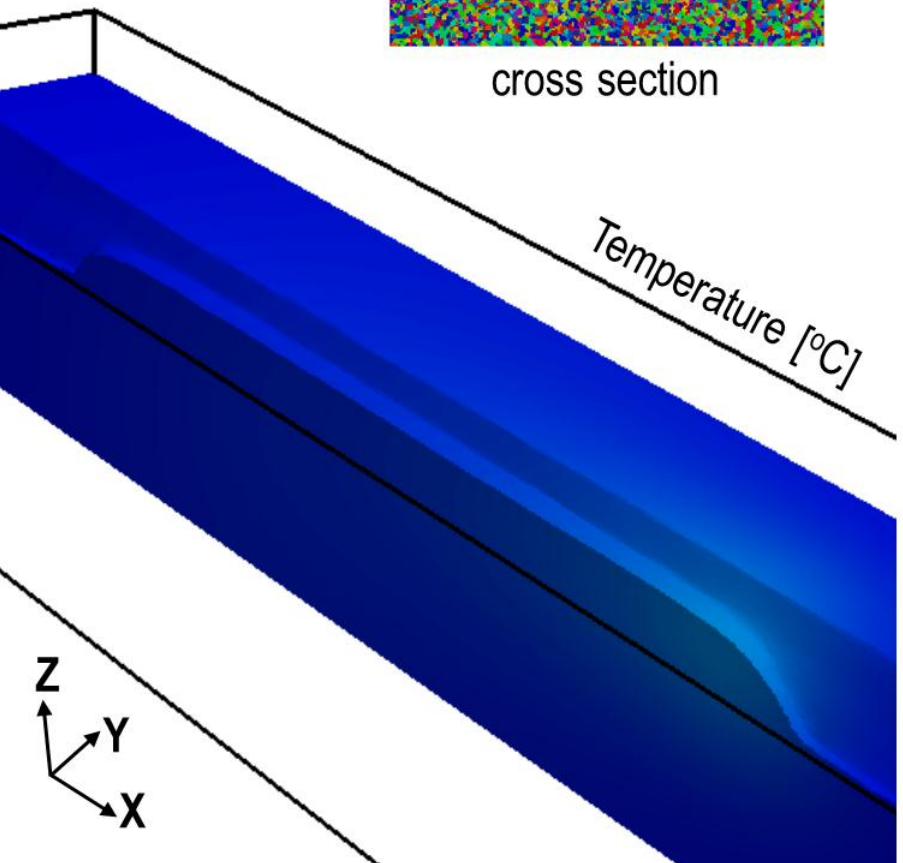
LINEAR MULTIPLE PASSES

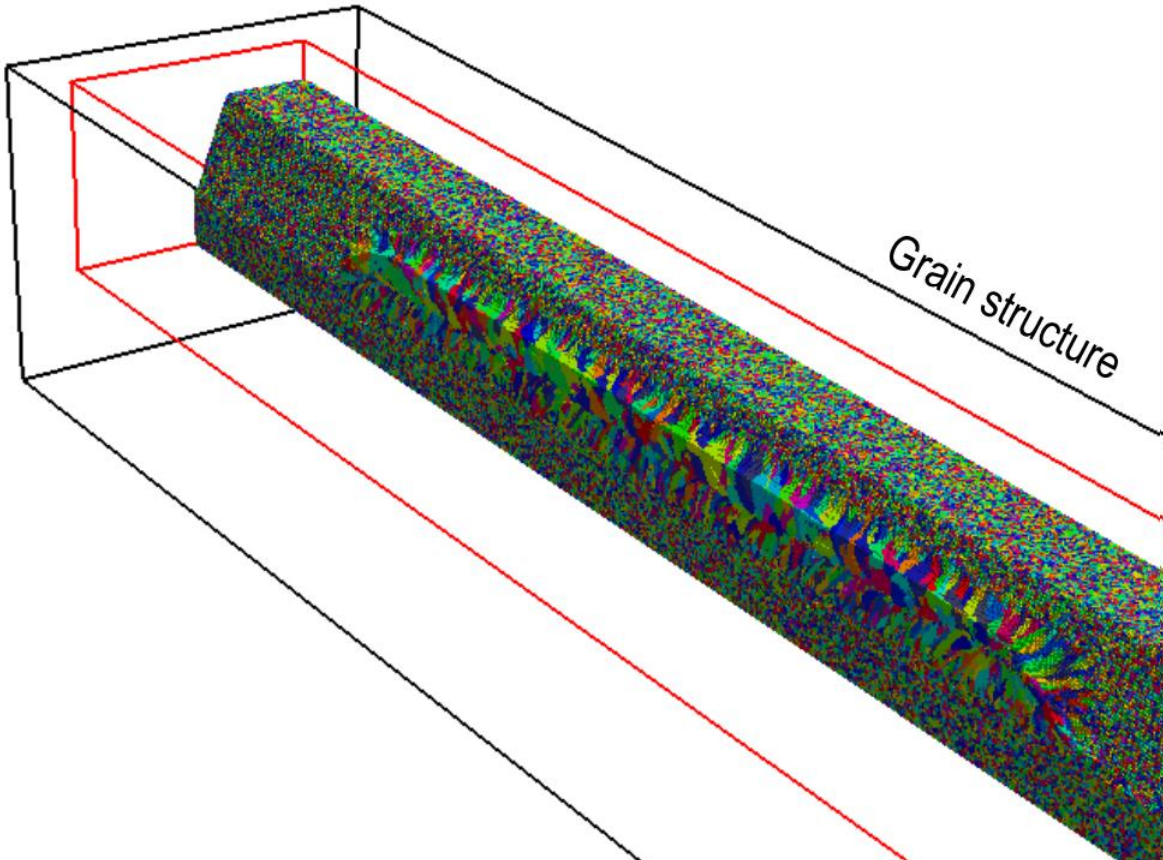
GMAW WITH A V-SHAPED CHAMFER

Pass #1



cross section

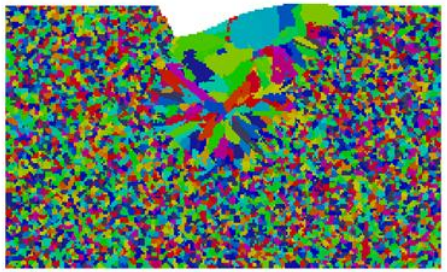




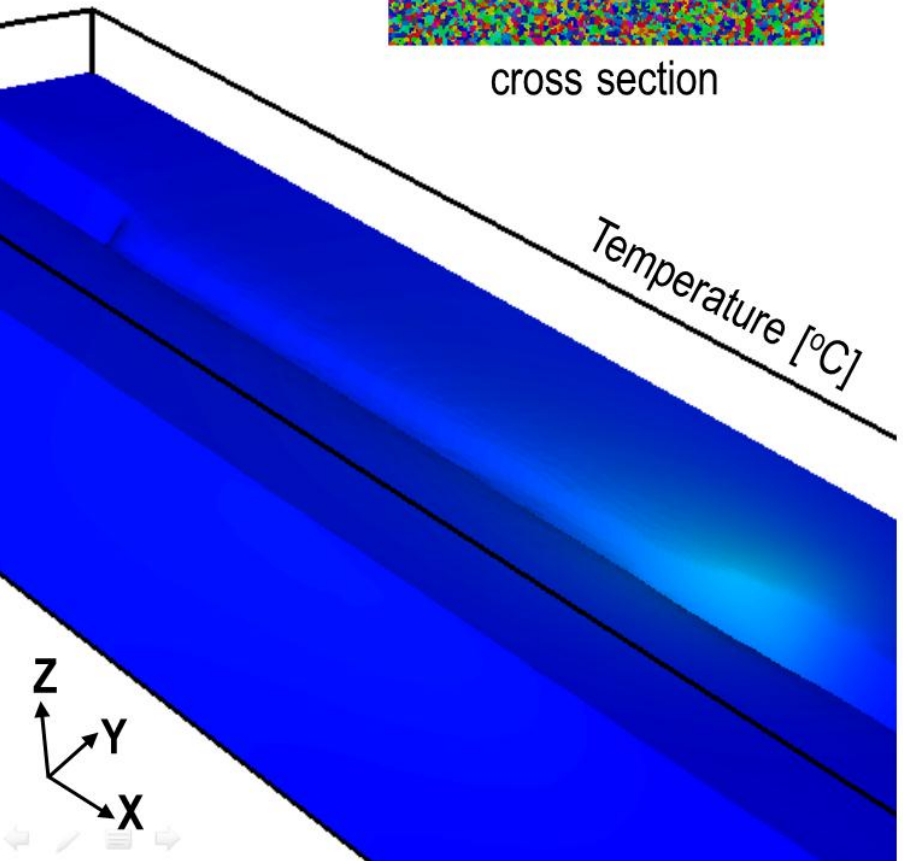
LINEAR MULTIPLE PASSES

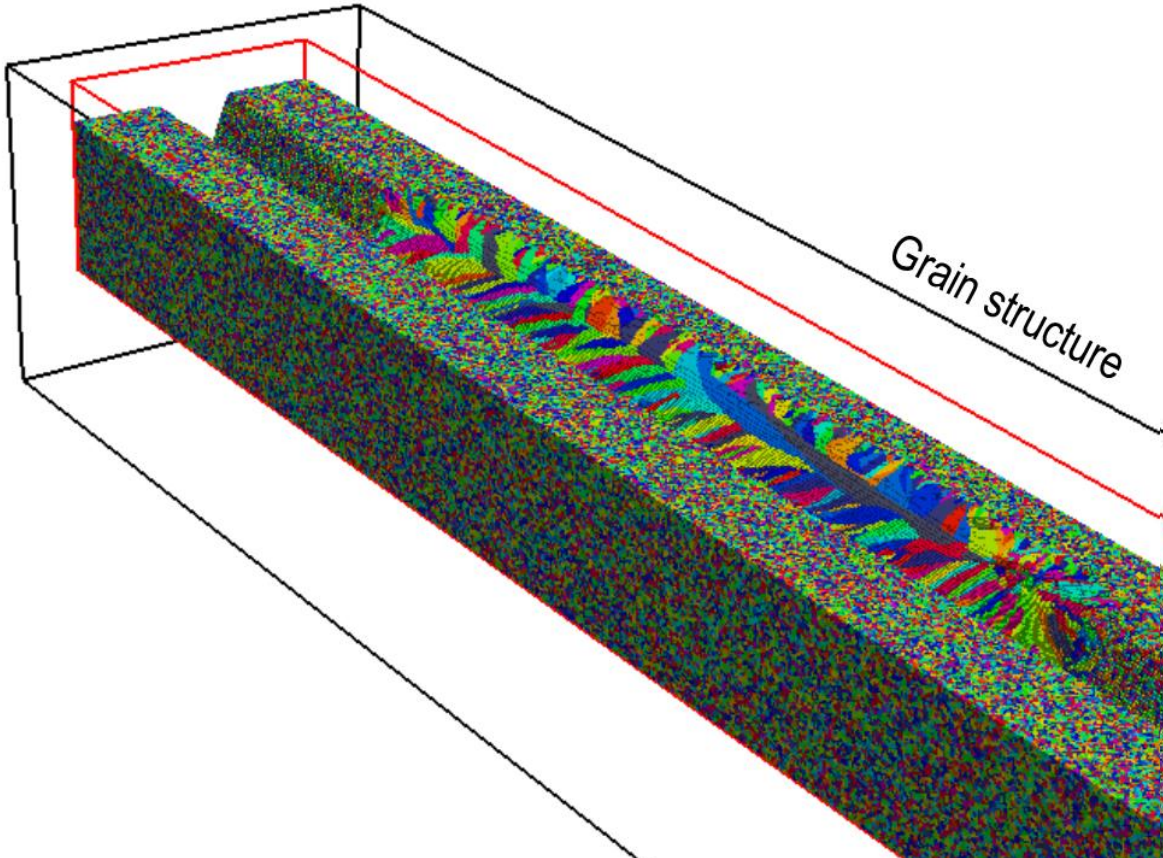
GMAW WITH A V-SHAPED CHAMFER

Pass #2



cross section

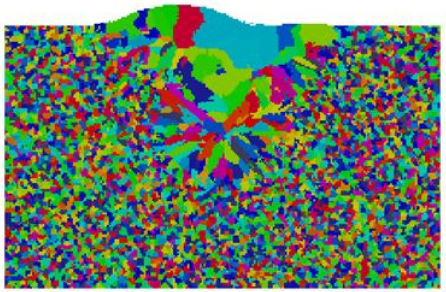




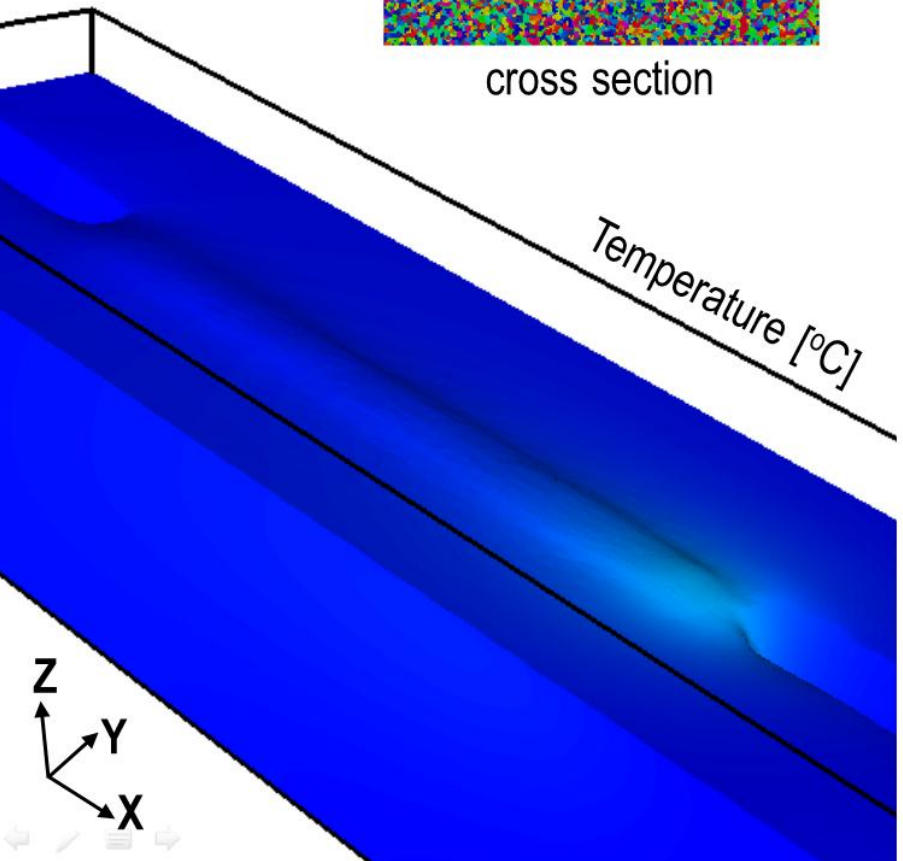
LINEAR MULTIPLE PASSES

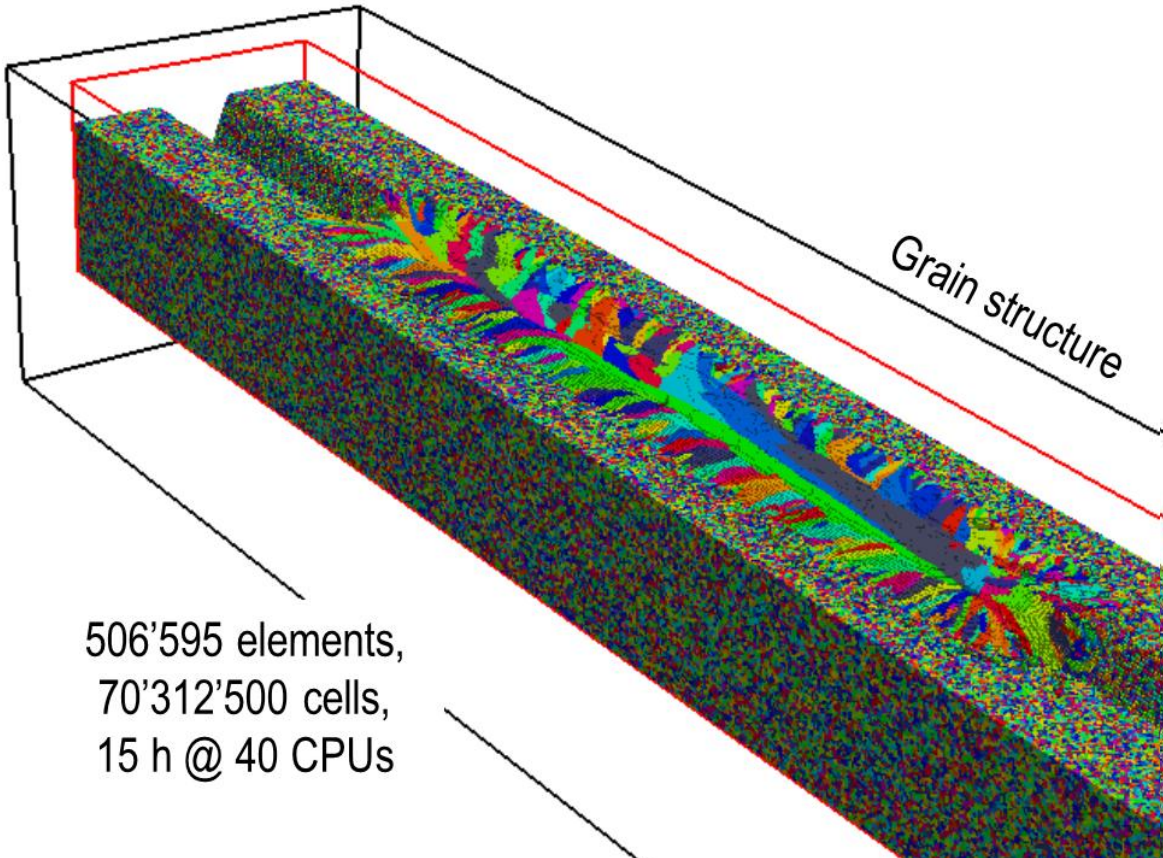
GMAW WITH A V-SHAPED CHAMFER

Pass #3



cross section





506’595 elements,
70’312’500 cells,
15 h @ 40 CPUs

Conclusions & perspectives

Direct macrostructure modeling for welding…

- gives access to the grain structure, its selection during growth, its crystallographic orientation,
- requires dynamic allocation and storage strategies to handle large quantities of information and to perform multipass simulations,
- provides realistic solidification structures when modifying the heat source velocity and power.

Perspectives

- coupling with solute mass balance would permit handling macrosegregation, studies for dissimilar material welding, effect of the filling material, …
- coupling with a grain structure inherited from simulation of a casting process,
- coupling with thermomechanical strains while accounting for the presence of the grain structure to develop a grain boundary dependent hot tearing sensitivity criterion.